5 Coal

5.1 Fossil Plant Residue with High Energy Potential

5.1.1 Coal Formation

Coals are solid, combustible, fossil sediments originated predominantly of dead organic material, which were subject to diagenetic changes after they were deposited and covered; these changes caused an enrichment of carbon (Pohl, 1992). Thus, coals are fossil residues of dead biomass. This organic material was deposited in swamps, in which organic material accumulated over time and peatbogs were created. Thick peatbogs developed, if a sufficient plant growth was possible in the swamp, if dead organic material was covered with water as protection against oxidation, if only small amounts of mineral sediment were introduced and a constant water level in the swamp prevented flooding and desiccation. The latter would either have resulted in a cessation of the growth of plants or the organic degradation and oxidation processes of the peat. Important coal basins with productive coal bearing formations and coal seam thicknesses of several meters to several tens of meters develop from peatbogs in slowly subsiding areas. This in part wide-ranging subsidence is frequently of tectonic origin, in some cases also caused by salt leaching and salt migration in the substratum, respectively. In the process the annual subsidence rates must approximately keep up with the growth of the swamp and thus with that of the organic material. The vertical growth of the swamp ranges approximately between 0.5 mm/a in cooler regions and up to 4 mm/a in tropical regions. The longer a peatbog can grow relatively undisturbed, the thicker the coal seams become in the end. Generally, approximately 6 m peat result in lignite (soft brown coal) seams of a thickness of about 3 m and hard coal seams of a thickness of approximately 1 m (Pohl, 1992). The reduction in thickness from peat via lignite to hard coal is caused by the diagenetic processes, which follow upon the end of the growth of the peatbog, and which mainly occur after the peatbogs have been covered by sediment layers. The increasing pressure of the covering rocks increasingly squeezes the water out of the peat and the temperature increases with increasing depth of burial. A multitude of biochemical and geochemical processes then convert the formerly soft peat into solid coal. With increasing coalification the dead organic material is transformed in accordance with the coalification series via peat, the different types of brown coal to hard coal (incl. anthracite). Also the vitrinite reflectance and the energy content of the coal increase, in addition to the carbon content. In return, the percentage of volatile matters and the bed moisture decrease (Fig. 2.4).

The formation of the largest occurrences and thus resources of hard coal mainly took place in the geological periods Carboniferous, Permian and Jurassic. Lignite originates primarily in the Tertiary. Coal occurrences consist of layered coal seams occurring mainly in extensive, continuous provinces. In comparison to their vertical thickness (seam thickness) they have considerable lateral dimensions. Laterally, coal seams can extend along hundreds of kilometers, whereas the seam thicknesses vary between a few centimeters and several tens of meters. In general, coal seams occur in interbedded strata with other sediments. Depending on the conditions of their formation, coal basins with several hundred coal seams layered one above the other can develop. Correspondingly, coal can be found in different depths. It can range from the ground level down to a depth of several thousand meters. The coal deposits investigated world-wide for which resource calculations and assessments have been conducted are located in depths down to 2000 m. Economically recoverable deposits are rarely located at depths below 600 m.

Most of today's coal production originates in coal basins, which have been assigned either to the platform type or to the geosynclinal type. Coal basins of the platform type were formed on so-called shields, which subsided slowly and over a very long time. For this type, relatively few, but very deep and undisturbed seams in shallow location with long horizontal dimensions are characteristic. The coal deposits and coal basins of South Africa and India with the Gondwana coal from the Upper Carboniferous to the Permian, the huge Siberian Tunguska Basin (Pohl, 1992) as well as the majority of the coal deposits in the north of China on the North China Platform (Sinic Shield) are typical representatives of this type (Fig. 5.1).

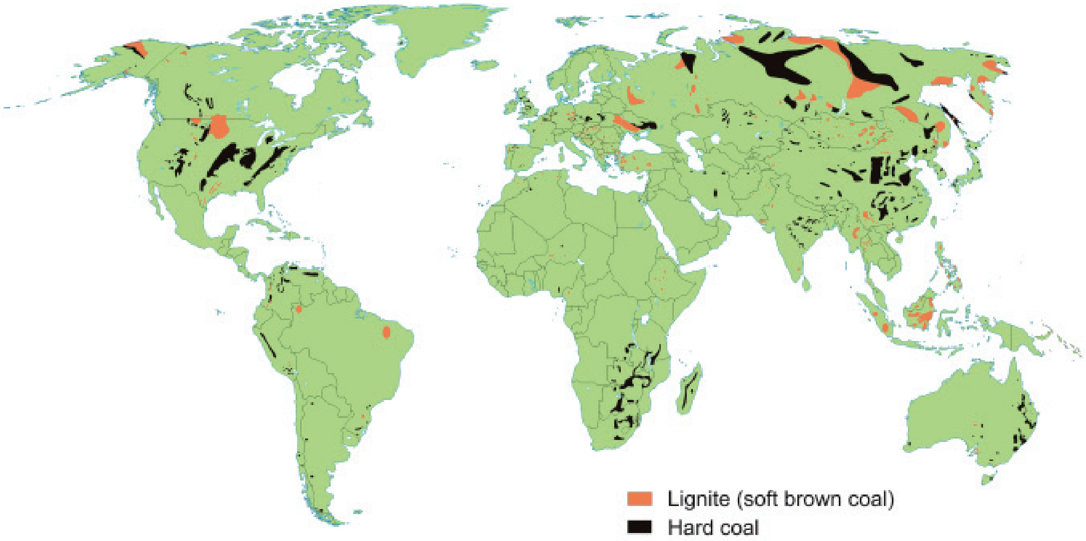

Figure 5.1: Geographic location of the most important coal deposits/basins of the world.

Coal seams of the geosynclinal type developed in quickly subsiding troughs in the foreland. Inclined to steeply dipping, folded coal seams in frequently thousands of meters thick stratigraphic sequences are characteristic. These coal basins usually contain a high number of irregularly formed as well as thin coal seams. Well-known representatives of this geosynclinal type are the German Ruhr Basin as well as coal deposits in the Appalachian Mountains in the US.

5.1.2 Composition and Characteristics of Coal

Coal consists of macerals, the organic pendant of minerals, and impurities, which are also called partings or dirt bands. The impurities usually consist of clay, shale or sandstone and form non-combustible and thus undesired components of coal (Pohl, 1992). Coals are thus heterogeneous mixtures of different organic substances and inorganic materials, in particular water and mineral admixtures. The carbon content, measured at the water and ash-free substance, is between 60 and 70 % for lignite. In hard coal, it can reach up to 97 % for anthracite. At higher levels of carbon, graphite is present, which may be used for instance as lubricant. Depending on the depositional environment, coal can contain higher contents of sulfur and chlorides. Increased sulfur contents generate correspondingly higher sulfur dioxide emissions during combustion. For this reason, commercially available coal rarely contains more than 1 % sulfur. Chlorides can result in harmful scaling and corrosion in the boilers during combustion, thus low chloride contents are required as well.

Whereas lignite is soft, sliceable with a knife and as a rule has a brownish color, hard coal is rigid and of black-brown to anthracite color and has a density between 1.2 and 1.45 g/cm^3. Today, peat has only a very limited, regional importance as a fuel. Peat is increasingly used in gardening and landscaping. Therefore, peat in its use as energy resource will not be dealt with.

5.1.3 Which Type of Coal for which Use?

Depending on the intended use, coal is subdivided into energetic and coking coal. Energetic coal comprises lignite and the majority of the hard coal types (Fig. 5.2). Power generation out of lignite is usually conducted at the place of production because of the high water content and the relatively low energy content and the associated high cost of transportation.

<table>
<tr><th>Subdivisions and classifications</th><th colspan="13">Increasing coal rank →</th></tr>
<tr><td>Internationally conventional classification</td><td colspan="2">lignite</td><td colspan="11">hard coal</td></tr>
<tr><td>Germany and countries to the east</td><td colspan="5">brown coal</td><td colspan="7">hard coal</td><td>anthracite</td></tr>
<tr><td>English speaking area</td><td>lignite</td><td colspan="5">sub-bituminous coal</td><td colspan="6">bituminous coal</td><td>anthracite</td></tr>
<tr><td>International Classification of in-Seam Coals (UN-ECE 1998)</td><td colspan="4">lignite</td><td colspan="2">sub-bituminous coal</td><td colspan="5">bituminous coal</td><td colspan="2">anthracite</td></tr>
<tr><td rowspan="3">commercial classification according to intended use</td><td colspan="3"></td><td colspan="5">steam coal</td><td colspan="2"></td><td colspan="3">steam coal</td></tr>
<tr><td colspan="7"></td><td colspan="4">coking coal</td><td colspan="2">anthracite</td></tr>
<tr><td colspan="6"></td><td colspan="3">PCI-coal</td><td colspan="3"></td><td>PCI -coal</td></tr>
</table>

Figure 5.2: Comparison of standard subdivisions and classifications of coal in accordance with the coalification (cf. also Fig. 2.4).

Energetically useable hard coal, which is called steam or thermal coal, is more common for transportation to the consumer due to its higher energy content. The dominant quality parameter for steam coal is a high calorific value. Besides low sulfur and chlorine contents, a low energy demand for crushing the coal, the so-called grindability, is advantageous, as in power plants mainly finely ground coal is used. The coal used for Pulverized Coal Injection (PCI-coal) is usually low-volatile steam coal, which is increasingly gaining importance as reduction agent for the pig iron production (IEA, 2006). There are significantly higher quality requirements for coking coal than for steam coal. The high-quality hard coking coal used in coke plants has to be low in ash as well as low in sulfur and, above all, needs corresponding coking properties, such as the caking power.

5.1.4 Coal as Global Power Source

Currently, coal is the second most important energy resource of the world after petroleum in view of the consumption. Due to its widespread and plentiful occurrences in comparison to other energy resources it is regarded as an important element of supply security in the energy sector. The remaining potential of coal, i.e. the total resources of reserves and resources, has been estimated by the BGR to be about 21 trillion Gt at the end of 2007. 16 404 Gt or about 79 % of these are hard coal and the remaining amount of 4345 Gt is lignite. Lignite and hard coal together have the greatest potential of all non-renewable energy resources at a percentage of about 55 %, corresponding to 722 Gtce, of the reserves and about 76 %, i.e. 14 866 Gtce of the resources. This is sufficient to meet the foreseeable demand for many decades.

In 2007, coal with a proportion of about 30 % (hard coal 28 %, lignite 2 %) of the global total primary energy supply took the runner-up position behind petroleum with a proportion of approximately 36 %. Today, coal is primarily used for power generation in power plants in the base and medium load range. For the global power generation (gross), coal was the most important energy resource at a percentage of 40 % (7620 TWh) in 2006 (IEA, 2008a). From a global point of view, this mainly refers to hard coal. Of the approximately 5.5 Gt of hard coal globally produced in 2007, approximately 4.77 Gt were steam coal and only 0.77 Gt were coking coal, indispensable for today’s steel production (IEA, 2008b). 0.98 Gt of lignite were produced, which is also nearly exclusively used in power plants, but which has a lower energy content in comparison to hard coal.

Modern power plant technologies today reach efficiencies of up to 45 % and thus contribute to the reduction of CO_2-emissions. The future development of coal´s share in the generation of primary energy in many industrial countries will also depend on the extent to which CO_2 capture and storage, CCS, can be developed, introduced and implemented, and on the corresponding costs (Info box 7). In emerging countries, the consumption of coal might increase short-term and mid-term, relatively independently of the CCS-development. New and more efficient technologies in the area of the surface and subsurface gasification and the liquefaction of coal (Info box 8) as well as the intensification of the energetic use of coalbed methane open new possibilities of use for the primary energy source coal.

5.2 Hard Coal

5.2.1 Total Resources of Hard Coal and Regional Distribution

The total resources of hard coal as of 2007 have been assessed at 16 404 Gt and can be divided into 4.4 %, corresponding 729.5 Gt reserves and 95.6 %, i.e. about 15 675 Gt resources. Regionally, hard coal is rather evenly distributed on the continents in comparison to petroleum and natural gas (Fig. 5.3). The globally highest total resources of hard coal are located in North America, about 6870 Gt (41.9 %), followed by the regions Austral-Asia at 34.9 % and the CIS at 18.3 %. The vast majority of the remaining approximately 664 Gt is located in Europe (Fig. 5.4).

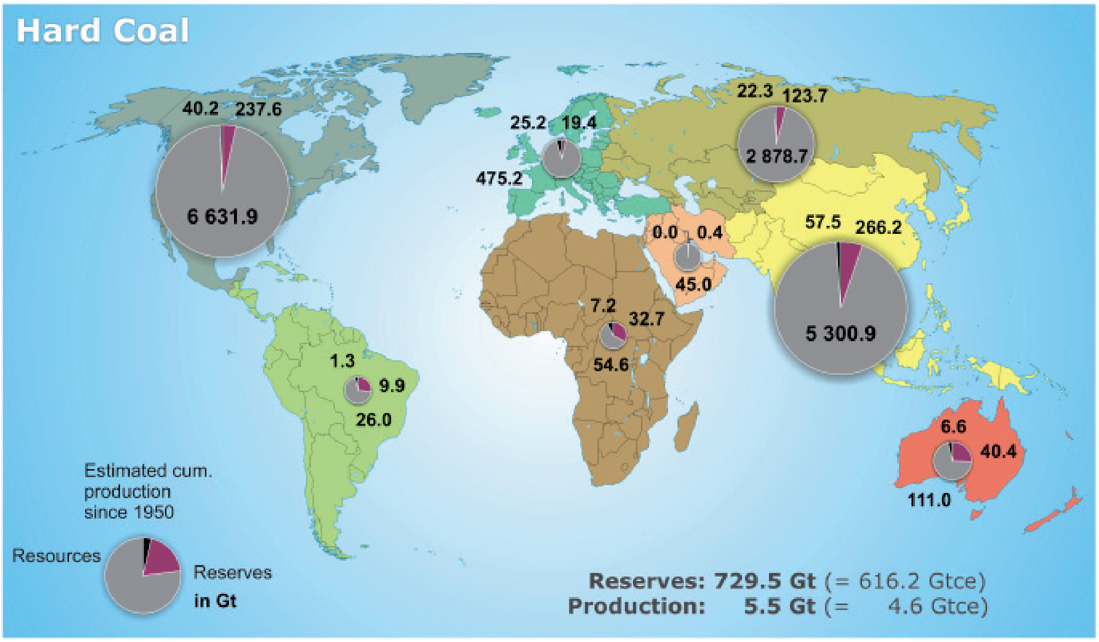

Figure 5.3: Regional distribution of the reserves, resources and the estimated cumulative production since 1950 of hard coal at the end of 2007.

According to countries, the most important total resources are located in the US, about 6720 Gt (41 %), followed by the PR China at 31.6 % and Russia at 16.7 % (Fig. 5.4). These three countries thus together possess more than 89 % of the currently known total resources of hard coal. All other countries have percentages in the single-digit percentage range. In comparison to the individual production of the countries, these comparatively low total resources still represent very large amounts. Germany ranks tenth for the total resources of hard coal at about 83 Gt.

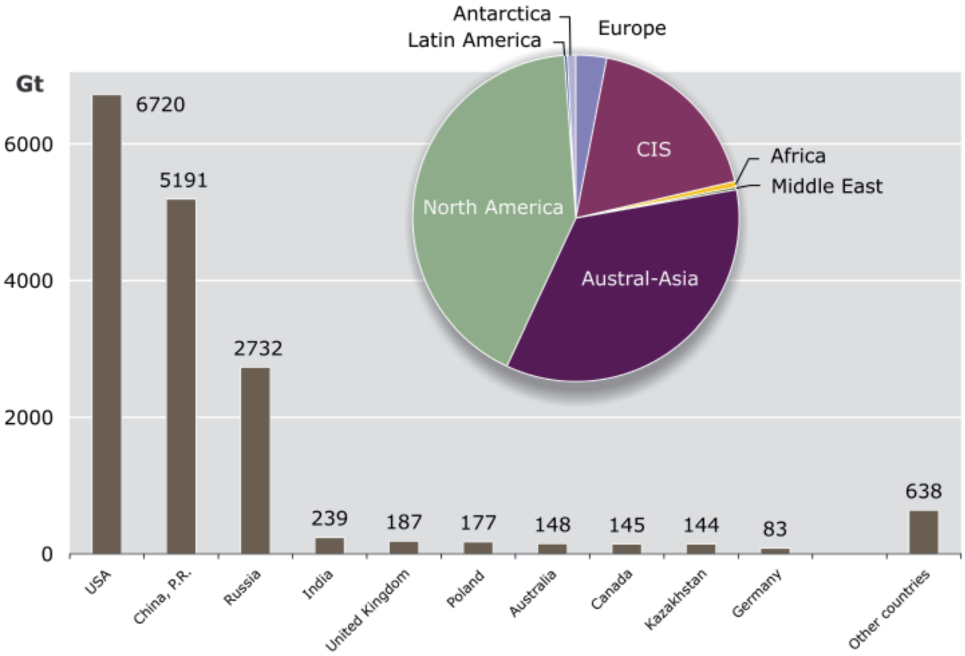

Figure 5.4: Total resources of hard coal (total 16 404 Gt) in 2007 of the top ten countries as well as their distribution by region.

5.2.2 Hard Coal Reserves

According to regions, most of the reserves of hard coal (91.6 %) are concentrated in Austral-Asia, North America and the CIS. 306.6 Gt of the reserves, 42 % are located in Austral-Asia, mainly the PR China, India and Australia with together about 297 Gt, approximately 96.7 %, (Fig. 5.5). North America possesses the second largest reserves of hard coal of 237.6 Gt (32.6 %). There, the US alone possess 97.6 % of the reserves. The CIS follows with 17 % (123.7 Gt) at rank three. There, the largest reserves of 69.9 Gt are located in Russia, in the Ukraine at 32 Gt and in Kazakhstan at 18.9 Gt. The regions Africa (32.7 Gt), Europe (19.4 Gt) and Latin America (app. 9 Gt) possess smaller, but still significant reserves of hard coal. In the Middle East there are only few hard coal reserves (0.4 Gt).

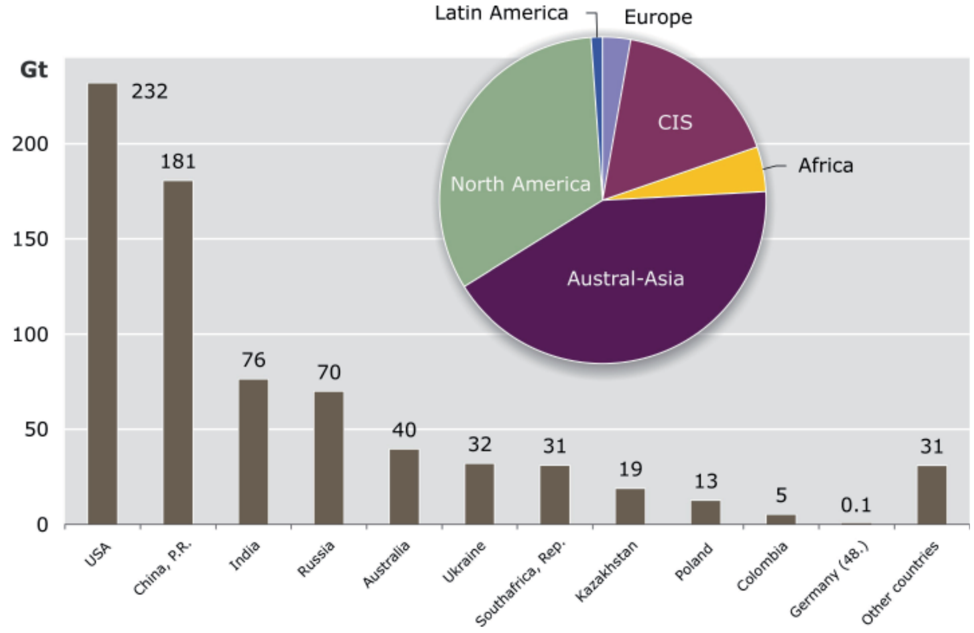

Figure 5.5: Reserves of hard coal (total 729.5 Gt) in 2007 of the top ten countries and Germany as well as their distribution by region.

5.2.3 Hard Coal Resources

Just as for hard coal reserves, the largest part, 95.2 %, of the global resources of hard coal are concentrated in the regions North America, Austral-Asia and the CIS (Fig. 5.6). At roughly 6632 Gt (42.3 %) North America dominates the resources, which are, however, mainly located in the still largely undeveloped areas of Alaska. The resources of hard coal in Austral-Asia amount to 5412 Gt (34.5 %). The resources of hard coal in Asia amount to 5301 Gt or 33.8 % of the global resources. In Oceania, the hard coal exporting country Australia accounts for the comparatively relatively small amount of about 109 Gt. The main part of the Asian resources of hard coal, 5010 Gt, is located in the PR China (Fig. 5.6).

The CIS-region also possesses considerable resources of hard coal, 2879 Gt (18.4 %). More than 80 % of these are located in the largely undeveloped areas of Siberia. There are also considerable resources located in Europe, about 475 Gt (3 %). The other regions only contain very small amounts of 1 % at most.

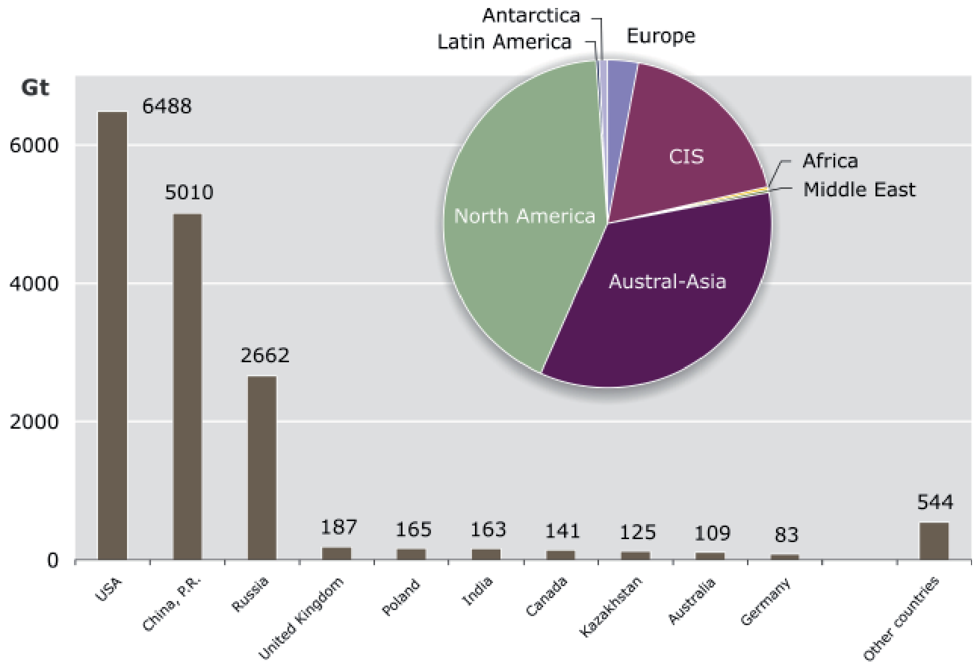

Figure 5.6: Resources of hard coal (total 15 675 Gt) in 2007 of the top ten countries as well as their distribution by region.

The comparatively low amounts of reserves and resources of hard coal in the regions Latin America and Africa can only be explained to a certain extent by the individual geological formation conditions for coal in these regions. For these regions – with the exception of South Africa – the historically grown degree of utilization of coal has to be considered. Because of the relatively low-volume use of coal, in comparison to Europe and North America, which has only started to increase in the past decades, up to now there had been little need for coal exploration. For the future, increased reserves and resources of coal can be expected in these regions due to the increased exploration efforts of the past years.

5.2.4 Hard Coal Production

Hard coal is produced via surface mining and underground mining. The surface mining is the more favourable alternative, because the use of large equipment (Fig. 5.7) and less personnel yields a significantly higher production rate. The most important criterion for an economic extraction in surface mining is the ratio of overburden that must be moved to extract one ton of coal, the so called strip ratio (in m^3/t). For coal seams in shallow depths to about 200 m and favorable strip ratios the production of hard coal in surface mines preponderates.

More than half of the globally produced hard coal is produced from underground coal mines. This is primarily due to the high share of the Chinese hard coal production from underground coal mines, which ranges at about 95 % (Schmidt, 2007). The extraction methods predominant in underground mining are the so-called longwall mining and the room and pillar mining. Underground hard coal production is mainly executed in depths up to 500 m. In particular in coal mining districts, in which hard coal has been extracted for more than 100 years on a large scale, significantly deeper average extraction depths can be reached. These comprise first of all the European coal basins such as the Polish Upper Silesian Coal Basin with an average extraction depth of about 800 m, the Ukrainian/Russian Donets Basin with approximately 720 m and the German Ruhr Basin at 1145 m. Progressive mechanization in underground mining resulted in a significant increase of productivity in the past decades. Simultaneously, the utilization of deposits decreased, as the mining of thin coal seams has become increasingly uneconomical. In particular the use of increasingly larger and heavier extraction machinery in longwall mining, such as shearers and plows, requires as thick as possible, little disturbed and horizontally bedded coal seams.

The numbers given about the hard coal production deal as a rule with the production of saleable hard coal. In contrast to raw coal (Fig. 5.7), the saleable product has frequently been treated in order to correspond to the quality requirements of the individual consumer. The specification only used in Germany of tons of useable production (Tonnen verwertbare Förderung/t v. F.) allows the comparison of the production from different German hard coal mines independently of the coal qualities produced. These production amounts standardized for purposes of comparison are on average 10 % lower than the actually saleable output (BGR, 2005). This has been taken into account for the comparison of the German amounts with the production of other countries.

Figure 5.7: Production of hard coal (raw coal) using truck and shovel in the surface mine Baganuur/Mongolia.

In 2007, the global production of hard coal amounted to approximately 5523 Mt. Nearly two thirds of this production or 3581 Gt were generated in Austral-Asia, followed by North America at 18.8 % and the CIS at 7.4 %. The other four regions Africa, Europe, Latin America and the Middle East together contributed less than 10 % of the produced hard coal (Fig. 5.8, Tab. 5.1). The three top producers of hard coal in 2007 were the PR China with a proportion of 44.9 % (2479 Mt), the USA with 17.5 % (968 Mt) and India with 8.2 % (about 452 Mt). Thus, more than 70 % of the global hard coal production originated from only three countries (Fig. 5.8). The by far predominant part of the production of these three countries is consumed in the country itself (Section 5.2.5). The following ranks are taken up by the four currently most important hard coal exporting countries Australia, the Republic of South Africa, Russia and Indonesia (Section 5.2.8). The most important European hard coal producing country in 2007 was Poland at about 88 Mt (globally at the ninth position), amounting to more than half of the EU-27-hard coal production of 159.1 Mt. Other important hard coal producing countries in Europe were Germany at 24.2 Mt, Great Britain at 16.8 Mt and the Czech Republic at 13.1 Mt.

An overview of the production and simultaneously the consumption of hard coal, the coke production and the coal trade, differentiated according to the two main purposes, steam coal and coking coal, is only possible if statistics of other institutions are included. These are primarily the International Energy Agency (IEA), the Statistik der Kohlenwirtschaft (SdK) and the German Coal Importers Association (VDKI). Due to differences in data acquisition and processing, differences between the BGR-data and the data of the other institutions may occur. As a rule, these differences are only marginal, at most in the single-digit percentage range. They are primarily based on the use of different sources as well as assessments and result from the difficulty of the different assignment of steam coal and coking coal based on different national coal classifications (Section 2.3.3).

