Challenges for Future Energy Usage

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December 24, 2009

Accepted for publication in The European Physical Journal, Special Topics

Abstract

In the last 2000 years the world's population and the worldwide total energy consumption have been continuously increasing, at a rate even greater than exponential. By now a situation has been reached in which energy resources are running short, which for a long time have been treated as though they were almost inexhaustible. The ongoing growth of the world's population and a growing hunger for energy in underdeveloped and emerging countries imply that the yearly overall energy consumption will continue to grow, by about 1.6 percent every year so that it would have doubled by 2050. This massive energy consumption has led to and is progressively leading to severe changes in our environment and is threatening a climatic state that, for the last 10 000 years, has been unusually benign. The coincidence of the shortage of conventional energy resources with the hazards of an impending climate change is a dangerous threat to the well-being of all, but is also a challenging opportunity for improvements in our energy usage. On a global scale, conventional methods such as the burning of coal, gas and oil or the use of nuclear fission will still dominate for some time. In their case, the challenge consists in making them more efficient and environmentally benign, and using them only where and when it is unavoidable. Alternative energies must be expanded and economically improved. Among these, promising techniques such as solar thermal and geothermal energy production should be promoted from a shadow existence and further advanced. New technologies, for instance nuclear fusion or transmutation of radioactive nuclear waste, are also quite promising. Finally, a careful analysis of the national and global energy flow systems and intelligent energy management, with emphasis on efficiency, overall-effectiveness and sustainability, will acquire increasing importance. Thereby, economic viability, political and legal issues as well as moral aspects such as fairness to disadvantaged countries or future generations must be taken into account as important constraints.

1 Evolution of the human energy usage and growth of the human population

1.1 Evolution of the energy usage

Man, like every living being, cannot exist without energy, and needs energy for all his activities. Man is composed of renewable material, and for most of his time on this planet – as homo sapiens sapiens for some hundred thousand years – all the energy he used was renewable. The driving forces for getting things done were his muscles, those of other humans, and of animals. His essential energy resources were food, i. e. plants and animals, wood and charcoal; the latter were first used for cooking and heating and later in addition for forging; finally he extracted energy from wind and water. Animals were used for transport on the ground. Energy was scarce (see Table 2) and affordable only by the rich. Slavery was one of the consequences. Slaves were employed in farming, mining, in the construction of buildings and roads, and were used as servants in private homes. Furthermore, they formed the back staff in battles and delivered the drive for battle ships. Buildings that are huge even by modern standards, such as the pyramids in Egypt or the Colosseum in Rome, were built with human muscle power, in the former by citizens and in the latter by prisoners of war.

Unusually benign climatic conditions over the last 10 000 years (see Sect. 2.1.2) have favored the cultural evolution of the mankind, and perhaps just made it possible at all. Before that time the total human population amounted to a few million people only. It grew to about 600 million by 1700 AD, the time immediately before the beginning of industrialization. On the assumption of an exponential growth, this occured with an average annual growth rate of approximately 0.05 percent (see Fig. 2 (b) for present values).

During most of that time, energetically relevant technical means were the use of fire, of the wheel as an energy-saving tool for transport on solid ground and of boats for transport on water, later on a small scale supported by wind and by geothermal heat for hot water. Wood was not only used for heating but was also the most important material for building houses and ships and for making all kinds of tools. Already in the ancient world this led to the first major environmental damages in that large parts of southern countries were deforested. Only in the middle ages did water and wind gain increasing importance as driving means for boats and for mills, which were used for different purposes. Coal was also used, if only to a very limited extent.

In 1712 Thomas Newcomen constructed the first usable coal-fired steam engine for pumping water out of mines, with an efficiency of 0.5 %. James Watt's steam engine raised the efficiency by a factor 4 and was patented in 1769. This was about the time when the use of coal increased dramatically: By 1700 worldwide 3 million tons of coal had been produced, by 1800 it was 13 million and by 1900 about 700 million. Hence coal was the main energy source of the 19th century.

In the last third of the 19th century, electricity very rapidly began its implementation as an easily transportable and universally applicable form of energy. 1866 Werner von Siemens invented the dynamo and triggered the breakthrough of the electric motor invented already in 1834 by Hermann Jacobi. In 1876 Alexander G. Bell invented the telephone, in 1879 Thomas A. Edison invented the light bulb and in 1882 the first electric power station was built in New York. London had its first electrically driven subway in 1890, and about the same time electrically driven automobiles were on their way.

In 1859, Edwin L. Drake was the first to drill for oil, and in 1870 John Rockefeller founded the Standard Oil Company. In 1876 the Otto engine was patented, which had been developed since 1862 by Nikolaus A. Otto. In 1886 Carl Benz constructed the first automobile driven by a combustion engine, and in 1892 Rudolf Diesel invented the Diesel engine. However, at first oil was rather expensive, and its broader use started only after the First World War. The detection of major oil reserves and the breakthrough of the automobile as a dominant means of private and commercial transportation around the middle of the last century assigned to oil, besides coal, a key role in the worldwide energy supply.

Natural gas started being used a long time before oil and electricity. In China it was used for drying salt already in 900 BC. In 1785 Johannes P. Minckeleers constructed the first working gas lamp. In 1812 the first gas company was founded in London by the German merchant Friedrich A. Winzer; the company produced gas and brought it to its customers via pipes. In 1814 the first public gas illumination was installed in London. However, broader usage of natural gas started only about 50 years ago.

Uranium became an important energy source after the Second World War. In 1954 worldwide the first nuclear power station went on line in Obninsk (close to Moscow, Russia), followed in 1956 by Calder Hall (England). The Chernobyl disaster in 1986, and the problems of proliferation and of the permanent disposal of nuclear waste were the reason why nuclear power did not gain the position that was originally intended.

1.2 Evolution of the human population and the per capita energy consumption

Industrialization, very briefly outlined above, triggered an incredibly fast growth of mankind that was even faster than exponential. This can be seen from Table 1, which shows that the doubling time, which would be constant for exponential growth, became shorter and shorter.

Table 1: Doubling times of the world population

Population	Year	Time difference
0.25 billion	1	
		← 1650
0.5 billion	1650	
		← 200
1 billion	1850	
		← 75
2 billion	1925	
		← 40
4 billion	1975	

The worldwide total energy consumption grew even faster than the world population because the average per capita energy consumption increased continuously. Fig. 1 shows the growth of the world's population and energy consumption during the last century.

Two thousand years ago the world population was about 250 million people and in 2006 it was 6.55 billion, [1], i. e. the population grew by a factor of about 26. Two thousand years ago the total energy consumption had an estimated value of about 1.5 EJ and in 2006 it was 491.5 EJ (see Table 6), growth by a factor of 328. On converting into an average energy consumption per capita and per second, this corresponds to a power of 190 W two thousand years ago and of 2380 W today (see Table 2).

The daily energy consumption for food of one person is 2700 kcal (in the industrialized countries 3500 and more, however not always to the benefit of the consumers). This corresponds to an average power supply of 130 W, of which about 75 W are radiated away. The

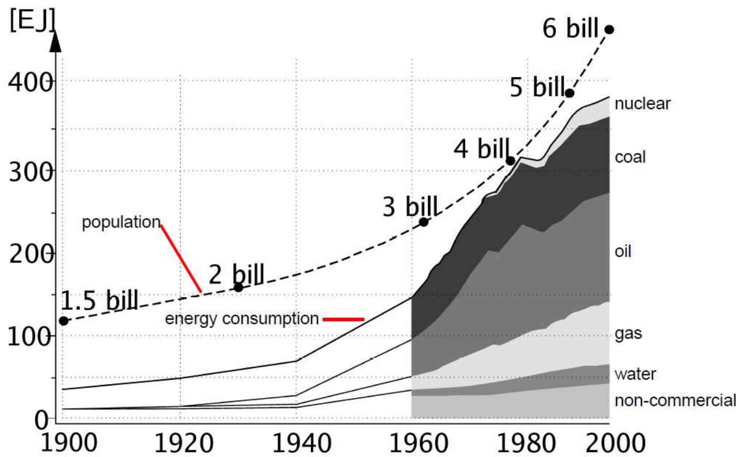


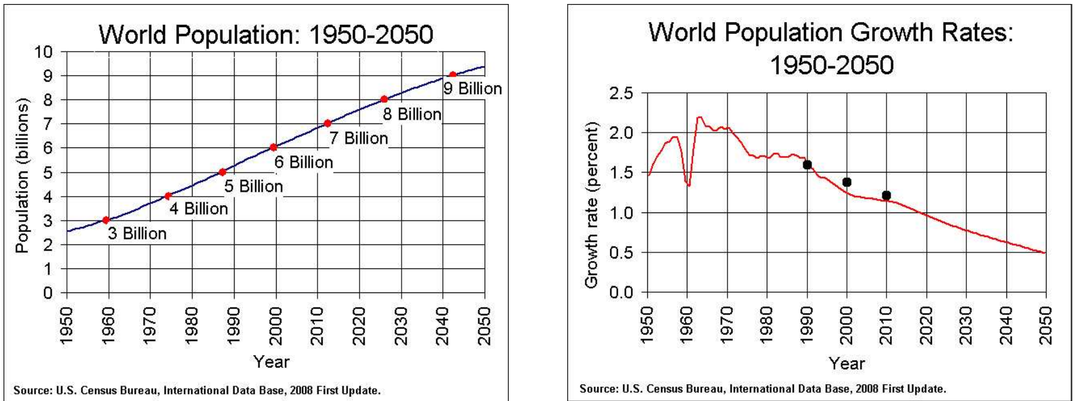
Figure 1: Growth of the world population and energy consumption in the twentieth century. The dashed curve shows the population, the curves below show the energy consumption, broken down into the main energy carriers (figure taken from [2], page 42).

Table 2: Time evolution of the global energy consumption. Z = number of people, E_{ty} = total energy consumption per year, P_{cs} = average energy consumption per capita and per second.

Year	Z	E_{ty}/EJ	P_{cs}/W
1	250 million	1.5	190
1650	500 million	10	635
2006	6.55 billion	491.5	2380

total power supply of 190 W in ancient times was only little above this lower limit. Today, this minimum consumption is exceeded by a factor of about 18.

The world population is still growing. Fig. 2 (a) indicates the evolution during the last 60 years and gives an estimate of future developments. Even more illuminating is a look at the development of the growth rate (Fig. 2 (b)). Between 1950 and 1990, on the average, the growth rate remained constant, which indicates still exponential growth. In 1990 one can see an almost abrupt transition to linear growth. (The dots indicate exact linear growth.) Even with this dramatically reduced growth, the population will reach 9 billion around 2045 and will continue to grow thereafter. The maximum of the world population is likely to be above this number, expectations ranging to values as high as $10 - 11$ billion. It is foreseeable that the per capita energy consumption will also continue to increase. This should by all means be prevented from happening in industrialized countries. With respect to underdeveloped or emerging regions of the world, the situation is quite different. There is a strong counter-correlation between economic welfare and growth of the population. In these regions, an explosive growth of the population can only be avoided or stopped by a greater share in prosperity, besides the fact that their well-being is also a question of fairness (see Table 3).



