清华大学学术专著

高温气冷堆工艺热应用（英文版）

High-Temperature Gas-cooled Reactor for Process Heat Applications

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内 容 简 介

本书介绍了模块式高温气冷堆核电站及其在工艺热应用方面的原理、结构、设计、运行、安全、主要设备、经济性及应用前景等方面的内容，为读者深入了解高温气冷堆在工艺热应用领域的原理、技术发展状况、关键设备、安全特性、与其他工厂的系统耦合和环境问题提供了详尽的阐述和充实的资料。

本书可作为普通高等学校核能和热能动力专业研究生的教学参考书，也可为从事高温气冷堆技术领域工作的科研开发人员、项目管理人员以及政府官员全面了解高温气冷堆提供参考。

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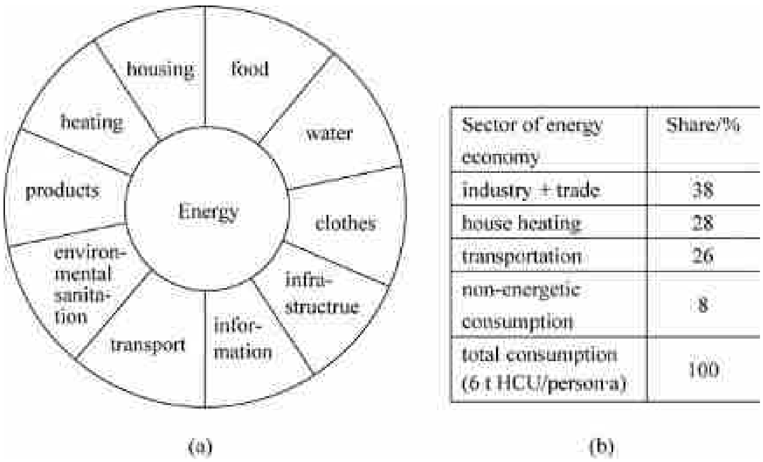
CONTENTS 目录

1

Aspects of energy economy

1.1 Importance of energy supply

A sufficient high, economic attractive and safe supply of energy is an essential condition for the welfare of the human beings[1-6]. For the production of food, water supply, for heating and cooling, for the transport sector and for the infrastructure as well as for the production of goods for consumption, large amounts of energy are necessary in industrialized countries. Energy for the organization and preservation of environment is necessary too with rising importance. Figure 1.1 gives an overview on these aspects and some numbers characteristic for German conditions. Transportation, industry and house heating require the major part of energy.



Sector of energy economy	Share/%
industry + trade	38
house heating	28
transportation	26
non-energetic consumption	8
total consumption (6 t HCU/person·a)	100

Figure 1.1 Overview on the importance of energy for the human life

(a) General overview on fields of application of energy; (b) Some data for Germany (consumption of primary energy in different sectors of energy economy; total = 6t HCU/(person · a), HCU = hard coal units)

Here and later often the unit HCU (hard coal unit) is applied to characterize energy carriers. The hard coal unit 1t HCU corresponds to 8.3MW · h (thermal) or 30GJ. For the different primary energy, conversion factors corresponding to Table 1.1 can be applied.

Table 1.1 Conversion factors for different energy carriers (in relation to hard coal units HCU)

Energy carrier	Heating value/(MJ/kg)	Heating value/(kW · h/kg)	Conversion/(kg HCU/kg)
hard coal	30	8.3	1
lignite	8	2.2	0.27
crude oil	43.9	12.2	1.4
natural gas	42	11.6	1.43
uranium *	605 000	170 000	20 480

* natural uranium, 0.7 wt% U235.

Sometimes energy balances use the unit 1 t of oil with a heating value of around 12.2kW • h or 43.9MJ as a further unit. Electrical energy often is valuated with an average efficiency of 33%. The delivery of 1kW • h_{el} from renewable or nuclear energy to the energy economy corresponds than to 3kW • h_{th}. The energy demand of the people has raised up very much during the past (Figure 1.2): from some 100kgHCU/(person • a) to around 6t HCU/(person • a) (in Germany) and around 2.3t HCU/(person • a) as an average value worldwide today.

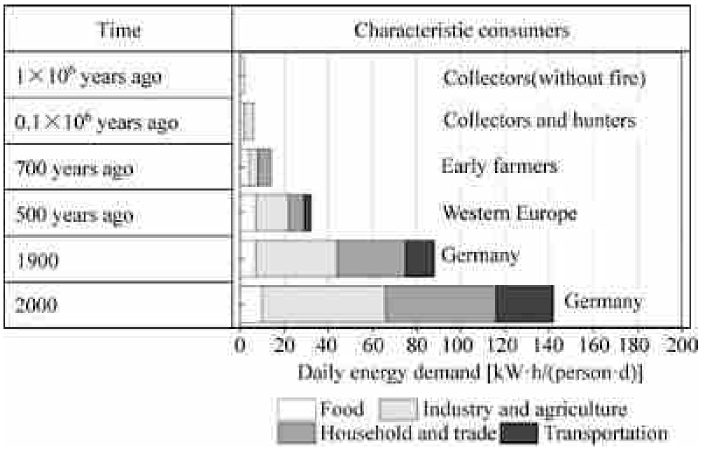


Figure 1.2 Daily demand on primary energy (kW • h/(person • d)) of people at different times of the human development

Further improvements regarding supply in many countries are necessary. Today as example in India just around 0.84t HCU/(person • a) are available. For many other countries similar numbers are relevant (Figure 1.3). This situation must be improved in the future to avoid large problems in the interaction of countries worldwide. To save energy, which is propagated mainly in western countries (as example for the conservation of climate), is necessary for those countries, but it is not a solution for countries, which don't have a sufficient energy supply today.

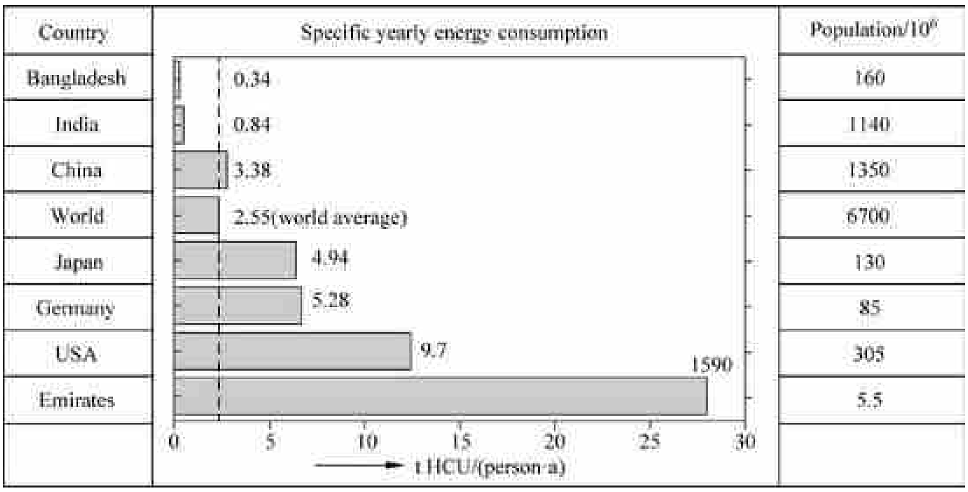
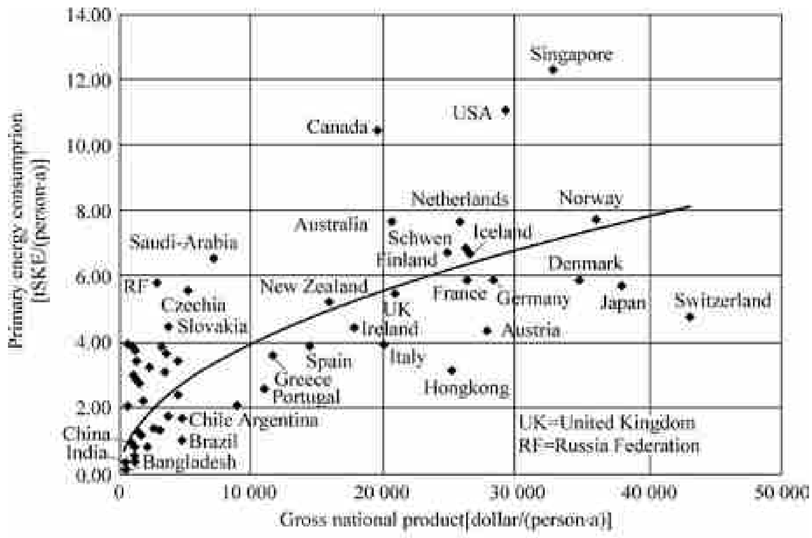


Figure 1.3 Specific consumption of primary energy in some countries and population (2019)

The energy supply furthermore is correlated to the Gross National Product (GNP) and to the quality of life. Maybe this can be expressed by the expectation of lifetime of people in different countries. Figure 1.4 shows the differences of GNP in countries indicating large differences of energy supply. Figure 1.5 correlates this value with the lifetime. The values in Figure 1.4 and Figure 1.5 are valid for the year 1997. In some countries, like China, the numbers have changed, for instance, the specific energy consumption is already in the order of 4.5t HCU/(person • a), the average life time today is in the order of 75 years.