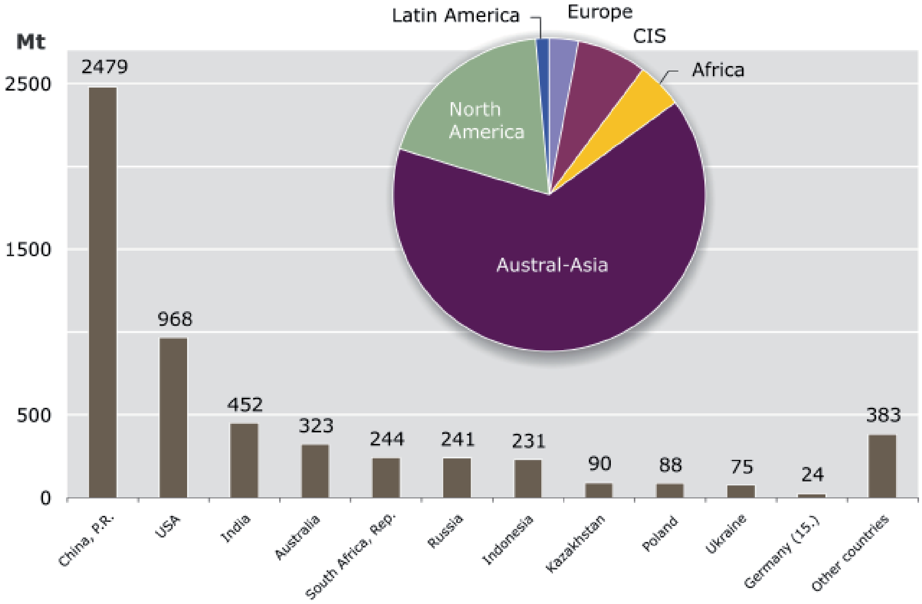

Figure 5.8: Hard coal production (total 5523 Mt) in 2007 of the top ten countries and Germany as well as their distribution by region.

According to IEA data, about 86 % of the global hard coal production of 5.54 Gt in 2007 consisted of steam coal and and only about 14 % of coking coal (IEA, 2008b). High-quality hard coking coal traded on the world market is only produced in relatively few countries, primarily in Australia, Canada and the US. However, the by far greatest coking coal producer with a production of 356 Mt (46 %) in 2007 was the PR China. For several years, Australia has been the second greatest coking coal producer and produced approximately 142 Mt in 2007. The share of coking coal of the Australian hard coal production is disproportionately high in comparison to all other important hard coal producing countries and was nearly 44 % in 2007. The currently third most important coking coal producer is Russia with a production of about 62 Mt in 2007. From these three countries together derived nearly three quarters (72.8 %) of the worldwide coking coal production.

Whereas the PR China and Russia consumed most of the coking coal domestically because of the high domestic demand, Australia currently exports more than 90 %. Coking coal accounted for about 13.8 Mt, corresponding to 57 % of Germany's total hard coal production of 24.2 Mt in 2007 (IEA, 2008b). Only 18 % (4 Mt v.F.) of the German hard coal production were consumed by the steel industry, whereas the majority was consumed in power plants and secondarily in the heat market (RAG AG, 2008). The reasons are probably insufficient coking coal qualities as well as long-term supply contracts with power plants.

The **production of hard coal** has doubled during the last 30 years to 5.5 Gt (Tab. 5.1). In particular since the start of the new millennium, the annual growth rate of the global hard coal production has ranged between five and nine percent. These growth rates considerably exceed the otherwise customary ten-year trend of 2.6 % (IEA, 2006). The development of the hard coal production during the observation period can be subdivided into three phases: 1.) gradual increase of the production up to the collapse of the Eastern Block 1990, 2.) lateral movements in the 1990s and 3.) rapid increase of production after the end of the

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CO_2 from Burning Coal, CCS in Germany?

A major challenge is using coal, as one of the most important fossil energy carriers in the world, while minimizing carbon dioxide emissions. The precipitation and subsequent storage of the carbon dioxide (CO_2) generated during combustion might provide a significant contribution. From a technical point of view, it may become possible to prevent 20 to 40 % of the global CO_2 emissions by 2050 using CO_2-precipitation and storage (Carbon Capture and Storage, CCS). CCS is not only possible for coal power plants, but also for other CO_2-emitting industries such as the steel or chemical industries.

The CO_2-precipitation in coal power plants takes place either before, during or after the coal is burnt. No explicit preferences for a certain process can be derived from the available cost analyses. The deterioration of the efficiency of the power plants due to CCS has to be considered. For transportation and storage purposes, CO_2 can be liquefied and transported through pipelines or in tankers to the storage location. Possible storage locations are exhausted deposits of petroleum and natural gas, salt-water bearing layers and possibly coal seams.

In Germany, primarily former natural gas fields and deep salt-water bearing layers can be used for CO_2-storage. Storage locations are located in particular in the North German area approximately to the north of an imaginary line between Berlin and Hannover up into the North Sea and the Baltic Sea. The Molasse Basin north of the Alps only has a low potential in comparatively small structures and also the Saar-Nahe depression and the Thuringian Basin are suitable to only a limited extent for geological reasons. In the Upper Rhine Graben the increased earthquake hazard limits the possibilities for CCS.

Currently the groundwork is laid for energy and climate change policy to implement the CCS-technology in Germany and in other countries. Up to now, CO_2-precipitation and storage are still in the research and development phase. For a final evaluation of the industrial applicability, pilot projects have to be conducted on an industrial scale.

Asian crisis since 2000. The quadruplication of the production in Austral-Asia in the course of the past 30 years is particularly striking (Tab. 5.1), in particular due to the increase in production in the PR China, in India, Australia (Tab. 5.2) and in Indonesia. Together, these four countries produced about 97 % (3.5 Gt) of the Austral-Asian output in 2007. After 1999, the hard coal production in this region alone doubled due the soaring energy demand.

In contrast to the global trend, the European hard coal production declined during the past thirty years. Whereas at the end of the 1970s nearly one fifth of the global hard coal production originated in Europe, in 2007 only 3 % of the global production remained (Tab. 5.1). This corresponds to a reduction of the European production by two thirds to about 166 Mt. The production of hard coal in the CIS dropped dramatically in the wake of the political-economic upheaval in the 1990s due to the dwindling demand. In the meantime, the hard coal demand and in consequence also the production in the CIS have increased again, which can mainly be attributed to the increased hard coal exports from this region. Current production is still significantly below the level of the 1980s (Tab. 5.1).

Table 5.1: Development of hard coal production according to regions from 1978 to 2007 (WEC, 1980; BGR, 1989, 2003).

Region	**Hard coal production in Mt** (Region´s share of the global annual production)				**Change 1978/2007** (%)
Year	**1978**	**1987**	**1999**	**2007**	
Europe	491.8 (18.4 %)	589.5 (16.6 %)	277.5 (7.8 %)	165.8 (3.0 %)	- 66
CIS	572.0 (21.4 %)	594.5 (16.7 %)	256.0 (7.2 %)	407.2 (7.4 %)	- 29
Africa	96.7 (3.6 %)	182.6 (5.1 %)	231.1 (6.5 %)	249.3 (4.5 %)	+ 158
Middle East	1.0 (0.0 %)	1.3 (0.0 %)	0.9 (0.0 %)	2.0 (0.0 %)	+ 100
Austral-Asia	895.2 (33.5 %)	1339.8 (37.7 %)	1763.2 (49.8 %)	3581.1 (64.8 %)	+ 300
Asia only	821.5 (30.8 %)	1188.7 (33.5 %)	1535.2 (43.3 %)	3253.5 (58.9)	+ 296
North America	604.0 (22.6 %)	820.4 (23.1 %)	964.5 (27.2 %)	1037.8 (18.8 %)	+ 72
Latin America	9.6 (0.4 %)	24.7 (0.7 %)	50.0 (1.4 %)	79.6 (1.4 %)	+ 733
WORLD	*2670.2* *(100 %)*	*3552.8* *(100 %)*	*3543.2* *(100 %)*	*5522.7* *(100 %)*	*+ 107*

From 1980 to 2007, the steam coal production increased from 2.270 Gt to 4.773 Gt (+ 110 %). This was significantly higher than the increase of coking coal production from 0.531 Gt to 0.769 Gt (+ 45 %) according to IEA (2008b). Thus, about 86 % of the global hard coal production in 2007 were steam coal and only about 14 % were coking coal (Fig. 5.9). The enormous expansion of the steam coal production can mainly be attributed to the soaring global demand for energy, primarily for power generation. For instance, the global consumption of electricity increased by about 130 % to 15 655 TWh between 1980 and 2006. In 2006, the OECD-countries accounted for most of it at about 58 %, followed by the PR China and India, which consumed 18 % together (IEA, 2008c).

Even though the pig iron production in furnaces nearly doubled to approximately 946 Mt between 1980 and 2007 (World Steel Association, 2009), the production of coke required for the production of pig iron increased only by little more than half (Section 5.2.6). Thus, the growth of the global coke production has the same order of magnitude as the increase in the production of coking coal, from which coke is produced. The low increase in the coke production in comparison to the pig iron production can be mainly attributed to the reduced use of coke per produced ton of pig iron. Thus, in 1980 in the countries of the EU-15, for the production of 1 t of pig iron about 500 kg of coke (dry) were still required, in 2006 only 349 kg (SdK, 1990; Ameling, 2007). This corresponds to a reduction by about 30 %. Today coke is mainly used as propping agent in modern furnaces. The functions as energy source and reducing agent have increasingly been taken over by PCI-coal (pulverized coal injection) and heavy oil.

Table 5.2: Production development of the top five hard coal producing countries of the year 2007 from 1978 to 2007 (WEC, 1980; BGR, 1989, 2003).

Country	**Hard coal production in Mt** (Region´s share of the global annual production)				**Change 1978/2007** (%)
Year	**1978**	**1987**	**1999**	**2007**	
China, PR	620.9 (23.3 %)	888.5 (25.0 %)	1045.0 (29.5 %)	2479.2 (44.9 %)	+ 299
USA	572.0 (21.4 %)	763.3 (21.5 %)	919.6 (26.0 %)	967.9 (17.5 %)	+ 69
India	101.3 (3.8 %)	178.5 (5.0 %)	292.2 (8.2 %)	451.6 (8.2 %)	+ 346
Australia	71.8 (2.7 %)	149.0 (4.2 %)	225.0 (6.4 %)	323.0 (5.8 %)	+ 350
South Africa, Rep.	90.4 (3.4 %)	176.5 (5.0 %)	222.3 (6.3 %)	243.6 (4.4 %)	+ 169
Total	1456.3 (54.5 %)	2155.8 (60.7 %)	2704.1 (76.3 %)	4465.2 (80.9 %)	
WORLD	*2670.2* *(100 %)*	*3552.8* *(100 %)*	*3543.2* *(100 %)*	*5522.7* *(100 %)*	*+ 107*

In spite of the wide regional spread, there are concentration tendencies among the **largest hard coal producing companies**. As the hard coal produced in China, the USA and India is mainly used domestically, 30 % of the steam coal traded by sea and even 47 % of the coking coal traded by sea are concentrated on the so-called Big Four (Wodopia, 2009). These four companies, also called RBXA Group, are Rio Tinto, BHP Billiton, Xstrata/Glencore International and Anglo Coal (Tab. 5.3).

The world market share of the ten largest corporations according to revenue amounted to 62 % for steam coal and to 71 % for coking coal in 2005 (VDI, 2006). Thus, the coal industry at this point in time ranges in the midfield of the extractive industry, whose highest degrees of concentration were reached for iron ore (97 %) and nickel (95 %). Lower concentration tendencies occurred for instance for copper at 54 %, zinc at 42 % and gold at 37 % (VDI, 2006). The degree of concentration in the coal sector will probably increase in the coming years mainly in the Asian area. According to the tenth Chinese five-year plan (2006 to 2010), only 13 really large coal companies were to exist in China, of which five to seven companies were to have a production capacity in the range of 100 Mt/a (Chen, 2006). In relation to the production of 2007, four Chinese coal producers were already amongst the twelve top global producers (Tab. 5.3).

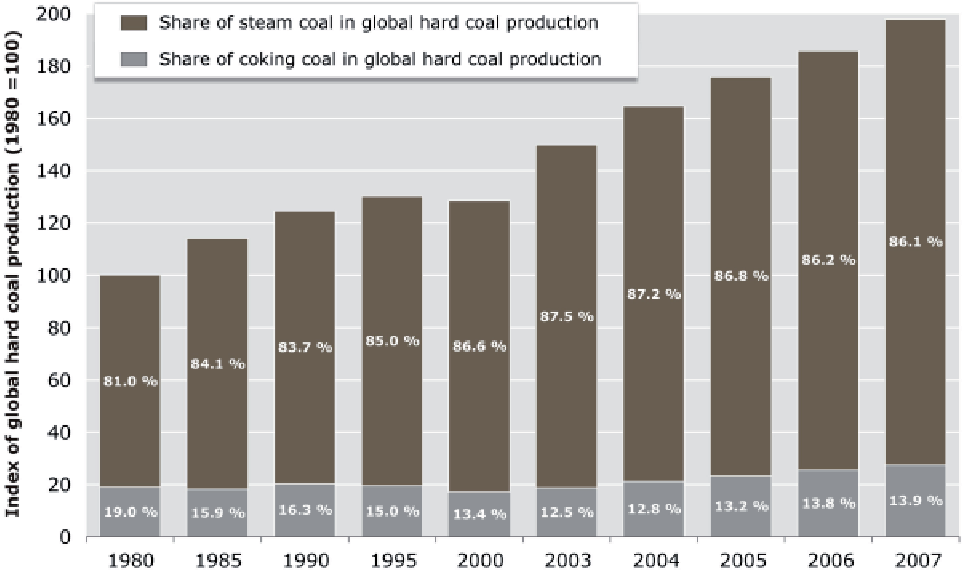

Figure 5.9: Development of the global hard coal production subdivided into coking coal and steam coal from 1980 to 2007 (IEA, 2008b).

Table 5.3: The top twelve hard coal producing companies in the world in 2007 (company information; The Tex Report, 2008; EIA, 2008b).

Company	Production locations	Production 2007 (Mt)	Remarks
Coal India Ltd.	India	379.5	raw coal production
Peabody Energy Group	Australia, USA, Venezuela	193.8	total of 215.7 Mt sold
China Shenhua Energy Company	China	158.0	total of 209.1 Mt sold
Rio Tinto	Australia, USA	155.7	
BHP Billiton	Australia, Colombia, South Africa, USA	122.9	
Arch Coal	USA	115.1	
Anglo Coal	Australia, Canada, Colombia, South Africa, Venezuela	95.6	
SUEK (Siberian Coal Energy Company)	Russia	90.9	
Xstrata/Glencore International	Australia, South Africa	82.8	
Shanxi Coking Coal Group	China	72.4	raw coal production; in total 74.4 Mt sold
China Coal Energy	China	69.3	in total 85.2 Mt sold
Datong Coal Mine Group	China	65.5	raw coal production; in total more than 100 Mt sold

The hard coal **production costs** vary significantly from country to country. They are primarily influenced by the type of production, in surface or underground mines. Important geological parameters are, besides the depth, the bedding conditions as well as the formation (undeformed/disturbed, thin/thick) of the coal seams (Fig. 5.10). In addition, the geographic location and the associated infrastructure as well as climatic conditions of the mining area are important as well.

Figure 5.10: Several meters thick hard coal seams in semisteep stratification in the surface mine Panian on Semirara Island, the greatest surface mine of the Philippines.

The prevailing part of the globally produced hard coal is consumed close to the deposit or in local power plants, respectively (Section 5.2.5). These are usually set to the regional coal qualities; this way, an extensive treatment of the coal can usually be avoided. If the coal is exported, however, frequently a treatment consisting of coal washing, screening and drying becomes necessary to attain the quality parameters required on the world market. Such treatment processes result in correspondingly higher production costs.

Typically those countries, where hard coal is produced mainly from surface mines, have the lowest production costs (Fig. 5.11). Accordingly primarily the countries exporting steam coal, such as Russia and Venezuela, followed by South Africa, Indonesia and Colombia, have the lowest production costs of approximately USD 15 to USD 30/t (Ritschel et al., 2005, 2007). Higher costs result for the production of coking coal in Canada in surface mines and in the US in underground mines. Whereas the costs listed in Figure 5.11 refer primarily to production costs of export mines in the individual countries, the comparatively low production costs in China are caused by the inclusion of the production costs of all mines.

From a technical point of view, there is no difference in mining between coking coal and steam coal. Because of higher quality requirements for coking coal, for instance concerning the ash content and coking characteristics, the number of possible deposits for the production of high-quality coking coal decreases. In addition, a higher beneficiation effort becomes necessary. As high-quality coking coal is produced in comparatively few deposits in the world, the producers can obtain higher prices on the world market. The higher revenue also allows a production at higher costs. The coking coal produced in underground mines in one of the oldest coal districts in the US in the central part of the Appalachian Mountains is considered a graphic example. In spite of large coal reserves, production costs of up to USD 80/t occur there, as the most accessible and thickest coal seams have already largely been exhausted. The production of coal from thin coal seams requires a much higher expenditure, which can only be procured, if the world market prices for coking coal permit it.

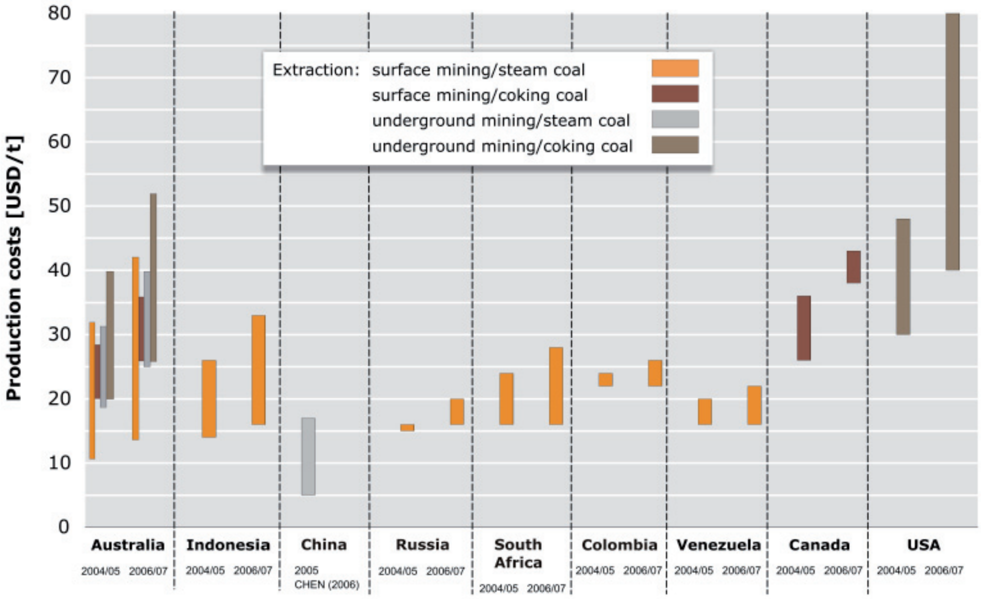

Figure 5.11: Hard coal production costs in selected countries comparing the years 2004/2005 and 2006/2007 (Chen, 2006; Ritschel et al., 2005, 2007).

In Australia, the most important hard coal exporting country, there is a relatively wide range of production costs. In some Australian surface mines, steam coal can be mined at lower production costs than in Russia or Venezuela, i.e. from approximately USD 14/t (2006/2007). In some cases they can be two or three times as high with costs of up to USD 42/t. The coking coal production costs in Australian surface mines at USD 26 up to USD 36/t are lower than in Canada (Fig. 5.11).

The Chinese production costs for hard coal which is nearly exclusively mined underground ranged in 2005 between USD 5 and USD 17/t (Chen, 2006). The very low production costs in the comparison to other countries probably refer to the whole Chinese coal sector and comprise the modern Chinese high-performance coal mines as well as the non-mechanized small mines with low capital expenditure and wages. Today the production costs of high-quality Chinese export coal can be even higher than the USD 17/t specified by Chen (2006), as shown by the example of the China Coal Energy Company (Tab. 5.4).

Table 5.4: Development of the hard coal production costs of selected companies according to annual reports and company presentations.

Country	Company (Producing region)	Remarks	Production costs (USD/t)							Change 2004/2008 (%)
			2002	2003	2004	2005	2006	2007	2008	
Canada	Elk Valley Coal/Teck Cominco www.teck.com	Surface mining; CC1)	17.2	20.1	20.0	27.2	35.3	39.1	50.1	+ 150
USA	Arch Coal www.archcoal.com						14.9	16.0	17.9	
	Powder River Basin	Surface mining; SC2)		6.0	6.8	7.9	9.6	10.3	11.3	+ 66
	Western Bituminous	underground SC2) mining;		17.0	17.3	18.1	17.2	21.6	24.0	+ 39
	Central Appalachian Mountains	primarily underground mining; SC2) and CC1)		34.0	38.4	47.7	50.8	48.9	55.2	+ 44
	Consol Energy www.consolenergy.com (Northern and central Appalachian Mountains)	primarily underground mining; SC2) and CC1)		28.9	30.4	33.1	35.9	37.1	45.9	+ 49
PR China	China Shenhua Energy Company Ltd. http://en.shenhuachina.com	underground and surface mining; primarily SC2)			6.4	7.0	8.3	9.9	13.7	+ 114
	China Coal Energy Company Ltd. www.chinacoalenergy.com/eng	underground and surface mining; primarily SC2)					21.7	22.7	29.4	
Indonesia	PT Bumi Resources www.bumiresources.com	Surface mining; SC2); Cash costs only (without amortization, depreciation, overhead etc.)			16.0	23.7	26.1	25.9	33.1	+ 107

1) CC – coking coal, 2) SC - steam coal

In the global comparison, the German production costs for the underground production of hard coal are significantly higher, mainly because of difficult mining conditions in great depths of 1145 m on average (SdK, 2008b). The German production costs in 2007 were 170 €/tce (VDKI, 2008) or USD 265/tce.

On average, the production costs in the most important hard coal exporting countries (Fig. 5.11) rose by 25 % between 2004/2005 and 2006/2007. This can be mainly attributed to the soaring energy costs during that period. However, it was possible to compensate these cost increases by risen revenues during the regarded period, as the price for coal also increased steadily (Section 5.2.9). The changes in the production costs of selected coal producers for 2008 show that the energy costs increased disproportionately in comparison to the previous years because of the soaring energy prices until the middle of 2008 (Tab. 5.4). The increased costs can also be attributed to increased expenditure for personnel and spare parts as well as increased mining fees.

5.2.5 Hard Coal Consumption

The global hard coal consumption was about 5.52 Gt in 2007. As for the production, Austral-Asia accounted for nearly two thirds of the global consumption at 3.54 Gt (Fig. 5.12), followed by North America at 18.4 % and Europe at 7.4 %. Of the remaining four regions, only the CIS at 5.7 % and Africa at 3.5 % show significant consumption, whereas Latin America and the Middle East at together 0.05 Gt consume a proportion of less than one percent.

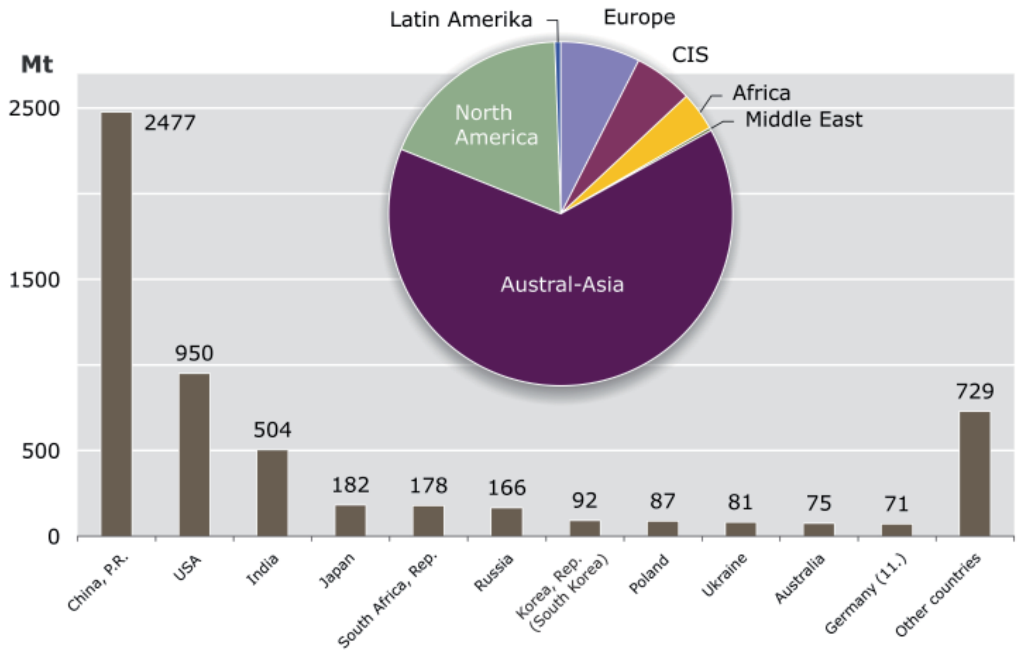

Figure 5.12: Hard coal consumption (total 5520 Mt) in 2007 of the top ten countries and Germany as well as their distribution by region.

As the main part of the globally produced hard coal is intended for individual domestic consumption, the three top producing countries are also the largest consumers. The PR China (Fig. 5.12) holds the leading position at a percentage of 44.9 %, followed by the US at 17.2 % and India at 9.1 %. The fourth-largest consumer at about 182 Mt (3.3 %) is Japan, which has to import nearly all its coal.

With the exception of South Korea at rank 7, which also imports its coal nearly entirely, the ten largest consumer countries (Fig. 5.12) are only those countries with a significant production of hard coal, i.e. South Africa, Russia, Poland, the Ukraine and Australia. Germany, with a hard coal consumption (including coke) of 71.3 Mt ranked eleventh in 2007. The three countries Poland, Germany and Great Britain accounted at about 221 Mt for nearly 59 % of the total hard coal consumption of the EU-27 in 2007.

About 87 % of the global hard coal consumption of 5.52 Gt in 2007 was steam coal and only about 13 % was coking coal (IEA, 2008b). The ranking of the largest consumers of steam coal (Tab. 5.5) differs only slightly from the ranking of the largest hard coal consuming countries (Fig. 5.12). This can be attributed to the high proportion of steam coal of the total hard coal consumption. In contrast, the demand and thus the ranking of the countries consuming coking coal is largely dependent on the pig iron production, which requires coke.

The PR China accounted for about half of the global coking coal consumption in 2007. With considerably less consumtion follow Japan and India, two more Asian countries, which rank second and third (Tab. 5.5). Germany ranked sixth with a consumption of 23 Mt of coking coal, corresponding to 3.2 % of the global consumption, behind Russia and the Ukraine.

The global **hard coal consumption** doubled between 1980 and 2007 according to IEA-data; however, the development was regionally very different (Fig. 5.13, Tab. 5.6). Whereas the hard coal consumption in Austral-Asia, North America and Latin America, the Middle East as well as in Africa increased significantly, the consumption in Europe and the CIS region decreased by nearly one third or about half (IEA, 2008b).

As the development of the hard coal consumption in principle does not differ from the production of hard coal, there will be no separate consideration.

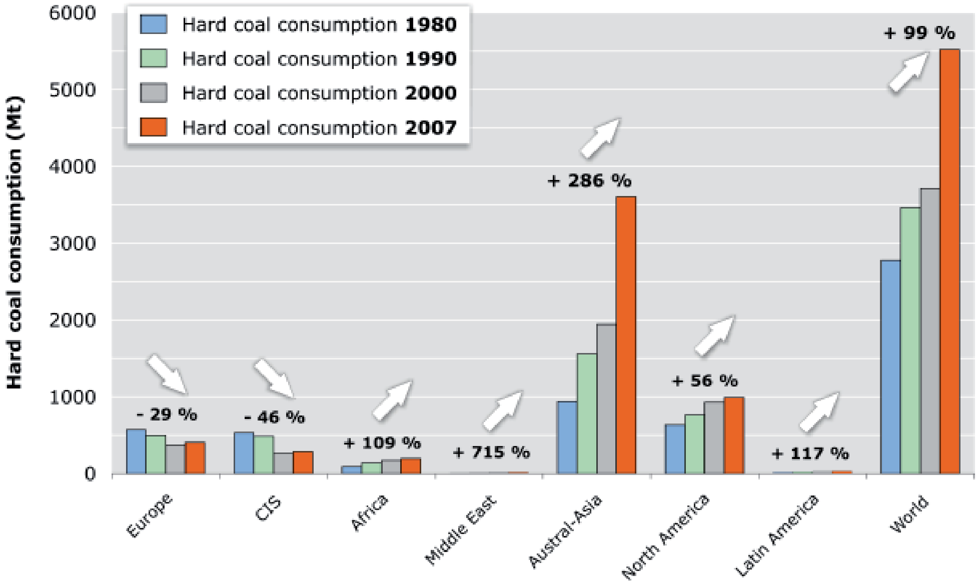

Figure 5.13: Development of the global hard coal consumption from 1980 to 2007 according to regions (IEA, 2008b).