(a) (b)

Figure 2: (a) Time evolution of the world population during the last 60 years and an estimate of future developments. (b) Time evolution of the corresponding growth rate. The dots indicate a linear growth starting in 1990.

Table 3: Regional differences in power usage per capita

Region	USA	Germany	China	Africa
[W]	10 000	5 100	1 500	385 (170 without South Africa)

2 Our present situation

2.1 Running short of conventional energy resources, and environmental hazards – the big problems of present energy usage

2.1.1 Running short of the conventional energy resources

A huge problem posed by our energy resources is that they are becoming scarce. A total of 81 percent of the 491.5 EJ energy consumption in the year 2006 derived from the combustion of fossil fuels (see [3]). In one year mankind consumes as much fossil fuel as nature has built several hundred million years ago in a time span of several million years.

Apart from fact that at present in developed countries food supply is plentiful and slavery has been abandoned because of the replacement of muscle power by machine power (much more than due to moral aspects), one of the greatest advantages of the technical development of our world is the gain in mobility provided by cars, trains, ships and air planes. It almost completely relies on our supply of oil, whose shortage can be foreseen most clearly.

Peak oil problem and the supply of oil

At present, fuels derived from crude oil are effectively the only propellants for the approximately 600 million automobiles on earth, a number that is rapidly increasing and is expected to lie between 1.4 and 2.7 billion in 2050, [4]. Large amounts of petroleum are also being burned in power plants and private homes for the production of electricity and heat. The per capita consumption of oil shows large regional differences, as can be seen from Table 4.

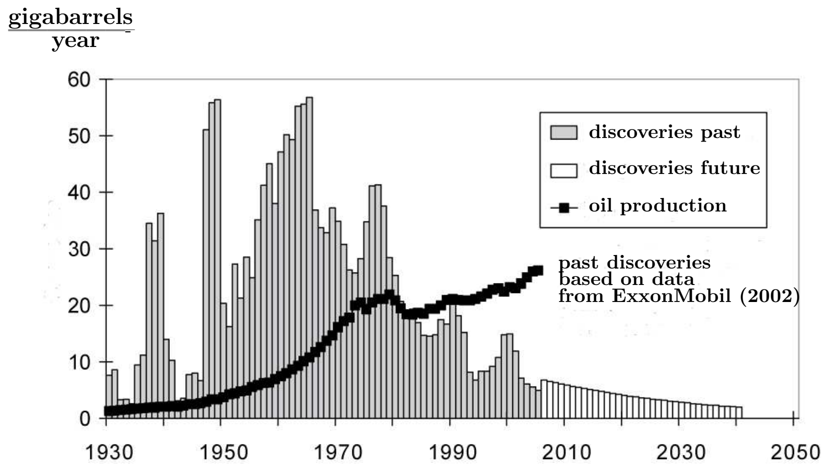


Figure 3: Annual oil production and oil discoveries since 1930. Since 1982 the production exceeds the discoveries.

Until 1965 more oil was found than produced, and people believed that this would continue. However, in 1966 up until now there was a sharp decline in the yearly oil findings while the worldwide oil consumption continuously increased, with the exception of short interruptions, especially after 1980 (Fig. 3). Until 1982 the yearly findings were still above the yearly production, but since then the situation was reversed.

Table 4: Regional differences in annual per capita oil consumption (2003)

Region	USA	Germany	China	India
Barrels	26	11.7	1.7	0.8

In 1956, the American geoscientist M. K. Hubbert presented the following theory about the time evolution of oil production rates [5]. In the course of time the production rate of an oil field will typically follow a symmetrical bell-shaped curve, which is given by the derivative of a logistic curve supposed to describe the lifetime production of the field (Fig. 4). Oil production starts slowly and rises faster and faster as more and more wells are drilled and ever better facilities are installed. It finally reaches a maximum that cannot be exceeded even by further enhancement of all efforts. At this point, about 50 percent of the field's reserves are exploited. After reaching this so-called depletion-mid-point, the production rate goes down inversely as it went up. It comes to an end when more energy is needed to extract, transport and process one barrel of oil than the latter contains. This happens long before the oil field is exhausted, at an exploitation rate that is 35 % at present, [6]. Hubbert‘s theory allows one to calculate future production rates of an oil field from those achieved in the past, at least approximately.

According to Hubbert, the summation over all oil fields of a country as well as the summation over all oil producing countries in the world will lead to a curve of the same kind. Peak oil is defined as the point in time when the global oil production reaches its maximum and is about to start its terminal decline.

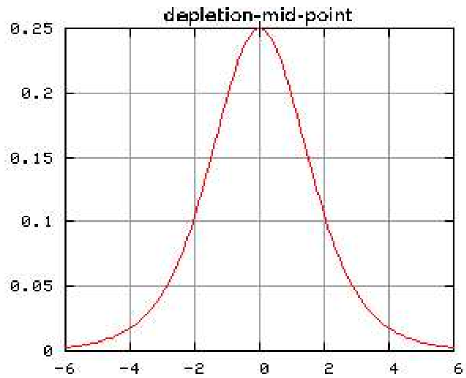


Figure 4: Hubbert curve

Hubbert‘s theory was considered a big success in that it correctly predicted the time of peak oil production in the USA. There are still other countries like Norway for which the oil production rate is very well represented by a Hubbert curve even beyond the depletion-mid-point. However, the rate of US oil production in the last years was considerably underestimated; in many cases the central peak was sharper than predicted, and a glance at Fig. 5 shows that in other cases the central peak is replaced by an undulating plateau. This means that for quantitative purposes Hubbert‘s theory is not fully reliable. The reason why it has proved to be useful only in special cases and cannot claim general validity is the following. Hubbert‘s theory presumes that basically all existing resources are already known. Furthermore, it is a static theory that does not account for technical progress in the exploitation of deposits already deployed, and in the opening of so far unexploited ones. Finally, the important influence of changing, and especially rising, energy prices is not taken into account. In consequence, predictions derived from Hubbert‘s theory about the future availability of oil and about the date of global peak oil production have become subject to harsh criticism, [6]. Nevertheless, for oil it is still the best theory available, especially when the production rate for a set of oil fields is calculated by superimposing the Hubbert curves for single fields.

It is believed that reaching peak oil will trigger an energy crisis because the availability of mineral oil will drop, and prices will rise, by international financial speculations even driven at an inadequate rate. Predictions based on Hubbert’s model place the time of world oil peaking into a time interval between 2005 and 2020. Peak oil has already been reached locally in several regions of the world. In 33 of the 48 largest oil producing countries the oil production is already in decline. Peak oil production occurred in 1967 in Germany, in 1971 in the USA and in 2004 even worldwide when OPEC and the former Soviet Union are excluded (Fig. 5). It has not yet occurred in Iraq, Kuwait and Saudi Arabia. Because of several uncertainties including the merely approximative character of Hubbert‘s theory as well as the intentional presentation of false data directed by commercial interests, the peaking of world oil production cannot precisely be predicted but only established in retrospect. The dramatic rise of oil prices since 2000 (Fig. 7 (b)) may be an indication that we are gradually approaching peak oil. In the middle of the year 2008 a sharp price peak of over 145 US-$/barrel was reached, the reasons remaining unclear. By some, approaching peak

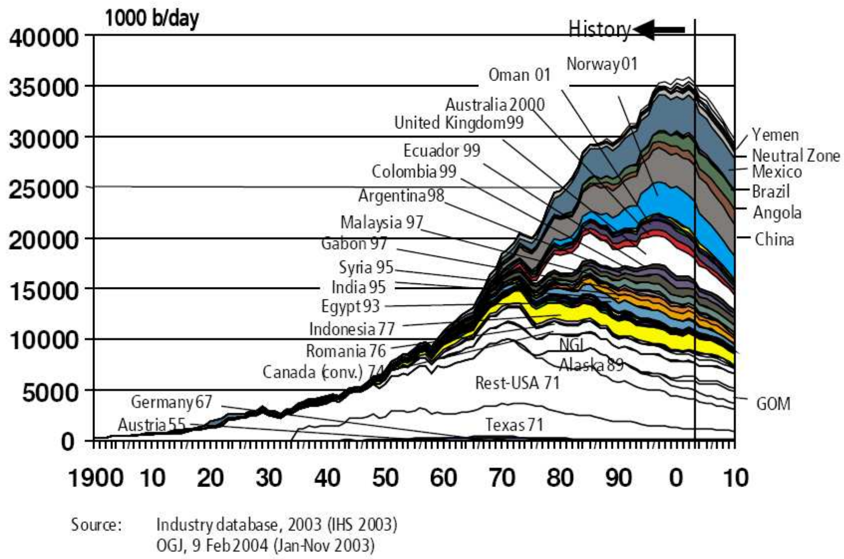


Figure 5: Oil production rate of different countries as a function of time

oil was held responsible; other causes invoked were growing demand, an artificial tightening of supply by OPEC, inflation of costs for equipment and staff, political instability in regions of exploitation, and, not least, a speculation bubble. The sharp decline of oil prices that occurred immediately after the peak was a consequence of the financial and economical crisis of that year and, unfortunately, is sure to be only transient.

In these considerations the dramatic growth of the world population is not even taken into account. If the worldwide annual oil production rates are divided by the total number of people in the world, one obtains the per capita oil production rates, and for them the peak has already occurred years ago in 1980 (Fig. 6). Since the annual growth rate of oil consumers is even larger than that of people, the consumer specific annual oil production rate had its peak still earlier.

Clearly, not all oil fields have been discovered, and with rising oil price other (non-conventional) oil sources like tar sands or oil shale become of economical interest. However, one cannot expect that very large reserves are still hidden. During the last decades exploration techniques have been considerably improved, especially due to observations from satellites, important progress in optical systems and advances in seismology (Ultra High Resolution 3D Seismic), and finally by the employment of computers in data analysis. Furthermore, oil production techniques have been refined so that much more oil is now obtained from an oil field than in the past, 35% in 2004 compared with 22% in 1980 (see [6]). However, these means of improvement are already largely exhausted, and for further progress efforts must appreciably be increased.