The discrepancies of these values worldwide is not acceptable in the future and will cause serious problems. Improvements are necessary.



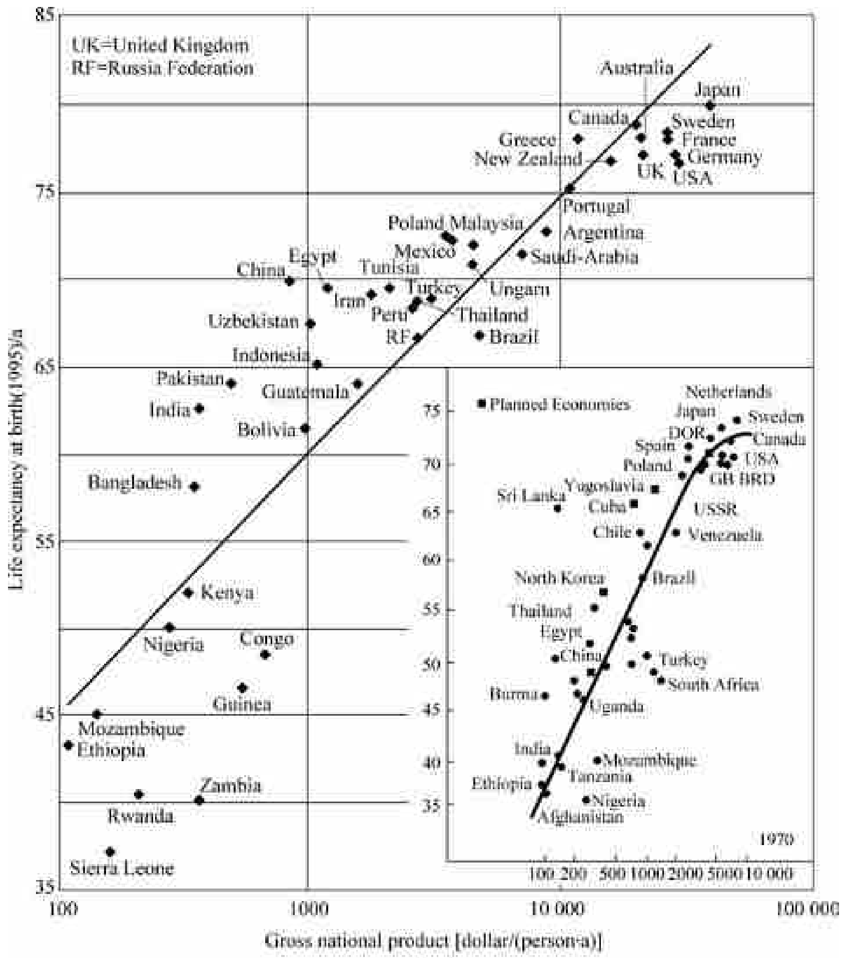
(a)

Year	Specific primary energy consumption /[kW·h$_{el}$/(person·a)]	Gross national product/ [dollar/(person·a)]
2000	1.3	1150
2010	2.8	4500
2019	3.3	10 100

(b)

Figure 1.4 Correlation between primary energy supply and gross national product

(a) Values in different countries and cities worldwide(status: 1997); (b) Development in China



(a)

Figure 1.5 Correlation between expected lifetime and the Gross National Product (1997)

(a) Values for some elected countries worldwide(status: 1997); (b) Development in China

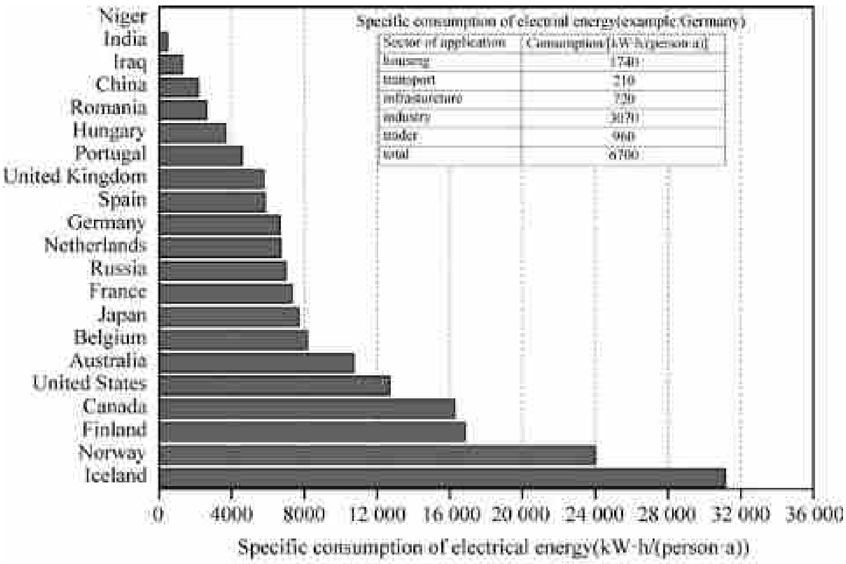
Year	Specific primary energy consumption /[kW·h$_{th}$/(person·a)]	Energy life time(years)
2000	1.3	71.4
2010	2.8	74.4
2019	3.3	75.8

(b)

Figure 1.5 (Continued)

In the meantime, some countries made large progress: as example, the values in China are now around 10 000 dollar/(person · a) for the gross national product and higher than 3.3t HCU/(person · a) for the specific energy consumption. The average life time became larger and has now a value about 75 years.

A sufficient high standard of life is a precondition for a good prognosis for expectation of lifetime of population worldwide. These standards are coupled with a sufficient high production of food, good standards of hygiene and medical services and a functioning infrastructure. All these aspects require a sufficient and effective structure of energy supply. To realize this goal worldwide will require large efforts and the investment of very large capitals. Additionally rising environmental problems have to be considered in this connection. Especially the CO_2-question will have importance. Similar consideration as for primary energy supply are valid for the supply with electrical energy. Figure 1.6(a) gives an overview on the status in some countries worldwide regarding this energy carrier, which indicate that there are large differences. In China much progress was realized with respect to the rise of the production of electrical energy. In the last 20 years there was a rise by a factor of 5(Figure1.6(b)).



(a)

Year	Specific electrical energy consumption /[kW·h$_{el}$/(person·a)]
2000	1100
2005	1700
2010	3200
2015	4000
2019	5100

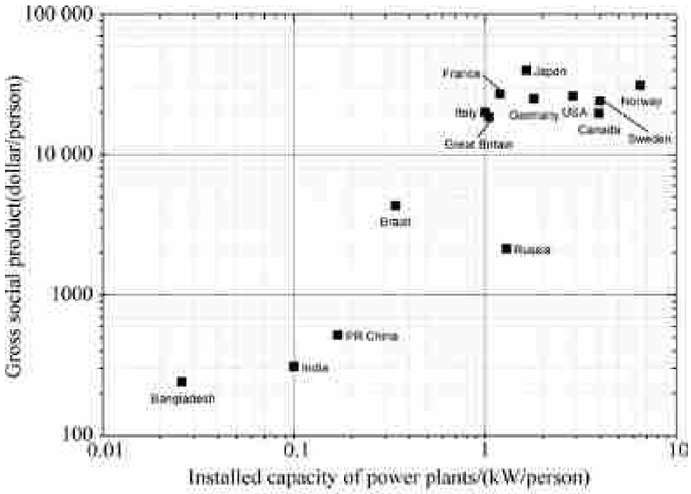
(b)

Figure 1.6 Production and consumption of electricity per year and per person

(a) Comparison for different countries (status: 1998); (b) Development in China

Around 30% of the primary energy, which is applied worldwide, is used to produce electricity. As an average around 3200kW · h$_{el}$/(person · a) is available for the world population; in Germany, this value is nearly 6700kW · h$_{el}$/(person · a). However in some countries like India even in 2019 just 1000kW · h$_{el}$/(person · a) is characteristic for the supply of the people. This situation, in more detail explained in Figure 1.6, requires intensive work and effort to improve the conditions of life worldwide.