Table 5.5: The top ten hard coal consumer countries differentiated according to steam and coking coal (IEA, 2008b).

Rank	Country	Steam coal consumption (Mt)	Share (%)	Rank	Country	Coking coal consumption (Mt)	Share (%)
1	China, PR	2 183.8	45.5	1	China, PR	359.3	49.7
2	USA	936.4	19.5	2	Japan	54.0	7.5
3	India	456.4	9.5	3	India	48.1	6.6
4	South Africa	176.1	3.7	4	Russia	47.1	6.5
5	Japan	128.3	2.7	5	Ukraine	29.8	4.1
6	Russia	105.4	2.2	6	Germany	23.0	3.2
7	Poland	73.8	1.5	7	South Korea	21.7	3.0
8	South Korea	70.4	1.5	8	USA	20.5	2.8
9	Australia	69.5	1.4	9	Poland	13.7	1.9
10	United Kingdom	62.7	1.3	10	Kazakhstan	10.8	1.5
	Total	4 262.6	88.8		Total	628.0	86.8
	WORLD	*4 798.6*	*100.0*		*WORLD*	*723.5*	*100.0*

Table 5.6: Regional development of the global hard coal consumption for 1980 and 2007 (IEA, 2008b).

Year	Consumption [Mt]	Region´s share of the global consumption in %						
		Europe	CIS	Africa	Middle East	Austral-Asia	North America	Latin America
1980	2777	20.6	19.1	3.3	0.1	33.7	22.8	0.5
2007	5522	7.3	5.2	3.5	0.3	65.3	17.9	0.5

5.2.6 Production and Consumption of Coke

The global coke production amounted to 544.4 Mt in 2007. At a proportion of 59.1 %, the PR China is the by far largest producer (Fig. 5.14), followed by the CIS-countries at 9.9 %, Japan at 7.1 %, India at 3.6 % and the USA at 2.7 %. Germany ranked ninth with a coke production of about 8.4 Mt (SdK, 2008a). Whereas the global coke production in the 1980s and 1990s varied between 330 and 375 Mt/a, it increased rapidly from 2001 onwards. Until 2007 the coke production increased by 197 Mt from 347 Mt to about 544 Mt. This growth is nearly exclusively due to the PR China with an increase of 190 Mt (SdK, 2008a).

Globally, the coke consumption in 2007 has the same order of magnitude as the production, at 544.3 Mt (SdK, 2008a). The largest coke consumer was also the PR China with a proportion of about 56 % (Fig. 5.15), followed by Japan at 9 % and Russia at approximately 5 %. Germany ranked seventh at 13.1 Mt coke (IEA, 2008b). The top ten coke consuming countries accounted for nearly 90 % of the global coke consumption of about 487 Mt.

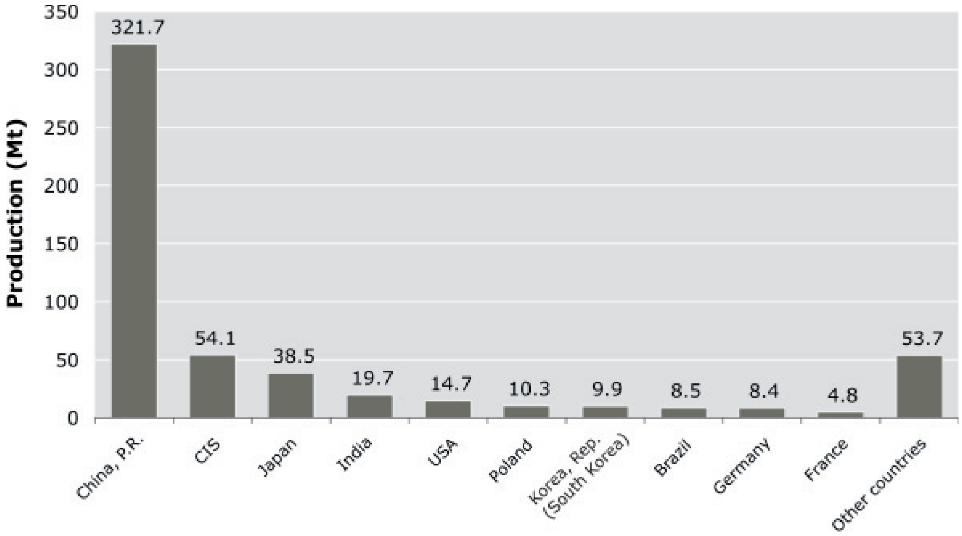

Figure 5.14: Coke production (total 544.4 Mt) in 2007 of the top ten countries (SdK, 2008a).

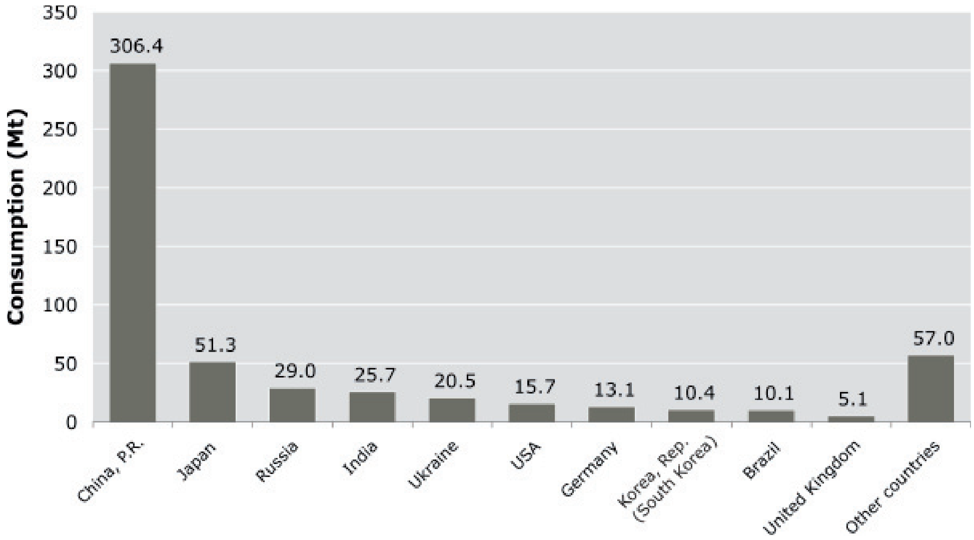

Figure 5.15: Coke consumption (total 544.3 Mt) in 2007 of the top ten countries (IEA, 2008b; Interfax, 2003-2009; SdK, 2008a).

5.2.7 Hard Coal Transportation

Generally, the long-distance transport of coal is conducted by ship and is thus in direct competition to other bulk goods such as ores or grain. Of the about 3 Gt of bulk goods transported by ship in 2007, nearly one quarter each was iron ore and coal. Iron ore at a plus of 76 % and coal at a plus of 50 %, since the year 2000, show the by far greatest growth rates of maritime transport (VDKI, 2008).

On principle, the freight costs depend on the size of the vessel and decrease with increasing tonnage. They are also influenced by seasonal fluctuations, for instance by increased grain exports after harvesting. Whereas the freight costs changed little in the 1990s, they increased significantly in 2003 and quadrupled or even quintupled by 2007 for all coal transportation routes (Fig. 5.16). This additionally increased the acceleration in prices of imported coal in the past years.

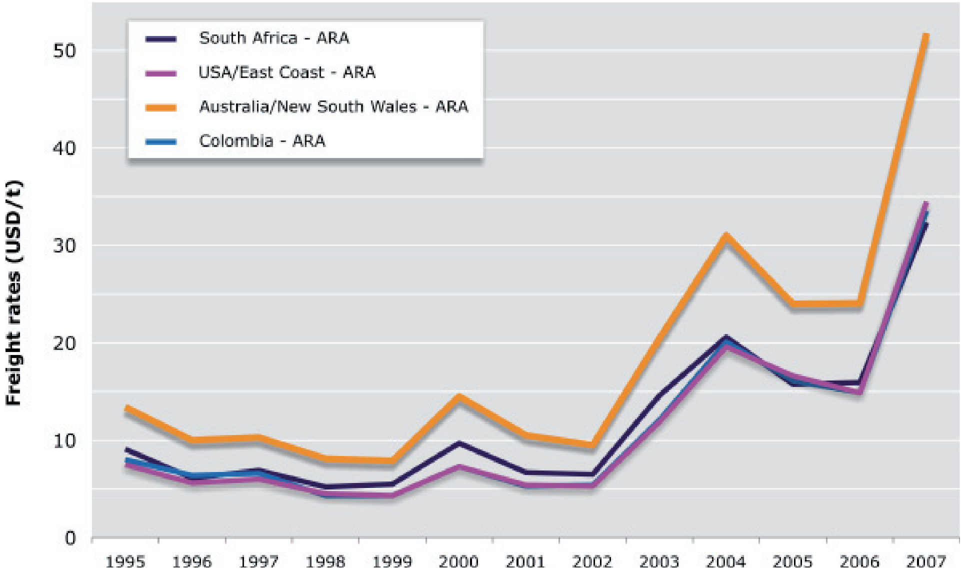

Figure 5.16: Development of the Capesize freight rates from 1995 to 2007 from different coal export countries to the large European ports Amsterdam, Rotterdam and Antwerp (ARA) (VDKI, 2006, 2008).

Investigations by Ritschel et al. (2007) show that the proportion of the sea freight and the port handling of the total costs in relation to the year 2006 amounted to approximately 28 to 37 % (USD 25 to USD 27/t) for coking coal and 36 to 46 % (USD 20 to USD 23/t) for steam coal. As the costs for the port handling with approximately USD 2 to USD 6/t cause a comparatively small share of the costs, the marine freight constitutes the second largest cost pool in most cases, the most important one being the production costs.

The inland transport from the mine to the export harbour is frequently covered by train. The coal export mines of the greatest hard coal exporter Australia are usually less than 200 km away from the ports, the South African export mines about 600 km (Productivity Commission, 1998). At 550 to 600 km, the distance from the Polish mines of the Upper Silesian Basin to the export harbors Gdansk, Gdynia and Swinoujscie is similar (UN-ECE, 1994). The main part of the Polish hard coal exports is transported to the adjoining countries by train. At 4500 km on average, Russian export coals are transported by rail over the greatest distances, as the majority is being produced in western Siberia (Rosinformugol, 2007). Such long transportation distances by land are only possible for subsidized railroad rates and for high coal prices on the world market (Schmidt et al., 2006). Depending on the local conditions, modern coal trains transport up to 10 000 t of coal. For a capacity of 100 t per railroad car, this corresponds to trains with 100 cars. Special trains, called Unit Trains, are primarily used in Canada, the US and Australia.

In 2006, the transport costs from the mine to the export port amounted to 15 to 17 % (USD 7 to USD 11/t) for steam coal and to 19 to 20 % (USD 16 to USD 21/t) for coking coal (Ritschel et al., 2007). In countries with transport distances of more than 600 km this proportion can even be higher. This mainly applies to coking coal, however. In the US this portion of costs for transports from the Appalachian Mountains to the east coast and in Canada from Alberta or Saskatchewan to the west coast is up to 33 %, in Russia, in spite of subsidies, it is above 40 %.

In Europe the better part of the imported coal is landed in ARA-ports. From there they are transported to the end consumers by train or river barges. According to data by the Bundesverband der Deutschen Binnenschiffahrt (BDB) in 2007 about 14.6 % or 36.3 Mt of the total cargo volume of the German inland navigation were solid mineral fuels (BDB, 2008).

5.2.8 World Market for Hard Coal

The beginnings of the international hard coal trade date back to the middle of the 19th century, when the onset of steam navigation resulted in a demand for coal as fuel in all major ports (Ritschel et al., 2005). In 1896, the coal trade volume amounted to approximately 68 Mt and was dominated by England at approximately 70 %. After the Second World War (1946), the global hard coal trade had a volume of about 85 Mt, half of which originated in North America (VDKI, 1996). The global hard coal trade only experienced a lasting upswing after the second oil price crisis in 1979/1980 (Fig. 5.17). Of the globally produced 5.5 Gt of hard coal in 2007, about 914 Mt were traded internationally. This corresponds to a proportion of 16.5 % of the global production. Other institutions specified the global trade at 906 Mt (VDKI, 2008) or 917 Mt (IEA, 2008b). Thus, the deviations of the two institutions listed above are less than 1 % in comparison to the BGR data. These differences are mainly based on the use of different sources. The historic considerations below are mainly based on the data of the VDKI.

The global hard coal trade increased 3.3-fold to 906 Mt between 1978 and 2007 (VDKI, 2008). The increase of the seaborne trade accounted for the main part, today it accounts for the better part of the global hard coal trade. According to information by the VDKI (2008) in 2007, approximately 820 Mt were transported by sea and only 86 Mt by land (intracontinental), mainly via train. At 37 %, the CIS accounted for the major part of the intracontinental trade in 2007, followed by Europe at 22 %, where transport takes place primarily from Poland and the Czech Republic to other EU-countries and North America at 21 %. The significantly increased Chinese coal demand also resulted in high growth rates of the intracontinental trade between the PR China and its neighboring countries North Korea, Mongolia and Vietnam (VDKI, 2008). The share of steam coal and coking coal for transportation both by sea and by land currently has a ratio of approximately 3 to 1.

Whereas in 1978 with a global hard coal trade of 210 Mt the proportion of hard coal transported by sea was 60 %, this proportion increased to about 90 % by the year 2007 (Fig. 5.17). Thus, during this period the maritime trade increased more than five-fold. Until the mid 1980s, mainly coking coal was traded by sea. Since the early 1990s steam coal dominates the global hard coal trade. After the Asian crisis had been overcome at the end of the 1990s, the maritime hard coal trade underwent a significant growth of about 9 %/a on average, this was mainly due to steam coal. Thus, the maritime steam coal trade doubled between 1999 and 2007 and increased from 309 to 618 Mt, whereas the maritime coking coal trade only increased by about 22 % from 166 to 202 Mt. The maritime traded proportion of the global hard coal production has increased nearly continuously from average 10 % in the 1980s until 2007 to about 16 % (miscellaneous annual VDKI reports).

Amongst the **hard coal exporting** regions, Austral-Asia with 538 Mt was the by far most important region in 2007, followed by the CIS with 128 Mt, North America with 83.9 Mt, Latin America with 73 Mt and Africa with 67.8 Mt. Nearly 98 % of the global hard coal ex-

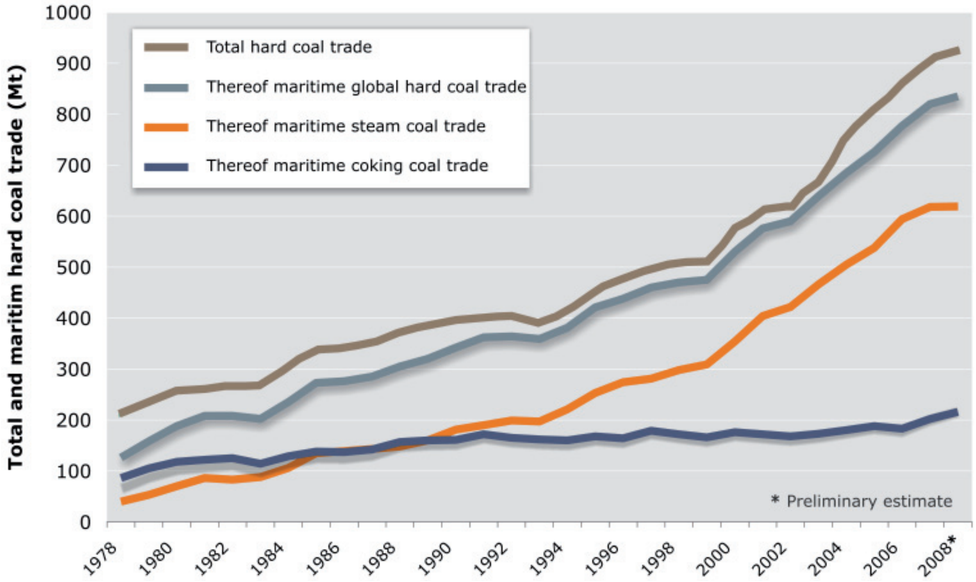

Figure 5.17: Development of the global hard coal trade since 1978 (annual VDKI reports since 1986).

ports of about 914 Mt originated in these five regions (Fig. 5.18, Fig. 5.19). Australia was by far the greatest exporting nation in 2007 with a share of about 27 % of the global hard coal exports (Fig. 5.19). Indonesia and Russia with a proportion of about 21 % and 11 % respectively, ranked second and third. The market share of the top ten hard coal exporting countries amounted to approximately 95 % in 2007.

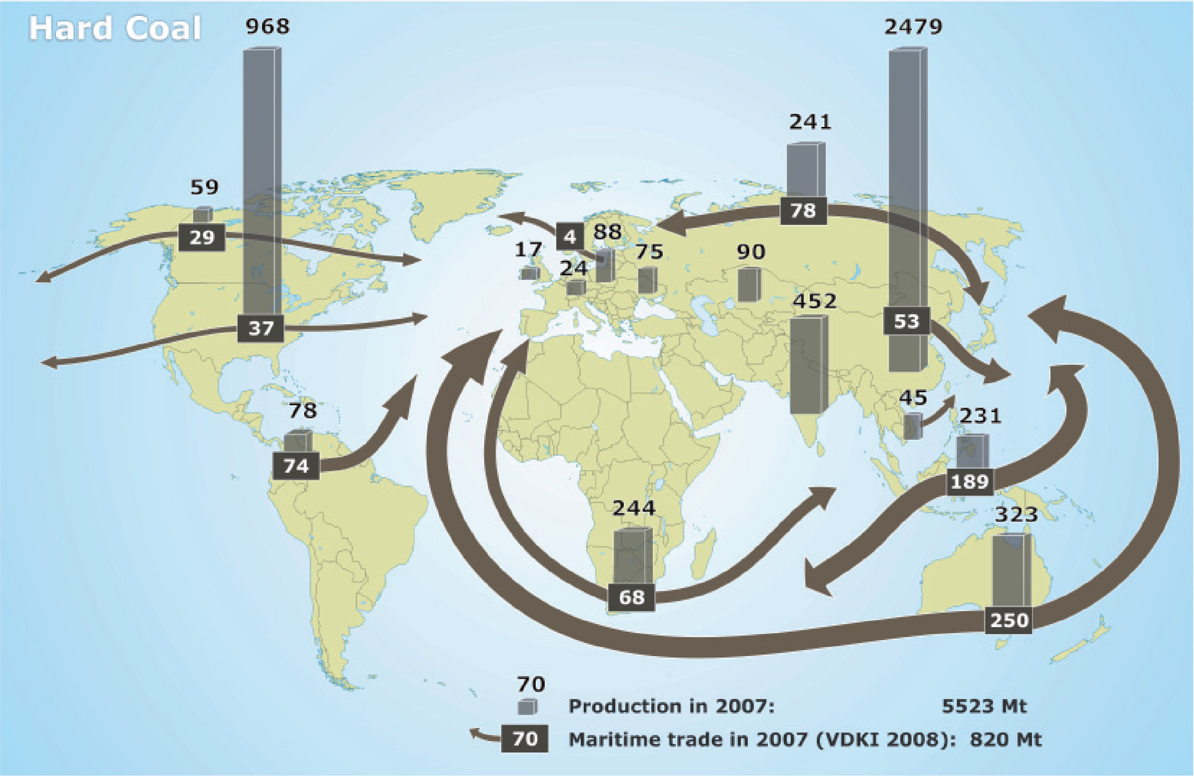

Figure 5.18: The largest hard coal producers and the maritime trade (in total 820 Mt) in 2007 (BGR, 2008; VDKI, 2008).

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Coal Liquefaction – An Alternative to Petroleum?

If petroleum prices keep rising in the mid-term and long-tern perspective, coal liquefaction might contribute to producing substitutes for petroleum. Methods for converting coal into liquid hydrocarbons (Coal-to-Liquid, CTL) have been known since the early 20th century. In 1913, the German Friedrich Bergius managed to liquefy coal for the first time (Bergius-Pier process). In 1931, he received the Nobel Prize in chemistry. In 1925, a patent for another method for coal liquefaction via synthesis gas and subsequent catalytic conversion into hydrocarbons and water was applied for by Fischer and Tropsch (Fischer-Tropsch-Synthese). Until 1945, both processes were used in Germany involving a total of 21 liquefaction plants. This way it was possible to meet the German demand for mineral oil during of the 2nd World War by primarily synthetically produced products. In spite of several approaches, large-scale coal liquefaction in Germany was never taken up again. The last German pilot plant for coal liquefaction was dismantled in 2004 and sold to the Chinese coal corporation Shenhua in Shanghai.

Outside Germany, the technology was developed further mainly in South Africa, as the country suffered from a lack of oil due to an embargo. In 1955, the South African Synthetic Oil Limited (SASOL) in Sasolburg started producing synthetic oil from coal. The corporation is still using a modified Fischer-Tropsch process today and currently generates about 150,000 b/d of CTL products out of about 45 Mt coal per year. This is used to supply approximately 40 % of the total South African demand for fuel. Besides South Africa, mainly China has been pushing the subject of coal liquefaction for years mainly as part of its energy policy agenda. Thus, the largest coal company in China (Shenhua) operates projects at eight different locations from experimental plants to large-scale industrial usage. The first large-scale commercial liquefaction plant was commissioned in Ordos in Inner Mongolia at the end of 2008. In China for the year 2020 up to 30 Mt CTL products have been planned, for whose production approximately 120 to 150 Mt coal are necessary per year.

The coking coal trade in 2007 was dominated by only three countries. Australia at 68 % took the undisputed first rank, followed by the US at 13 % and Canada at 12.5 %. 93.5 % of the altogether 202 Mt of maritime coking coal originated in these three countries. Indonesia dominated the maritime steam coal market (Fig. 5.21) at a percentage of 30.6 %, followed by Australia at 17.5 %, Russia at 11.7 %, South Africa at 11.3 % and Colombia at 9.9 %. Thus, the five most important steam coal exporters accounted for about 81 % (618 Mt) of the maritime hard coal trade (VDKI, 2008).

The most important hard coal importing regions in 2007 were Austral-Asia at 500.4 Mt and Europe at 267 Mt. Together they accounted for nearly 84 % of the global hard coal imports of about 915 Mt (Fig. 5.20). The largest hard coal importers were only Asian countries with a volume of together 448.4 Mt, corresponding to 49 %. Behind Japan (20.3 %), South Korea (9.7 %) and Taiwan (7.5 %), two more Asian countries, India (5.9 %) and the PR China (5.6 %), followed for the first time. Only then, European countries with Great Britain (5.5 %) and Germany (5.2 %) appear in the ranking. At 239.8 Mt the European Union (EU-27) accounted for nearly 26 % of the global hard coal imports.

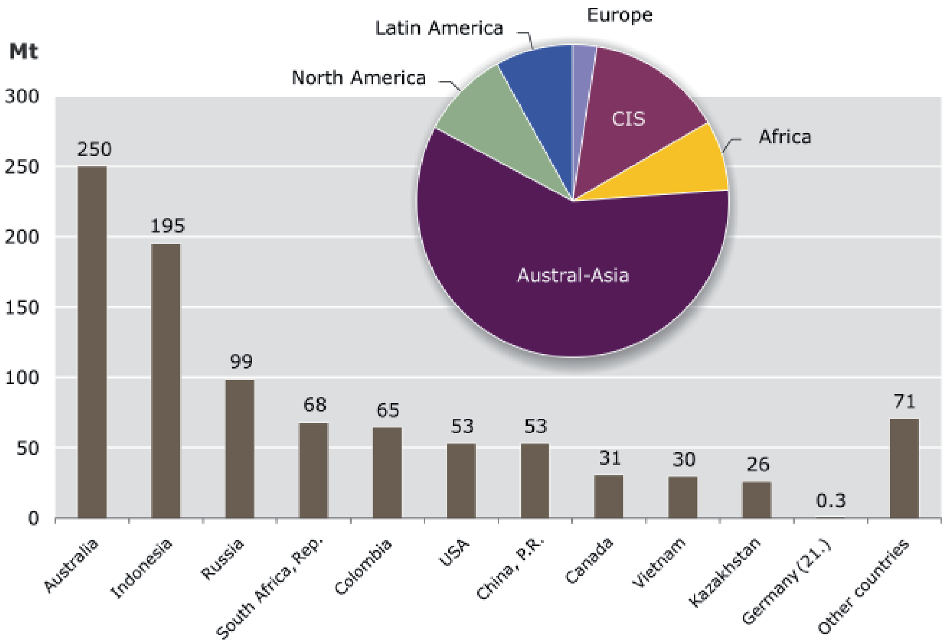

Figure 5.19: Hard coal exports (total 914 Mt) in 2007 of the top ten countries and Germany as well as their distribution by region.

According to IEA information, Austral-Asia accounted for about 57 % of the global coking coal imports of 207 Mt and these were exclusively Asian countries. Japan dominates at a proportion of about 26 %, India and South Korea follow suit at approximately 11 % each. Europe at 61 Mt was the second largest importing region of coking coal. Europe's most important and globally fourth largest importing nation of coking coal in 2007 was Germany at about 9.6 Mt. The ranking of the most important steam coal importing countries differs only slightly from the ranking of the most important hard coal importing countries (Fig. 5.20), as the amount of steam coal in the global hard coal market is approximately three times as high as the amount of coking coal. Only for India there is a change in the ranking. Due to the relatively high coking coal import share of 23.3 Mt in the Indian hard coal imports, it ranks eighth amongst the largest steam coal importing countries (IEA, 2008b).

The world market for steam coal is subdivided into a Pacific and an Atlantic market. Whereas Europe, Africa and North America supply the hard coal demand in the Atlantic market mainly via South Africa, Colombia, Venezuela and Russia, the Pacific importers such as Japan, South Korea and Taiwan are mainly supplied by Indonesia, Australia and the PR China. The main reason for the subdivision into two markets is primarily the portion of freight charge of the import coal costs. Thus, the exchange between the Atlantic and the Pacific market in the year 2007 was only a few million tons (VDKI, 2008). Indonesia and Australia supplied at 26 Mt about 10 % of the steam coal import demand of the Atlantic market. Conversely, South Africa and Colombia together supplied 13 Mt or about 3 % of the imported steam coal in the Pacific market. In contrast there is a uniform global market for coking coal which is not influenced as much by freight cost, as the small number of supplier countries and the globally dispersed consumers generate higher revenues than for steam coal. For this reason, the portion of freight charge of the total costs is lower than for steam coal.