According to a statistical review by the oil company BP (British Petroleum), [7], the worldwide oil reserves considered to be recoverable with reasonable certainty were 1238 Gb (Gb=gigabarrel) by the end of 2007. Divided by the annual production rate of 29.8 Gb per

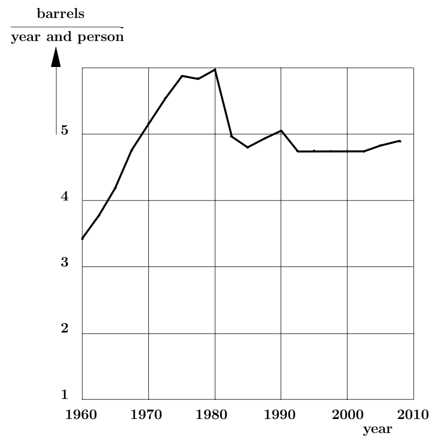


Figure 6: Time evolution of the worldwide per capita oil production rate since 1960

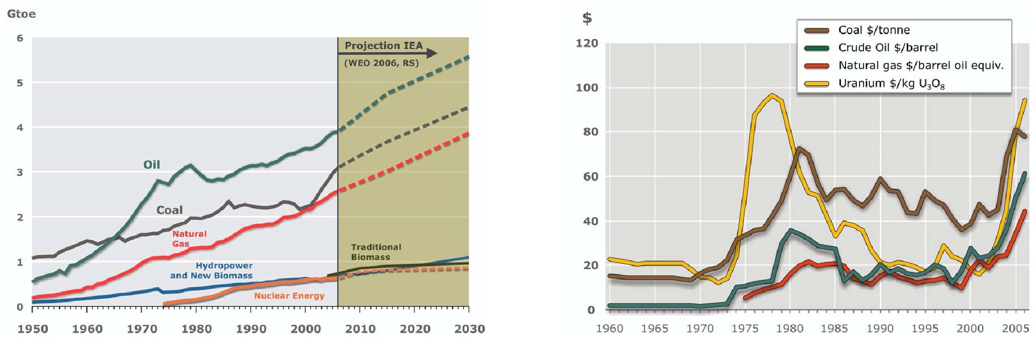
year in 2007, this number yields a projected reserve lifetime of 41.5 years from 2007 or 40.5 years from now until all oil reserves are depleted. Taking into account the still rising demand for oil and oil products, some expect the drying up of all oil sources already in 22 years from now. Further technical progress in the recovery and the refining of non-conventional oil resources supported by increasing energy prices, as well as a gradual transition to non-conventional oil may shift the end of the oil era somewhat into the future. It would be unwise, however, to rely on this.

Crude oil consists of about 17 000 chemical constituents. Only about 7 percent of oil production is not burned but used as raw material for many chemical products such as pharmaceuticals, solvents, fertilizers, pesticides, paints and coatings, detergents, plastics and so on. Without oil it will become much harder, more expensive and much more energy consuming to produce the same products, and for some of them an oil-substitute is not even available. In view of this, it is a shame that we have nothing better to do than just burn this rare and valuable natural resource. *To find a substitute for oil used as a fuel or heating material appears to be a predominant and urgent challenge for the years to come.*

Supply of coal, gas and uranium

Frequently, albeit less successfully, Hubbert‘s theory is also applied to other commodities whose deposits, like those of oil, are known to be finite, especially to coal, gas and uranium, or to industrial minerals and metals. As with oil, the production will first start slowly and then grow ever faster with increasing equipment and rising effort. And just for logical reasons, the production rate of any finite commodity must have a maximum (peak). Nevertheless, oil is the only commodity to which Hubbert‘s theory can be applied with some reliability, because only for oil basically all existing deposits are already known (see below). For other commodities the time of peak production cannot be reasonably predicted.

The total resources of a commodity, ingredients of which are irreversibly used up by its consumption (like exergy in the case of non-renewable energy carriers), are composed of three shares: 1. reserves comprising the part which can economically be extracted, 2. resources comprising the part which, with considerable certainty, is known to exist but is not economically extractable with present technology, and 3. potential resources (also called geopotential) that are not yet known but can be expected to exist by geophysical reasoning



(a) (b)

Figure 7: (a) Development of primary energy consumption worldwide and projections of IEA until 2030 (sources: BP and IEA, 2006a), (b) Development of nominal fuel prices from 1960 to 2006 (annual averages). (Figures taken from Ref. [9].)

and can be discovered with modern exploration techniques. (For commodities that are not subject to irreversible transformations during their consumption like many industrial metals, there is a fourth resource: recycling of used material, building the so-called technosphere. This aspect is mentioned for use in Sect. 4.) The sum of reserves and resources is called remaining potential or total resources.

The boundaries between the different shares are not fixed, but change in time. Progress in technology, rising prices and political influences will transform known resources into reserves, and active exploration as well as progress in exploration techniques will shift the boundary between known and potential reserves.

For the present availability of a commodity, the quantity of reserves is the relevant figure. It has become usual to characterize it by a relative measure, the so-called "life index" or "lifetime", defined by the ratio of reserves to production rate. It indicates how long the present reserves would last when year for year they would be produced at the same rate. However, since both the reserves and the production rate are dynamical quantities, their ratio will change in time, too. For many commodities it nevertheless remained constant or actually grew even at rising production rate because the reserves grew even faster. In general it is therefore impossible to conclude from the life index how long a commodity will finally last. An estimate of the total remaining lifetime is only possible when besides the reserves, the production rate and an estimate for the time evolution of the latter, all resources including the potential ones are known.

At present the only commodity for which this is possible is oil, for the following reasons [8]: 1. For oil deposits there exists a depth limitation, the so-called "oil window" that extends from 1500m to 3000m. 2. Horizontally, the large sedimentary basins in which oil was able to build are essentially known. 3. A large fraction of all oil reserves is contained in a few giant, super- and mega-giant oil fields, and it is extremely unlikely that more fields of this kind have so far remained undetected. On the other hand, the contribution from medium sized and small fields, more of which may still be discovered, will only marginally influence the total balance.

On average, the consumption of a commodity equals its production because differences between them show up in an accumulation or reduction of stocks and balance out over economic cycles. During the last decades the consumption of all primary energies has dramatically increased (Fig. 7 (a)). The exceptionally fast rise of coal consumption since 2002 is due to China. Since 2004 a dramatic increase in prices took place as well (Fig. 7 (b)), which at least in part is because supply could not keep up with demand.

Table 5 shows the reserves, resources (sum of known and potential ones), production and life indexes for the non-renewable primary energy carriers in the year 2007. In the first line the energy equivalent for the sum of all is represented. The lines below show the percentage shares of the different carriers. The life indexes for conventional oil and gas were calculated by neglecting unconventional contributions. In comparison with the numbers for the year 2006, the sum of all resources has increased by 48%. This is due to the inclusion of coal reserves in the USA (especially Alaska), which have so far been disregarded.

Table 5: Reserves, resources, production and life index for non-renewable primary energy carriers in the year 2007. All numbers are taken from Ref.[9]. Due to roundoff errors the sum of the percentages can slightly deviate from 100 %.

Energy carrier	Reserves	Resources	Production	Life index
total	39 105 EJ	504 161 EJ	440	89 y
Oil (conventional)	17,5%	0,7%	36,6%	43 y
Oil (unconvent.)	7%	2,1%		
Natural gas (conventional)	17,8%	1,3%	25,5%	62 y
Natural gas (unconvent.)	0,1%	9,9%		
Coal	53.3%	84,5%	32,7%	145 y
Uranium	1,9%	1,3%	5,7%	30 y
Thorium	2,2%	0,2%		

Roughly speaking, coal can be classified into hard coal and soft brown coal (lignite), where, with respect to energy content, the ratio is 15 : 1 for consumption, 5.5 : 1 for reserves and 7.4 : 1 for resources. Because of its relatively low energy and high water content, soft brown coal is brought to conversion into electricity close to where it is exploited; transport and trading are profitable only for hard coal. Differently from oil and natural gas deposits of coal are not concentrated in only a few countries, which in general makes coal much more easily available. In addition, coal has the highest potential. In the reserves its share is 53.3% and in the resources it is even 84.5 % (see Table 5). A look at the life index of the reserves (145 years) shows that coal will be available for many more decades, and for the present life index of the total resources a value as high as 3100 years is obtained.

From 1985 to 2002 the consumption of coal was stagnant. Since then it has dramatically increased (Fig. 7 (a)), which is mainly due to a rapidly rising demand in Asiatic countries. This has led to a corresponding increase in prices, subsequently inducing a marked expansion in exploration activities. It may be expected that as a consequence the already huge total resources will increase still further. Since coal is relatively easily recoverable, easy to transport and cheaper than oil and gas, it can be expected that worldwide it will gain an increasing role within the next decades.

Natural gas is the third most important of all primary energy carriers. During the past years, its consumption showed especially high growth rates. With respect to energy content, according to Table 5 its remaining potential is 44% higher than that of conventional oil. Its life index indicates that it will last well beyond the middle of this century if the consumption rate remains constant. Rapid development of the conventional and, with advancing technology, unconventional resources allow us to expect that this will remain true even at increasing consumptions. An increasing production of synthetic fuels from natural gas could slightly reduce the actual lifetime.

Worldwide, the enthusiasm for nuclear power has cooled down, and in consequence the exploration of uranium has stagnated for many years. Furthermore, the exploitation of uranium was confined to very few companies. Therefore, when required a marked increase of reserves and resources can be envisaged. In distinction from all other non-renewable energy carriers, for uranium the production is lower than the consumption, amounting to only one-half up to two-thirds of the latter. This deficit is compensated by uranium stock levels formerly compiled for civilian and military purposes, especially in Russia and the USA. For future consumption it may become possible to draw on uranium from disarmed nuclear weapons or reprocessed fuel assemblies.

In 2008 worldwide there existed 438 nuclear power stations. Within the next decades this number is likely to grow, and by 2050 it may even have doubled (see section 2.3). The consumption rate of uranium must not simultaneously increase because future nuclear reactors will make much better use of the nuclear fuel (see section 3.3.1). Therefore, assuming an unchanged consumption rate, it can be concluded from the life index of uranium given in Table 5 that uranium reserves will last for several decades. Resources with a present life index of 262 years will last for several centuries if uranium consumption remains at the same level as today.

Thorium is contained in Table 5 because it is provided for as the fuel of a new type of fission reactor, which for several reasons is considered as a promising alternative to reactors burning uranium (see section 3.3.1). For our present energy supply, it has no relevance.

Considering all non-renewable energy carriers as a whole, their present life indexes of 89 years for the reserves and 1235 years for the remaining potential indicate that they will be available for many more decades, only that a substitute for oil must be found rather soon. However, for all of them a better use than merely burning them would be more appropriate. As outlined in the next section threatening climate changes enforce a reduction in our corresponding consumption habits all the more. That a rearrangement in our lifestyle will take some time must thereby be accepted.

2.1.2 Environmental problems caused by conventional energy sources

Our use of conventional energies is the cause of much ecological damage, including

- pollution, erosion, contamination and flooding of soils,
- pollution and contamination of waters,
- local and global pollution and contamination of the atmosphere with consequential damage to fauna and flora,
- environmental burdens through the release of heat,
- local and global climate changes, especially due to the man-made enhancement of the greenhouse effect.