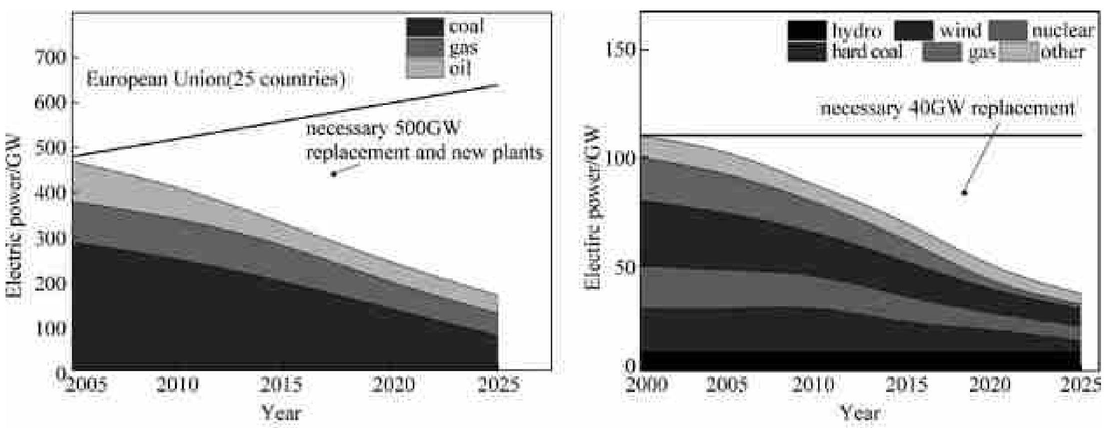
Corresponding to this disadvantageous supply for people in many countries, the height of installed capacities for the production of electrical energy today still is extremely different in important countries (Figure 1.7). Countries with an insufficient height of installed electrical capacity have low values of gross national product and low standards of life. Figure 1.7 shows that there is a huge demand of additional power plants, transportation systems and grids to be built in the future. Additionally many old power plants have to be replaced by new ones, because they have reached their end of life and



(a)

Country	Population/10^6	Installed capacity/GW_{el}
Africa	1370	
Asia	4650	
Europe	740	
North America	370	
South America	660	
Oceania	50	
Total world	7850	
China	1410	1974
India	1370	400
France	67	130
Bangladesh	165	10
Brazil	212	122

(b)



(c) (d)

Figure 1.7 Aspects of supply with electrical energy: time dependent development of capacities

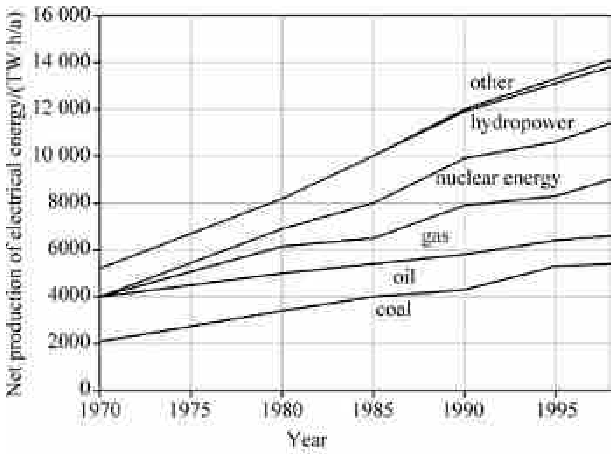
(a) Correlation between gross national product and installed capacity of power plants (kW/person) in different countries(status: 1998); (b) Population and installed capacities in different regions of the world(status: 2019); (c) Development of capacities of power plants in the past and expectations (example: European Union (25 countries)); (d) Development of capacity of power plants in a country (example: Germany): time dependence in the past and expectations efficiencies should be improved. Furthermore, storage systems for electrical energy have to be developed and introduced, if the share of renewable energies rises up.

As example in the European Union(EU), where a capacity of around 600GW_{el} is installed, in the next 30 years additional 200GW_{el} have to be added to the grid. Furthermore, old plants have to be substituted. Some countries with lower state of development have huge demand. In totally it is estimated that around 500GW_{el} have to be built in the EU. In Germany, the number is 40GW in the next 10 years (expectation 2015). This must be mainly base load plants. Because in the meantime political decisions have been made in Germany to go out of use of fossil fuels and of nuclear power reacts the capacities of wind energy converters and of photo voltaic installations have been enlarged drastically.

The wind capacity was 6.1GW_{el} in 2000 and 62GW_{el} in 2019. The photo voltaic installations rised up from 0.1GW_{el} in 2000 to 54GW_{el} in 2019. These changes were realized by massive subventions from the government. Especially the changing offer of wind energy and solar energy require the installation of very large capacities and storages.

Some differences regarding the supply structures worldwide can be explained by climatic conditions naturally too. However, it is understandable that all countries, which have values below average worldwide numbers, aspire changes and progress. This is the case at least for more than 50% of the world population. In totally the energy demand of the world will rise up dramatically in the next decades and one of the most important questions of future worldwide development will be to fulfill this requirement. It is important for the people in the world to establish similar conditions of life everywhere (Figure 1.8 (a)).

The safe, economic reliable energy supply is very important for all requirements of daily life. However, in many countries the intensive use of fossil fuels is connected to burden for the environment, as example of CO_2 emission. Data in Figure 1.8 (b) indicates the big differences regarding important data for some countries and of the worldwide average. Therefore it is understandable that there is a big movement in the world to change the conditions and to equalize the differences.



(a)

Year	Production of electricity/(TW·h/a)
1990	12 000
1995	13 200
2000	15 400
2005	18 300
2010	21 600
2015	24 300
2019	26 000

(b)

Figure 1.8 Aspects of energy supply in different countries of the world

(a) Worldwide electricity production (in the past till 1997); (b) Development of production of electricity in the world since 1990; (c) Some data relevant for life conditions in different countries(status: 2019)

Aspect	Dimension	World average	Germany	China	India
Primary energy	t HCU /(person · a)	2.3	5	3.3	< 1.0
Consumption of electrical energy	$kW \cdot h_{el}$/(person · a)	3200	6800	5100	1000
Power plant capacity	kW/ (person · a)	<1	2.6*	1.4	< 0.3
CO_2 emission	t CO_2/(person · a)	4.6	8.6	7	1.8
Gross National Product	dollar/(person · a)	≈1100	35 000	10 000	2800

*The high value is caused by the high share of wind energy converters and photo voltaic installations

(c)

Figure 1.8 (Continued)

1.2 Development in the past and status of world energy economy

The worldwide primary energy supply has been raised up strongly during the last decades (Figure 1.9)[6]. The doubling time in the past was around 30 years. In 2019 nearly 1.8×10^{10} t HCU/a worldwide were inserted for the supply. This corresponded at a population of the world of 7.7×10^{9} people to an average supply of 2.3t/HCU/(person · a).

The world population has raised up in the last 100 years by a factor of more than 4, mainly caused by medical progress and improved structures of food supply. Even severe disturbances like World War 1 and 2 or big crisis of oil supply and very high oil prices did not influence the general tendencies of rise of world population and of energy demand very much (Figure 1.9 (b)).