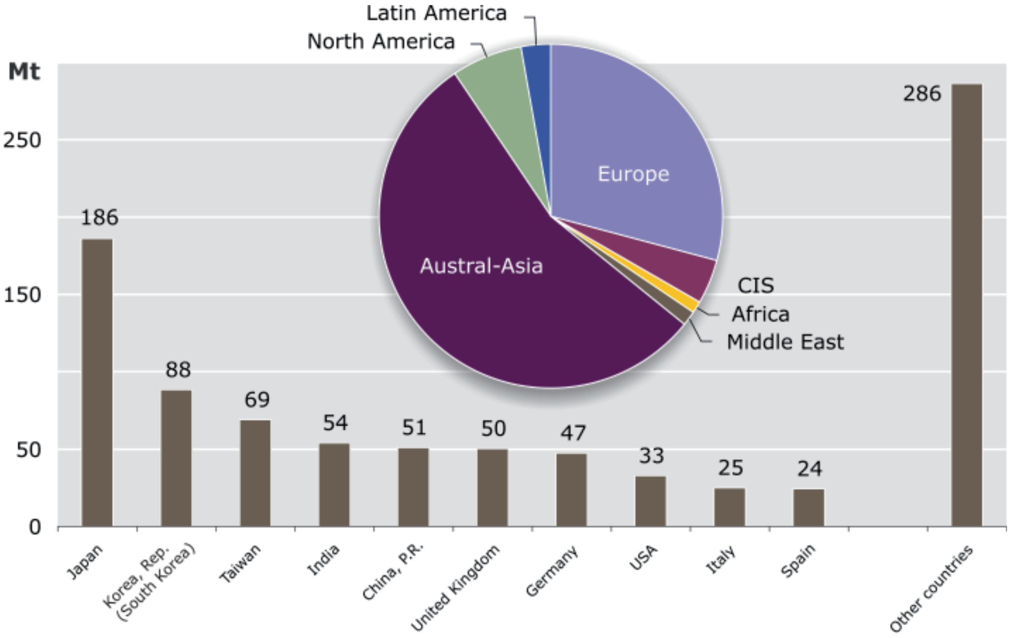

Figure 5.20: Hard coal imports (total 915 Mt) in 2007 of the top ten countries as well as their distribution by region.

In 2007 the maritime steam coal trade amounted to 618 Mt. The Atlantic market accounted for about 229 Mt and the Pacific market for 389 Mt (VDKI, 2008). The most important steam coal suppliers of the Atlantic market in 2007 were Colombia, South Africa and Russia, whereas mainly Indonesia, Australia and the PR China supplied the Pacific market (Fig. 5.21).

The comparatively high sales of Indonesian steam coal in the Atlantic market can be attributed to their high quality at low sulfur contents and relatively low prices. The Australian deliveries in the Atlantic market are only to a lesser degree steam coal and nearly exclusively high-quality coking coal. Russia can serve both markets due to its geographic location, as there are suitable ports in the European area as well as in the Far East. The South African deliveries in the Pacific area were predominantly intended for India, which is increasingly also dependent on imports from the Atlantic market.

With about 5 % only a small part of the global coke production is traded globally (VDKI, 2008). The PR China is by far the greatest coke producer (Section 5.2.6) and also the greatest exporter of coke. Even though the PR China exported at 15.3 Mt only 4.8 % of the domestic output in 2007, still it corresponded to a world market share of approximately 49 %. Thus, the PR China dominates the world market for coke. The second largest coke exporting country in 2007 with a share of approximately 20 % (6.3 Mt) was Poland (PIG, 2009). Amongst the coke importing countries, Germany was second to none world-wide in 2007 at 4.1 Mt (VDKI, 2008). Runners up with coke imports of 2 to 3 Mt were Japan, South Korea and the USA. A continuously increasing demand was also noted for Brazil, which imported about 1.6 Mt coke in 2007 (McCloskey, 2003-2009).

Coal Fires – Destruction of Resources and Environmental Protection

Coal seams close to the surface can ignite spontaneously, if they are supplied with a sufficient amount of oxygen. Such coal fires are known all over the world in coal deposits. Some underground coal fires are caused by mining, if coal comes into contact with oxygen due to mine ventilation.

Fires in coal seams close to the surface are a global problem. In the process, resources are destroyed on a large scale. In addition, climate-related gases, such as CO_2, methane and different toxic gases are being emitted into the atmosphere. In China such fires have been raging for many years in a belt crossing the north of the country. Hundreds of burning areas are known, in which 10 to 20 Mt of coal burn annually. An amount of coal approximately ten times as large becomes unusable, as in the environment of the fires no mining activities can take place.

Coal fires can only be extinguished at great expenditure, i.e. removing energy by water cooling, separating fuel by digging ditches or creating barriers as well as cutting off the oxygen supply by applying an extensive cover of loam or clay. In the interdisciplinary geo-scientific joint project *Sino-German Coal Fire Research* (BMBF, support code 0330490) the development of innovative technologies for the exploration, fighting and monitoring of coal fire in Northern China is currently being advanced.

Coal fire in the Wuda mining district, Inner Mongolia, PR China

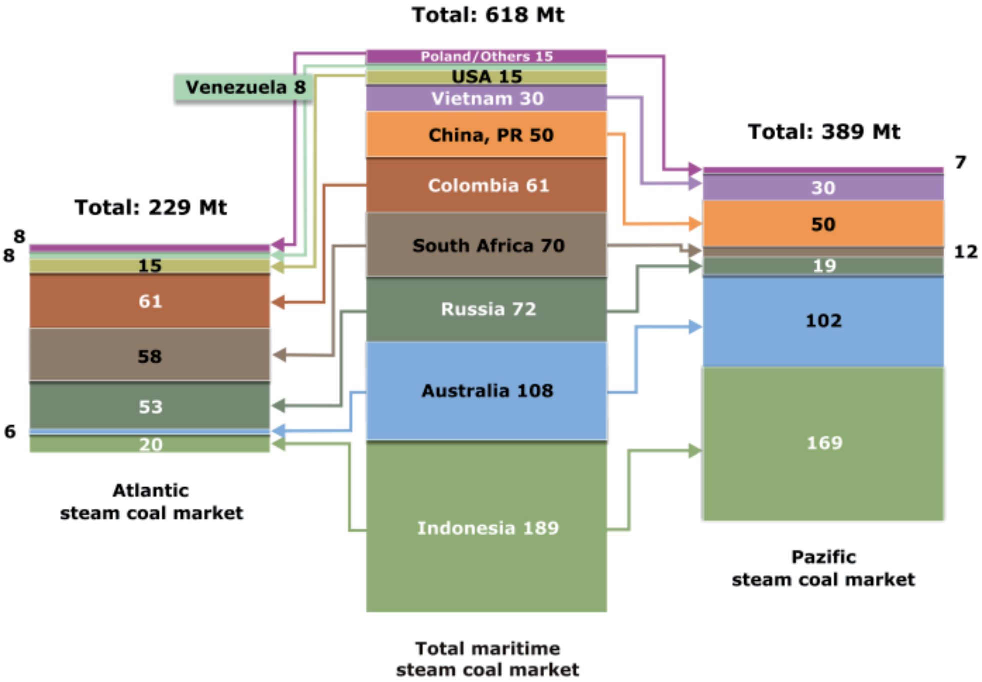

Figure 5.21: Supplier and recipient countries of the maritime steam coal trade in 2007 (VDKI, 2008).

5.2.9 Hard Coal Prices

The average annual import costs for the steam coal imported into the EU, according to the prices in the landing ports, ranged between USD 34.43 and USD 82.81/t cif (cost, insurance and freight) for the past 22 years (Fig. 5.22). The range for coking coal was USD 47.88 to USD 125.86/t cif. These prices constitute average prices in USD of the individual years, which the IEA received from the corresponding public import authorities on the total import volume and contained the total value of the imports. The average prices comprise all coal qualities, without consideration of the final usage or the contract conditions. Whereas the EU import prices between 1986 and 2003 for steam coal largely ranged in a price range from USD 35 to USD 50/t and those for coking coal ranged from USD 50 to USD 65/t, the import prices rose steeply from 2004 onwards. The nominally highest prices for steam coal and coking coal were reached in 2006/2007, after the import prices for steam coal in comparison to the low price marked in 1999 had increased by about 141 % to USD 82.81/t cif in 2007 and the coking coal import prices even increased by about 163 % to USD 125.86/t in the year 2006 in comparison to 2000 (IEA, 2008b). Taking into account the spot market prices in 2008, which had risen to more than USD 200/t for steam coal and coking coal prices of more than USD 300/t, the EU import prices probably increased significantly in 2008 as well.

The coal import prices have been listed in Figure 5.22, they are also listed as real prices in USD, taking inflation into account as of 2007. The import prices for steam coal or coking coal have been deflated using the US Consumer Price Index /All Urban Consumers (CPI-U) from the Bureau of Labor Statistics (Bureau of Labor Statistics, 2009). On closer examination of the real prices for imported steam coal in the course of the past 22 years it turns out that in spite of the immense nominal rise in prices since 2003 the real steam coal import price only reached the inflation adjusted level of the years 1986 to 1990 in 2007.

For coking coal, however, the price rises resulted in an increase of the real prices by 18 and 14 %, respectively, between 2006 and 2007 in comparison to the inflation adjusted maximum price of USD 109.7/t in 1986.

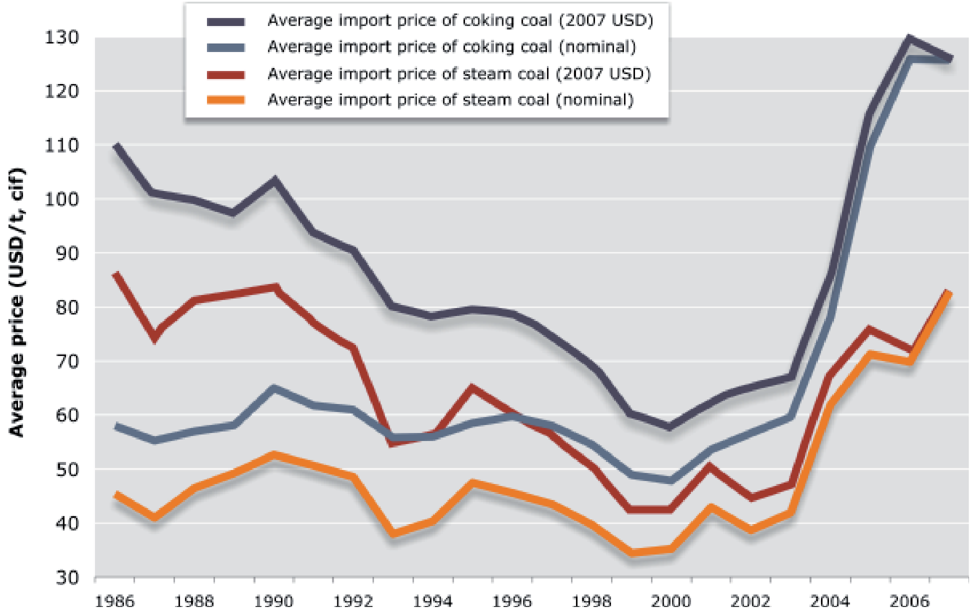

Figure 5.22: Price history for steam coal and coking coal imported into the EU from 1986 to 2007 (IEA, 2007, 2008b).

The **spot market for steam coal and the development of its prices** have changed lastingly in the past years due to the increasing publication of daily, weekly and monthly prices for globally traded hard coal. McCloskey, along with Platts the best known information server in the hard coal market sector, publishes two price indices, the *MCIS NW Europe steam coal marker* for North-Western Europe and the *MCIS Asian steam coal marker* for Asia. Only the European price index will be dealt with, which is based on cif-prices for steam coal delivered to North Western Europe (ARA-ports) with a standard quality for a heating value of 6000 kcal/kg (25.1 MJ/kg) and a sulfur content of 1 % at most. The VDKI regularly publishes the MCIS NW Europe steam coal marker-prices on its internet pages, however referring to a heating value of 7000 kcal/kg (29.3 MJ/kg, which corresponds to the energy content of 1 (hard) coal equivalent per kg), for this reason the price is listed in USD/tce, a customary specification in particular in Germany. In comparison to the EU import prices given annually (Fig. 5.22), the current supply and demand situation becomes much more apparent in the spot market prices specified on a monthly basis.

In the 1990s and until the middle of 2003, the *MCIS NW Europe steam coal marker* price varied approximately in five-year cycles relatively steadily between USD 25/t and USD 45/t cif. Between May 2003 and July 2004, the price increased by about 140 % to USD 78.70/t cif due to growing demand with a simultaneous shortage of freight capacities (Fig. 5.23). In 2005 the prices decreased by approximately 20 % to just USD 50/t cif. Subsequently, caused in particular by the cold winter in Europe and the continuously rising prices for the other fossil fuels, the spot market prices boomed again and in September 2006 they were still about 94 % above the bottom price in May 2003. Starting in early 2007, the spot market price for steam coal then developed in parallel to the oil price. Within the year

2007, which was mainly characterized by a vastly increased demand for imported coal in India and China, the price increased by about 91 % to a nominal price of USD 127/t cif which had been hitherto unheard of. Backed by a severe onset of winter with production and transport losses in China, severe flooding of important Australian export coal mines as well as of a rapidly rising oil price the *MCIS NW Europe steam coal marker* price rose again by 72 % between January 2008 and July 2008 to its highest level to date of USD 219/t cif. Thus, the spot market price for steam coal rose from its lowest level in August 2002 at nearly USD 26/t until July 2008 by nearly seven-and-a-half times. Until April 2009, the spot market price for steam coal decreased by about 70 % to USD 66/t in comparison to July 2008, which is still a quite high nominal price level in comparison to the 1990s and the start of the new century.

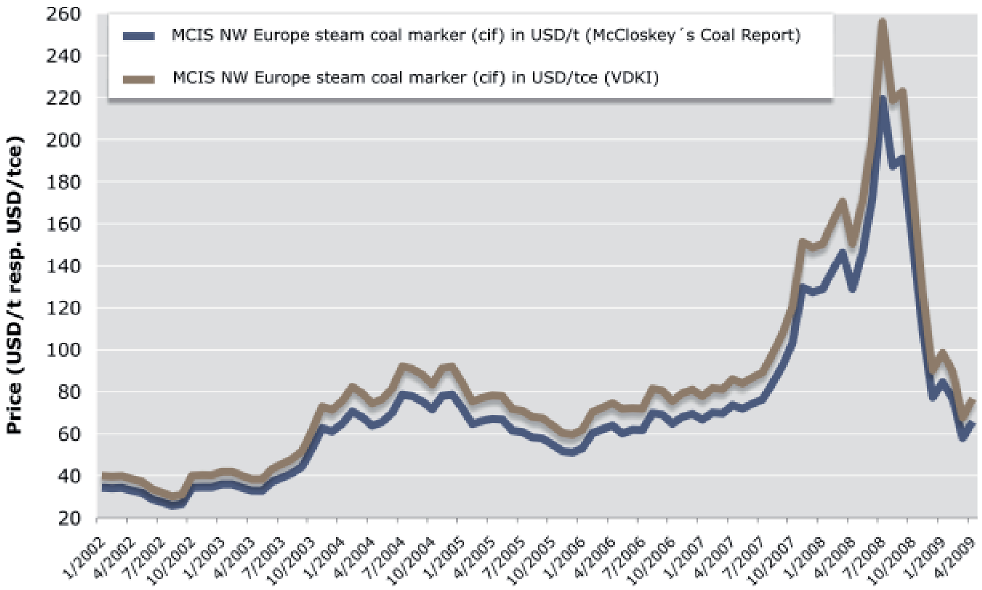

Figure 5.23: Development of the MCIS NW Europe steam coal marker price from January 2002 to April 2009 (McCloskey, 2003 – 2009; VDKI, 2003 - 2009).

5.3 Lignite

5.3.1 Total Resources of Lignite, Regional Distribution

The total global resources of lignite amount to 4345 Gt. Of these, 268.9 Gt, approximately 6.2 %, have been classified as reserves. Thus, the resources with 93.8 % account for the main part of the total lignite resources. In particular, in comparison with petroleum and natural gas, these total resources are relatively evenly distributed worldwide (Fig. 5.24).

The largest global total resources of lignite occur at 33.5 %, or approximately 1454 Gt, in North America, followed by the CIS at 31.8 % and Austral-Asia at 25.9 %. Of the remaining roughly 383 Gt (8.8 %) of the total resources, about 358 Gt are located in Europe (Fig. 5.25). In North America and the CIS the total resources of lignite are nearly exclusively located in the two countries covering large areas, the US at 1401 Gt and Russia at 1371 Gt.

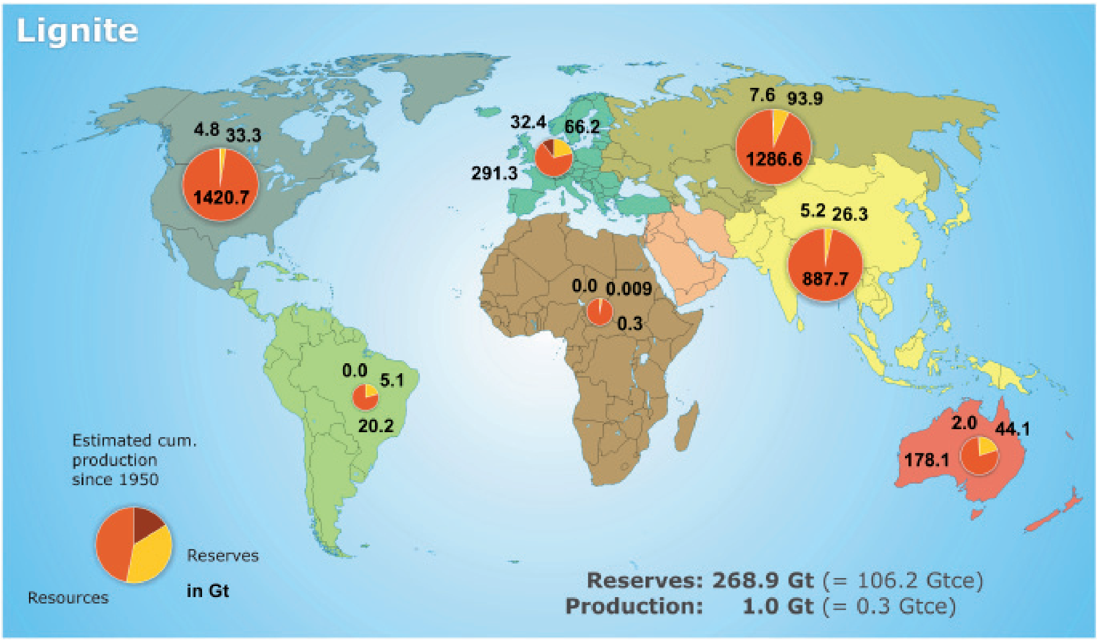

Figure 5.24: Regional distribution of the reserves, resources and the estimated cumulative production of lignite since 1950 at the end of 2007.

In Austral-Asia Australia, Vietnam, Pakistan and Mongolia besides the PR China possess large total resources. In Europe the total lignite resources are mainly located in Poland and Germany, which ranks ninth in the world. In these two countries, nearly 84 % of the European total lignite resources are located.

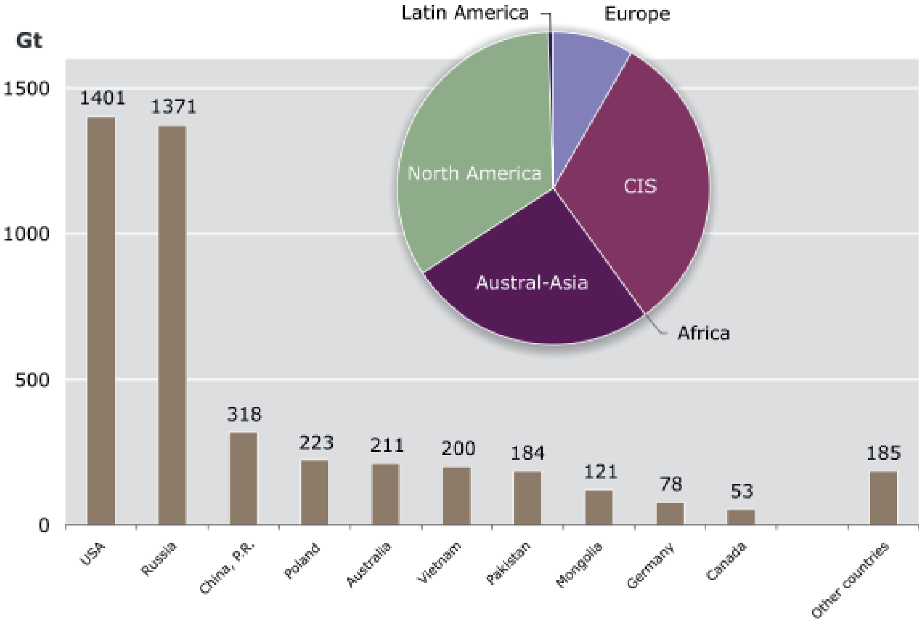

Figure 5.25: Total resources of lignite (total 4345 Gt) in 2007 of the top ten countries as well as their distribution by region.

5.3.2 Lignite Reserves

The three extensive regions CIS, Austral-Asia and North America account for 197.6 Gt or nearly 74 % of the global lignite reserves. Thus, the degree of concentration of these three regions is lower for lignite than for the reserves of hard coal (Section 5.2.2). At 34.9 %, corresponding to 93.9 Gt, the largest lignite reserves (in this case including hard brown coal) are located in the CIS, to which Russia at 91.6 Gt contributes in particular (Fig. 5.26).

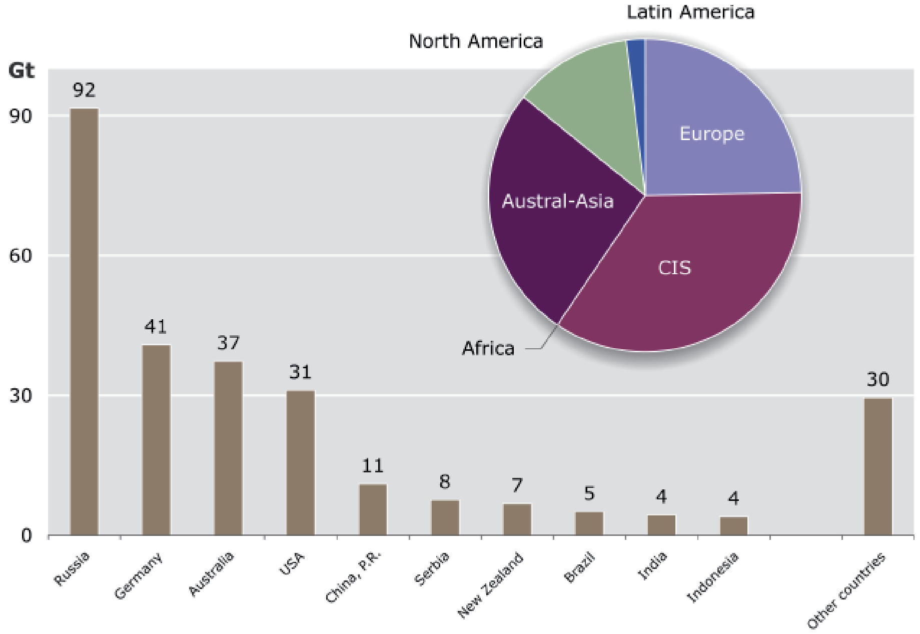

Figure 5.26: Lignite reserves (total 269 Gt) in 2007 of the top ten countries as well as their distribution by region.

Austral-Asia at 26.2 % possesses the second largest lignite reserves, which are mainly located in Australia (37.3 Gt) and the PR China (11 Gt). Europe possesses at 66.2 Gt (24.6 %) the third-largest lignite reserves, with Germany (40.8 Gt) being the second largest owner of reserves in the world. Important amounts of lignite reserves are also located in North America, 33.3 Gt, and there primarily in the US at 31 Gt. The regions Latin America at 5.1 Gt and Africa at 9 Mt have comparatively small lignite reserves (Fig. 5.26). In the Middle East there are no known lignite reserves.

5.3.3 Lignite Resources

In contrast to the situation for the reserves, about 92.4 % of the total resources of lignite, 3764 Gt, are located in the three regions North America, CIS and Austral-Asia (Fig. 5.27).

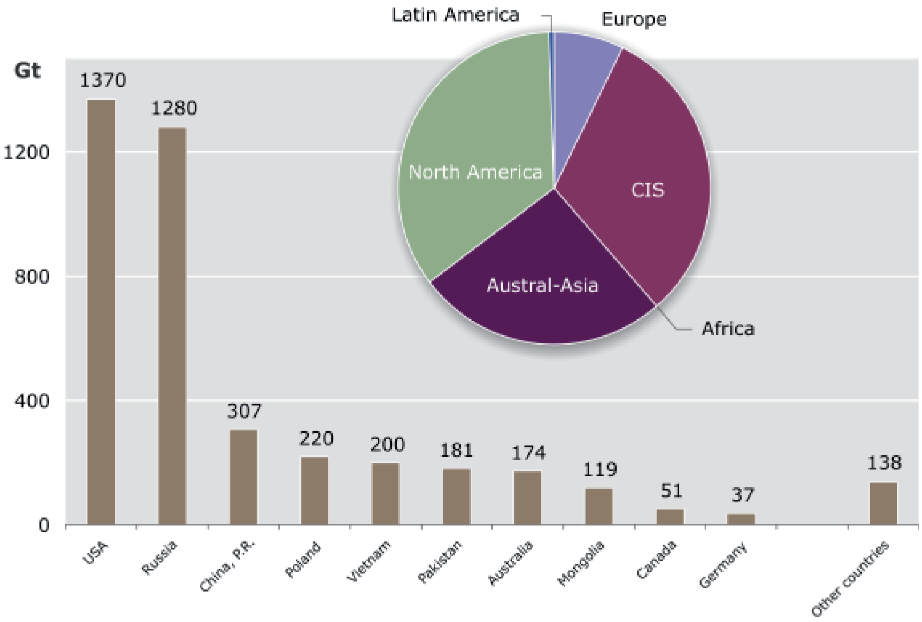

Figure 5.27: Lignite resources (total 4076 Gt) in 2007 of the top ten countries as well as their distribution by region.

Approximately one third each of the global resources of lignite are located in North America (1421 Gt), and the CIS (1287 Gt, including hard brown coal), the most important countries being the US at 1370 Gt as well as Russia at 1280 Gt (including hard brown coal). At about 1057 Gt (26.2 %) Austral-Asia holds rank three, as there are large lignite resources in the PR China (307 Gt), in Vietnam (200 Gt), Pakistan (181 Gt), Australia (173.5 Gt) and Mongolia (119 Gt, including hard brown coal). Europe at 291 Gt also possesses important lignite resources. These are mainly located in Poland and Germany, which takes rank 10 in the world (Fig. 5.27).

5.3.4 Lignite Production

With few local exceptions, lignite is only mined in surface mines. Internationally, production depths below 200 m are rarely surpassed. Germany is an exception; there the employment of large equipment for surface mining makes the production of lignite profitable down to depths of 400 m.

The global lignite production was about 978 Mt in 2007. At 566 Mt, more than half of the global production was generated in Europe, followed by Austral-Asia at 237 Mt (Fig. 5.28). Large amounts of lignite (90 Mt) were produced in North America and the CIS (79 Mt, including hard brown coal). Latin America at 5.8 Mt and the Middle East at 0.6 Mt together possessed on a proportion of 0.7 % of the global lignite production (Fig. 5.28). From Africa no lignite production is known.

The by far most important lignite producing country in 2007 was Germany with a share of 18.4 % of the global production corresponding to 180.4 Mt. Runners up, with a production of at least 70 Mt, were Australia, Russia (including hard brown coal), the USA, Turkey and the PR China (Fig. 5.28). Due to a significant production of lignite in European countries such as Greece, Poland and the Czech Republic, the production in the EU-27 amounted to app. 443 Mt. In 2007 this corresponded to a proportion of the global production of 45.3 %. The high proportion of the EU-27 of the global lignite production also reflects the great importance of lignite for the power supply of the European Union. For some EU-member countries, in particular for Germany, it is the most important domestic energy resource.