Special attention is now drawn to already observed climate changes and even more to climate changes that are expected. Since 1850 the concentration of methane has doubled in our atmosphere, and that of CO_2 has increased by 35 percent, from about 280 ppm to 384 ppm. At least during the last 650 thousand years, the atmospheric CO_2 concentration

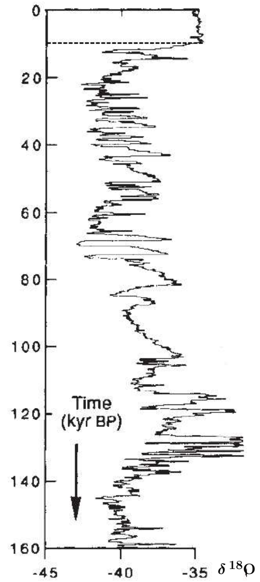


Figure 8: Variations of the stable oxygen isotope ^{18}O in Greenland during the last 160 thousand years, concluded from the GRIP (Greenland Ice-core Project) ice core from Summit, central Greenland. ^{18}O is a well established climate indicator, strongly depending on the air temperature in the northern hemisphere. Its variations are also linked to atmospheric circulation changes. The figure clearly shows that during the last 10 thousand years (above the dashed line) the climatic conditions were extremely stable (figure taken from [10]).

has never been as high as it is today (see Fig. 136 on page 300 of Ref. [11]), although in the Earth's climate history appreciable fluctuations of comparable size have occurred, essentially driven by temperature fluctuations during and between the different ice ages. However, these fluctuations oscillated about an average value appreciably below the pre-industrial value of about 280 ppm and exceeded this value only marginally in their maximum. In consequence there is no doubt that the increase in greenhouse gases since 1850 is essentially man-made. During the last century, the average temperature of the Earth's lower atmosphere increased by 0.7 ^{0}C, and the average sea level rose by 17 cm (uncertainty $\pm$5 cm) (see page 310 of Ref. [11]). According to the IPCC, [12], with a probability of more than 90% most of this is due to the observed increase in greenhouse gases. Consequences are that deserts are expanding, vegetation zones are shifting, and animal and plant species are dying out or forced to resettle. Since 1950 the damage worldwide caused by extreme weather conditions has increased by a factor of ten, and extremely hot years have cumulated in the immediate past. Based on six IPCC-scenarios with more or less pessimistic assumptions about greenhouse gas emissions and derived from 23 different elaborate computer simulations, projections for the next 100 years see a temperature rise between 1.1 ^{0}C and 6.4 ^{0}C (variances between the different computer simulations being taken into account), accompanied by a rise of the globally averaged sea level between 18 and 59 cm or even more (see page 360 of Ref. [11]). Higher temperatures of the lower atmosphere mean that more energy is available, which can be discharged in much heavier thunderstorms, tornadoes and hurricanes: no good prospects for the years to come.

For those who tend to rely on the numbers of the most optimistic scenario, in the following an additional argument is presented, which urges that immediate action should be taken. It is known that the weather system is chaotic, and the climate of a region is the entirety of different weather conditions that are possible in that region, including long time averages of characteristic parameters. A typical property of chaotic systems is their extreme sensitivity in that small perturbations may have large consequences. For the last 10 thousand years the climate on earth was especially stable (Fig. 8), and it is not yet understood why. The Eemian interglacial period that lasted from 126 to 115 thousand years before now had average temperatures slightly above those of today and is therefore often considered as an analogue for the climate expected in our near future. However, the Eemian climate was much more unstable than ours, revealing fluctuations of the average temperature up to 15 ^{0}C within a few decades. This would have catastrophic effects on fauna and flora as well as on human society. Even if the situation of a more optimistic scenario should occur, we are still playing with fire: every year emitting over 30 billion metric tons of CO_2 into the atmosphere that will remain there for 50–100 years is a major impact on a system known to be extremely sensitive and cannot be called anything but foolish.

2.2 Identification of the biggest and most ineffective energy spenders

In order to cope with the the severe problems depicted above, it is good to know where to concentrate our efforts for a remedy. In this respect it is helpful to find out where energy is spent, how it is spent, where it is spent most ineffectively and where environmental burdens through it are especially large.

The 491.5 EJ of worldwide primary energy consumption in 2006 were distributed among the different energy carriers according to Table 6. (For comparison, the corresponding numbers for Germany with a primary energy consumption of 14 EJ are also presented.)

Table 6: Distribution of primary energy consumption among the different energy carriers in 2006, worldwide (numbers from [3]) and in Germany (numbers from [13]). The percentages are calculated according to the efficiency method (primary energy = end energy divided by the efficiency, where efficiency has the usual meaning for oil, gas and coal; for water, wind and photovoltaic power it is set equal to 1, and for nuclear power equal to 1/3). The column Renewables pertains to wind, solar, tidal and wave energy, all bioenergy (including that from waste biomass) except for heat from solid biomass. Except for tidal and wave energy, renewable energy from water is listed separately in the column Hydroelectric.

Region	Oil	Gas	Coal	Hydroelectric	Nuclear	Renewables	Solid biomass
World	34.3 %	20.5 %	26.2 %	2.3 %	6.2 %	1%	9.5 %
Germany	34.7 %	22 %	24 %	0.5 %	12.4 %	6.4%	—

In general, primary energy cannot directly be used but must be converted into a usable form like electricity, heat or gasoline, called end energy. In the conversion process about 27 percent is lost. Finally, on average, the user can extract only about 50 percent from the end energy as usable energy; the other 50 percent is waste energy (Fig. 9). Thus, on average only little more than one third of the primary energy serves its intended purpose, and two thirds is lost. This is a huge waste, and we can thus identify a *first item with respect to which our use of energy can be improved: saving of energy by enhancing the efficiency in the conversion and the usage of energy.*

It is useful, too, to have a look at the shares of the different energy forms in which energy is brought to the users on a percentage basis, and at the percentages of the different kinds

Table 7: Percentages of the different forms of end energy, about 25 % coming from electricity production (data taken from [13]).

Mechan. energy	Process heat	Room heat	Light
43.4 %	28.1 %	26.1 %	2.4 %

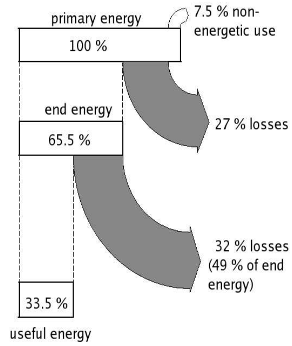


Figure 9: Energy losses from primary source to final usage. Roughly the relation *primary energy : end energy: finally used energy = 3 : 2 : 1* holds. Non-energetic use is essentially for chemicals and synthetics. (Figure taken from [2], page 38.)

of users. This is shown in Tables 7 and 8 for the example of Germany in the year 2007 (data from Ref. [14]).

Table 8: Percentages of end energy consumed by different users

Traffic	Homes	Small-scale consumers	Industry
29.7 %	26.5 %	15.9 %	27.9 %

In the domains industry, homes and small-scale consumers more than 50 percent of the end energy becomes usable energy, while in traffic only about 20 percent is finally used, which is mainly due to the poor efficiency of combustion engines. This means that only about 14 percent of the primary energy is finally used in traffic; 86 percent is losses. On the other hand traffic is the biggest user. This identifies a *second field where it looks promising to search for improvements and new ideas: traffic.*

A third important item is provided by the fact that in industrialized countries like Germany more than one half of the end energy is heat, split almost by 1 : 1 into room heating and industrial process heat. In room heating a lot can be improved by better isolation, using better heaters, employing heat pumps or building energy saving houses. (In this volume, a special article, [15] is dedicated to modern houses with reduced energy demand. The results are astonishing.) As for industrial heat the situation is more difficult when extreme temperatures are needed.

As already mentioned, at present and worldwide 81 percent of the total annual energy consumption is obtained from the combustion of fossil fuels. Both shortage and the hazards of a climate change are forcing us to change this very soon. Perhaps the time left for doing so is in the shortest supply of all. *Therefore, we must achieve a transition from fossil fuels to appropriate substitutes as fast as possible.*

2.3 Fission reactors – end of an era or renaissance?

The fission of 1 g uranium 235, contained in about 143 g natural uranium, yields the same energy as 2.7 t coal, and not a single gram of CO_2 or any other greenhouse gas is emitted in this process. A fission reactor has very low electricity production costs because in spite of rather high prices for natural uranium (until 2005 up to 90 \$/(kg U_3O_8) (see Fig. 7 (b)) corresponding to 106\$/(kg U), and after a high of 286\$/(kg U_3O_8) (or 338\$/(kg U)) in the middle of the year 2007 about 143\$/(kg U_3O_8) (or 169\$/(kg U)) in the middle of the year 2008) the fuel costs per kWh generated electricity are very low (about 0.3 Eurocents/kWh at a price of 170\$/(kg U)) due to the extremely low fuel consumption. Furthermore, because of few down times fission reactors are very dependable and therefore optimally suited for base load supply. Owing to these positive properties, in the first years after their introduction

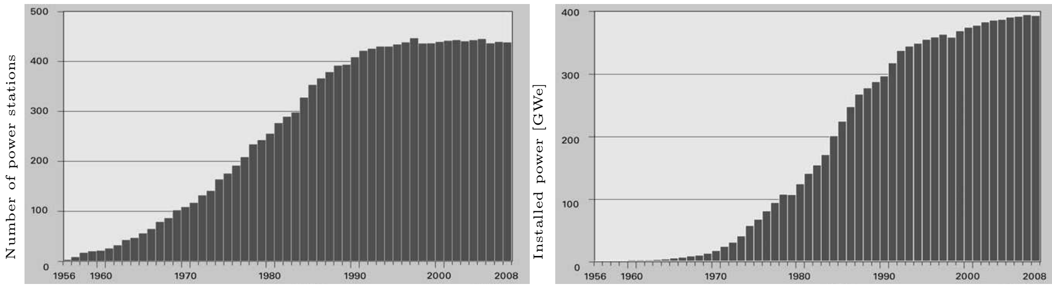
(1954, see Sect. 1.1) nuclear power plants based on nuclear fission evoked a real euphoria. At first environmental friendliness did not play a role; it became important with growing ecological awareness only much later.

After the serious Three Miles Island accident in Harrisburg (1979) with partial core meltdown and the Chernobyl disaster (1986) with complete destruction of the reactor unit, the initial euphoria vanished rather quickly. With respect to security concerns especially evoked by the Chernobyl disaster the following should be noted: The (graphite-moderated) Chernobyl reactor was of a special type designed to breed weapons-grade plutonium besides electric power generation. It exhibited striking safety defects, among others the absence of a containment, and was built in relatively few other places. All other reactors are much safer. Security concerns are not the only drawbacks of fission reactors. Disposal of their radioactive waste is still considered to be an unsolved problem. Furthermore, there is the problem of proliferation. In spite of international agreements and widely accepted international control, refusing cooperation or violating the agreements, it is possible to breed weapons-grade nuclear material. This is done by using illegal additional equipment in facilities not designed for this purpose but for the uranium enrichment of the nuclear fuel. The illegally breeded material can then be either used for building nuclear weapons or sold to interested parties with criminal intent. Even the knowledge about the processes involved may be subject to proliferation. The cumbersome negotiations with Iran are exemplary witness of this.