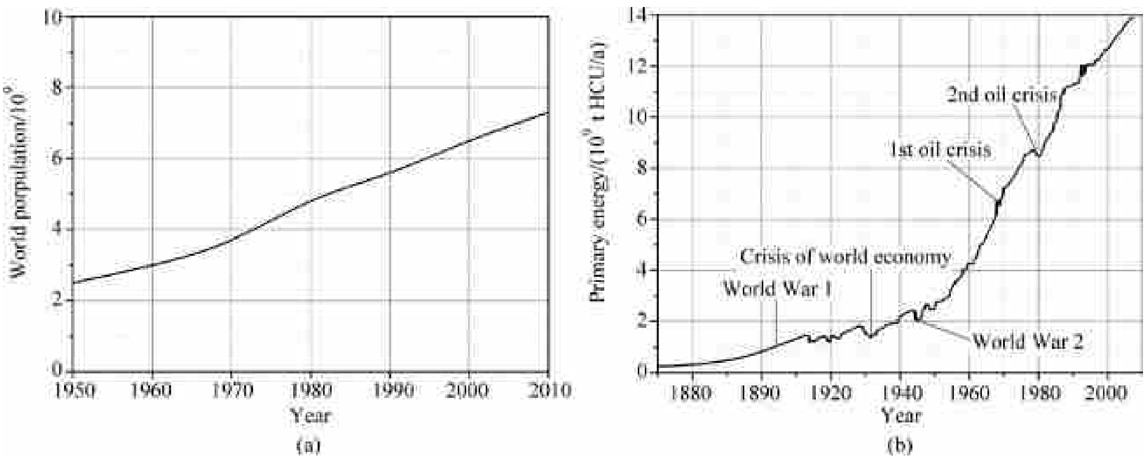


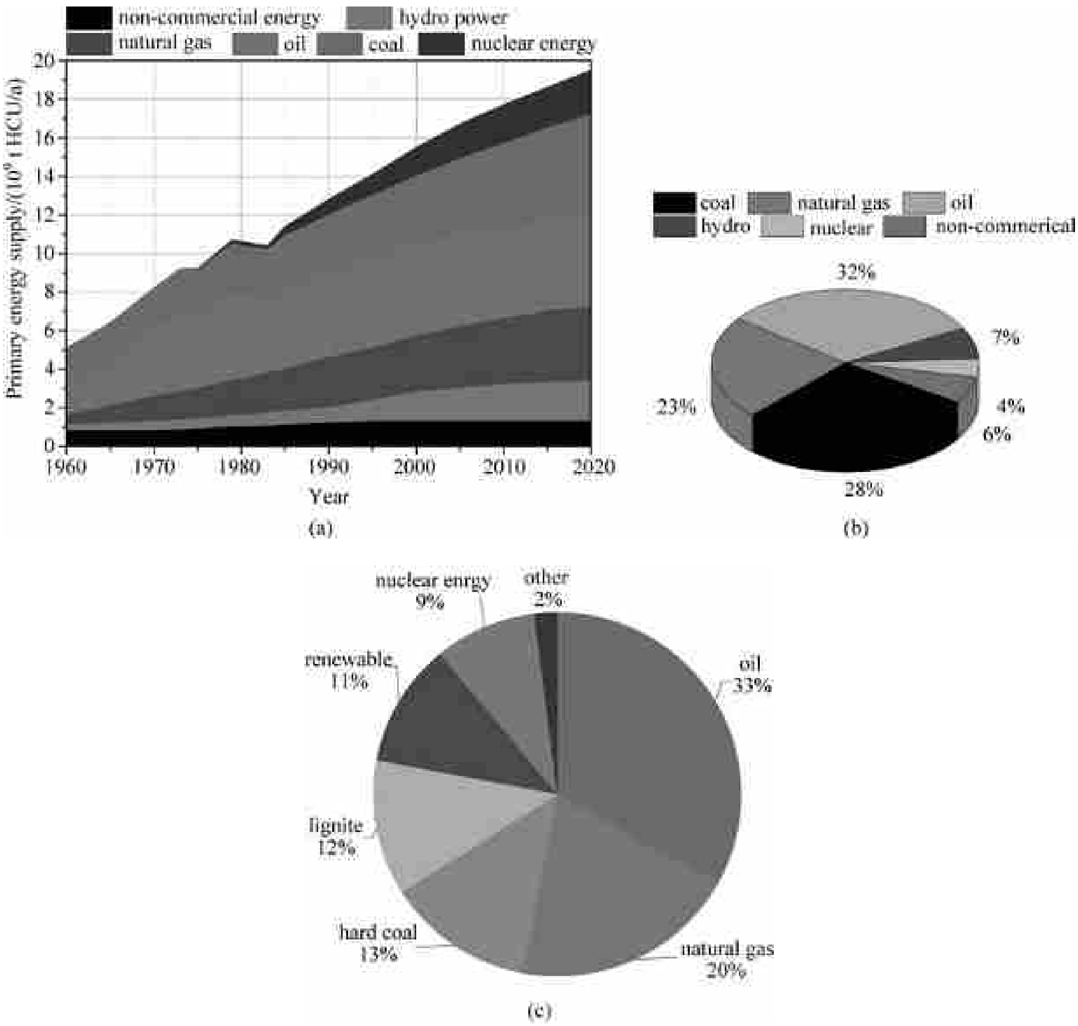
Figure 1.9 Development of the world population and the energy supply in the world (in the past)

(a) World population(value in 2019: 7.7×10^{9}); (b) Primary energy supply worldwide(value in 2019: 1.8×10^{10} t HCU/a)

Mainly the increase of population in the world and improvements of standard of life in some countries caused this development on the energy sector. Figure 1.3 to Figure 1.7 indicated however, that there are still large differences of consumption and therefore of life conditions worldwide. There are countries with very large population in the world like India, Pakistan, Bangladesh or many states in Africa, where the specific consumption of electrical energy is smaller by a factor of 4 compared to the average value worldwide. Naturally the supply in these countries must be improved in the future to a large extent to avoid social problems, migration of people and wars. In the countries indicated above as example, the transportation sector today is practically not at all developed compared to the situation in USA, Europe or some countries in Asia like China and Japan.

Until now the supply was based mainly on the fossil energy carriers as coal, crude oil and natural gas

(Figure 1.10). Renewable and nuclear energy play a role in the order of just 10% of the total supply structure. However their importance is growing up. The expectation is that they will take over a share of nearly 30% of the demand after the next three decades worldwide. To estimate the share of noncommercial energy carriers always contains some uncertainties. In some countries they represent the most important part of the energy supply.



Region (country)	Share of supply of world in 2019/%	Change from year 2010 to 2019/%
Europe	13.85	−5
Africa	3.6	+24
Asia	46	+31
North America	21	+3
South America	5.1	+8
China	25.5	+36.5
India	6.1	+51
Germany	2.3	−5
World	100	+10.3

(d)

Figure 1.10 Contribution of different energy carriers to the worldwide supply with primary energy

(a) Development of different energy carriers (worldwide); (b) Shares of different primary energy carriers on the worldwide energy supply (example: 2012; total energy supply: 1.7×10^{10} t HCU/a); (c) Shares of different primary energy carries on the energy supply of a country (example: Germany; 2012; total energy supply: 4.60×10^{8} t HCU/a); (d) Shares and changes of primary energy consumption in different regions and specific countries (2019)

Special developments took place in the last decades in the field of worldwide electricity production. Table 1.2 includes some data for production differentiated to the energy carriers. The supply of regions was already shown in Figure 1.8. Sometimes strong changes in the energy supply systems can occur. An example is Germany, where after the accident in Fukushima (2011) the decision was made to shut down 7 large nuclear plants immediately and to go out of nuclear supply totally till the year 2022. The substitution of the missing electrical energy shall be done by use of wind energy and electricity from photovoltaic systems (Table 1.2(b)). Naturally as a consequence in future, large storage capacities and extended grids for transport have to be realized. Furthermore, much higher capacities and costs for electrical energy have to be accepted.