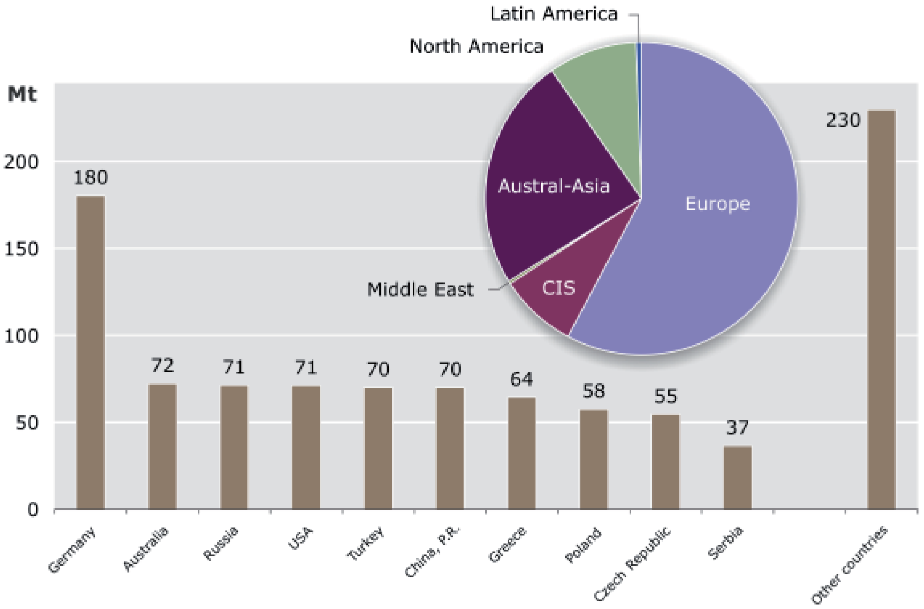

Figure 5.28: Lignite production (total 978 Mt) in 2007 of the top ten countries as well as their distribution by region.

Whereas the global hard coal production doubled in the course of the past 30 years (Section 5.2.4), the global lignite production increased only by about 83 Mt (9 %) to 978 Mt in the period from 1978 to 2007 (Tab. 5.7). The global lignite production rose significantly by 186 Mt (21 %) to about 1081 Mt until 1987. The decrease in the global lignite production in the 1990s by more than 200 Mt to about 856 Mt in 1999 can be attributed to the political and economical changes in the territory of the former GDR, in the east-European countries as well as in the former Soviet Union. In particular the collapse of the Council for Mutual Economic Assistance (COMECON) resulted in a massive reduction of the production of industrial goods, due to the slump in demand for COMECON-industrial goods. Thus, the power demand was reduced as well. In the newly-formed German states the lignite production decreased from 309 Mt in 1987 by about 244 Mt (minus 79 %) to 65 Mt in 1999.

In comparison to 1999, the lignite production in nearly all regions increased in the new Millennium. Only in the CIS, production decreased distinctly during that period (Tab. 5.7).

Table 5.7: Development of lignite production according to regions from 1978 to 2007 (WEC, 1980; BGR, 1989, 2003).

Region Year	**Lignite Production in Mt** (Region´s share of the global annual production) **1978**	 **1987**	 **1999**	 **2007**
Europe	670.5 (74.9 %)	738.8 (68.4 %)	507.6 (59.3 %)	566.1 (57.9 %)
CIS	152.0 (17.0 %)	164.0 (15.2 %)	90.1 (10.5 %)	79.0 (8.1 %)
Africa	0.0 (0.0 %)	0.0 (0.0 %)	0.0 (0.0 %)	0.0 (0.0 %)
Middle East	0.0 (0.0 %)	0.0 (0.0 %)	0.0 (0.0 %)	0.6 (0.1 %)
Austral-Asia	40.4 (4.5 %)	97.3 (9.0 %)	167.2 (19.5 %)	236.8 (24.2 %)
North America	32.1 (3.6 %)	80.8 (7.5 %)	90.8 (10.6 %)	89.7 (9.2 %)
Latin America	0.0 (0.0 %)	0.0 (0.0 %)	0.0 (0.0 %)	5.8 (0.6 %)
WORLD	*894.9* *(100 %)*	*1080.9* *(100 %)*	*855.7* *(100 %)*	*978.0* *(100 %)*

Whereas in 1978 three quarters of the global lignite production still originated in Europe, this proportion decreased continually over the past 30 years and was about 58 % in 2007. Austral-Asia showed the largest increases in lignite production where the production increased six-fold, thus the proportion of this region in the global lignite production increased from less than 5 % in 1978 to about 24 % in 2007 (Tab. 5.7). This can be primarily attributed to the expansion of the production in Indonesia, Thailand, India, the PR China and Australia (Tab. 5.8).

Table 5.8: Development of the production of lignite of the five largest producing countries in 2007 for the years 1978 to 2007 (WEC, 1980; BGR, 1989, 2003).

Country **Year**	**Lignite Production in Mt** (Region´s share of the global annual production) **1978**	 **1987**	 **1999**	 **2007**	**Change 1978/2007 (%)**
Germany (FRG+GDR until 1987)	376.9 (42.1 %)	417.8 (38.7 %)	161.3 (18.8 %)	180.4 (18.4 %)	- 52
Australia	33.0 (3.7 %)	40.5 (3.7 %)	65.0 (7.6 %)	72.3 (7.4 %)	+ 119
Russia (former Soviet Union until 1987)	152.0 (17.0 %)	164.0 (15.2 %)	83.5 (9.8 %)	71.3 (7.3 %)	(- 53)
USA	27.0 (3.0 %)	68.3 (6.3 %)	79.1 (9.2 %)	71.2 (7.3 %)	+ 164
Turkey	14.8 (1.6 %)	40.5 (3.7 %)	64.8 (7.6 %)	70.0 (7.2 %)	+ 374
Total	603.7 (67.5 %)	731.1 (67.6 %)	453.7 (53.0 %)	465.2 (47.6 %)	
WORLD	*894.9* *(100 %)*	*1080.9* *(100 %)*	*855.7* *(100 %)*	*978.0* *(100 %)*	+ 9

In principle the same geological, geographical and climatic factors are decisive for the amount of the lignite production costs as for the production of hard coal (Section 5.2.4). As the energy content of lignite is two thirds lower than that of hard coal, the revenues from lignite sale are essentially lower than for the sale of hard coal. Thus, an economic lignite production is only possible for lower production costs. Thus, the production is nearly exclusively done in competitive surface mines. In addition, to keep production costs down, there is usually no beneficiation or a lengthy transport of lignite. Instead, lignite is largely converted into power in power plants in the vicinity of the mines.

There are only few countries specifying tangible mining/production costs. An example is the Electricity Generating Authority of Thailand (EGAT). The purchasing prices indicated in their annual business reports for lignite ranged between USD 11 and USD 13/t and Euro 9 and 10/t, respectively, for the past years. EGAT is also owner of the largest Thai lignite surface mine, Mae-Moh, where 88 % of the Thai lignite production in 2007 originated. Thus the purchasing prices specified in the EGAT business reports probably largely correspond to the production costs (Tab. 5.9).

Table 5.9: Development of the lignite purchasing prices (~production costs) in Thailand (EGAT, 2007, 2008).

Production costs/year	2005	2006	2007
in Thai Baht/t	433.6	424.7	437.2
in USD/t	10.8	11.2	13.5
in Euro/t	8.7	8.9	9.9

Thus, the lignite production costs in Thailand range in the same order of magnitude as in Germany, where production costs of approximately Euro 8 to Euro 11/t accrue (BGR, 2003). The Metalworld Research Team (2008) specifies lignite (raw lignite) production costs of USD 14 to USD 16/t, i.e. Euro 10 to Euro 12/t for India in 2007. Considering additional costs, for instance for beneficiation, the Indian lignite production costs amounted to USD 16 to USD 18/t (Euro 11 to Euro 13/t). The largest Bulgarian lignite producer, the company Mini Maritsa Iztok EAD, produced 23.9 Mt of lignite in 2007 from three surface mines, corresponding to 94 % of the Bulgarian lignite production. The production costs amounted to app. USD 11/t, i.e. Euro 8/t (Mini Maritsa Iztok EAD, 2009). The sole Canadian lignite producer, Sherritt International Corporation, specified its costs for surface mining of lignite in Saskatchewan as well as of hard brown coal (sub-bituminous coal) in Alberta at USD 9.2/t, i.e. Euro 6.7/t in 2007 (Sherritt International Corporation, 2008).

The majority of the globally mined lignite from surface mines is produced at production costs between Euro 7/t and Euro 15/t according to the E.ON Kraftwerke GmbH (pers. com. Bayer). For lignite with higher calorific values, which in reality is hard brown coal and which is ranked among the hard coal (Section 2.3.3), an economical production is still possible even at higher production costs. For the few existing lignite underground mines the production costs are probably higher than the range from Euro 7 to Euro 15/t specified for surface mines.

5.3.5 Lignite Consumption

As there is only very little cross-border trade of lignite, the situation for consumption is nearly identical to that of production. The global consumption of lignite amounted to app. 977 Mt in 2007. Europe accounted for more than half of the global consumption of about 565 Mt, followed by Austral-Asia at 237 Mt. Significant amounts of lignite were also consumed in the regions North America at 90 Mt and the CIS at 79 Mt (Fig. 5.29).

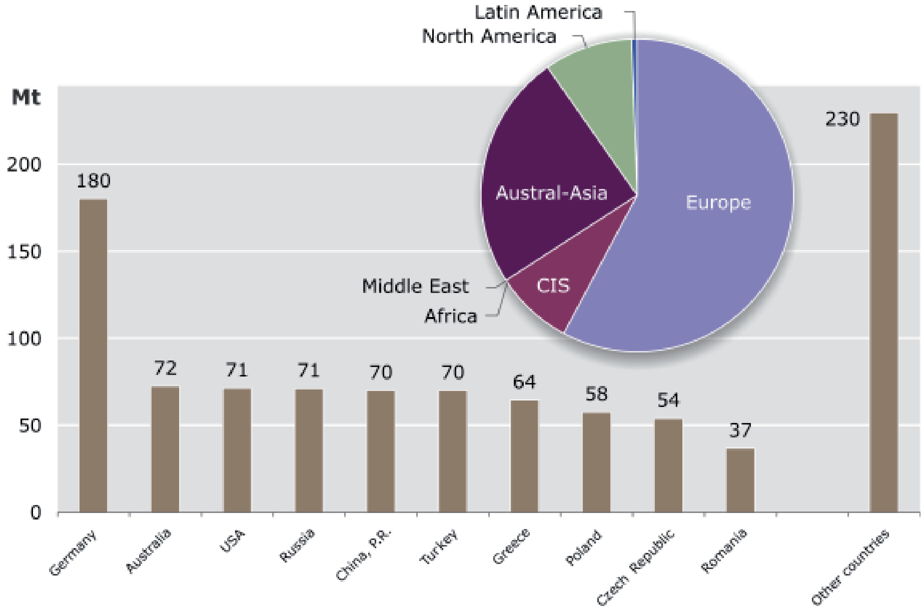

Figure 5.29: Lignite consumption (total 977 Mt) in 2007 of the top ten countries as well as their distribution by region.

In 2007 Germany had the highest lignite consumption of all countries at 18.4 % (180 Mt) (Fig. 5.29). Runners up, with a consumption of at least 70 Mt, were Australia, Russia (including hard brown coal), the USA, Turkey and the PR China (Fig. 5.30). The lignite consumption in the EU-27 amounted to app. 443 Mt. This corresponded to a proportion of the global lignite consumption of 45.3 %.

Between 1980 and 2007, the global lignite consumption decreased slightly by 3.3 % (IEA, 2008b). Whereas the global consumption still increased significantly in the 1980s (Fig. 5.30), it decreased in particular in the 1990s for the reasons already mentioned (Section 5.3.4). The development of the lignite production in the individual regions was in phase with consumption during the whole period reviewed here. Whereas the lignite consumption in Austral-Asia, North and Latin America as well as in the Middle East doubled and tripled, respectively (Fig. 5.30), the consumption in Europe and the CIS area decreased by one fifth and about two fifths, respectively (IEA, 2008b).

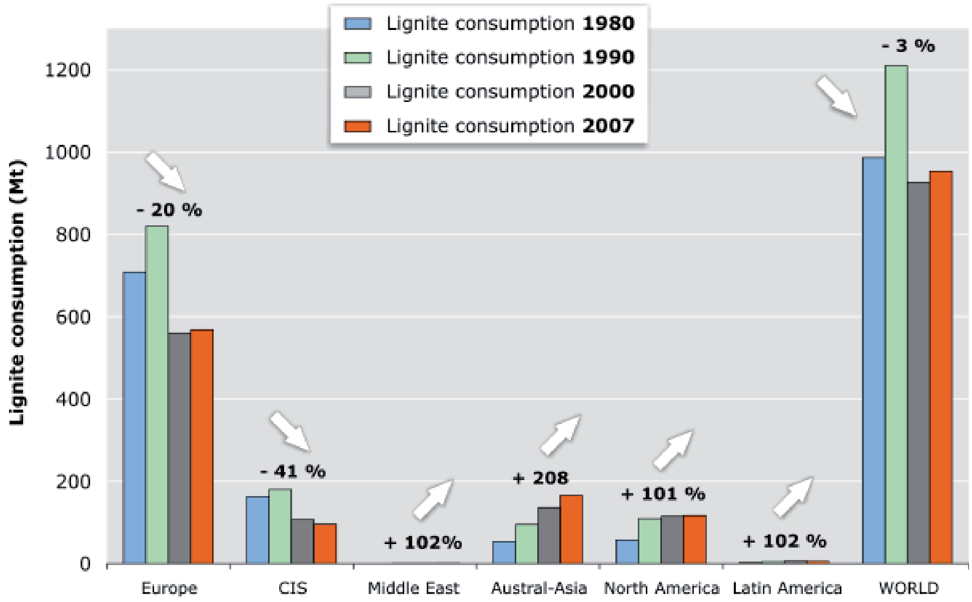

Figure 5.30: Development of the global lignite consumption from 1980 to 2007 according to regions (IEA, 2008b).

5.3.6 Lignite Trade

There is no global market for lignite. Because of its low energy content and high water content, lignite is traded only in exceptional cases. This mainly refers to trade of small amounts of (raw) lignite in the areas close to borders between the Czech Republic, Poland and Germany as well as of lignite products such as briquets, pulverized coal or coke from Germany to Belgium, France or the Netherlands. In 2007, German imports amounted to several tens of thousand tons; the exports amounted to several hundreds of thousand tons, which is way below 1 % of the annual German lignite production (SdK, 2008a). In Germany in the past years nearly 93 % of the annual lignite production was sold to power plants for the general power supply and another 1 % to 2 % for power generation in mine power plants. Only small amounts of lignite are refined. These products made of German lignite consist mainly of briquets as well as of pulverized coal and to a lesser degree of fluidized-bed lignite as well as of lignite coke (SdK, 2008a).

Relatively small amounts of several 100 000 t annually of Russian lignite (hard brown coal) are exported to Japan. This hard brown coal originates from the Russian island of Sachalin (Rosinformugol, 2008). Canada also exported about 100 000 t of lignite from the surface lignite mines close to the border in the south of Saskatchewan into the US in 2007 (Stone, 2008). A small part of the Indonesian coal exports are probably also lignite.

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6 Nuclear Fuel

6.1 Uranium

At the beginning of 2009, 436 nuclear power plants in 30 countries with a total power of 372 GW_e were operating. In 2008 nuclear power plants around the world produced 2 601 TWh power. Nuclear energy thus had a share of about 15 % of the global power generation. Approximately 65 405 t of uranium are required annually for supplying the current power plant pool. All over the world, numerous countries such as the PR China, Finland, Russia, South Korea, Japan and India announced the construction of new power plants. Simultaneously, the amount of uranium being mined increases only slowly.

6.1.1 Uranium Occurrences

Uranium is a natural component of the rocks constituting the earth crust. For an economic recoverability, uranium has to be enriched in the rocks. Uranium deposits can have developed in nearly all geological ages based on very different formation conditions. Their configurations, sizes and contents vary. Currently the following types of deposits are of economic importance:

Unconformity-related deposits contain uranium at 10 000 to more than 200 000 t U. Examples for this type of mine are Key Lake, McArthur River, Cigar Lake in Canada and Ranger, Jabiluka in Australia.

Sandstone deposits are common all around the world and contain between 0.1 and 0.2 % U. Medium-sized to large deposits host several thousand to more than 100 000 t U.

Hydrothermal vein-type deposits are also widely spread. A number of German deposits in the Erzgebirge belonged to this type. The uranium contents vary between 0.5 and more than 1 % totaling up to 10 000 t U for single deposits of this type.

Quartz-pebble conglomerate deposits are typically associated with gold for instance in the Witwatersrand (Rep. South Africa) or Elliot Lake (Canada) with typical concentrations between 0.01 % and 0.1 % U. Typical uranium deposits host up to 100 000 t U.

In **breccia complex deposits** uranium occurs as a by-product of the copper-gold production. In the currently sole deposit of this type, Olympic Dam, Australia, there are uranium reserves of 222 000 t U at average values of 0.06 %.

Intrusive and metasomatite deposits are large-scale but low-grade uranium deposits. Examples for this type are represented by Rössing in Namibia with more than 100 000 t U at an average value of 0.04 % U and Lagoa Real in Brazil with more than 20 000 t U at 0.3 % U.

Uranium can occur in rock and in water at percentages above those of the normal geological background contents, but still insufficient for a formation of economically extractible deposits. Uranium, however, can be associated with other raw materials and be produced as a byproduct. Contents of 2 up to 5 ppm uranium in granite, of 3 ppm in black shales and concentrations of 0.003 ppm in seawater may be suitable for extraction, given very high commodity prices. The technical challenge and the associated costs would be very high, for that reason these occurrences will not be dealt with in this study. The largest non-conventional uranium deposits are associated with phosphorites with 120 ppm U on average. Uranium can, if the economic conditions are favorable, be produced as a byproduct in the course of the processing of phosphates to phosphoric acid. In the US, uranium has been extracted from domestic phosphorites for a number of years, in Belgium from imported phosphorites from Morocco. In Kazakhstan, uranium was produced from fossil bones in marine sediments. Very few such occurrences have, however, been evaluated as resources.

6.1.2 Total Potential of Uranium, Historical Development

In the 1970s a strong growth of the nuclear energy for the future decades was forecast. There were concerns that the conventional uranium supply might not meet the demand. On an international level, efforts to evaluate the global potential of conventional uranium deposits were supported. This action complemented the global collections by the Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA), which have been conducting evaluations of the uranium supplies every two years since 1965. NEA and IAEA recorded the speculative uranium supplies in excess of that and presented the results of the *International Uranium Resources Evaluation Project* (IUREP) in the study *World Uranium potential* for 185 countries in 1978. The development of the uranium supplies since 1965 has been described in detail in the studies *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen* 1995 and 1998 (BGR, 1995, 1999). An overview of this study is presented here.

From 1965 to 1981, the supplies were recoded by NEA and IAEA in the categories *Reasonably Assured Resources* (RAR) and *Estimated Additional Resources* (EAR) at extraction costs of up to USD 80/kg U. Since 1983, a segmentation into EAR category I and category II (EAR-I, EAR-II) was conducted. EAR-I supplies are mainly those occurring in the vicinity of RAR occurrences, whereas EAR-II are less well explored and number amongst the so-called undiscovered resources. In addition, in all categories supplies with extraction costs up to USD 130/kg U were listed from 1977 onwards. In 1995 the class of the extraction costs up to USD 40/kg U was introduced. From 1991 to 1995 the assignment of the supplies of the CIS and a number of other countries in central and Eastern Europe to categories and cost classes was only possible to a limited degree; since 1995 it was implemented in stages. The integration of the supplies of China and India is not possible due to a lack of data.

The changes of the classification of reserves take into account the changes of the state of knowledge and the economic requirements, in particular the extraction costs. This resulted in changes of the reserves and reserve categories as well as the class of the extraction costs; a direct comparison becomes more difficult. The data for the RAR, recoverable up to USD 80/kg U are most reliable. These have been determined since 1965 and can thus be used as references. Global statements are restricted by the fact that there are no data of the countries of the former Warsaw Pact until the beginning of the 1990s, which only then gradually became available according to the required definitions. The development of the reserves until 1993 thus took into account only the countries of the *World Outside Centrally Planned Economy Areas* (WOCA).

1965 was excluded from the consideration as this was the first year of the determination of reserves, and only a limited number of countries was covered. Between 1967 and 1993, RAR recoverable up to USD 80/kg U of 1.4 Mt U and 1.85 Mt U were conveyed in the WOCA-area. This variation range can be explained from the changes in national data due to changes of reserve categories. 1991 and 1993, these reserves amounted to 1.5 Mt U. Between 1967 and 1993, in the WOCA-area a total of 0.8 Mt U was produced. The produced reserves have thus been more than balanced by new discoveries in the observation period.

For the EAR reserves a greater change occurred in 1983 as a consequence of the distinction into EAR-I and EAR-II. Between 1967 and 1981, EAR varied between 1.48 Mt U (1979) and 1.74 Mt U (1967). In the wake of the distinction into EAR-I and EAR-II in 1983, the EAR-I reserves decreased to 0.79 and to 0.93 Mt U, respectively. The US have not fully implemented this distinction. According to agreement, their reserves have been listed in category EAR-II. In 1994 the IAEA did not conduct a determination of the reserves.

Since 1995 the reserves in the category RAR, recoverable up to USD 80/kg U, have been recorded globally in accordance with uniform definitions. The former centrally planned economies have taken over the classification of reserves of NEA and IAEA in stages. If reserves without deductions for extraction losses (in-situ) had been reported, corresponding corrections were made. Since 1995 the RAR recoverable up to USD 80/kg U varied little, between 2.12 Mt U and 2.34 Mt U. In 2001 2.24 Mt U were recorded globally, whereas the reserves of China and India were not taken into account. The increase of the RAR recoverable up to USD 80/kg U to about 0.6 Mt U between 1995 and 2001 has been mainly attributed to the reserves of the CIS. Between 1995 and 2001, globally approximately 0.25 Mt U were produced. As no reduction of the reserves was noted between 1995 and 2001, the produced amounts have been more than balanced by the transition from lower-level classes (EAR). As a consequence of an increasing number of country statements, the RAR recoverable up to USD 40/kg U have increased from 0.5 Mt U to approximately 1.5 Mt U between 1995 and 2002.

Since 2003 the reserve category EAR-I has been defined as Assumed Reserves, the former *Known Conventional Resources* as *Identified Resources* (Chapter 2.4.3). Due to the lasting market upturn, the RAR recoverable up to USD 40/kg U have been chosen as the reference cost category.

The identified uranium deposits have increased significantly in all cost categories in the period 2001 to 2007 (Tab. 6.1). This can be mainly attributed to successes in the exploration and the expansion of production as a consequence of the significant increase in prices for uranium. The cost category <USD 40/kg U comprised 2.97 Mt U globally in 2007. The increase in RAR recoverable up to USD 40/kg U during the same period by approximately 0.2 Mt U to more than 1.76 Mt U can mainly be attributed to new reserves in Kazakhstan. No reduction of the reserves in spite of ongoing production occurred, i.e. the produced amounts have been more than balanced by transition from the lower-level reserve classes and cost categories.

Table 6.1: Development of the global reserves and resources of uranium in Mt (2001 to 2007).

Category of resources	**2001**	**2003**	**2005**	**2007**	**Changes 2001-2007**
Identified (gesamt)					
<USD 130/kg U	3 933	4 588	4 743	5 469	+1 536
<USD 80/kg U	3 107	3 537	3 804	>4 456	+1 349
<USD 40/kg U	>2 086	>2 523	>2 746	2 970	+884
RAR					
<USD 130/kg U	2 853	3 169	3 297	>3 338	+485
<USD 80/kg U	2 242	2 458	2 643	2 598	+356
<USD 40/kg U	>1 534	>1 730	>1 947	>1 766	+232
Assumed					
<USD 130/kg U	1 080	1 419	1 446	>2 130	+1 050
<USD 80/kg U	865	1 079	1 161	>1 858	+993
<USD 40/kg U	>552	>793	>799	1 204	+652

In order to assess the **total potential of uranium,** a task force of NEA and IAEA determined the speculative uranium reserves and in 1980 presented the results of the *International Uranium Resources Evaluation Project* (IUREP) in *World Uranium potential* for 185 countries of the world (IUREP, 1980). Accordingly, the speculative reserves for 1977 in the WOCA countries had been estimated at 6.6 to 14.8 Mt U, for the USSR, the countries in Eastern Europe and the PR China at 3.3 up to 7.3 Mt U. In conjunction with the known reserves of about 4.3 Mt U, the resulting conventional resources total at 9.0 to 22.1 Mt U. The wide range is due to uncertainties in the recoding and evaluation of regions of the earth that are geologically little explored.

In 1976 the BGR gave conservative estimates of the total resources at about 10 Mt U in the study *Das Angebot von Energie-Rohstoffen*, of these approximately 3.5 Mt U were identified reserves (Mixius et al., 1976). Since 1979 the Uranium Group of NEA and IAEA evaluates the conventional global uranium reserves, including the speculative uranium reserves on the base of national data. Accordingly, the current total potential, balancing the conventional reserves and resources at the end of 2007, was 16.0 Mt U. An analysis of the total resources by the BGR resulted in 18.2 Mt U, including high cost resources previously not considered.

The total potential of uranium is regionally distributed quite uniformly (Fig. 6.1). The detailed distribution of the reserves, resources, the production and of the consumption have been depicted below.

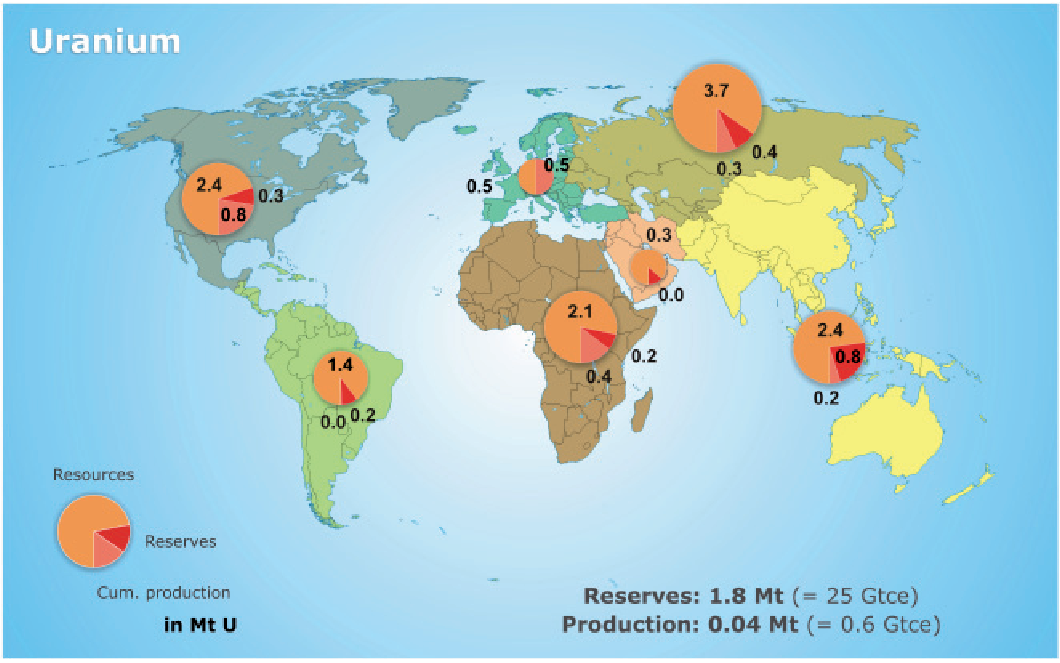

Figure 6.1: Distribution of the total potential of uranium 2007 according to regions.

6.1.3 Uranium Reserves

The mining reserves comprise mainly the recoverable reasonably assured reserves (RAR) up to USD 40/kg U (Chapter 2.4.3). An overview as of January 1st, 2007, was published by NEA/OECD and IAEA (NEA/OECD – IAEA, 2008) (Tab. A 6-2). Accordingly, the reserves of 1766 Mt U recoverable up to USD 40/kg U (Tab. A 6-1) are unevenly distributed among the countries (Fig. 6.2).