Surprisingly the Chernobyl disaster had no dramatic impact on the usage of nuclear energy as can be concluded from Figs. 10 (a) and (b). After all, the number of nuclear power stations in the world still grew, from 300 in 1985 to 443 in 2006, while their electricity production almost doubled. In 1985 only a transition from accelerated to decelerated growth occured. Since about 1995 the number of plants essentially stagnated, whereas the electricity production grew until 2006. The reason for the stagnation may partially be due to the Chernobyl disaster. Another reason may have had an even larger impact: The construction of a nuclear power plant is relatively expensive and requires high initial investments, which are compensated by the low fuel costs only later. For quite some time the high initial finance requirements in combination with uncertainties about the politically accepted and approved run times have kept the interest of operator companies in new nuclear power plants at a rather low level.

Worldwide 443 nuclear power stations were in operation in 2006. They delivered 6% of the world‘s primary energy consumption and 16% of its electricity. (For Germany the corresponding numbers in 2007 were 12.3% of primary energy and 22.1% of electricity.) They were distributed as follows: 104 in the USA, 59 in France, 56 in Japan, 31 in Russia, 23 in Great Britain, 20 in Korea 18 in Canada and 17 in Germany etc. Summing up the ones explicitly mentioned, one sees that 74 % of all nuclear power plants were located in just 8 countries.

In Germany, according to an agreement in the year 2000 and an amendment of the Atomic Energy Act in the year 2002, a complete pull-out from nuclear energy was decided on. It is foreseen that the last nuclear power plant will be decommissioned in about 2022, [17]. In other countries the attitude is quite different. According to Ref. [14], in 2008 worldwide 42 nuclear power stations were under construction (10 of them in China, 6 in India, and only 1 in the USA), 80 were applied for (26 in the USA, 16 in China and 11 in Japan) and 128 were in the process of planning (16 in China and 15 in South Africa). A simple calculation (number of existing units divided by the average remaining lifetime $\leq$ 60-23, see below)



(a) (b)

Figure 10: (a) Evolution of the number of operating nuclear power stations in the world since 1956. (b) Evolution of the corresponding installed electric power. (Figures taken from Ref. [16].)

shows that in order to maintain the number of existing nuclear power plants, depending on the size, worldwide about ten plants would have to be built every year. Adding the numbers of plants under construction, in the process of application and of planning (42+80+128=250) and dividing the result by the number of years from 2008 to 2020 (i.e. by 12) shows that in future the number of nuclear power plants will increase, even in the case that not all 250 plants will ever be finished. According to the OECD Nuclear Energy Agency (NEA), a boom of nuclear energy will occur, which will raise the worldwide nuclear capacity from about 400 GWe in 2008 to at least 600 GWe up 1400 GWe in 2050, [18]. (For the number of nuclear power stations approximately the same numbers apply.)

How to deal with the existing nuclear power plants must be considered independently of the construction of new ones. From a technical point of view, nuclear power stations can be safely operated for 60 years if they are appropriately upgraded. The average age of the 443 units that existed in 2006 was 23 years, so they had less than one-half of their possible lifetime behind them. In Germany, in spite of a design for 40 years (without upgrading), a lifetime of only 32 years was admitted, which is far below the technically possible and the internationally usual. In contrast, in the USA, for several plants the lifetime was extended to 50 years, and for some even 60 years are envisaged. In Germany the lifetimes could well be prolonged without taking any additional risks. This way it would become much easier, if not achievable, to meet all requirements or promises for climate protection. Furthermore, nuclear technology could fully play its role as a bridge technology until it becomes clear whether other energy technologies, especially renewables, can take over. In a study of its working group on energy ([19]) the German Physical Society has highly recommended extending the operating life of German nuclear power plants: "What we must do is to prolong the phase-out plans over a realistic period of time commensurate with the reduction of CO_2 emissions. This applies regardless of whether nuclear power is revived or completely phased out. To shut down these power plants according to plan would make nonsense of all the efforts made so far to reduce the CO_2 emissions."

2.4 Boom of renewable energies

After the oil crisis in the seventies of the last century, a marked change of thinking took place concerning energy usage in Germany. Energy saving appeared at the agenda, especially the saving of thermal heat by better isolation of houses, which was enforced by fiercer regulations and supported by state funding. Furthermore, a growing engagement with renewable energies emerged, initially because it was promising a greater independence from the import of conventional energy sources, in particular from oil. Later on this trend was enhanced by a growing awareness of the environmental damage caused by the conventional energy sources. All in all, for the last decades this has led to a veritable boom of renewable energies.

The energy radiated from the Sun to the Earth is about twenty thousand-fold greater than mankind's present needs. Some of it goes into the weather system and can be used by extracting energy from wind or moving water or from plants that obtained their energy from the Sun by photosynthesis. What comes down to the ground on solid landmass still exceeds mankind's needs by a factor of about three thousand and is ready to be converted into electricity or heat. If not, it is transformed into heat and radiated back to outer space as thermal radiation. Energy that is diverted from natural processes in our environment for human use, externally powered by the Sun or the Earth, is called renewable. According to human standards it is inexhaustible, and it is essentially CO_2 neutral in that no CO_2 is emitted at all or only to the same amount as was extracted from the atmosphere by plants before use. *CO_2 neutrality and inexhaustibility of renewable energies assign them an outstanding role in our task of preventing a dramatic climate change and of coping with the running out of fossil energies.*

Renewable energies directly or indirectly due to the Sun are

- hydro-electric power
- wind power
- solar power
- energy from biomass.

Renewable energy coming from the Earth's interior is

- geothermal heat.

In 2006, about 3.3 % of the global primary energy consumption came from renewables (including hydroelectric, but not solid biomass, see Table 6). In Germany, for a number of years the use of renewables has increased continuously, most of the time even exponentially (Fig. 11). Some other countries like Spain, USA or China experience a similar boom.

In the following a short survey of the advantages, disadvantages and potential of the different kinds of renewable energy is given.

2.4.1 Water power

Water power from hydroelectric dams (water storage power plants) and (smaller) damless hydraulic power stations has the longest tradition of all renewable energies, and the techniques involved are already well-engineered. In Germany, about 4–5 percent of electricity production comes from water power (page 243 of Ref. [21]), but further enhancement is very limited. Worldwide 17 percent of the electricity production is water powered (page 245 of Ref. [21]), and this percentage can still appreciably be enhanced. Development potential lies in wave power, tidal power and tidal stream power.

Hydroelectric dams are the most powerful. Their advantage is that they can handle seasonal and even daily high peak loads. However, they strongly interfere with the environment, leading to appreciable changes in the ecological system. In the case of the Three Gorges Dam, a Chinese hydroelectric river dam with a (planned) maximum electric power output of 22.5 GW, 1 million people had to be relocated, with 0.5 million more expecting the same fate.

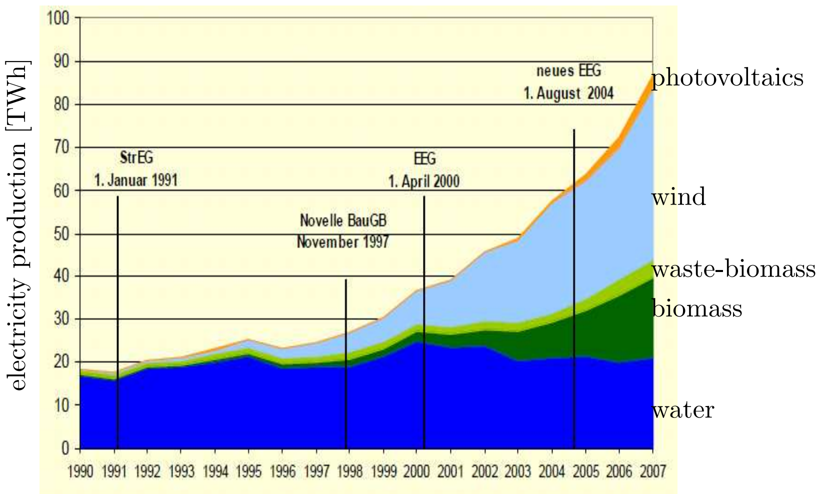


Figure 11: Electric energy production by renewable energies in Germany since 1990. (Figure taken from page 13 of [3].)

2.4.2 Wind power[1]

Wind power is the fastest growing of the renewable energy technologies, and some years ago, in Germany, its contribution to the power supply even overtook that of water power. In 2007, in Germany 6.4 %, in Denmark 19 % and worldwide less than 1 % of the respective electricity production came from wind power (see [3]). After a first approach with a very large wind turbine in Germany (GROWIAN) failed, technology started with small turbines and developed slowly to larger ones. Now the magnitude has almost reached a limit, which cannot be exceeded because of transport problems. The largest wind turbines of today can produce 5 MW electric power at full wind (nominal value). The real value of the energy production depends strongly on the wind quality at the site. From 1996 to 2008, the height above ground of windmills installed in Germany rose by a factor 2, but the value of the annually produced wind energy remained at about 20 % of the nominal value.

Wind power is still subsidized. At present, in Germany the subsidy is between 5.5 and 8.7 eurocents/kWh onshore and 9.1 eurocents/kWh offshore, although this is much less than the subsidy for photovoltaic power (about 40 eurocents/kWh). On the other hand, for new windmills the installation costs per kWh annual output have continuously decreased, from about 0.82 Euro/kWh in 1990 to about 0.38 Euro/kWh in 2003. However, the largest part of this reduction (about 80 %) was achieved between 1990 and 1996 and pertains to only about 10 % of the windmills that were installed until 2003. After 1996 the progress in cost-reduction was appreciably smaller (see Fig. 5-5 on page 38 of Ref. [19]). Due to appreciably increased material costs, the present installation costs are probably higher than those of 2003. Nevertheless the German Department of the Environment expects that with growing prices for fossil energy and still falling prices for wind energy, financial break-even will be

[1]This volume contains a special article on wind power, [20].

reached between 2010 and 2015. It may well be possible that in the not too distant future wind energy can compete with fossil energy without subsidy at least at favorable sites.

In Germany the expansion of land-based wind farms is close to completion, partly due to the lack of further areas of higher wind resources (in regions with fewer windmills like southern Germany, wind power is half as cost-effective as in the coastal regions), and partly due to resistance of people (who find wind turbines noisy and visually intrusive). Some potential for further enhancement lies in upgrading (re-powering) windmills of outdated facilities. However, according to the German Energy Agency dena this potential is limited to about 12%, [22].

In 1991 Denmark started a first attempt with a small offshore wind farm. Offshore wind farms are more expensive and will require an appreciable additional amount of transmission lines; on the other hand, they are quite more productive. Therefore, in Germany large units are projected, some with a power output in the range of gigawatts. However, the companies engaged in this business are approaching it rather cautiously. For lack of sufficient experience, many uncertainties and incalculable risks are still involved.