Table 1.2 Aspects of development of the production of electrical energy TW・h/a

Year	Coal	Nuclear energy	Oil	Natural gas	Hydro power + renewable	Total
1970	2075	80	1625	—	1175	4955
1980	3163	714	1661	976	1802	8316
1990	4286	1989	1216	1632	2212	11 335
2000	5759	2407	1402	2664	2968	15 200
2005	7040	2640	1240	3750	3550	18 220
2010	8330	2725	828	4560	4290	20 733
2015	8950	2330	900	4750	4900	≈22 500
2019						≈27 000

(a) Development of electrical energy production worldwide (share of energy carriers)

Primary energy carrier	Capacity of plants/GW	Share of capacity/%	Production of electricity(brutto) /(TW・h/a)	Share of production/%	Remark
Lignite	20.9	9.7	136.5	22	Massive reduction(1)
Hard coal	25.3	11.7	84.4	13.6	Massive reduction(2)
Nuclear energy	10.8	5.0	72.0	11.6	Massive reduction(3)
Natural gas	29.8	13.8	83.8	13.5	Massive reduction(4)
Oil + other	6.6	3.7	18.0	8.9	Massive reduction(5)
Wind energy	55.7	25.8	104.2	16.8	Massive subvention
Bio mass	7.8	3.6	49.0	7.9	Massive subvention
Photovoltaic	43.2	20.0	39.8	6.4	Massive subvention
Hydro energy	5.6	2.6	19.8	3.2	Massive subvention
Other	10	4.7	12.4	2.1	Massive subvention
Total	≈216	100	≈620	100	

(b) Production of electricity and capacities of plants (example: Germany, 2017)

1,2—coal production has been reduced; since 2018 no more have coal mining in Germany; 3—large nuclear power reacts were taken out of operation after the accidents in Fukushima(2011); 4—massive reduction of use of natural gas in future; 5—oil for electricity production in Gase load plants is practicly forbidden

Worldwide today 70% of the electricity is produced on the basis of fossil fuel. Europe and North America still consume more than 60% of the electricity. Africa and South America need large progress regarding the production of electrical energy. Large investments in power plants, grids and distribution systems are necessary to realize this goal.

The need and supply of energy develops very fast in some countries worldwide, as example in China. Figure 1.11 and Figure 1.12 indicate some important parameters of the energy economy in China.

All data related to consumption and supply is rising up strongly, corresponding to the progress in this country. Further aspects related to special branches of energy economy are explained by Figure 1.12.

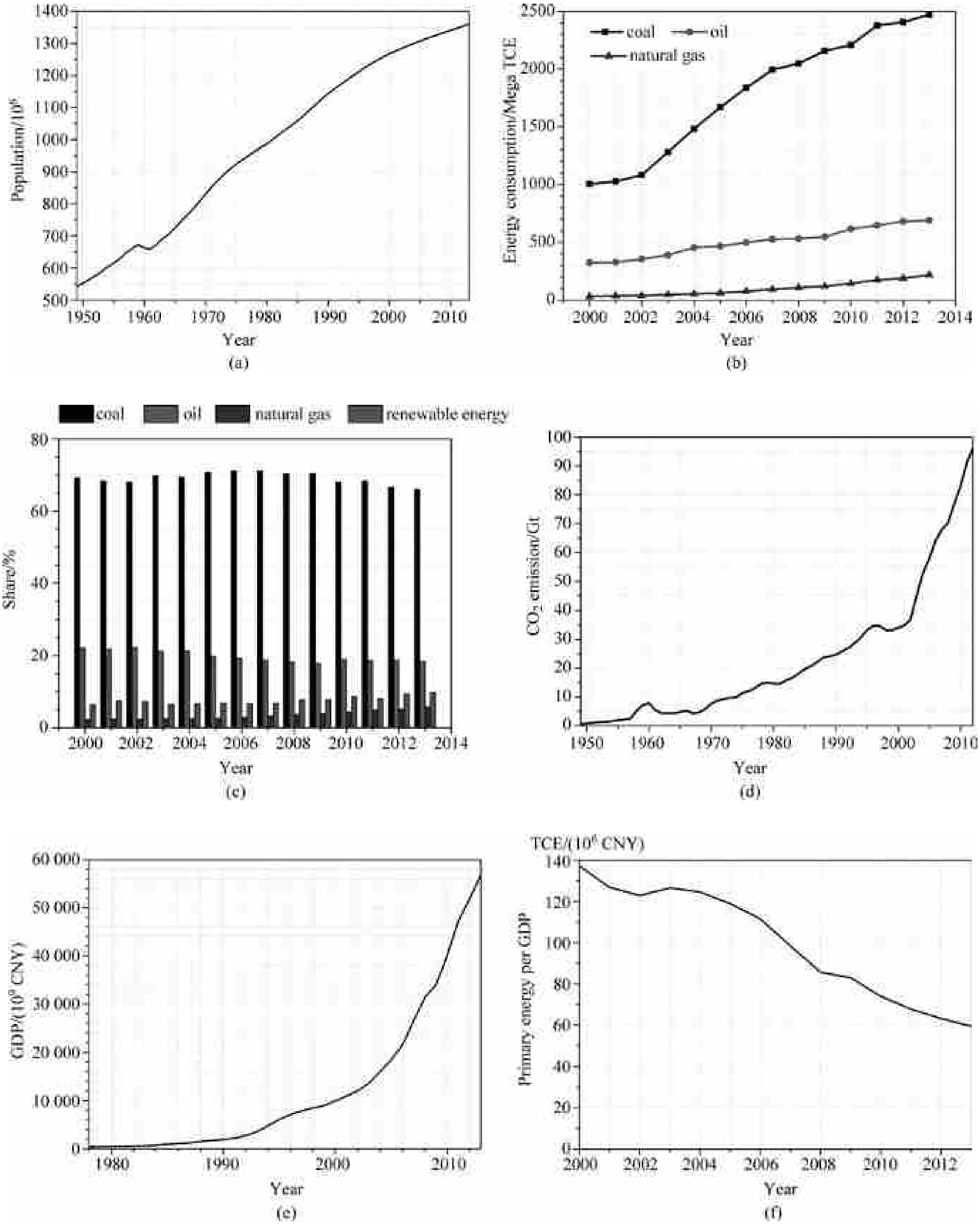
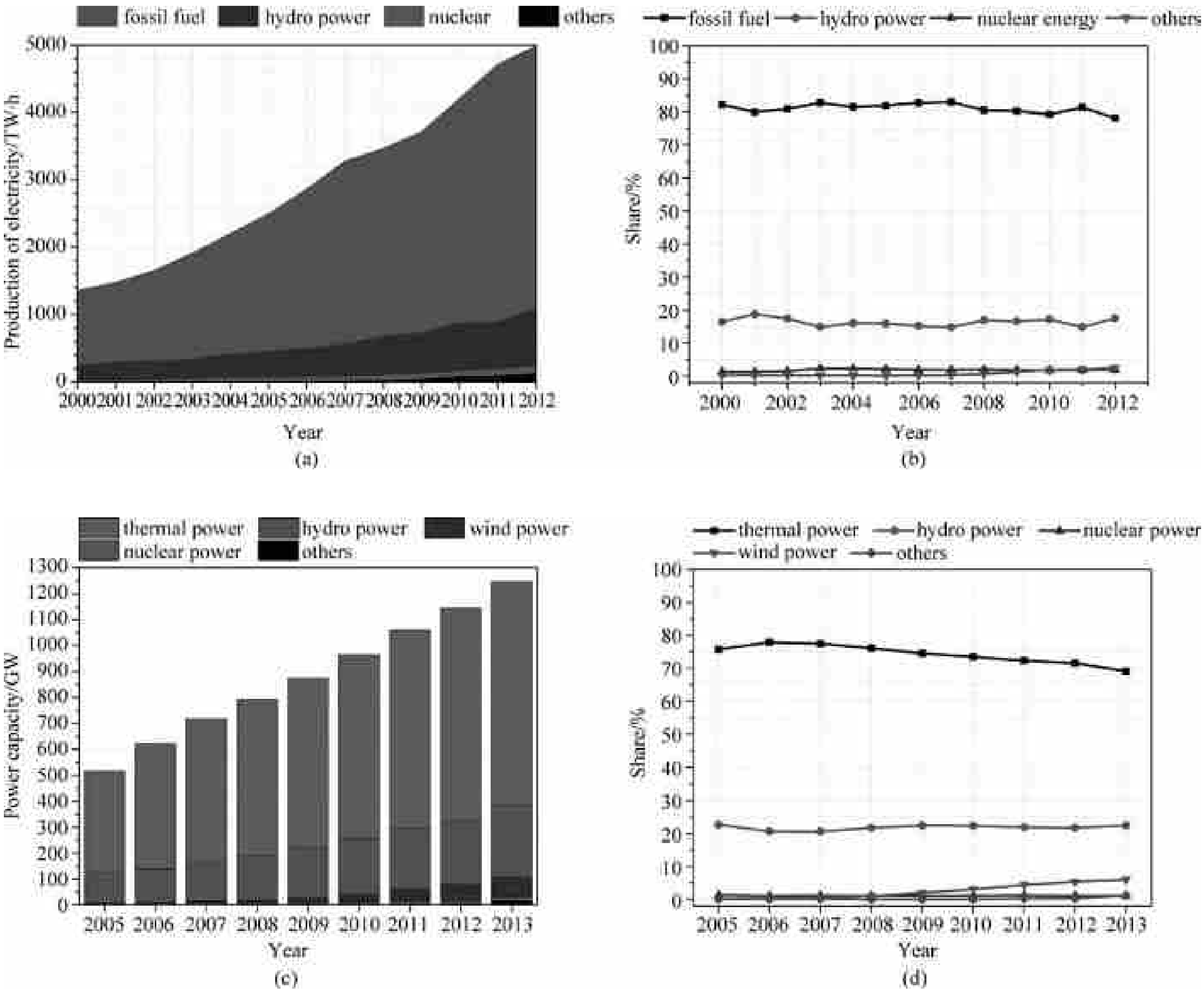