Besides geology, differing degrees of exploration as well as economic, infrastructural and political conditions are responsible for the uneven distribution. Australia possesses the highest proportion of uranium reserves at more than 40 %, followed by the CIS at approximately 20 %, North America at approximately 15 % and Africa at 11 % (Fig. 6.2). Europe possesses at 0.1 % only small reserves, as the known deposits have been exhausted. By economy policy regions, the OECD ranks first at more than 55 %. The CIS provides nearly 21 % of the reserves and the developing countries about 15 %. The EU possesses only 0.1 % of the uranium reserves of this cost category.

Besides the reasonably assured reserves (RAR) recoverable up to USD 40/kg U, reserves at these extraction costs are also included in the category inferred reserves (IR). This category frequently plays a more important role for the determination of reserves and plans than reserves with higher extraction costs. In early 2007 the global reserves in this category amounted to 1.2 Mt U (Tab. A 6-3). The Identified Reserves in accordance with NEA and IAEA, the sum of the categories of reasonably assured reserves and inferred reserves (Chapter 2.4.3), recoverable up to USD 40/kg U, globally amounted to 2.97 Mt U at the beginning of 2007.

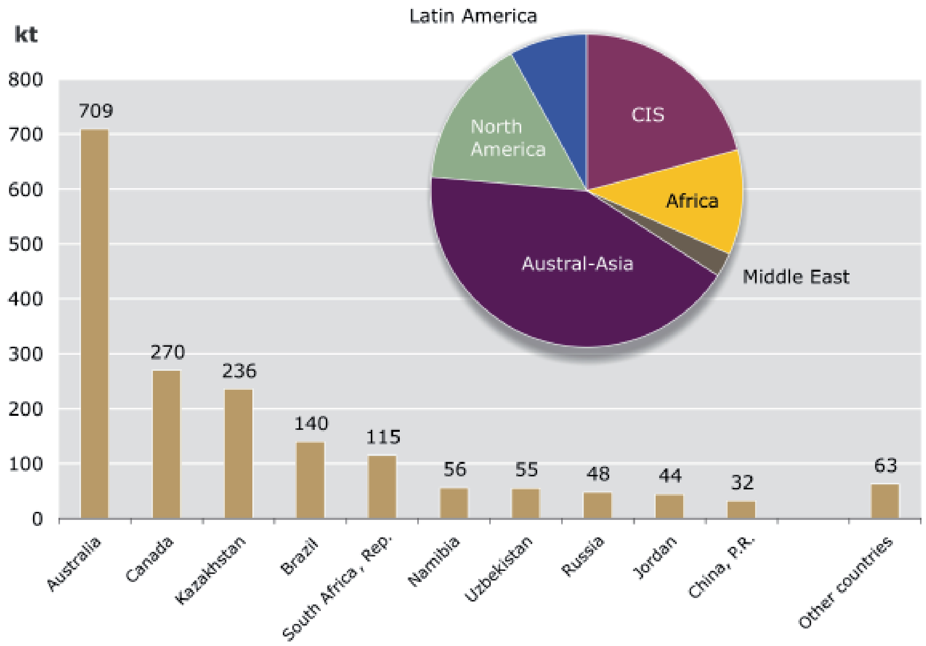

Figure 6.2: Uranium reserves in 2007 (total 1766 Mt U) recoverable up to USD 40/kg U of the top ten countries as well as their distribution by region. The reserve data of the countries with in situ-reserves has been converted to recoverable amounts.

6.1.4 Uranium Resources

The categories exceeding reserves in **conventional uranium occurrences**, in some cases recorded with a high certainty of proof, have been classified as resources. In spite of significantly higher market rates since 2005, the reasonably assured reserves (RAR) have also been included in the cost categories USD 40 to <80/kg U and USD 80 to <130/kg U. As the RAR have been determined with a high degree of certainty, they constitute the reserves for higher prices. From the 1990s until 2004 they were not recoverable at economic conditions due to the low price level and were thus assigned to the subeconomic resources. With increasing prices many of these resources became reserves. As the spot market only represents a small trade volume and uranium is traded mainly based on long-term delivery contracts slightly above the USD 40/kg category, these categories will continue to be classified as resources. The inferred reserves (IR), recoverable at costs between USD 40 and USD 80/kg U as well as between USD 80 and USD 130/kg U will be treated the same way. Their degree of proof is lower than for RAR.

The surveys of uranium reserves by NEA and IAEA (NEA/OECD – IAEA, 2008) also extend to undiscovered resources (Chapter 2.4.3). They are registered in the cost categories recoverable up to USD 80/kg U and recoverable up to USD 130/kg U. In Table A 6-3 only the resources determined up to USD 130/kg U are depicted together. The speculative resources (Tab. A 6-3) have been listed without extraction costs, as due to its speculative nature only the total amount is of interest.

The global distribution of the resources amounting in total to 14.2 Mt U is similar to the distribution of the uranium reserves (Fig. 6.2). At nearly 28 % North America possesses the largest resources of uranium, of these the US, as the country with the largest resources, possess 2.95 Mt U and Canada hosts approximately 1 Mt U (Fig. 6.3). The second most important region consists of the countries of the CIS at a proportion of slightly more than 25 %.

Mainly Russia at 1.49 Mt U, Kazakhstan at 1.38 Mt U and the Ukraine at 0.45 Mt U account for these resources. Important regions are also Australasia with the dominant position of Australia with 0.53 Mt U and Africa, where the Republic of South Africa alone hosts 1.54 Mt U as reserves, with a resource proportion of 17 % (Fig. 6.3). Germany is listed globally on rank 21 of the resource countries, with 81 kt U. The countries important for uranium, Australia and Namibia do not list undiscovered resources, which seems implausible. Thus it can be assumed that the data on the global resources are on the conservative side.

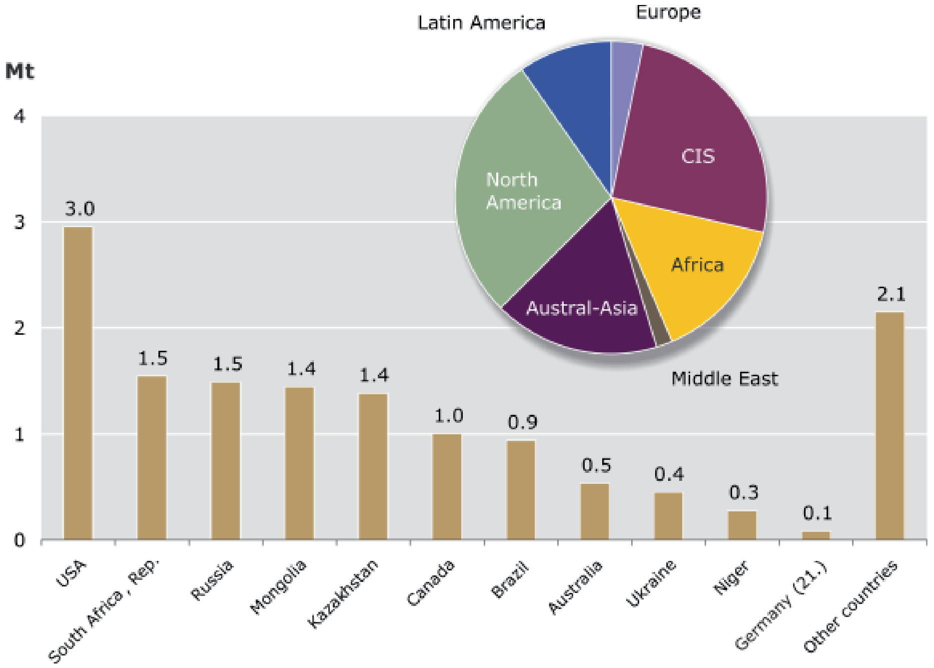

Figure 6.3: Uranium resources (14 243 Mt) in 2007 of the top ten countries and Germany as well as their distribution by region.

The resources recoverable at costs of more than USD 130/kg U are currently no longer recorded in detail. Thus, they were not included in the evaluation of this study in Table A 6-3. The last time they were determined in a study was for ‘Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 1998’ (BGR, 1999) on the basis of older documents with about 419 000 t U for the RAR >USD 130/t U and about 497 000 t U for the IR >USD 130/t U. As these investigations date back more than 30 years, there are limitations concerning the scope of these data. The values specified in Table A 6-3 were compiled from the most current sources such as NEA/OECD – IAEA (2008) and World Nuclear Association (WNA, 2008) including proprietary data of the BGR. For the IR for the USA data were used from the WNA, as NEA/OECD – IAEA (2008) does not contain complete data.

In the past decades, the amounts of non-conventional uranium reserves have been assessed very optimistically in some cases. Thus, the possibility of extracting uranium from phosphates (phosphorites) during the production of phosphoric acid resulted in very optimistic assessments. Different studies have specified the uranium contents of marine phosphate deposits worldwide as 15 to 30 Mt U. From available phosphoric acid plants, a theoretical annual production of 5000 to 10 000 t U had been assumed. These assumptions turned out to be unrealistic; in the meantime all plants for producing uranium via the phosphoric acid process have been shut down. In Belgium approximately 690 t U were produced from imported Moroccan phosphates between 1975 and 1999. In Florida in the US a total of 17 150 t U were produced from phosphate rock between 1954 and 1962. A plant in Kazakhstan produced approximately 40 000 t U between 1959 and 1993. Lately some countries have renewed their interest in uranium occurrences in domestic phosphate mines. Since 2007 Jordan has been exploring its deposits with an estimated uranium content of 59 360 t.

All other non-conventional resources have not yet achieved economic importance. In the former GDR between 1947 and 1955 as well as from 1968 to 1989 about 3000 t U were produced from the coals of the Freitaler Revier in Saxony. The US pursued the extraction of uranium from bituminous coal, the produced amounts, however, were low. In Sweden the shale deposit Ranstad yielded approximately 200 t U. The extraction of uranium from granite also aroused temporal interest. Based on the example of the deposit Rössing in Namibia with uranium contents between 200 and 300 ppm U, similar occurrences were explored for in many regions. Even though granite with elevated uranium contents and potential of several Mt U has been taken into account, a true economic potential is currently not perceptible. Likewise do economic reasons currently cast doubt on the uranium extraction from seawater with estimated 4.5 Gt U. In 2006 Japan, however, resumed research on corresponding extraction technologies. Researchers managed to enrich approximately 1.5 g U under natural conditions in the ocean during a period of 30 days. The system used can be designed for an annual production of approximately 1,200 t U at extraction costs of about USD 700/kg U.

6.1.5 Additional Uranium Stocks

Additional sources are represented in uranium which was previously produced for different purposes. The uranium, however, can have different forms. From 1945 until the end of 2007 2.3 Mt U were produced globally, but only about 1.7 Mt U were used for civil purposes. The remaining 0.6 Mt U were kept in readiness for use by the military as well as for stock kept for safeguarding the supply by consumers, producers and public institutions. Neither the uranium used in the reactors nor the uranium for nuclear weapons has been exhausted. According to the World Nuclear Association (WNA, 2008), the nuclear fuel that has not been consumed in the nuclear reactors can be reused, uranium as Reprocessed Uranium, REPU and plutonium as mixed oxide (MOX). The REPU that will be available until 2020 corresponds to 26 500 to 52 000 t U, depending on the demand scenario, the plutonium used as MOX corresponds to approximately 24 000 to 48 000 t U.

The uranium used by the military constitutes a further resource. The US and Russia negotiated the disarmament of highly enriched uranium (HEU) from nuclear weapons. 500 t HEU from Russian nuclear weapons have been and will be disarmed between 1993 and 2013 and depleted in Russia for civil usage (Low Enriched Uranium, LEU). This amount converted to natural uranium corresponds to about 152 000 t U, until June 2007 approximately 93 000 t U had been processed. 8 939 t LEU have been delivered to the USA for usage in commercial reactors. This delivery corresponds to the disarmament of 12 231 nuclear warheads. Of intended 174.3 t of American HEU 151 t are to be made available for research purposes and commercial demand. Until 2006, 94 t HEU had been converted to 1051 t LEU. The amounts theoretically becoming available in the market correspond to approximately 358 000 to 408 000 t U. The annually available amounts depend on contractual agreements as well as on the economic situation. Between 1500 and 3000 t U annually can be made available from

REPU until 2030, from MOX between 1200 and 2400 t U for the same period. In total, that would correspond to approximately 8 % of the currently foreseeable annual demand.

The depleted uranium resulting from enrichment for civil usage (reduced in 3 to 5 % ^{235}U) and military usage (>90 % ^{235}U) also constitutes a potential source. The total amount has been estimated to be 1.2 to 1.35 Mt of depleted uranium (0.3 % ^{235}U or smaller). After re-enrichment to the natural ^{235}U-concentration of 0.7 % these amounts would correspond to 440 000 to 500 000 t U. The depleted uranium is already being used for civil purposes by mixing with HEU to produce LEU or can be re-enriched in case of unused enrichment capacities.

6.1.6 Uranium Production

Between 1945 and 2007 a total of 2.3 Mt U were produced. The global mining production during this period was determined by many factors. Thus until the break up of the Soviet Union and of the Warsaw Pact it was mainly controlled by military requirements. In the Western countries the military requirements resulted in a continuous growth of production up to approximately 33 000 t U in the year 1959. A decreasing military demand and low civil demand resulted in a decrease until the middle of 1960s to about 16 000 t U. Based on the expectation of a high growth of the use of nuclear energy, from 1970 onwards an increase in production began, which reached a maximum at 44 000 t U annually in 1980 and 1981 and significantly exceeded consumption. For supply-strategic considerations governments, consumers and producers established stocks, which exceeded significantly the customary stockpiling of approximately two annual consumptions of the conversion and enrichments plants as well as of the power supply company. In the wake of the decelerated growth of the civil usage of nuclear energy production in the Western countries decreased until 2001 to approximately 27 000 t U annually.

For the former Eastern Block and the PR China only an assessment of the annual development of the production can be made, based on the overall output or assumptions. Accordingly a continuous increase of the production to more than 26 000 t U annually occurred until the middle of 1980s, controlled by the production of nuclear weapons and the demand of the civil usage for the reactor programs the Soviet Union. The political upheaval in the early 1990s changed the area of the uranium production, as the dominant military importance ceased to exist. The integrated state-owned companies had to adapt to free-enterprise conditions, to reception restrictions of some countries for uranium from the GUS. The re-orientation of the supply in the countries of central and Eastern Europe were decisive factors for a reduction of the uranium production. By the mid 1990s the output in the GUS has decreased to approximately 6400 t U, but recovered until 2007 to about 13 200 t U. The uranium production of the previous years, which had been largely required by the military and the civil demand, which had not been up to expectation, have resulted in the existence of stocks. The amounts of uranium available from current production have significantly undershot the demand since the early 1990s.

The production capacities existing in 2007 in deposits with reserves <USD 40/kg U amount to 41 000 t U, i.e. it would be impossible to meet the demand by the mining production alone. The current production capacities, based on reserves available, including the category inferred reserves, up to USD 80/kg U, amount to about 55 000 t U/a.

From 1995 to 2007 Canada took top rank of all producing countries with a total of 141 176 t U. This corresponds to 29.5 % of the global production during this period. Canada's annual output varied with the exception of 1999 between 9500 and more than 12 000 t U and amounted to 9476 t U in 2007 (Fig. 6.4). The decrease in 1999 can be attributed to the discontinuation of production in the pit Key Lake and the start of production in the mines McArthur River and McClean Lake. This change in production sites was finished in 2000, when the former production volume of more than 10 000 t U was reached again. In 2001 in Canada a production maximum was reached at 12 522 t U. Lower grade ore in the deposits McClean Lake and Rabbit Lake have reduced the output to approximately 9500 t U after 2005.

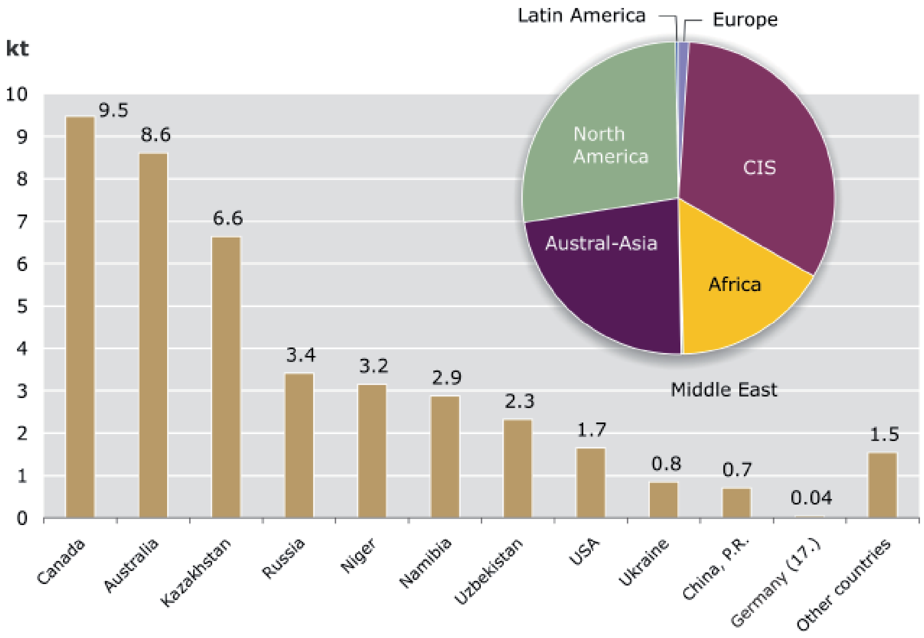

Figure 6.4: Uranium resources (14 243 t U) in 2007 of the top ten countries and Germany as well as their distribution by region.

Australia with a total of 89 440 t U or 18.6 % of the global production is the second largest producer of the years 1995 to 2007 (Fig. 6.4). The annual production rose with interruptions in 1998 and 2002 continually from 3712 t U in 1995 to 8611 t U in 2007, with a maximum of 9512 t U in 2005.

The development of the uranium production in the CIS-countries took very different courses. For Kazakhstan 1998 a significant increase in production to 6637 t U in 2007 occurred. Kazakhstan thus has risen to be the third-largest uranium producer worldwide (Fig. 6.4). The growth is based mainly on the expansion of the previous output as well as on the development of new deposits. Russia moderately increased its output until 2007 to 3413 t U in order to fulfill its delivery commitments for reactors of soviet origin in third countries and its domestic demand. Ukraine, also with a domestic usage of nuclear energy, has kept the output stable at annually approximately 800 t U. The mining production in Uzbekistan shows a slight growth since 1995, due to improved production methods.

Production in the US showed a significant downward trend from 1995 to 2003. Market-related factors, abandonment of operations that were no longer profitable, such as the uranium production from phosphoric acid by-products and low-cost acquisition from Canada's rich ore mines have been decisive factors in this context. Since 2004 the output has increased again due to increased exploration efforts and improved conditions and has reached the production volume of 1998.

Because the deposits have been depleted and operations that were no longer profitable were shut down, the uranium production in Europe has decreased from 2279 t U in 1995 to only 425 t U in 2007. France, Hungary and Romania have ceased commercial production and deliver like Germany remaining quantities from the remediation of old production centers. The sole relevant mining production takes place in the Czech Republic at annually 300 t U and decreasing trend.

From 1997 to 2007 the uranium production was controlled all over the world by take-overs, amalgamations and shut-downs by a few nationally and internationally operating corporations, which controlled between 70 and 80 % of the production during that period. As a consequence only seven companies were responsible for 86 % of the global mining production in 2007 (Tab. 6.2).

The twelve most important uranium deposits provided about 70 % of the global output in 2007 (Tab. 6.3). Dominant by far was the rich ore deposit McArthur River in Canada, where 7199 t U or 17 % of the annual global production were mined. Ranks two and three were taken by the Australian mines Ranger and Olympic Dam at 4589 and 3388 t U, together they provided about 19 % of the global production in 2007.

Corresponding to the multitude of the possible occurrences of uranium (Chapter 6.1.1) the output in 2007 was not dominated by one extraction technology. In principle the four processes open-pit mining, underground mining, in-situ leach mining (ISL) and production as by-product are to be distinguished, which all provided relevant amounts of uranium (Tab. 6.3). Open-pit mining varied in the past 20 years between 28 and 40 % with decreasing tendency. Between 31 and 51 % were mined underground, on average approximately 40 %. The proportion of in-situ leach mining increased from approximately 6 % to 29 % today in the period from 1990 to 2007. By-product extraction, which currently mainly takes place in the deposit Olympic Dam, has an overall proportion of 10 %and shows increasing tendencies.

Table 6.2: Uranium production of the most important mining companies in 2007.

Mining company	Uranium production 2007 (t U)	Proportion (%)
Cameco	7 770	19
Rio Tinto	7 172	17
Areva	6 046	15
KazAtomProm	4 795	12
ARMZ	3 413	8
BHP Billiton	3 388	8
Navoi	2 320	6
Uranium One	784	2
GA/ Heathgate	673	2
Andere	4 919	12
TOTAL	*41 279*	*100*

Table 6.3: The most important uranium deposits in 2007 with the corresponding mining process (ISL = in-situ leach mining) and the ownership structures of the individual corporations.

Mine	Country	Main owner	Type	Production 2007 (t U)	Proportion (%)
McArthur River	Canada	Cameco	underground	7 199	17
Ranger	Australia	ERA (Rio Tinto 68 %)	surface	4 589	11
Olympic Dam	Australia	BHP Billiton	by-product	3 388	8
Kraznokamensk	Russia	ARMZ	underground	3 037	7
Rossing	Namibia	Rio Tinto (69 %)	surface	2 583	6
Arlit	Niger	Areva/Onarem	surface	1 750	4
Rabbit Lake	Canada	Cameco	underground	1 544	4
Akouta	Niger	Areva/Onarem	underground	1 403	3
Akdala	Kazakhstan	Uranium One	ISL	1 000	2
Zafarabad	Uzbekistan	Navoi	ISL	900	2
McClean Lake	Canada	Areva	surface	734	2
Beverley	Australia	Heathgate	ISL	634	1,5
SUMME				*28 760*	*70*

6.1.7 Uranium consumption

Numbers of consumption for uranium are published by different national and official international organizations as well as commercial companies. The numbers published by NEA and IAEA in the regular publications (NEA/OECD – IAEA, 2008) are based on surveys of public institutions and can thus be regarded as reliable. The commercial World Nuclear Association (WNA) publishes consumption numbers, which are based on surveys of companies (WNA, 2008). With the exception of slight deviations, which presumably result from the differences in collecting data described above, no significant differences for the consumption between 1995 and 2007 were found between NEA/OECD and IAEA as well as WNA. For estimates of the future consumption NEA and IAEA considered a High and Low Scenario from 2010 to 2030. For this period the WNA included a Reference Scenario.

Between 1995 and 2007 the demand of natural uranium increased from 61 378 t U according to NEA/OECD - IAEA (2008) and 57 783 t U, respectively, according to WNA (2008) to 69 110 t U (NEA/OECD - IAEA, 2008) and 66 529 t U (WNA, 2008), respectively. This corresponds to a significant increase of nearly 13 % and 15 %, respectively. At the same time the annual production increased from 35 635 to 41 870 t U between 2003 and 2007 in comparison to 2002. As a consequence competitive new projects were tackled and production operations, which had formerly not been economic, remained in production or have even been upgraded. Countries such as Bulgaria, Spain, Hungary, France and Gabon, which had been producing uranium at higher cost for meeting domestic demand, terminated production. Other countries such as Kazakhstan and Malawi have recently entered the group of uranium producers, continue production, such as the Czech Republic and South Africa or plan the resumption of production such as currently Argentine and the DR Congo.

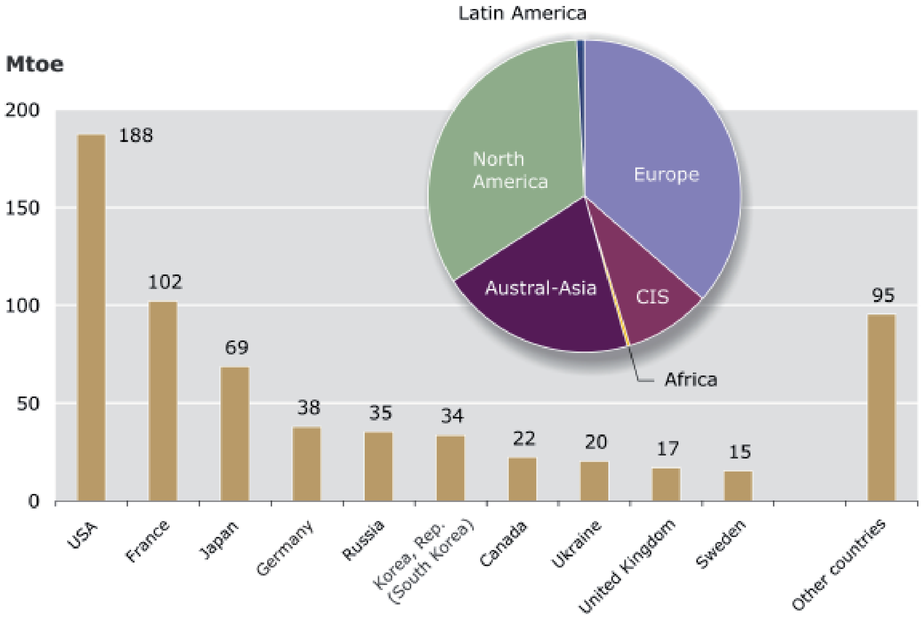

Figure 6.5: Consumption of uranium (636 Mtoe) in 2007 of the top ten countries as well as their distribution by region.

The by far most important consumer countries in 2007 were the US, France and Japan with a joint proportion of 57 %; Germany, Russia and South Korea come close (Fig. 6.5). These six countries jointly covered about three quarters of the global uranium consumption in 2007.

The future consumption of uranium depends on the further development and the implementation of the ambitious plans of national nuclear energy programs. The Low Scenario by NEA/OECD and IAEA assumes, in contrast to previous forecasts a growth to 70 395 t U from 2010 with a further increase until 2030 to about 93 775 t U (NEA/OECD – IAEA, 2008). The global renaissance of nuclear energy in countries with previously decreasing consumption such as the US, Russia or Canada, new users such as the United Arab Emirates, Thailand, Turkey or Vietnam and most of all the intended massive construction of new power plant capacities in the PR China, India, Russia, Japan, South Korea and the US will result in an increased demand. The High Scenario by NEA and IAEA anticipates a significantly increasing demand to 98 600 t U until 2020. Accordingly for 2030 a demand of 121 955 t U is expected (NEA/OECD – IAEA, 2008). In the Reference Scenario of the WNA an increase to 80 500 t U in 2020 is assumed, for 2030 the demand accordingly reaches 110 000 t U (WNA, 2008).

6.1.8 Nuclear Fuel Cycle and Trade

Uranium is traded globally. As it undergoes several treatment stages until it is used in a nuclear reactor, the individual treatment products are frequently transported over long distances. The concentrate packaged in barrels (Yellow Cake) is either stored temporarily at the treatment plant or directly delivered to conversion plants because of purchase contracts with the recipient. There, the concentrate is converted to gaseous uranium hexafluoride (UF_6), before it is enriched in processing plants to the desired ^{235}U-composition. The enriched uranium is then processed in separate fuel elements for its ultimate use. The individual steps are executed depending on availability and the form of contract in different countries.

The conversion is conducted, with the exception of a number of national institutions, in large plants, operated by Cameco in Canada and Great Britain, Areva in France, Conver Dyn in the US, Atomenergoprom in Russia as well as CNNC in China. The European conversion capacities cover approximately 25 % of the global demand. At the suggestion of the IAEA and Russia and in coordination with the American Global Nuclear Energy Partnership (GNEP) there are efforts being undertaken for setting up international centers for the enrichment of uranium. The first of such centers exists in Siberia, Russia. It is called Angarsk IUEC and operated with Kazakh participation. The French Atomic Energy Agency has suggested the new plant Georges Besse II for an international opening under comparable conditions. Another proposal for an international enrichment center is being expected from South Africa.