An obvious disadvantage of wind power is that wind does not blow continuously, and the demand for power does not care for dead calms. Therefore, conventional power stations of equal capacity must be kept in reserve. During operation, wind power is completely renewable and produces no greenhouse gases at all. The payback time for the energy used for construction is just a few months of operation. On the other hand, it is becoming a problem that for the production of windmill turbines large amounts of materials (like copper) are needed, which are increasingly running short.

2.4.3 Solar power

The solar irradiation on the Earth's surface, subject to day and night, seasonal and geographical variations, can reach up to 1 kW/m^2. This energy can directly be used as heat (solar thermal applications) or converted into electricity (solar electricity).

Solar thermal applications include

- heating of air in homes and greenhouses
- heating of water in solar thermal collectors (warm water supply in homes, swimming pools, etc.)
- cooking with solar box cookers or concentrating solar cookers like the solar bowl
- water distillation, desalination and disinfection
- solar chemical processes (heat from solar concentrators)
- low-energy houses (employing a combination of several of the above-mentioned technologies with solar lighting included).

Relative to other solar applications, solar water (or liquid) heating technologies have the highest efficiencies.

Solar electricity can be generated either directly by utilizing semiconductor effects (photovoltaics) or indirectly by concentration of light as a heat source for a conventional power plant (solar thermal power plant).

Photovoltaic (PV) electricity generation is more flexible and ranges from very small-scale applications like the powering of pocket calculators to large multi-megawatt PV power plants. It does not depend on direct sunlight but can still take advantage of diffuse sunlight on cloudy days. In small- and medium-sized applications, electricity is produced and used at the same place. This is a big advantage because no transport losses arise. Present PV panels typically convert about 15 percent of incident light energy into electricity. For almost 20 years in Germany photovoltaic electricity generation has rapidly grown with a doubling time of 2–3 years at first, and of little more than one year since about 2000. By now Germany is the world leader in the installation of PV devices, not however in the production (where still Japan is number one).

Photovoltaic electricity is not completely CO_2-free energy because for production and installation CO_2-burdened energy is used. In 2006 crystalline silicon PV systems had energy pay-back times of 1.5-2 years for South-European and 2.7-3.5 years for Middle-European locations while thin film technologies had pay-back times of 1-1.5 years in Southern Europe, [23]. (The total energy balance is positive because the operational life span of PV panels is 20–40 years.) Economically photovoltaic electricity is still far from profitable. In Germany every kWh is supported by about tenfold the price for the production of a kWh of conventional electricity. It is questionable wether subsidizing the utilization of solar panels is the best choice. In this way, rooftops are rapidly covered with present-day technology, which due to rather long financial payback periods will not be available to more advanced technology for several decades. Better still, technological progress and innovations should be subsidized. On the other hand, since 1990 production costs have gone down by a factor greater than two, and this trend is still continuing. Furthermore, in order to be competitive, photovoltaic electricity must not reach the low costs of electricity from fossil or nuclear power stations because it does not make use of the grid or other infrastructure. Since it is fed directly from the rooftop into the house, it suffices that it reaches grid parity, i.e. reaches the point at which its price equals or beats the retail price for electricity from the grid. The grid is nevertheless necessary in order to adapt the fluctuating power of the Sun to steady demand.

As of today, silicon is the main material used for photovoltaic cells. However, the search for new materials that improve the efficiency, cut down the costs or achieve both is intensively pursued. Some metal alloys may provide appreciably higher efficiencies, and organic polymers coated on flexible skins promise much lower costs in combination with increased flexibility. Another field of progress is seen in concentrator cells, allowing large power output from a relatively small system. In this case burning lenses concentrate light onto water-cooled photo cells. In contrast to usual PV panels the whole device must be pivotable and tracked to the changing angle of incidence of solar radiation. For off-grid PV power, generally electricity storage is required. Unfortunately, batteries with the necessary capacity do not exist yet.

In **solar thermal power plants**, sunlight is concentrated by linear parabolic reflectors that focus light onto a cylindrical receiver filled with a liquid (mostly oil and sometimes high pressure water steam), parabolic reflectors with a Stirling engine at the focal point, or by an array of dual-axis tracking reflectors that focus light on a central receiver atop a tower. In each case the reflectors are pivotable and equipped with a one- or two-dimensional tracking mechanism to follow the Sun. With each method high-temperatures (in the case of parabolic reflectors 400 ^{0} C, central receivers 1000 ^{0} C and solar furnaces 2500 ^{0} C, the latter ones aiming at industrial high temperature applications and as yet being in an experimental state), and correspondingly high thermodynamic efficiencies can be reached; the techniques used for the conversion of heat into electricity via heat exchangers and steam turbines are conventional and highly developed. Taking advantage of the high heat capacity or latent heat of molten salt mixtures, the storage of heat accumulated during the day is possible for many hours. This allows one to operate the power plant at full power up to 7.5 hours during the night or during a spell of bad weather (see [26]). Furthermore, combination with fossil power production in a hybrid power station is possible.

Solar thermal electricity is essentially CO_2-free because the time for energetic amortization is only a few months. A disadvantage is that direct and strong sunlight is needed. This condition restricts the generation of solar thermal power at an economically interesting level to southern countries with dependable weather conditions. This may be the reason why solar thermal electricity production has not yet experienced a boom as in the case of photovoltaics. Deserts are ideal locations but require very long high-voltage DC transmission lines or new transportation techniques, apart from the problem that, in view of high investment costs, politically stable conditions are an essential requirement. Due to as yet very high installation costs, financial support is still necessary, although at a considerably lower level than for photovoltaics. Higher numbers of manufacturing allow us to expect a steep reduction in costs. In the study of its working group on energy ([19]) already mentioned before, the German Physical Society has enunciated a plea for solar thermal power plants in southern latitudes, which is quoted below in section 3.2.

An important problem of both photovoltaic and solar thermal electricity is the fluctuation of sunlight between day and night as well as between summer and winter. In the case of photovoltaics, efficient energy storage is as yet an open problem. Furthermore, in both cases the costs are still very high and should be reduced quickly.

2.4.4 Bioenergy [2]

Bioenergy is energy from biomass, i.e. material derived from biological sources. Biomass contains chemical energy that is converted from radiation energy of sunlight via photosynthesis. Examples of biomass are wood, straw, sugar cane, corn and animal excrements. The energy content of biomass is relatively high: 3 tons of dry biomass contain about the same energy as 1 ton petroleum. Bioenergy is an all-round energy because it can be used for the production of

- heat
- electricity
- liquid fuels
- biogas.

In addition, bioenergy can be used round the clock because bioenergy or fuels derived from it are energy stores. As long as biomass is not consumed faster than it grows again, it is sustainable and, in principle, CO_2 neutral. To produce liquid fuels for transportation from biomass, and in this way to replace fossil fuels at least in part, is a big chance on the one hand and a great challenge on the other.

[2] This volume contains a special article on energy from biomass, [27].

One option consists in growing sugar crops such as sugar cane or corn, and then producing ethanol by fermentation. Another option consists in growing plants that (naturally) contain oils such as oil palms or soybeans. These oils can be either burned directly in a diesel engine or chemically processed into fuels such as biodiesel. The fuels thus obtained – obtained from plants that must be grown for this purpose – are called **first-generation biofuels**. The disadvantages are large needs for space, high consumption of energy, water and fertilizers in the processes of plant growing and fuel production, release of greenhouse gases in the production of fertilizers, environmental damage by application of pesticides, drying and erosion of soils, and deforestation in favor of cultivation areas. Furthermore, competition can arise between the growing of plants for food and for fuel (**food versus fuel debate**). Eventually it is the very small efficiency of photosynthesis that limits this kind of fuel production to an amount that cannot supply our energy requirements on a sustainable basis.

Second-generation biofuels including biogas made from non-food crops, waste biomass or organically loaded waste waters, and **third-generation biofuels** made from algae are much more promising because almost all of the above-mentioned disadvantages do not apply (although some disadvantages may apply to the primary non-waste products). Ecologically uncritical synthetic fuels like "sundiesel" or biogas for electric power generation can be produced in this way. Economically, fuels of this kind are not yet competitive and must be subsidized. With falling costs, advances of technology and rising prices of conventional energy, the situation may change for the better in the not too distant future.

2.4.5 Geothermal heat, a widely neglected energy source

Geothermal energy is heat stored below the Earth's surface. Close to the surface it essentially is low temperature heat converted from sunlight and can be used for the heating of homes with the aid of **heat pumps**. In deeper layers it comes from the Earth's interior, is mainly due to radioactivity and can reach temperatures that qualify it for **electric power generation** as well as for **industrial process heat**. (On Iceland, the Alcoa company uses it for the production of aluminum.) Because of the high expenses for drilling, the use of geothermal heat from deeper layers is concentrated to areas of geothermal anomalies like in the vicinity of burning or extinct volcanoes. Geothermal power plants are unaffected by changing weather conditions and can work continuously, day and night, which makes them appropriate for base load. Apart from the energy used to make the bores, the geothermal processes release no greenhouse gases, and except for the ones mentioned below, almost no negative environmental effects are known.

The following disadvantages are possible: enhanced geothermal systems injecting water into hot dry rock can adversely affect land stability in their surroundings. Systems that are too large for a site may cool down the latter. (However, the site will recover later). Capital costs are very high due to the high drilling costs, and since the success of a drilling project is not guaranteed, there are high financial risks involved.

In 2007, worldwide geothermics contributed only 0.4% of the world's total power supply (page 62 of [3]). The potential is, however, enormous. According to a MIT report, in hard rocks located in depths of 3 – 10 km below the United States, theoretically there is enough geothermal energy to cover the energy needs of the whole mankind for about 30 thousand years, [29]. Even in Germany the geothermal energy contained in the ground down to 7 km is 500 times the present demand of heat and electricity, [30].

3 Options for our future energy sources

Within the next decades, major changes will take place in the energy sector. In spite of the problems connected with them, fossil energies will still play a dominant role for quite some time. The extension of renewable energies will be promoted with all one‘s might. And many countries will not abandon or even advance nuclear fission energy because of its CO_2 independence. Which kind of energy will finally prevail depends on technological progress as well as on political developments and decisions.

3.1 Fossil energies

According to a projection of the International Energy Agency (IEA) shown in Fig. 7 (a), notwithstanding the converse efforts of several countries, worldwide the usage of fossil energies will still increase for at least two decades. Concerning oil, a switch from conventional to non-conventional resources will take place. Natural gas will show a marked upward trend, besides high energy density favored by fewer emissions of CO_2 as well as almost vanishing emissions of sulfur dioxide and nitrous gases. The transport of gas as a deep-frozen liquid, called LNG (Liquefied Natural Gas), will yield more independence of the import from nearby countries to which it is restricted when it takes place via pipe lines. Because of its relatively low price and its huge total reserves also the usage of coal will increase, although of all fossil energy carriers it has by far the worst CO_2 record. The CO_2 emissions per kWh electric energy produced from coal exceed those of oil by a factor 1.4 and those of gas by a factor 1.8.