Figure 1.11 Important parameters of energy economy developing in time (example: China)[7-8]

(a) Population(value in 2019: 1.4×10^9); (b) Primary energy (CE = coal equivalent)(value in 2019: 4.76×10^9 t HCU/a); (c) Shares of energy carriers; (d) CO_2 emission(value in 2019: $\approx1\times10^{10}$ t CO_2/a); (e) Gross national product(value in 2019: 10 000 dollar/(person · a)); (f) Ratio of primary energy applied to the gross national products



Year	2000	2005	2010	2015	2019
Specific electric energy consumption[(kW·h_{el}/(person·a)]	1100	1700	3200	4000	5100

(e)

Figure 1.12 Characteristic data of electricity economy developing in time (example: China)[7-8]
(a) Production of electricity (value in 2019: 7800TW · h/a); (b) Shares of energy carriers for the production of electricity; (c) Capacity of power plants (value in 2019: 2000GW_{el}); (d) Shares of type of power plants (value in 2019: fossil: 68%; regen. + hydro: 27%; nuclear: 5%); (e) Specific electricity supply (per person)

There are further indicators, which characterize the change of economical conditions in a country and demonstrate the progress as is shown in Figure 1.13. The consumption of steel and cement are mainly correlated to the growing sections of industry, infrastructure and private houses. The strong rising up of private cars is an indicator for the growing welfare of people. This makes it necessary to supply more oil for this sector of the energy economy. There is the expectation that electrical energy for this sector will become more important in the future[9].

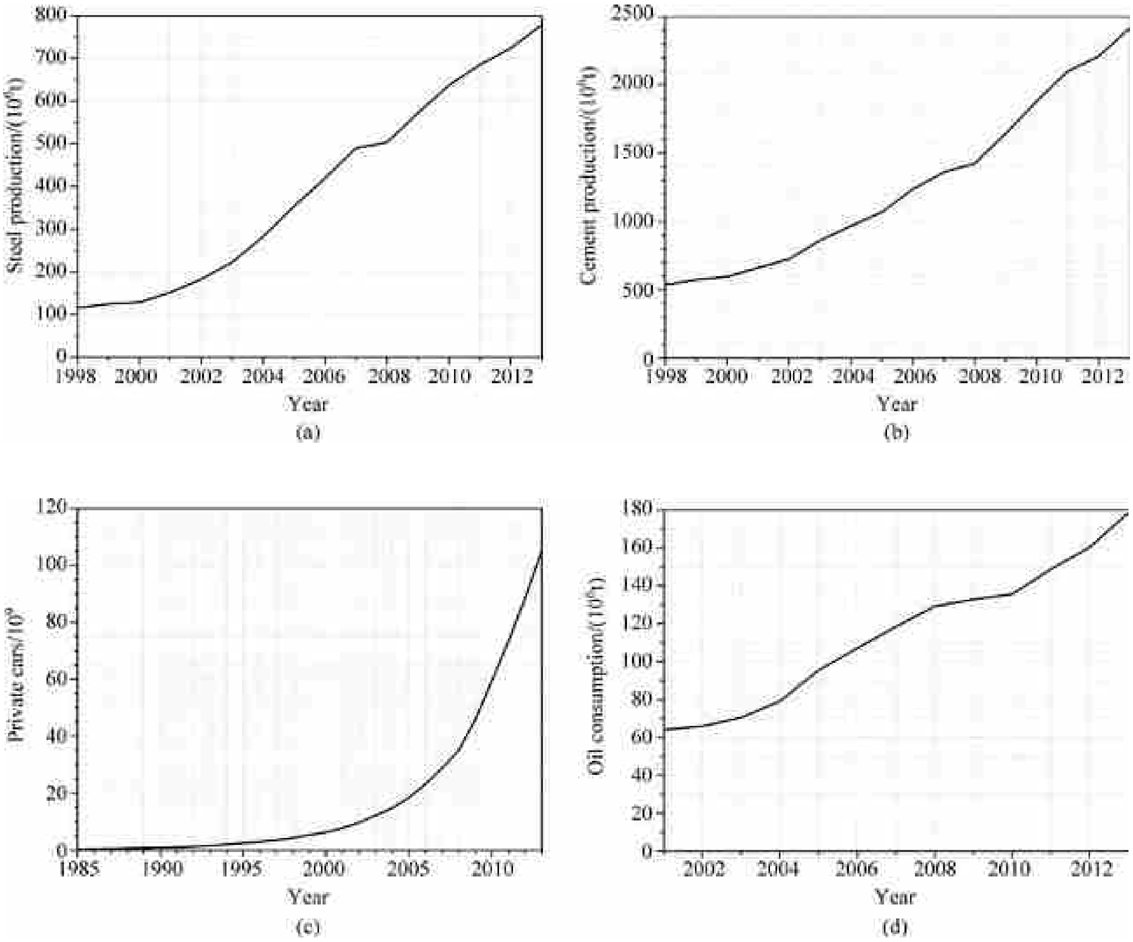


Figure 1.13 Characteristic change of masses of some products depending on time (example: China)[7-8]

(a) Steel production(value in 2019: $\approx 10^9$ t/a); (b) Cement production(value in 2019: 2.37×10^9 t/a); (c) Number of private cars(value in 2019: 2.07×10^8 cars); (d) Consumption of oil for transportation sector(value in 2019: $\approx 3.5\times10^8$/a)

These enormous growth rates of energy demand will drive the worldwide energy need. Similar analysis for other countries show rising energy demand for the different sectors too. India, Indouesia or Brasil are example for these developments.

The rising up of efficiency in all steps of the chain of energy conversion and use are decisive measures to reach this requirement. Until now just around 30% of the primary energy are converted into end-energy for application in different sectors of the energy economy. The future production of electricity has to be economically acceptable, shall fulfill "ecological high as possible" standards and shall be based on a safe and reliable supply with fuel.

Energy supply includes dynamical processes of substitution of different energy carriers and of technologies to use it (Figure 1.14). Traditional biomass, which was the main energy in the 18th and 19th century, was substituted by coal. Coal was substituted by oil and gas. From the middle of the 20th century nuclear energy started to get importance; however in the moment because of some safety concerns regarding today established technologies, the market introduction of these technologies was delayed. In the last decades renewable energies made some progress, and there is the expectation that they could cover a substantial part of the future energy market. These substitution effects in the future will continue, regarding aspects like easy handling, saving resources and avoiding CO_2 emissions. Economic conditions and development of energy price play a role as they are generally expected in energy economy. The development and substitution effects can be different in countries for some time. A characteristic example in the moment is Germany, where nuclear energy is stopped and renewable energy is accelerated by massive subventions.