Urenco (Germany, Netherlands, Great Britain), Areva (France), US Enrichment Corp (USA), Atomenergoprom (Russia), JNFL (Japan) and CNNC (China) operate enrichment plants on a large scale. Fuel elements are produced in 17 countries. The largest plants are located in the US, Russia, Japan and Canada. The annual enrichment capacity in Germany corresponds to a global proportion of nearly 16 %.

The power supply companies as consumers procure their fuel directly from producers or via traders. The delivered quantities, qualities and times are governed by contracts. In Europe these have to be presented to EURATOM for approval purposes. For trading purposes the following groups of countries can be distinguished: Exporting countries with production without domestic demand, such as Australia, Niger, Namibia, Uzbekistan and Kazakhstan; exporting consumer countries, whose production is significantly higher than the domestic demand such as Canada and South Africa; importing countries with domestic production such as the US, Russia, Ukraine, the Czech Republic, Romania and India as well as importing countries with their own nuclear power plants but without domestic production. Among the last category there are many large consumer countries, such as Germany, Great Britain, Sweden, Finland, Belgium, Switzerland, Japan, South Korea, France, Spain and Argentine. Russia takes a special position, in that it produced less uranium than it consumes, but it possesses stock and secondary sources.

The supply of the EU, whose demand in 2007 was 21 280 t U, is only covered to a small proportion by the domestic production of annually approximately 425 t U and by stock. With exception of the last remaining primary production in the Czech Republic and small amounts from the remediation of former production centers in France, Romania and Germany, the EU is nearly completely dependent on imports from third countries. The delivery contracts for consumers in the EU are handled by EURATOM Supply Agency. In the last years annually 20 to 25 % of the demand, i.e. between 3000 and 3500 t U have been supplied by Canada. The deliveries from Russia, Kazakhstan and Uzbekistan reached with 3500 to more than 5000 t U annually more than 30 % of the demand. As a consequence concerns about a one-sided dependency resulted in import restrictions. Russia's uranium deliveries to the EU contain probably also uranium of Kazakh, Uzbek and Ukrainian origin. In 2007 Russia at nearly 25 % of the deliveries, corresponding to 5144 t U, superseded Canada after many years as most important uranium provider of the EU. The Canadian deliveries decreased by 25 % to 3786 t U. Further important provider countries for the EU were Niger at a proportion of 17 %, corresponding to 3531 t U and Australia, which contributed 3209 t U or about 15 %. The imports from South Africa and Namibia have decreased significantly in the past years to 4.8 % now.

6.1.9 Uranium Prices

On principle two price structures can be distinguished: Prices for multiannual contracts and for immediate deliveries (Spot). Most of the uranium is traded based on long-term contracts. The price quotations are usually in USD per pound (lb) U_3O_8.

Reliable data on production costs of uranium are not internationally published. The production costs are determined usually by the individual mining and production methods as a function of the geological deposit parameters. The described changes of the proportions of the different mining methods (Chapter 6.1.6) reflect the efforts of the producer, even in times of high commoditiy prices, to lower production costs. Since 1990 this has been realized by concentrating on underground mining of rich ore deposits and by optimizing the in-situ leach mining. This way the prices for multiannual contracts for deliveries in the EU dropped from USD 17.48/lb U_3O_8 to USD 13.18/lb U_3O_8 until 2001. Then the price for long-term deliveries rose to approximately USD 21.60/lb U_3O_8 until 2007.

For spot deliveries, which account for about 3 % of the trade volume, the price decreased between 1990 and 2001. After a significant market recovery an all-time high occurred in June 2007 at USD 136 00/lb U_3O_8. Until the end of 2008 the prices dropped again as part of the adjustment of the market. They consolidated however in spite of the looming financial crisis above USD 45.00/lb U_3O_8. This market recovery has resulted in an increased economic profitability even of low-grade uranium ore. sales revenue of USD 13 to USD 15/lb U_3O_8 and deducting sales costs and suitable yield of the invested capital pure production costs of significantly less than USD 10/lb U_3O_8 are taken into account. Revenues in the spot market were not considered, as this uranium was mainly from stock. The mean EURATOM spot market price in 2007 was USD 64.21/lb U_3O_8. This corresponds to an increase by 127 % in comparison to 2006.

The rapid economic development in populous emerging markets, a rapidly increasing energy demand in these countries as well as the development of the global climate policy have resulted in many countries in a renaissance in the interest in an expansion of the civil use of nuclear energy. Simultaneously mining production has lagged behind demand for many years; the latter was only met by mining stock and other secondary sources (Chapter 6.1.5). As a consequence since 2003 the uranium prices increased significantly and the market underwent a lasting recovery. This entailed high capital expenditure in exploration, the new development of new uranium mines as well as an expansion of the production from known mines.

6.2 Thorium

6.2.1 Thorium as Nuclear Fuel

Thorium can be used as nuclear fuel for the generation of energy in special reactors. In the 1960s and 1970s different types of reactors for power generation, for generating heat, for coal gasification and for other processes were developed. Thorium was supposed to complement uranium as nuclear fuel in case of a possible shortage. In addition thorium was favored as fuel in countries, which, like India, do not possess sufficient uranium deposits. After the development of thorium-based test and prototype reactors further development was stopped, as the expected increase of the usage of nuclear power did not occur and existing uranium deposits ensured the supply. The German thorium high-temperature reactor THTR Hamm-Uentrop with 300 MW_e was shut down in 1989 after a short operating time.
In South Africa a high-temperature gas-cooled reactor with Thorium as fuel was developed further. South Africa and China have agreed on a future cooperation and the construction of a test reactor until 2015. India has been developing a proprietary type of reactor based on thorium as fuel for some time. The start of production is not anticipated before 2020.

6.2.2 Supply of Thorium

The situation of the reserves and resources for Thorium has not changed by much since the BGR-Energy Study 1998 (BGR, 1998), as a lack of demand has precluded new supply determinations. The global thorium reserves (<USD 80/kg Th) thus amount to 2.57 Mt Th. In addition resources of approximately 1.8 Mt Th have been the forecast.

6.2.3 Production and Consumption of Thorium

There are no reliable numbers on the production of thorium available, as thorium is not mined separately as a resource. Thorium is usually a by-product of the fabrication of monazite for the mining of rare earth elements. Monazite in turn is a by-product of the production of heavy mineral sands on ilmenite, rutile and zircon. On average monazite contains approximately 10 % thorium dioxide (ThO_2). Considerable amounts are available from previous mining of ore containing uranium-thorium on uranium like in Madagascar. During the past years monazite was produced in particular in India, Malaysia and Sri Lanka. The global output of monazite amounted to 6000 to 6350 t per year. Monazite also used to be produced in the US. There production was stopped in 1995. The non-energetic application of thorium and compounds containing thorium in high-temperature ceramics, catalytic converters and welding electrodes decreased due to the radioactivity of thorium.

The current use of thorium in research reactors is restricted to small amounts. The demand can be met from existing stock. In the USA more than 3000 t of thorium compounds are being kept as stock. The stock in other countries is not known, but it is assumed to be considerable in producing countries, such as India and South Africa.

6.3 References on Nuclear Fuel

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7 Geothermal Energy

7.1 Heat from the Earth for Usage as Energy

Energy stored as heat underneath the surface of the solid earth is called geothermal energy. The enthalpy of the earth can be traced back in part to the initial heat when the earth was formed, in part to the decay of radioactive isotopes in the rock of the earth crust. The high temperatures in the earth's interior cause a constant heat flow towards the earth's surface. The total heat flow is theoretically sufficiently high to supply a considerable part of the global energy demand; the heat flux of about 70 mW/m^2 is rather low in the global mean, however. The use of geothermal energy from the deeper basement thus, as a rule, refers to a local extraction of stored geothermal heat. In most cases, the amount of heat removed is much greater than the heat rising from the depth within a reasonable time frame.

An exploited geothermal deposit will regenerate due to the heat flow from the depth, but this process can take more or less time. Depending on the geological situation, a deep reservoir can take centuries to regenerate. In comparison to the other renewable energies this is a long period, in relation to the formation time of fossil energy resources a short period of time, however. The geothermal energy thus numbers amongst the regenerative energy sources, but on the other hand it is also a 'mineable' resource (BGR, 1999).

For use near the surface down to approximately 20 m depth the heat from the earth's interior is available in addition to the amount of heat provided by solar irradiation. The radiation of the sun exceeds the heat flow from the earth's interior many times over. The near-surface thermal energy is still part of the geothermal energy, because the energy is stored underground and taken from there. The earth's surface acts like a solar-thermal plant, absorbing part of the insolation and conducting the heat downwards. The yearly fluctuation of the temperature penetrates only a few tens of meters into the substratum, climate variations penetrate far deeper, however. For near-surface usage, the cooled area of the underground is comparatively quickly re-heated by insolation.

The most important process of the heat transmission in the earth crust is the conduction of heat. The resulting vertical temperature gradient, the so-called geothermal gradient, amounts to 30 °C/km in the continental mean. Based on the surface temperature, which corresponds to the local mean annual temperature, in Germany approximately 7 to 11 °C, at a depth of about 2000 m thus temperatures of app. 70 °C occur. In a depth of 5000 m these exceed 160 °C as a rule. In areas with rising ground water heat is also transported to the surface by convection. In such areas, as for instance near Landau in the Oberrhein Graben, temperatures of more than 100 °C are measured in depths of 1000 m.

The energy content of a geothermal deposit is determined by the temperature as well as by the heat capacity. For rocks this is in the range from 700 to 1200 J/(K·kg). A rock volume of 1 km^3 and a mass of $2.65 \cdot 10^{12}$ kg at a heat capacity of 850 J/(K·kg) contains a thermal energy of 2.3 PJ/°C. If this volume is cooled down by 10 °C, an energy of 23 PJ and $6.4 \cdot 10^6$ MWh, respectively, is drawn from it. This energy is sufficient to provide an average thermal power of 25 MW over a period of 30 years. The enthalpy of the rock is added to the enthalpy of the fluids in form of water or vapor, which is stored in the pores and fissures of the rock. Its mass-specific energy content, in particular that of vapor, is greater than that of the rock, but its mass fraction in the dense crustal rock is very low, thus rock heat prevails by far.

Crustal rock in general is a poor heat conductor with a heat conductivity between 2 and 4 W/(m·K). As a consequence, the heat of the deeper basement cannot be mined directly via drill holes. For an effective utilisation a carrier medium such as water or vapor is required, which flows through the rock and transports the heat to the drill holes. This in turn implies a sufficient permeability of the rock, which is usually only attained by highly porous sandstone and intensely fissured or karstified rock formations. The low permeability of the rock is thus one of the greatest obstacles for a wide exploitation of geothermal energy. In research projects the improvement of the exploitability by creating artificial flow paths through hydraulically generated fractures in the rock is currently being worked on.

In the following, the use of thermal heat energy is subdivided into direct use for heating purposes as primary geothermal energy and secondary use, i.e. geothermal energy is converted into electrical energy. When the geothermal energy is converted into electric power, the efficiency of the geothermal power generation has to be taken into account. This depends on the temperature and on the conversion technology used. The gross efficiency, which does not include the station supply needed for operating the plant, for instance the pumps, amounts to 9 to 14 % for current systems.

Installations for the direct use of geothermal heat are differentiated according to their temperature levels. The high temperature range can be used to supply district heating systems, industrial companies and companies of the food industry, the low temperature range to supply agricultural companies, for instance for greenhouses or drying plants, as well as pools and fish farms. Another use of geothermal energy in particular for industrial companies is cooling, using absorption refrigeration.

The greatest contingent by far of the globally installed non-electrical power is engaged by heat pump systems (Fig. 7.1). The power of the installed heat pumps has tripled globally since 2000. Pools, direct room heating without heat pumps and greenhouse heaters follow in the incidence of utilisation. The rest taken together amounts to less than 10 % and comprises also very specialized local usage processes (Fig. 7.1).

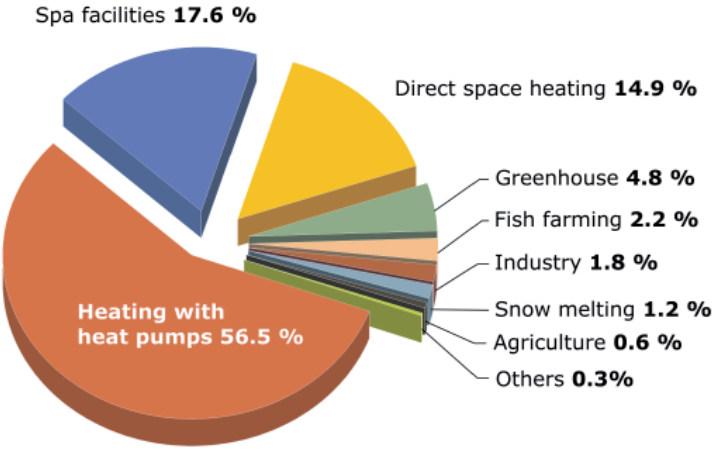

Figure 7.1: Distribution of the globally installed non-electric geothermal energy of 27 825 MWth in total to the different types of use in 2005 (Lund et al., 2005).

7.2 Sources of Geothermal Energy

7.2.1 Near-surface Substratum

The near surface basement is an economic heat source in view of the accessibility and the low development risk. In near-surface layers of the earth the temperatures change with the rhythm of the air temperatures, the temperature fluctuations decrease quickly with increasing depth and are barely detectable (<0.1 K) beneath 15 to 20 m of depth. As the energy flux introduced by insolation in these top meters of the soil is approximately 2000 times greater than the heat flow from the interior of the earth, the thermal use of the shallow substratum is mainly provided by solar energy.

Due to the low temperature, the energy stored in the shallow substratum cannot be used for direct heating. A heating system which uses the heat of the shallow underground mainly consists of the components soil heat exchanger, circulating pump, heat pump, storage tank and low temperature heating system. Soil heat exchangers are usually inserted as vertical geothermal probes in depths of mostly down to about 100 m, in individual cases up to 400 m, executed as horizontal heat exchanger loops or as spiral type heat exchangers. In summer these installations can directly cool buildings by circulating the brine, bypassing the heat pump. In addition, ground water extraction can produce heat from the ground. Typically not only a producing well, but also a re-injection drilling is required, in which the ground water cooled in a heat exchanger is re-injected into the ground.

A great advantage of the named technologies is that, with exception of the groundwater-coupled heat pump, it can in principle be employed anywhere. The savings in primary energy, which can be attained with such, in general electrically powered heat pump systems, are rather small, however. At the low temperature of the shallow substratum, heat pumps generally reach performance coefficients (COPs) between 3.5 and 4. This means that with every unit of electrical power, which is provided for the heat pumps, 3.5 to 4 units of thermal power are reached. For generating the power used for the pumps, efficiencies between 30 and 50 % are reached. If the consumed primary energy is included, this results in COPs between 1 and 2 in total (BGR 1999).

7.2.2 Hydrothermal Occurrences of Low Temperatures

Hydrothermal resources of low temperatures are warm and hot water aquifers with temperatures between 30 and 150 °C. Their occurrence is not connected to geothermal anomalies. They are frequently regionally widespread and can also be used in areas with normal temperature gradients. The permeability of the rock and the hydraulic conductivity (transmissibility) of the aquifer are essential. The lower the temperatures and the deeper the required drill hole, the higher the permeability of the rock and the hydraulic conductivity have to be. In general, production flow rates between 30 m^3/h and 300 m^3/h at temperatures above 60 °C are required for an economic operation of such large district heatings. To warrant these production flow rates with acceptable energy input for the production and injection pumps, a transmissibility of the aquifer between 10 and 100 Dm (Darcymeter) is needed. These values can only be attained in deep, very porous sandstone formations and in extremely fractured or karstified rock areas, such as zones of joints or fault zones. The high hydrostatic pressure in these depths prevents the water from boiling; therefore, even at temperatures far higher than 100 °C there is no vapor in the formation. When assessing the energy contents of such deposits, it has to be taken into account that only part of the total extractible amount of heat is stored in the water, whereas the greater part is in the rock surrounding the fluid.

Usually warm and hot water systems are accessed via well pairs, so-called doublets. In the production well the hot water is extracted, whereas the cooled water is subsequently returned to the ground through the reinjection well. The energy for production and transmission through the parts of the plant that are above ground is supplied by a submersible pump, which is installed in depths from 200 to 600 m, depending on the conditions. Systems with only one well are rare. Here the processed and cooled water is reinjected through the same well using well-isolated pipes or it is treated and discharged into a drinking water system or a discharge system.

In individual cases, electricity is also generated from low temperature resources using Organic Rankine Cycle (ORC)-plants. To this end, the steam turbines are operated using an organic substance with a boiling point lower than that of water. The efficiency is only approximately 10 % (BGR 1999), however. The so-called Kalina-process constitutes an alternative to the ORC-process. Here two-component substances, for example ammonia and water, are used as working media. It provides a higher efficiency and lower power generation costs, in particular for lower temperatures, but technically it is not as advanced as the ORC-process.

7.2.3 Hydrothermal Occurrences of High Temperatures

Hydrothermal resources of high temperatures are hot water or steam occurrences with temperatures of more than 150 °C. They are located mainly in geologically recent tensile zones of the upper earth crust, such as oceanic rift systems, graben systems and at the edges of lithospheric slabs, frequently in connection with volcanoes.

In vapor-dominated deposits, the reservoir pressure is lower than the steam pressure, according to the reservoir temperature. For this reason, there is mainly water vapor in the deposit, whose discharge is prevented or hampered by an impermeable cap rock. Vapor dominated deposits are the highest quality and most easily useable geothermal deposits. The temperatures of the known and frequently already used vapor reservoirs mainly range between 200 and 300 °C. The liquid dominated deposits reach similarly high temperatures. A higher hydrostatic pressure prevents boiling, thus in these deposits the liquid state predominates.

The geothermal energy of the vapor reservoirs is nearly exclusively used for power generation via steam turbines. After the thermal energy of the vapor has been used, the remaining water typically with a temperature of 70 to 80 °C is reinjected into the ground. If this is not done, a pressure drop in the deposit may occur, which can cause the power plant to shut down in the worst case. If the vapor temperatures are below 200 °C, ORC-plants (Chapter 7.2.2) can be used, just as for low temperature reservoirs.

7.2.4 Hot-Dry-Rock Occurrences

Rocks with very low hydraulic permeability and porosity as well as comparatively high temperatures are assigned to the category of the hot dry rocks. For an effective use of these rocks special exploitation methods have to be used, the Hot-Dry-Rock (HDR) technology becomes necessary. For this technology artificially produced fractures between at least two deep boreholes are used to create large-scale heat exchangers. The water is circulating between the wells, thus cooling down the surrounding rocks and attaining heat from the environment of the connecting fractures. The fracture areas between the injection and the extraction wells constitute the underground heat exchanger. The problem of realization consists in generating an adequate fracture area of permeable hydraulic connections between the drilled wells, which permits circulation by production and reinjection of large amounts of hot water.

The HDR-technology was significantly advanced in a European Community initiative in Soultz-sous-Forêts in France after first attempts in the US near Los Alamos. Further projects for testing the technology have been started lately. The experience gained during HDR-projects showed that the assumption the term Hot-Dry-Rock was based on, i.e. of finding dry rock formations in deep depths, is not correct. In the HDR-Project Soultz, natural fault zones contribute significantly to water circulation between the boreholes. For this reason there are additional names for the heat exploitation of nearly impermeable rock formations, such as for instance Hot-Wet-Rock (HWR), Hot-Fractured-Rock (HFR) or Enhanced-Geothermal-Systems (EGS).

7.3 Geothermal Resources

7.3.1 Quantitative Analysis of Geothermal Resources

The definition of the term geothermal resource provided in Section 2.5 does leave the question, for which geological conditions and for which technology the individual value of useable heat has been specified, unanswered. The amount of energy to be specified depends on the depth, in particular on the maximum depth, on the minimum temperature necessary for the individual technical conversion and on the residual temperature after the amount of used heat has been subtracted. In view of these peculiarities of geothermal energy the following parameters can be used for the quantitative analysis of hydrothermal and HDR-resources:

(1) The total amount of heat stored in the underground of an area from the surface down to a certain depth (Haenel & Staroste, 1988; Kaltschmitt & Wiese, 1997).

(2) The ratio of the amount of heat specified in (1), which is stored in potentially water bearing rock formations (Haenel & Staroste, 1988; Kayser, 1999).

(3) The ratio of the amount of heat specified in (2), which is maximum extractible, if no minimum energy per well pair has been specified. The maximum extractible amount of energy is then determined by the assumed exploition technology and the residual temperature of the water after heat extraction. From this the so-called extraction

factor results, which in typical cases amounts to approximately 0.12 to 0.33 for hydrothermal resources. The definition of resources is based on the assumption of a maximum areal density of dublets and does not take any restrictions of the land use into account (Haenel & Staroste, 1988; Kaltschmitt & Wiese, 1997; Kayser, 1999; Jung et al., 2002).

(4) The ratio of amount of heat specified in (3), which is realistically extractible after specification of a minimum energy per well pair and a maximum duration of the energy generation at the site. The fraction mainly results from the relative size of the partial areas, where with high probability sufficiently large hydraulic permeabilities are encountered or can be produced, which are sufficient for reaching the specified minimum power. In addition the present restrictions of the land use (usage for other purposes, possibly vicinity to consumers) are taken into account.

An energy amount assessment according to definition (1) gives little information on the amounts of energy exploitable under realistic conditions for hydrothermal resources. A realistic assessment of resources according to definition (4) can be lower by several orders of magnitude than the amount of heat assessed according to definition (1). A rough assessment of existing amounts of energy according to definition (1) can be conducted without detailed knowledge of geology. Even the restriction to water bearing formations (2) requires extensive knowledge on the geological composition of the substratum, in particular on the lithological composition, the extent, the depth and the temperatures of the relevant layers. The subsequent calculation of a maximum exploitable amount of energy using the extraction factor (3) requires no major additional geological data.

The assessment, in which partial areas and with which probabilities sufficiently high permeabilities are to be expected in the substratum, may cause great difficulty. This applies in particular to layers with spatially very variable hydraulic characteristics, such as Karst rock. Statistically representative statements can only be made based on hydraulic investigations at numerous wells, which are usually only available in sufficient numbers in very few areas. For this reason there are only very few resource data according to definition (4). At a required minimum power, which would permit economic generation of energy under today's conditions, this definition would provide geothermal reserves.

The elaborations above refer to the evaluation of hydrothermal resources. For the evaluation of resources based on HDR technology using technical means, the consideration of the natural rock permeabilities are not relevant, as this method is based on the artificial generation of permeable structures using technical means. For this case, analyses are based on the heat capacity of a total rock volume and a maximum exploitable amount of energy (3) is calculated via a mean extraction factor between 0.02 and 0.07. Such resource data are based on the prerequisite that a successful, large-scale application of HDR-engineering is possible with full coverage. As this method is still in the research and development stage and up to now only few experiences exist, corresponding data are associated with great uncertainties.

For the near-surface heat energy, which is rebuilt in the seasonal cycle due to insolation, it does not make sense to quantify resources in the sense mentioned above. Instead, data on the annually sustainable exploitable amounts of energy are given for the near-surface area. Two different sizes are used:

(5) The amount of heat, which can be gained from the near surface substratum in an area without causing a long-term cool-down. In this case the whole earth's subsurface can be used by ground heat collector (Kaltschmitt & Wiese, 1997).

(6) The reasonable ratio of the amount of exploitable heat specified in (5), which is regarded in consideration of the restrictions of the land use (building density, usage for other purposes, soil/ground structure, groundwater protection areas) and the proximity to the consumer (Kaltschmitt & Wiese, 1997).

7.3.2 Global Usage of the Geothermal Energy

The ratio of the geothermal energy of the global energy supply was low in 2004 at 0.414 %, but still higher than the proportion of solar and wind energy (Fig. 7.2). Whereas in 1975 only ten countries produced electricity geothermally, in 2005 24 countries were doing so, with a total annual power of nearly 57 000 GWh/a. This corresponds to approximately 0.4 % of the annual global power consumption (Bertani, 2008). Since 2000, in 19 countries altogether 290 wells have been drilled for geothermal power generation with an average depth of 1.9 km. In the same period, the installed power plant capacity in Costa Rica, France, Iceland, Indonesia, Italy, Kenya, Mexico, Nicaragua and Russia increased by more than 10 %. Until 2010, in all likelihood countries like Armenia, Canada, Chile, Djibouti, Dominica, Greece, Honduras, Hungary, India, Iran, Korea, Nevis, Rwanda, Salomon-Islands, Slovakia, St. Lucia, Switzerland, Taiwan, Tanzania, Uganda, Vietnam and Yemen, will start operations for geothermal power generation (Gawell & Greenberg, 2007).

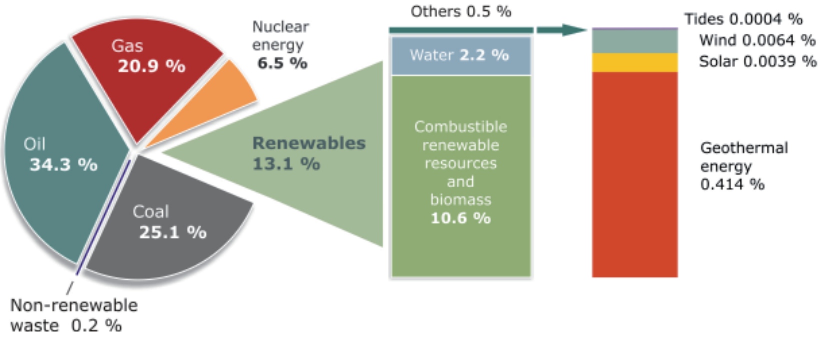

Figure 7.2: Ratio of the geothermal energy in the global power supply 2004 (IEA, 2007).

At an installed power of 2504 MWe for electricity generation and 7817 MWth for the direct use of heat, the US stand out from the other countries as the largest user of geothermal energy world-wide (Fig. 7.3, Tab. A 7-2 & A 7-3). Sweden takes rank 2, because of the significant increase in the direct use of geothermal energy, before China. The geothermal electricity generation in Germany is comparatively low (240 kW_e in 2005), altogether Germany takes rank 15 in the use of geothermal energy (Fig. 7.3).

Globally, the electricity generation from geothermal energy has been increasing significantly every year since the middle of the 1990s (Fig. 7.4). The very much higher increases for the direct use of geothermal energy in many countries are mainly due to the growth of local heating systems using heat pumps. This growth is expected to keep on in future decades (Nitsch, 2001) however the base is rather inaccurate there. In the past years, heating systems using heat pumps were not included in the statistic of individual countries, the use of thermal water in pools was also documented differently in different countries (Lund & Freeston, 2001; Lund et al., 2005).

In individual countries, the low temperature usage is increasingly and to different degrees included in the energy balance. Thus, the real growth is probably somewhat lower than shown here (Fig. 7.4). In 1985, geothermal energy was used directly in 24 countries, in 1995 28 countries, in 2000 48 countries and in 2005 already 59 countries.

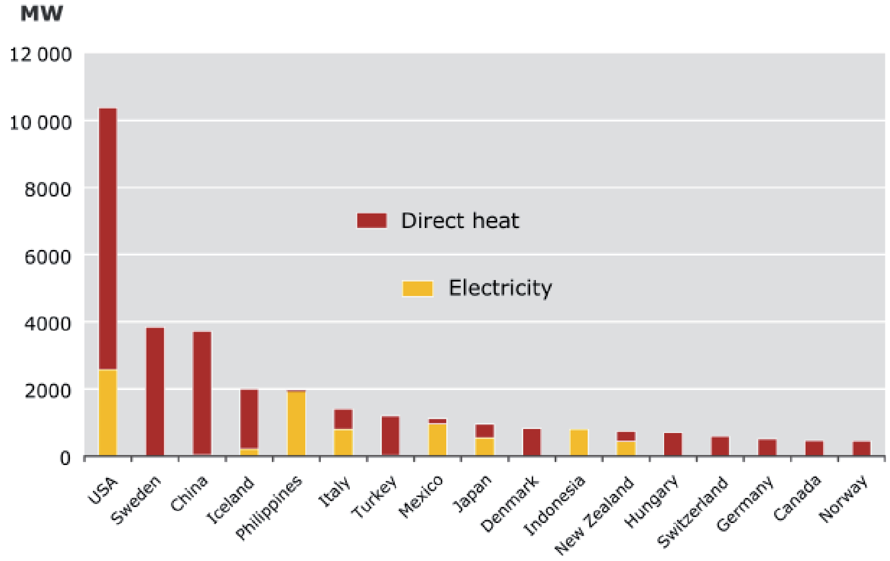

Figure 7.3: Installed power for electricity generation from geothermal energy [MWe] and for direct use of geothermal energy [MWth] for the 17 largest user countries 2005 (Lund et al., 2005; Bertani, 2005).