Unless utmost efforts are taken with respect to climate hazards, dramatic climate changes could enforce an abrupt about-turn in our usage of fossil energies. There are many ideas about the reduction of CO_2 emissions. Mostly they concern the separation of CO_2 in the process of burning and the successive deposition of the separated CO_2.

One idea consists in freezing the separated CO_2 and embedding the dry ice obtained in this way heat-insulated into the ground. Another concept developed in the USA plans to bond the CO_2 to algae induced to grow by pouring huge amounts of pulverized iron into the Antarctic polar sea. Yet other concepts envisage capturing CO_2 directly from the air by employing microorganisms that may even produce fuels such as methane or hydrogen in this process (see [31]). Out of all the concepts, the following appears to be the most realistic.

CO_2 sequestration. Almost 40 percent of global CO_2 emissions come from coal, making coal the climate killer number one. Enhancement of the efficiency of coal-fired electric power plants is taking place continuously, but cutting down CO_2 emissions to the level of gas and steam power plants is beyond reach.

CO_2 sequestration, i.e. the separation and deposition of CO_2 from fossil combustion in heat- and/or power-generating stations, would solve the environmental problems of coal. The price for this is an energy penalty, which consists in a reduction of efficiency by about 10 percent points, the exact number depending on the degree of CO_2 retention, and in higher energy costs. A cost-saving option is to combine CO_2 deposition with an enhancement of oil recovery from heavy oil reservoirs when the latter is chosen as the site for deposition.

Within the North Sea just off the Norwegian coast, there is the Sleipner platform built for natural gas extraction. From 3000 m below sea level not only natural gas but also CO_2 is forwarded, the latter in a fraction of roughly 10 percent. After separation from the gas the CO_2 is pumped back down into a sandstone layer at a depth of 800 meters below sea level, which absorbs CO_2 like a sponge. Above that layer there is a hard rock layer that, like a cap, prevents CO_2 from escaping. Since years no leakage has been observed, which demonstrates that CO_2 sequestration is a viable method with promising future perspectives.

In Germany, by 2020 about 50 percent of the existing coal-fired electric power plants will have to be replaced. The challenging question is how to built them: with or without CO_2 sequestration?

3.2 Renewable energies

In the scenarios for our future energy supply, a prominent role must be assigned to the renewable energies. In principle, the most urgent problems of fossil energies would be removed by a complete switch to renewables. This is why their technological development is so vigorously advanced, evermore even worldwide. Basically, the global energy demand could be covered entirely by renewable energies. In view of the present climatic hazards, it is an important question as to when this transition can be achieved. It is striven for and assumed by many (see e.g. [3]) that they can at least catch up with the conventional energies by the middle of this century. As discussed in more detail below this goal will very likely be reached by several countries including Germany; worldwide it may be missed.

In Germany an annual growth of 4.8 % (during the last years the annual growth was about 20 %, [3]) would suffice for the transitiont from a contribution of 6.4 % in 2006 (see Table 6) to 50 % in 2050, provided the total primary energy consumption does not increase. In the case of a reduction that is politically aimed at and practically within reach, even a slower growth would do. In contrast, for the whole world the step from 1 % in 2006 (see Table 6) to 50 % in 2050 would require an annual growth of 9.3 % if the total primary energy consumption remains constant, and of 11 % if it doubles until 2050. This shows that the goal of a worldwide equipartition between renewable and conventional energies in 2050 is extremely ambitious and likely to be missed.

The author of this paper is convinced that in the long term the dominant share of our energy supply will come from renewables – the huge amounts of energy radiated from the Sun to the Earth and the tremendous heat stored in the Earth‘s interior are nothing less than provoking this. From an optimistic point of view, in some countries the predominance of renewables may even occur in this century. More realistically, and worldwide, it will take centuries rather than decades for this to occur.

A major problem of many renewables is presented by strong variations of their availability, which is not adapted to demand. For better adaption, major improvements, if not sweeping innovations in energy storage technologies, are necessary. Furthermore, like sunlight renewable energies are offered by nature in very low concentrations, i.e. they must be collected from large areas that must be provided. Furthermore, they require large amounts of materials, some of which are scarce and running short (see section 4). The shortage of materials may provide a serious limitation to the further expansion of some renewable energies.

Another problem is financial competitiveness, which will be the key to the aimed-at predominance. For this, rising energy prices of conventional energies and rising output figures will be as helpful as state funding and, not least, the technological progress. However, for the longer term the renewables must win through without funding. State funding is a privilege that is intended as a launching assistance and makes no sense as a permanent arrangement.

Among the renewables, energy from solar thermal power plants in southern latitudes could play a major role and should finally be promoted from a shadow existence to which it is still linked in spite of some recent progress. This has been suggested by the German Physical Society since long and once again has been put to the agenda by the following plea, [19].

"**Plea for solar thermal power plants in southern latitudes.** Seen from a physical and technical point of view, there can be no doubt that solar thermal power plants in southern latitudes represent one of the best options for supplying the requisite large quantities of CO_2-free electricity. The relevant research and development activities have been in progress for about 25 years, and have reached a stage where it is time to energetically pursue their commercialization. The Deutsche Physikalische Gesellschaft appeals to all the parties involved – industry, energy providers and the appropriate Government bodies – to do everything in their power to promote the launch of the outlined program to create a market for solar thermal power plants in the Earth's equatorial sun belt."

3.3 Nuclear energies

3.3.1 Nuclear fission

The first reactors, phase-out models of which are still in operation (Great Britain), were so-called generation I reactors. Around 1970 they were taken over from generation II reactors, which comprise the majority (more than 400, see [32]) of all present-day reactors. The future reactors are of generation III, first samples of it already being in operation (Japan) or a few years before (Finland and France). Finally, an advanced type of reactors with not yet tested innovative technology, called generation IV reactors, is currently being researched.

Generation III reactors. Generation III reactors are based on the field-tested technology of generation II reactors. In general, they are advanced boiling or pressurized water reactors moderated and cooled with light water. Advances over generation II reactors consist in improved fuel technology, higher efficiency, enhanced safety (in so-called advanced passive plants involving passive safety systems independent of a permanently provided emergency power supply), lower costs and longer operational lifetime. Some types (occasionally called generation III+ reactors) offer still further economical and safety improvements. Among them is the European Pressurized Reactor (EPR), for which the new Finnish reactor will provide the first field test. It is designed to master even a complete core melt down by using a huge ceramic basin of 6 m thickness, the core-catcher, to catch the reactor core when it melts. As in the case of generation II reactors, the application field of generation III reactors is base load supply.

Generation IV reactors. Generation IV reactors are no derivatives of former ones, but comprise an entirely new line of development. Studies on them were prompted by an American initiative. The countries Argentina, Brazil, Canada, China, France, Japan, South Korea, Russia, South Africa, Switzerland, United Kingdom and USA, and the organizations Euratom of the EU, NEA of the OECD and IAEA are cooperating in the so-called Generation IV International Forum (GIF, founded in 2002) to do the basic research. From 21 reactor types initially considered, the GIF focused on the technologically most promising lines of research that are most likely to meet the goals of a "top-ranked-sustainability":

- *Economical efficiency* by raising the plant efficiency beyond 40 %, simplifying the construction and optimizing the size of the plant. Goals are markedly reduced capital and operational costs establishing financial risks comparable with those of other energy sources.

- *Sustainability* due to minimal fuel consumption and nuclear waste production.
- *Enhanced safety* by inherent safety properties and reliable operation. In a worst-case accident no influence outside the power plant should be exerted.
- *Maximal proliferation resistance.*

The reactor types to be investigated can be subdivided into two categories.
1. *Thermal reactors:*

- The *Very-High-Temperature-Reactor (VHTR)* is helium cooled, graphite moderated and has a modular structure. Its prismatic core is designed for temperatures up to 1000 ^{0}C. (An example is provided by the pebble bed reactor, which was invented in Germany in the sixties of last century. It is inherently safe in that a core melt accident is physically impossible when the reactor is sufficiently small.)
- The *Supercritical-Water-Cooled Reactor (SCWR)* is cooled with supercritical water (water in a phase beyond the critical point – 374 ^{0}C and 22.1 MPa – where the difference between liquid and gas no longer exists) simultaneously used for driving the turbines, and it may have no moderator.
- The *Molten-Salt-Reactor (MSR)* is graphite moderated, and it uses molten fluoride salt, with the nuclear fuel dissolved in it, as coolant and fuel simultaneously. Core temperatures can go up to 800 ^{0}C. An advantage of the MSR is high proliferation resistance.

2. *Fast reactors:*

- The *Gas-Cooled Fast Reactor (GFR)* is helium cooled, has no moderator and uses fast neutrons for fuel production.
- The *Sodium-Cooled Fast Reactor (SFR)* is cooled by liquid sodium, has no moderator, and uses fast neutrons for an efficient use of uranium fuel.
- The *Led-Cooled Fast Reactor (LFR)* is cooled with a liquid-metal alloy of led and bismuth and has no moderator. An advantage is high passive safety.

In Ref. [33] it is proposed to operate a molten salt reactor as a breeder on a thorium-^{233}U fuel cycle, thus not only opening substantial resources of a new reactor fuel – thorium – but also providing major advantages with respect to proliferation resistance and waste production.

Unlike the reactors of generation III, in general the GIF reactors are no base load suppliers but are rather suited for special purposes: many and fast power-ups and -downs of small units in order to compensate performance fluctuations of wind or solar power or provision of high temperature heat for industrial purposes such as the production of hydrogen. GIF projects include all branches of the nuclear energy usage, from production and distribution of fuel over development and construction of power plants to reprocessing nuclear fuel rods, waste disposal and finally even to applications of nuclear energy (e.g. water desalination, hydrogen production or district heating).

Preliminary research and development results of GIF activities, culminating in the construction of a demonstration reactor, are scheduled for the time interval 2020 – 2030. So far the financiation of all GIF projects is essentially based on research funds. There is no support from the energy industry whose activities are still focused on advancing field-tested development lines like the light-water reactor.

Transition from open to closed fuel cycles. For all reactor types an important issue is the treatment of the used fuel. Present day reactors employ an open "once-through-cycle" with direct final deposition. For GIF reactors, employing chemical separation methods in a closed cycle, a recirculation of the actinides (transuranic elements and plutonium generated in the process of nuclear fission) back into the cycle is aimed at. (The plutonium remains mixed with the highly radioactive actinides and can therefore not be accessed without risking one's life.) In this way relatively little radioactivity will be produced, and a much better utilization of the nuclear fuel can be achieved.

Transmutation and nuclear waste deposition. With the same purpose in mind another possibility envisaged is transmutation, the externally induced conversion of highly radioactive elements into other chemical elements with lesser radioactivity of shorter durability or none at all. In principle this can be achieved with neutron beams for the conversion and chemical methods for the subsequent separation of the elements. More details are found in Ref. [24] of this volume.