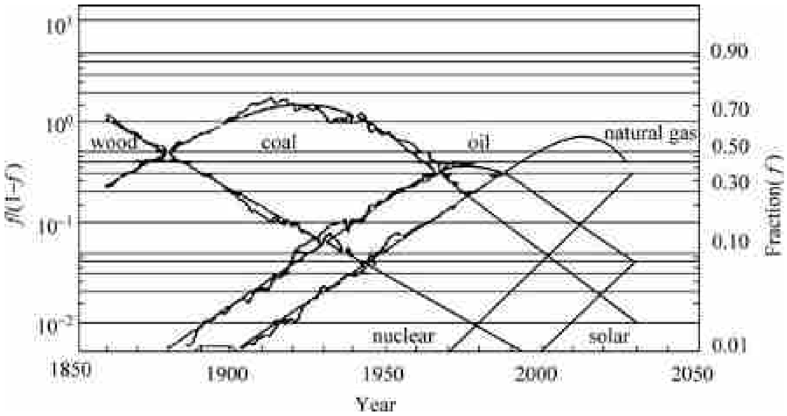


Figure 1.14 Effects of substitution of energy carriers in the world economy[10]

It is interesting to recognize that similar substitution effects happened in industrial processes too. Figure 1. 15 shows a very important example, the steel production following different process technologies. Processes have been changed corresponding to requirements of higher material qualities, reduction of specific energy consumption or environmental requirements. This principle of substitution can be seen in many fields of industry and in the energy sector. As example in the transportation sector, the different systems like transport by trains and ships, by cars and airplanes, show similar tendencies of substitution. Furthermore, optimizations are always necessary. Generally for industrial processes or in the energy economy, compromises have to be found between the aspects of efficiency (technology), economics (production costs), environmental requirements (emission) and saving resources (minimal consumption of raw materials, energy and minimal waste) and needs of the consumer. In the last decades, in many countries gaseous fuels became more important compared to solid fuels because of environmental aspects. Furthermore, liquefied gases in some countries were preferred from the same reasons. Especially under the influence of the CO_2-question and climate protection, many changes in the energy economy have been initiated or will be carried out in future.

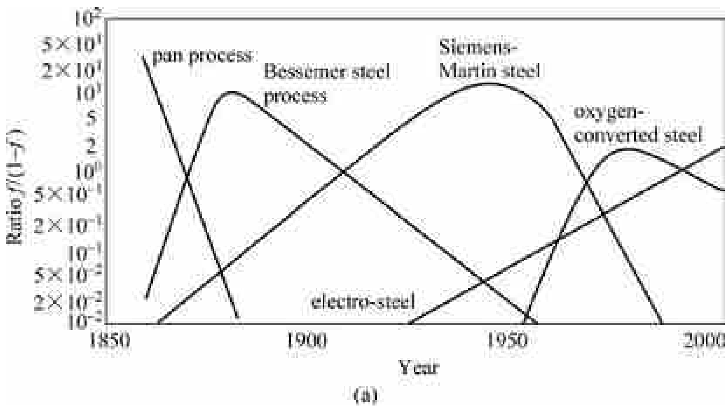


Figure 1.15 Some examples of substitution in the energy economy[10]

(a) Substitution of processes for steel production in the last decades; (b) Substitution in the transport infrastructure (USA);
(c) Substitution in the secondary energy supply sector (Germany)

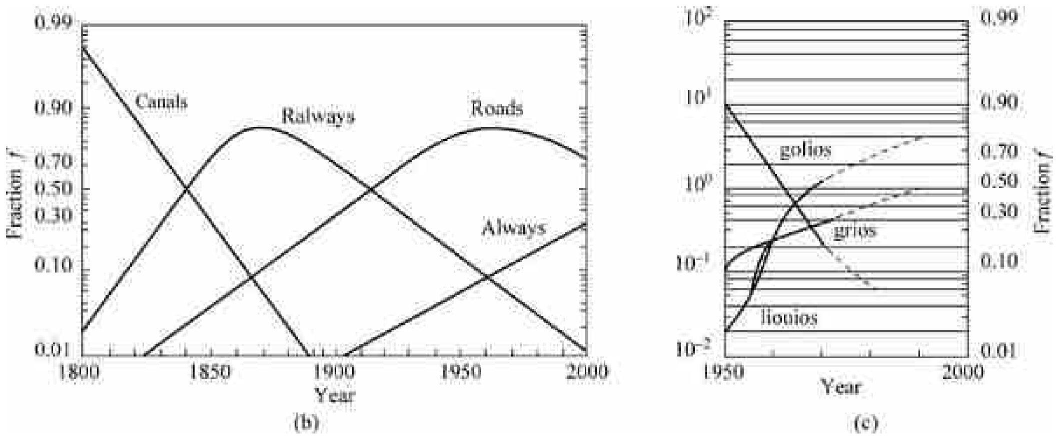
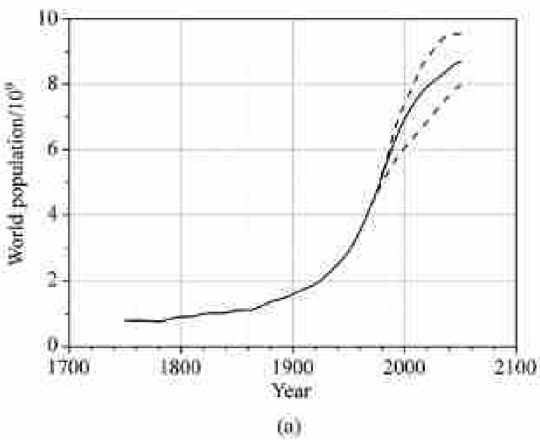


Figure 1.15 (Continued)

1.3 Prognosis on energy demand

For the future world energy economy[11-12], the questions of development of the population and the standards of life are the destinating parameters. Naturally the aspects of fulfilling the economical and environmental conditions of energy supply have to be taken into account too. Therefore it is difficult to make a tight prognosis of the future energy demand of the world. Estimations of different organizations naturally come to partly strong different results. In any case the population of the world is still growing up and this tendency will continue. Today an average growth rate is around 2%/a. This causes that the population will rise up from around 6.7×10^9 in 2010 to nearly 9×10^9 in 2050 (Figure 1.16). The growing rate in the southern part of the world is much larger (factor of about 2.5) than that in the northern part.



Countries	Growth rate /(%/a) (1990—2011)	Growth rate expected/(%/a)
Bangladesh	1.7	1.0
China	0.8	0.2
Germany	0.2	-0.2
India	1.7	1.1
USA	1.0	0.8
Russia	-0.2	-0.2
Indonesia	1.3	0.8
Brazil	1.3	0.6
Africa*	2~3	2
World	1.3	<1

(b)

Figure 1.16 Estimation of the development of the population in the world[12]

(a) Estimated growth of population in the world; (b) Growth rates in regions and some large countries (* average values for many states in Africa)

Many models using to estimate the development of energy demand are applied in energy economy. The following three models in Figure 1.17 are characteristic. They differ from each other regarding the expected growth rates.

constant growth: $\frac{dN}{dt} = a$; $N(t) = N_0(1 + a \cdot t/N_0)$

exponential growth: $b \cdot N$; $N(t) = N_0 \cdot \exp(b \cdot t)$

growth with saturation: $\frac{dN}{dt} = c \cdot N \cdot \left(1 - \frac{N}{N_\infty}\right)$; $N(t) = N_\infty \Big/ \left[1 - \frac{N_0 - N_\infty}{N_0} N_0 \cdot \exp(-c \cdot t)\right]$

Figure 1.17 Models for description of growth

The last indicated tendency of growth with saturation normally is estimated as the most probable. The equation, which was used to describe saturation

$$\frac{dN}{dt} = c \cdot N \cdot \left(1 - \frac{N}{N_\infty}\right)$$

describes two tendencies. On the one hand, the population growth is proportional to the number of already living people (N); on the other side, the growth of the number will be limited by an upper value (N_∞) and a thinkable increase ($N \to N_\infty$). The differential equation can be solved by partial integration

$$\int A \cdot \frac{dN}{N} + \int B \cdot \frac{dN}{1 - N/N_\infty} = c \cdot t + \text{const.}$$

Introducing the starting condition $t = 0$, $N = N_0$, one gets the solution

$$N(t) = N_\infty \cdot \frac{1}{1 - (N_0 - N_\infty)/N_0 \cdot \exp(-c \cdot t)}$$

This curve describing saturation generally is used in many models to establish prognosis. It is applied for population growth, energy supply, use of raw materials and supply with products. Figure 1.18(a) shows this curve. Uncertainties are large as shown for an example resulting from the electrical economy (Figure 1.18(b)).