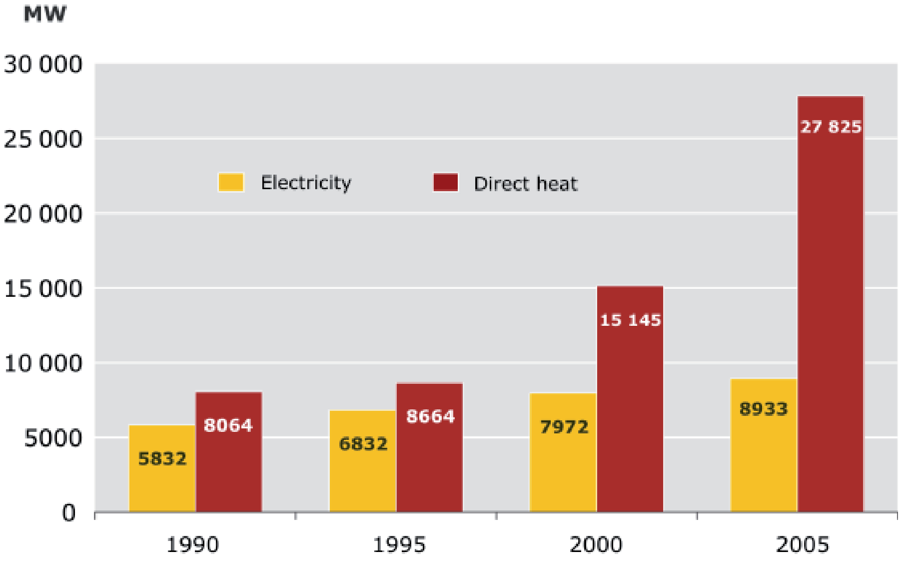

Figure 7.4: Global development of the direct use of geothermal heat and the installed power for geothermal electricity generation between 1990 and 2005.

7.3.3 Regional Distribution of Used Occurrences

Due to the inconsistent compilation of the resources and only incomplete data no globally uniform presentation of the geothermal resources and the current usage of geothermal energy is possible. The known projects and resources will be reported according to region below.

Europe

The geothermal resources are used very differently in the countries of Europe. High-enthalpy deposits exist in Europe in particular in countries with active volcanism, such as Iceland and Italy, but also in Greece and Turkey. In the past years, the geothermal electricity generation as well as the direct use of geothermal energy has been continuously developed. Besides Italy, Island and Turkey geothermal power is now also produced in Germany (Chapter 8.6) and Austria. In addition, power generation in the European HDR-research location Soultz-sous-Forêts in France started in June 2008. Mainly because of steeply rising heating costs of the private households but also because of state subsidies, the use of geothermal heat pumps in local heating systems has risen steeply between 2000 and 2007. Sweden (270 000 units) had taken up the pole position, followed by Germany (90 000), Austria (40 000) and Switzerland (30 000 units) (Forseo, 2008). Today Sweden is the largest user of direct geothermal energy in Europe (Fig. 7.5). Sweden replaced Iceland at the top position only in 2002, in Iceland 87 % of the houses are heated using geothermal energy (BGR, 2003). In Europe, 28 countries benefit from geothermal energy as primary energy with a total installed output of 13 344 MW_{th}.

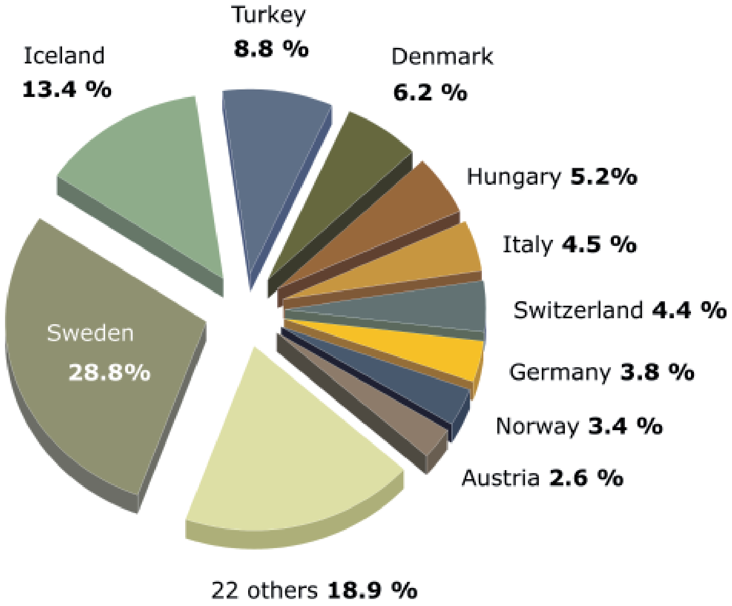

Figure 7.5: Distribution of the directly used geothermal heat installed in Europe, including near-surface geothermal heat (in total 13 344 MWth) according to countries (Lund et al., 2005).

Whereas in the Paris Basin large amounts of thermal water of low temperatures of 60 up to 80 °C can be used directly for heating purposes, in the other large user countries, such as Sweden, Germany, Austria or Switzerland mainly individual systems using heat pumps are employed, to draw heat even from lower temperature water.

For the non-electric usage of energy Hungary plays an important part, producing 694.2 MW$_{th}$. The Pannonian Basin is just like the Paris Basin a large recent depression area, from which large amounts of water can be extracted. A large part of the installed thermal output is used in agriculture for greenhouses and drying plants.

Italy with 791 MW$_{e}$ is far in the lead of the European countries generating electricity from geothermal energy, followed by Iceland, Turkey, France (Guadeloupe), Italy, Portugal (Azores), Austria and Germany (Fig. 7.6). For electricity generation, Iceland at 202 MW$_{e}$ took rank 2 behind Italy in 2005. In the meantime, three more power plants have taken up operation, thus the installed power is 569 MW$_{e}$ by now. Iceland uses 1791 MW$_{th}$ of geothermal primary energy and is thus after Sweden the second largest user in Europe.

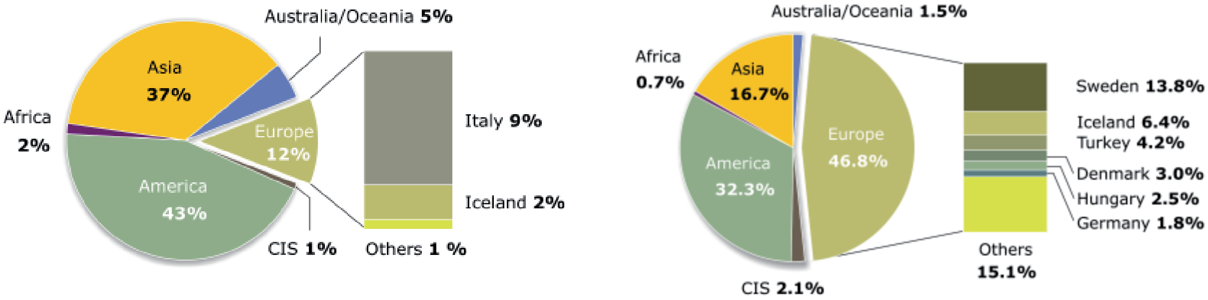

Figure 7.6: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use of geothermal energy (right) and individual percentages of single European countries in 2005 (Bertani, 2005; Lund et al., 2005).

In Turkey in the past years considerable efforts have been undertaken to use the existing geothermal energy deposits. For heating purposes, for pools and agriculture plants with a power of 1,177 MW$_{th}$ in total were installed there in 2005. Electricity generation has remained unchanged at 20 MW$_{e}$ for a long time; extensive increases are being planned, however.

Commonwealth of Independent States (CIS).
In all, the proportion of the CIS countries in the global use of geothermal energy in 2005 as power generation amounted to approximately 0.9 % and for direct use to about 2.1 % (Fig. 7.7). Russia used geothermal energy for electricity generation - 79 MW$_{e}$ installed (Bertani, 2005) - as well as for heating purposes, for heating pools and as process heat (327 MW$_{th}$) in all in 2005 (Lund et al., 2005).

According to recent estimates, in Kamtchatka alone geothermal power plants with a capacity of about 1 GW$_{e}$ can be installed. In Georgia thermal water is used for heating purposes, for greenhouses and for operating pools. The installed power of 250 MW$_{th}$ has remained unchanged for a lengthy period of time.

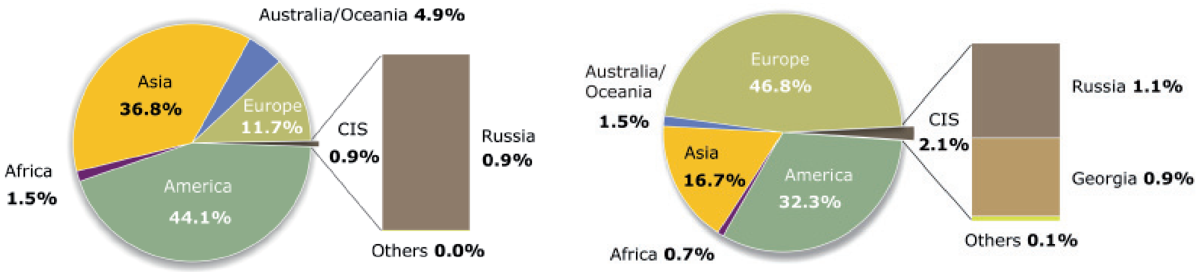

Figure 7.7: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use (right) and individual percentages of the CIS states in 2005 (Bertani, 2005; Lund et al., 2005).

Africa

In some African countries geothermal deposits have been explored increasingly in the past years with power generation in mind. They are mainly located in tectonically active areas of the east African Graben and have an immense potential of about 7000 MW_e (Gawel & Greenberg, 2007). These resources are still being used to a minor degree only, in spite of the increased efforts. The proportion of Africa in the global use of geothermal energy as primary energy source is comparatively low at 0.7 %. For electricity generation this percentage is approximately 1.4 % (Fig. 7.8).

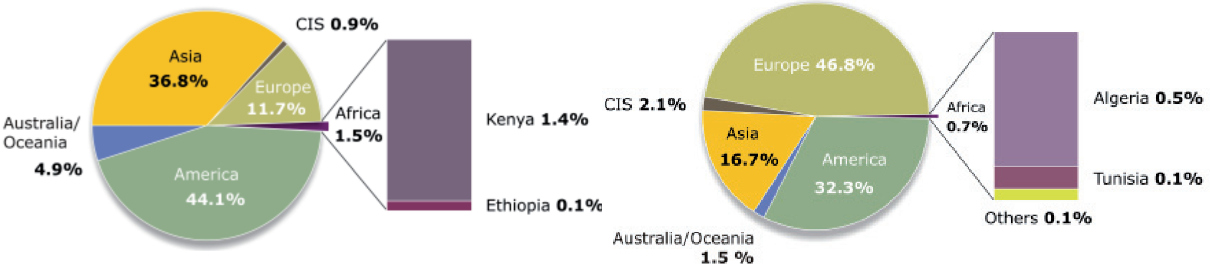

Figure 7.8: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use (right) and individual percentages of the African countries in 2005 (Bertani, 2005; Lund et al., 2005).

In Africa, Kenya is dominating the use of geothermal energy (Fig. 7.8). In contrast to other east African countries, Kenya has been continuously expanding the usage of geothermal resources for years due to specific government programs. Whereas in the last study on energy resources (BGR, 2003) for Kenya 45 MW_e were listed, by now already 129 MW_e of power have been installed. Further locations such as Eburru, Olkaria IV and Menengai have been extensively explored. The three currently existing geothermal power plants in Olkaria (Fig. 7.9) provide 11 % of the electricity supply of the country. Close to the Olkaria power plant geothermal heat with an energy of about 10 MW_{th} is directly used in greenhouses for growing flowers and there is a smaller binary-cycle power plant of 1.8 MW_e for supplying power to the large flower farms.

In Ethiopia there is a small plant of 8.5 MW_e, which only operated for a short period of time, however. It is currently being repaired with American aid. Feasibility studies have been conducted for further potential locations as part of GEOTHERM in Kenya (Menengai) and Uganda (Buranga). Currently such studies are also being conducted for Ethiopia, Eritrea, Djibouti, Rwanda and Tanzania (Info box GEOTHERM).

The direct use of thermal water has been reported apart from Kenya from different countries in Northern Africa: Egypt: 1 MW_{th}, Algeria: 152.3 MW_{th} and Tunisia: 25.4 MW_{th}. Thermal water is being used in particular for greenhouses, for the pool operations and therapeutic applications.

Figure 7.9: The geothermal power plant Olkaria I in Kenya started generating power from geothermal energy in 1981. Currently 45 MWe have been installed; the average availability is more than 98%.

America

In North America, as well as in Central and South America there are very large geothermal resources. The American users head the field at 44 % of the globally installed power for geothermal power generation, whereas they take second rank behind Europe in the direct use (Fig. 7.10). The US keep on being the largest consumer of geothermal energy in the world with an installed power for electricity generation of 2564 MW_e (Lund et al., 2005). Power generation from high temperature deposits has the largest percentages, which are mainly located in the western states, in particular in the geothermal field *The Geysers* in California. The installed power since 1989 was increased by only 110 MW_e. In 2005, Congress passed a tax incentive system for the use of geothermal energy (*Production Tax Credit*) due to which 61 new geothermal energy projects were started. This way in the next years an increase in output of 2,100 to 2,400 MW_e is expected (GEA, 2006). The direct use in the US comprises all known applications. Between 1994 and 2000 it has doubled from 1,874 to 3,766 MW_{th} (Lund & Freeston, 2001). A similar increase to 7,817.4 MW_{th} occurred until 2005 (Lund et al., 2005). The local near-surface use of geothermal energy using heat pumps has the highest growth rates.

Mexico possesses large high temperature deposits dominated by liquids, which have been used for many years for power generation purposes. The geothermal field Cerro Prieto, in which brine of a mean temperature of 316 °C is being extracted from nearly 200 drill i10

GEOTHERM – Technical Cooperation in Geothermal Energy

Since 2003 the BGR has been conducting the program GEOTHERM as part of the Technical Cooperation. To this end, projects for the use of geothermal energy in developing countries are supported by different actions in concrete regional development. GEOTHERM projects are mainly concentrated in the countries of eastern Africa. In this region, in parts there is a severe shortage of electrical power. Simultaneously there are significant high enthalpy geothermal resources. Thus, in particular projects for geothermal power generation are conducted.

Main tasks of GEOTHERM are geoscientific evaluation of resources, advisory services in technical implementation, geoscientific site investigations (pre-feasibility study) and training as well as educational measures. Environmental Impact Assessments, profitability analyses and financial advising can be conducted by suitable partners as part of GEOTHERM. The chance for a successful site development is decisive for the selection of a suggested project.

After the geothermal sites have been explored and evaluated in the first project phase, in the next stage the development of the site is to be continued based on Feasibility Studies with exploration wells and testing. Difficult are not so much the high costs of drilling, but rather the considerable prospecting and development risk. For positive results of the exploration wells and tests the BGR assumes that investors for production wells and the construction of power plants can be found, who will take over the further development of the site.

Production at an exploration well in the geothermal field Tendaho, Ethiopia

holes, has the highest installed power plant rating next to the Californian geothermal field *The Geysers*. Besides, currently in Los Azufres, Los Humeros and Las Tres Virgenes three more geothermal fields are being exploited. In 2005 the installed power amounted to 953 MW_e (Bertani 2005). In the next years a further expansion of the geothermal resources has been planned in the geothermal fields Acoculco, Domo San Pedro und La Soledad.

The data for the direct use of geothermal energy have remained virtually unchanged since 1999 with an installed power of 164 MW_{th} (Lund et al., 2005).

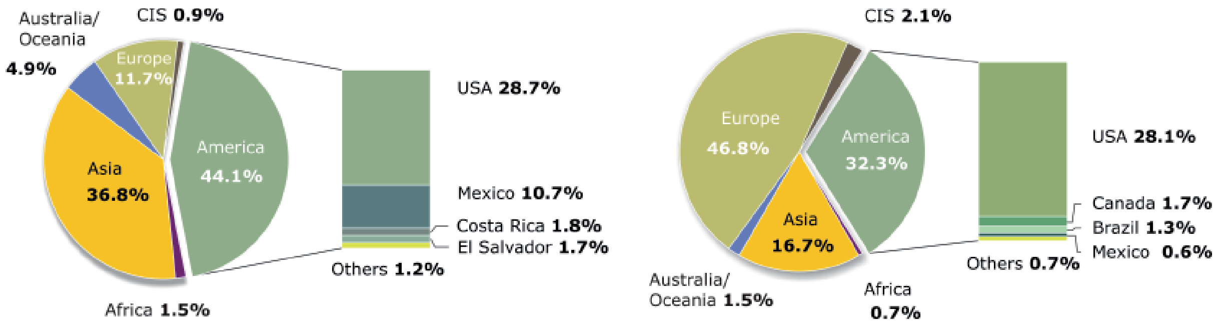

Figure 7.10: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use (right) and individual percentages of the American countries in 2005 (Bertani, 2005; Lund et al., 2005).

Canada is the third largest consumer of geothermal energy in America, even though it does not have high temperature deposits. This use is limited to the direct use for the approximately 36,000 local heating systems using heat pumps with an installed power of 435 MW_{th} which are being operated in Canada (Lund et al., 2005). In addition, thermal water is used for pools and water from shutdown mines is used for heating purposes. In total, the installed power for the direct use of geothermal energy in Canada amounts to 461 MW_{th}.

In Central America, in several countries high and low temperature deposits are being used either for power generation or for pools, drying plants or similar. Many countries in Central America, such as El Salvador, Guatemala and Honduras, are planning the construction of geothermal power plants. On a number of Eastern Caribbean islands, such as Nevis, St. Lucia or Dominica, exploration projects for finding geothermal energy have been started (Gawell & Greenberg, 2007). The largest electricity producers from geothermal energy are currently El Salvador (151 MW_e) and Costa Rica (163 MW_e). There are also geothermally operated generators in Nicaragua (77 MW_e), Guatemala (33.4 MW_e) and Guadeloupe (15 MW_e). Low temperature deposits are currently used for bathing in Honduras and on the Caribbean Islands. In Nicaragua and Guatemala drying plants and fish farms are supplied with geothermal heat.

In South America there are high temperature resources along the volcanic belt of the Andes in Venezuela, Columbia, Ecuador, Peru, Bolivia, Chile and Argentine. Due to the low energy demand in these frequently sparsely inhabited regions these resources have not been tapped up to now. Brazil is with 360.1 MW_{th} of installed power currently the largest user of direct heat, mainly for pools. Argentine is using 149.9 MW_{th} of geothermal heat as primary energy also for pools as well as for heating buildings and greenhouses, for melting snow and in fish farms. Columbia uses 14.4 MW_{th} in warm water in 41 public baths. In Chile, Ecuador, Peru and Venezuela public baths are heated by thermal water, which together supply only a few MW_{th} power.

Asia

Important hydrothermal high temperature occurrences, which have in part been used for several decades for electricity generation purposes, are located on the Japanese islands at the edge of the Eurasian plate. Another of the largest geothermal zones in the world is the geothermal belt of the Himalaya with huge hydrothermal high temperature occurrences in the countries India, China and Thailand. Great hot water occurrences and deposits with low temperatures exist in the sedimentary basin in Eastern China. Not long ago China was the largest direct user of geothermal heat in the world, but has been replaced by Sweden in this regard. For Asia China is up to today the most important direct user with an installed power 2005 of 3,687 MW_{th} (Fig. 7.11).

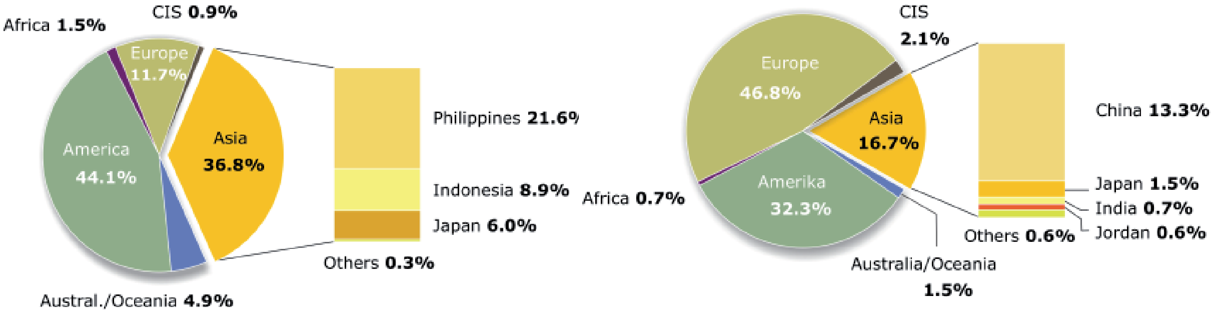

Figure 7.11: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use (right) and individual percentages of the Asian countries in 2005 (Bertani, 2005; Lund et al., 2005).

In comparison to 2000 this means an increase by slightly more than 1400 MW_{th}. The total consumption amounted to 45,373 TJ/a (Zheng et al., 2005). The heat is used for heating buildings and greenhouses, for pools, for industrial plants and fish farms. The electricity generation from geothermal energy in China with an installed power of 29.2 MW_e has not changed since 2000. Up to now geothermal energy for power generation in China is used only in Tibet and in Taiwan. In all, geothermal electricity generation, which started at the end of the eighties, is still in its infancy there, in view of the resources existing in China. The Tibetan capital Lhasa receives about half of its electric power from a geothermal power plant of a power of 24 MW_e, however.

The Philippines take top rank in the generation of electric power from geothermal energy in Asia (Fig. 7.11). With an installed power of 1,930 MW_e they even took rank 2 behind the US in 2005. In 2007 the power was even expanded by another 200 MW_e. The Philippines are seeking to become the largest power producer from geothermal energy in the world during the next two decades. Moreover, the Philippine government is aiming at expanding the direct use of thermal water (Benito et al., 2005), the installed power amounted to 3.3 MW_{th} in 2005 (Lund et al., 2005).

Japan is the third largest user of geothermal energy in Asia. Electricity generation from geothermal energy has been conducted there since 1966. The currently installed power amounts to 535 MW_e in 19 power plants on 17 geothermal fields of the three main islands and has remained practically unchanged in comparison to 2000. In Japan the use of thermal springs in baths has an age-long tradition. In 1998 2,839 thermal springs with 5,525 public baths and 15,638 hotels and guesthouses were registered as users of thermal water. The thermal springs were not included in the last report of the World Geothermal Congress (2005), i.e.

the older and current numbers cannot be compared (Kawazoe & Shirakura, 2005). Besides the baths, thermal water is also used as an energy source in agriculture and fish farms.

Indonesia is, with an installed power of 797 MW_e, the second largest producer of electrical power from geothermal energy in Asia (Abb. 7.11). Even though Indonesia is considered by many authors to be the country with the greatest geothermal potential worldwide, the installed power has not perceptibly changed since 2002. There are, however, advanced construction plans and since 2003 there is a Geothermal Law. On Java near Bandung there is the geothermal power plant Wayang Windu, which is currently under construction. Block I with an installed power of 110 MW_e is supplemented by block II (110 MW_e), which will be completed soon. Another block is being planned. Just as in the Philippines, in Indonesia the primary energy use (2.3 MW_{th}) is only of minor importance.

Several countries in Asia Minor, where thermal water of low temperatures is being used, range far behind the countries named above. Among these number Jordan (153.3 MW_{th}), followed by Israel (63.3 MW_{th}) and Yemen (1 MW_{th}). The geothermal energy is mainly used for public baths and for therapeutic purposes, in Israel also in greenhouses and fish farms.

In India the geothermal use of thermal water has been expanded from 80 MW_{th} in 2000 to 203 MW_{th} in 2005 (Lund et al., 2005). Increases in the use of thermal water have also been reported from Nepal from 1.1 to 2.1 MW_{th} and from Korea.

Australia /Oceania

New Zealand is the most important user of geothermal energy in the region Australia /Oceania (Fig. 7.12). New Zealand has important high temperature deposits with temperatures of more than 300 °C, which have already been used for power generation purposes since 1960. After a stagnation in the early 1990s the annual power generation rates have continually increased since 1995. In 2005 the installed power was 435 MW_e. The stable growth of the use of geothermal power in New Zealand relies on private investments as well as on government aid. The country is well on its way of making use of the total existing power generation potential. The numbers dealing with the direct use of geothermal energy have changed little in the past ten years, however. In 2005 the installed power was 308.1 MW_{th} and in total 7,086 TJ/a were used. The proportion of local heating systems is still comparatively low at 22 MW_{th}. The largest consumer is the paper industry, followed by fish farms, building and greenhouse heating systems, drying plants and pools.

Australia does not possess volcanic high temperature deposits. There are, however, extensive warm and hot water aquifers, whose utilization renders Australia the second largest direct user of geothermal heat in the region Australia /Oceania (Fig. 7.12). In the small town of Birdsville power is generated in a small ORC-plant of 0.12 MW_e mainly for cooling purposes in the summer. This baseload power plant is fed from a well that is 1,200 m deep, from which water of 98 °C is produced. The statement of the Australian government of generating 2 % of the annual power consumption from renewable energy sources by 2010, has stimulated HDR-research. Currently five HDR-projects for geothermal power plants are being planned in the Cooper Basin, of which the first is supposed to start operation in 2010. Large granite intrusions in a depth of approximately 3.5 km constitute the heat source. The measured temperatures in a depth of 4000 m surpass 240 °C. In Australia the installed power for the direct use of thermal energy amounted to 109.5 MW_{th} at a consumption of 2,968 TJ in 2005.

The use of heat pumps for air conditioning and heating is widespread, whereas in pools only approximately 8 MW_{th} were installed and 226 TJ/a were consumed.

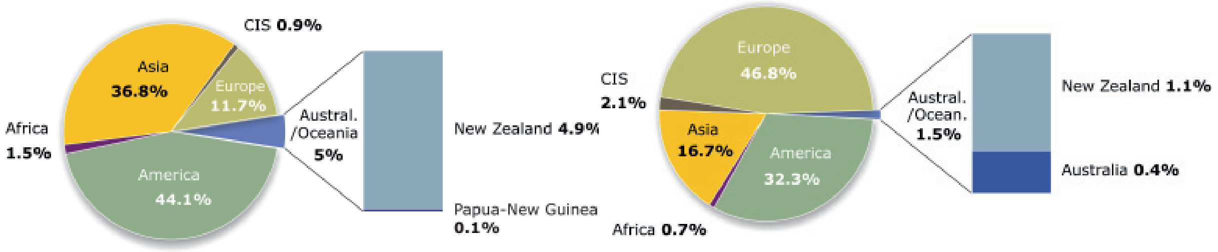

Figure 7.12: Regional distribution of the globally installed geothermal power for electricity generation (left side) and for direct use (right) and individual percentages of the countries of the region Australia/Oceania in 2005 (Bertani, 2005; Lund et al., 2005).

Papua-New Guinea has been using direct heat to a small extent of 0.1 MW_{th} as tourist attraction. Lately the power supply of a gold mine has been switched from diesel generators to geothermal power. To this end, water at 250 °C is extracted from mine drainage wells in a depth of 1000 m and used. Since 2007 the installed electrical output has therefore been 56 MW_e.

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