All concepts for the final disposal of nuclear waste have so far not been accepted. Given the opportunity to transmute waste into elements with lesser radioactivity of shorter durability, the, at present, quite generally favored concept of final disposal appears questionable. Scientifically, transmutation can be considered feasible – the (not so easy) problem left consists in advancing it to an economically meaningful technique. Even if the present generations are not successful in this respect, one can feel confident that a task of such outstanding importance will ultimately be accomplished by later generations. For them the radioactive waste produced by us may become a precious resource from which not only energy but also valuable materials can be extracted. Instead of final disposal safe interim storage would appear to be a more viable concept. The storage should be so secure that each abusive access is averted. However, for later generations an access without major technical problems and financial expenditures should still be possible.

3.3.2 Nuclear fusion[3]

For the operation of a fusion reactor the only fuels needed are lithium (contained in stones, salt lakes, mineral springs, and sea water) and water. Both are so abundant on Earth that the energy supply of the whole of mankind can be assured for all foreseeable future. A large set of difficult problems on the way to a fusion reactor have already been solved or are close to a solution. To overcome other still open problems requires a maximum effort of all physicists and engineers involved in the project. If all tasks can be accomplished and all goals reached within the currently foreseen timespan, and if no unpleasant surprises come up, according to a "fast track" study of the United Kingdom Atomic Energy Authority (UKAEA) in Culham, Great Britain, a first demonstration reactor could deliver power in 30 years, [25]. It will still take some time until the first commercial electric power station based on nuclear fusion will come into operation. This is too late to contribute to the overcoming of the

[3]This section is restricted to a few remarks. Nuclear fusion is dealt with in more detail in Ref. [25] of this volume.

environmental problems provoked by our present methods of energy production; powerful measures must be adopted now. Some consider this as a reason to withdraw financial support for research and technology development in nuclear fusion. Against this it must be held that, *at present, there is no other energy source in sight with the same potential for a sustainable and environment-friendly base load supply as nuclear fusion.*

At least ten years could have been saved if politicians had come to an agreement about the approval and the site for the next step on the way to a fusion reactor, the International Experimental Reactor ITER, earlier. In June 2005 it was finally decided that ITER would be built in Cadarache (France) at a cost of 5 billion euros. After construction it is intended to operate for 20 years. If successful, the next step will be the construction of the demonstration reactor.

3.4 Centralized and decentralized energy supply

Most of the present day power stations provide a centralized energy supply, i.e. they produce huge amounts of electric energy at a relatively large distance from consumers and dispose the heat produced in the process as waste product. In our future energy supply there will also be technologies that are centralized intrinsically. Among them are offshore wind parks as well as solar thermal power stations. Also, new fossil or nuclear power stations apting for base load supply will be built as large units and located away from consumers. In all these cases it is important that power transmission via transmission lines is as free of losses as possible, especially when it must travel over large distances as in the case of solar thermal power stations (see [26]).

Whenever the electric power generation is associated with heat production, it is desirable that the latter also is utilized. The co-generation of heat and power is meaningful only when it takes place close to customers who consume the heat in addition to electricity, and when heat transport takes place without major heat conduction losses. This necessarily leads to smaller units which supply just a few or even single houses. Heat losses can be avoided to a large extent if, in future, the heating systems of private or small-scale consumers are replaced by **small combined heat and power stations**.

Hydrogen-powered fuel cells could feed electric current into electric motors that, in turn, could drive our cars. The hydrogen needed as a fuel is supposed to be produced by electric dissociation of water in solar farms or fission reactors. This dream of a locally and globally ecofriendly driving of our automobiles has been circulating since years, but is still far from implementation. Many obstacles are still in the way, not least of them the problems of sustainable storage as well as of handling techniques for hydrogen that are safe and without losses (cf. Ref. [28]).

Stationary fuel cells used for the combined production of heat and electricity in houses are presently more promising. They are not directly fueled with hydrogen (or methane or some other hydrocarbon in other types of fuel cells), but with natural gas from which the ultimate fuel is obtained by chemical transformation. High efficiency of electricity generation and the qualification for co-generation of heat and power are promising advantages of the fuel cell concept. If one day the use of fuel cells for driving cars should become successful, hydrogen could become the future fuel in the traffic sector.

In southern Europe it can be meaningful to pool solar panels in small- to medium-sized power stations. In northern Europe only their decentralized use in single buildings is profitable. Heat pumps are intrinsically apt only for decentralized use.

In the future decentralized power supply will appreciable gain importance, but centralized supply will still play an important role.

4 Outlook

The coincidence of the shortage of conventional energy resources with the hazards of an impending climate change is a dangerous threat to the well-being of all, but simultaneously it is a challenging opportunity for improvements in our energy usage.

According to the Energy Information Administration (USA), from 1980 to 2006 the world‘s energy consumption rose from 299 to 498 EJ (see [34]; the number for 2006 differs marginally from that given in Ref. [3] and used in Table 6) which corresponds to an average annual growth of almost 2 %. Due to the ongoing growth of the world's population and a growing hunger for energy in underdeveloped and emerging countries, it will continue to rise. Estimates of the International Energy Agency predict an annual increase of 1.6 % till 2030, [35]. Assuming the same annual increase for the time thereafter leads to a doubling of the global energy consumption by 2050, and it can only be hoped that it will not be more.

Energy saving *is one of the most effective means* of coping with the energy problem. There are several possibilities serving this purpose.

- **Raising efficiency** at all stages, from processing the primary energy carrier, to refining techniques, to the final usage.
- **Streamlined energy usage** by efficient energy management employing the continuous observation of energy-consuming processes and elaborate logistics in their control. (Examples are an efficient control of traffic on ground, on water and in the air, or the use of waste heat.)
- **Substituting** energy sources, e.g. fossil by renewable ones, or substituting energy consuming devices by more energy-saving ones or those with lesser emissions.
- **Sacrificing energy use.** In many cases this can be done without affecting the quality of life.

Identifying the future fuel(s) for our means of transportation is a task that concerns one of the most important achievements of modern life: our mobility. It must be mastered in the near future because the drying up of our oil supply is foreseeable. For some time **synthetic fuels from coal or gas liquefaction** (using the Fischer-Tropsch process in the case of coal) or liquid gas itself (LNG) may become the future fuel since biofuels will not be available in sufficient amounts. Otherwise, cars may be driven by electro-motors. However, this requires the development of rechargeable batteries or storage capacitors with much shorter charging periods and with capacities exceeding those of today by a multiple. Although locally ecofriendly they will be environmentally sustainable on a global scale only when the electricity for recharging them comes from CO_2-free power sources. As already mentioned, hydrogen for fuel cells is another promising candidate.

Not only conventional energy resources but also a number of materials needed for industrial and other purposes are running short, [8]. Among them are rare metals like platinum and and even abundant substances like copper or water. According to a joint study of the Institut für Zukunftstudien und Technologiebewertung (IZT, Berlin) and the Fraunhofer Institut für System- und Innovationsforschung (ISI, Karlsruhe), [36], in the coming decades the shortage of expensive commodities will no longer release us but will lead to economical bottle necks and may even inflame international conflicts. When raw materials are becoming scarce and cannot be substituted, the only possibility left is to recycle them, i. e. extract them from the technosphere (see Sect. 2.1.1). Today recycling is restricted to situations with small energetic and financial costs. This may change dramatically when a material is sold out. Then, recycling at any cost may become necessary, and in time will be the case for more and more materials. Therefore, in future, **additional energy expenditures for recycling** should be taken into account.

Reducing our emission of greenhouse gases *has a high priority and must be addressed without delay.* Fauna and flora can, at least to some extent, adjust to changes in average temperature. Politically a maximum increase of 2 ^{0}C above pre-industrial temperatures is considered tolerable, (see page 381 of Ref. [11]; 0.7 ^{0}C of this allowance has already been spent in the last century.) This limit can only be observed when the global greenhouse emissions, and especially CO_2 emissions, are appreciably reduced. Computer simulations carried out on behalf of the IPPC (see section 2.1.2) suggest that stabilization of CO_2 concentration in the atmosphere well above its present value (384 ppm) at 450 ppm could require that, averaged over the 21st century, annual CO_2 emissions be reduced from approximately 24.6 Gt CO_2 (corresponding to the average emissions between 1995 and 2005) to approximately 18 Gt CO_2, [37]. In other words, emissions during the years around 2000 should be reduced by 27 %. (Note that the 27 % pertains to an average over hundred years. On the exemplary assumption of a linear decrease, a reduction of 27 % should already be achieved in 2050, and of 54 % in 2100.) In order to give underdeveloped and emerging countries a fair chance for further development, industrialized countries must achieve an appreciably higher reduction. (The German Department of the environment uses the following numbers for the reduction: 30 % globally and 70 % for the indusrialized countries, [38].) Since from 2000 until today emissions have still increased, the reduction should be even larger. Furthermore, for climatologists the 450 ppm CO_2 concentration underlying the presented reduction numbers are still too high. In oder to maintain the above-mentioned 2 ^{0}C threshold of temperature increase, the CO_2 concentration should settle at a value markedly below 450 ppm (page 381 of Ref. [11]). Even its stabilization at the level of the year 2000 would still lead to a further temperature increase of about 0.6 ^{0}C (see page 360 of Ref. [11]).

According to a summary (for the British Government) of a report released in 2006 by economist Nicholas Stern, [39], on average it will cost roughly one percent of global gross domestic product per annum in order to avoid the worst effects of climate change. Failing to implement this and waiting until damages by climate change become obvious would raise the annual costs by at least a factor of 5 and in the worst case even by a factor of 20. However, the reduction of our emissions is not an easy goal. In Germany both industry and government have made tremendous efforts in this respect – year by year increasing amounts in the range of some tenths of a percent of the gross domestic product were annually invested – but nevertheless the results are disappointing: At the present reduction rate of 0.6 % per annum, Germany will still be discharging 786 million metric tons in 2020, which was its target for 2005.

The shortage of conventional energy resources and the climate change due to our energy usage are both **global problems**. This must be kept in mind when money is spent in moderating them. It does not make sense to spend a lot of money in one part of the world to only achieve insignificant improvement, when the same amount of money would yield a much better effect in another part of the world. **Emission certificates** are a reasonable way of taking into account the global aspect, although they should be traded worldwide for a sweeping effect, efficient trading regulations being an important constraint.

The problems posed by the shortage of energy resources and the hazards of a threatening climate change have the potential of inducing major conflicts if not wars. Already now some nations have started to wrangle about claims in the arctic region with the run for oil as impetus. To avoid all of this, and to keep our planet in a condition that is hit to live on for the generations after us is a challenge for the sciences, especially physics, chemistry, biology, engineering, informatics, and computing, a challenge for the decision-makers, especially in industry, politics, economy and the financial systems, and also a challenge for each of us individually.

Acknowledgments: The author expresses his gratitude towards Walter Blum for constructive criticism and stimulating suggestions. Valuable discussions with Gerhard Luther as well as a critical review of section 3.3.1 by Eike Gelfort and of the section on wind power by Andreas Otto are also gratefully acknowledged.

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