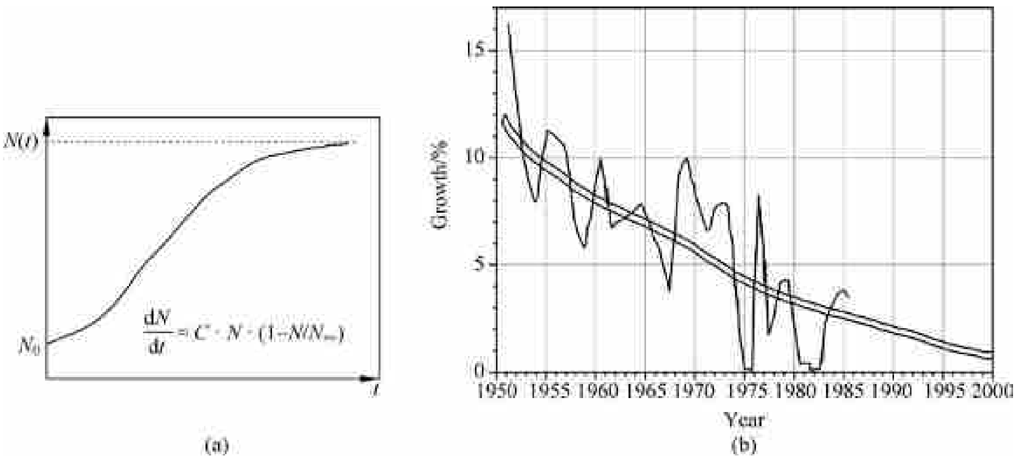


Figure 1.18 Aspects of prognosis for growth of energy demand

(a) Estimation of growth with saturation; (b) Uncertainties: growth rate for electricity production and prognosis (example: Germany)

Many studies have been carried out to estimate the future worldwide demand on energy. This includes some assumptions on the changes of standards of life too. Figure 1.19 gives an overview on possible development of the specific energy consumption per person and per year. Today this value is around 2.4t HCU/(person · a). For 7.2×10^9 people in 2010, this means a primary energy demand of around 17×10^9 t HCU/a.

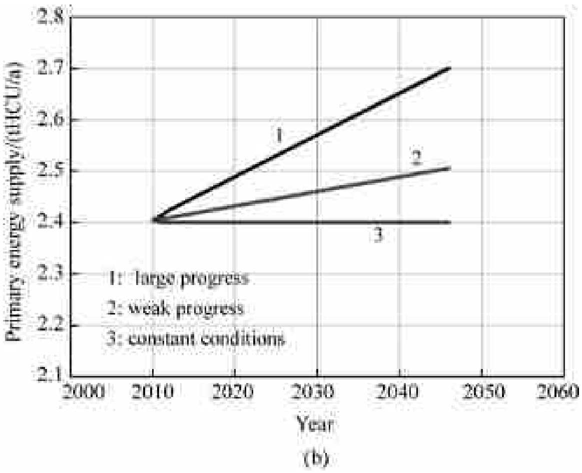
The growth rates in the actual time are very different for countries worldwide (Figure 1.19(a)). An average growth rate of around 2%/a worldwide is considered as a minimal value because this value corresponds already to the growth rate of population in some countries with large population.

In this case no or only little progress in many countries which have large population and low specific energy demand, would be assumed. This situation will not be accepted in the future.

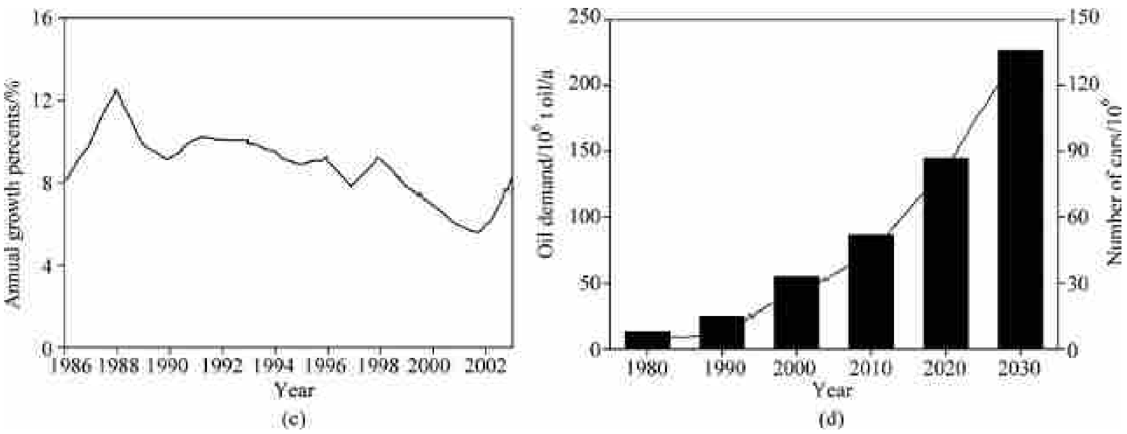
The economic growth and the strong rise of energy demand connected to this development is especially visible in countries like China (Figure 1.19(c) and Figure 1.19(d)). There is the expectation that the production of electricity and the delivery of energy for the transportation sector will rise up significantly in the future (see Figure 1.19(b)). A rise of the capacity of power plants of around 8%/a and doubling the number of cars in 15 years are expected.

Country	Actual growth rate/(%/a)	Estimated future growth rate/(%/a)
Germany	≈0	<1
China	>5	>5
USA	<1	<2
India	<1	>3
World average	>2	>2

(a)



(b)



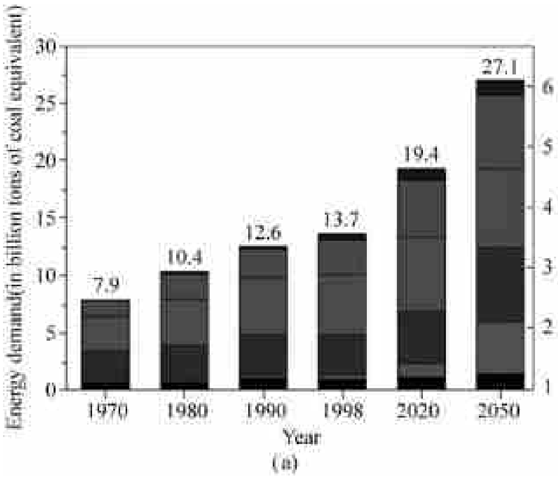
(c) (d)

Figure 1.19 Some relevant aspects for development of energy economy: influences of estimations of growth rates
(a) Growth rate of energy in different countries (2010); (b) Estimation of growth of specific energy supply (worldwide, average); (c) Annual growth of installed capacity of power plants (example: China)[7-8]; (d) Oil demand and number of cars for road transport (example: China)[7-8]

Naturally the reliable prediction of future development in a complex field like the world energy economy is difficult. Applying detailed models for many countries in the world, different organizations came to results for the future worldwide energy demand (Figure 1.20). There is a wide spreading depending on assumptions and expectations.

A model with 8×10^9 people in the year 2020 and a specific energy demand of 2.5t HCU/(person · a) results in a demand of around 2×10^{10}t HCU/a. This number would not include real progress in many countries.

Differences indicated in Figure 1.20 can be explained by different economic growth rates or political conditions as concepts for saving resources, CO_2-penalties, or oeko scenarios. Furthermore, it should be stated that the additional demand on energy mainly exists in countries which are characterized as developing or nearly developed countries.



Source	Primary energy in 2020/(10^9t HCU/a)	Primary energy in 2050/(10^9t HCU/a)
Shell	24	30
WEC 1995	19.4	27
IAEA 1998	22	
Öko-scenario	16	18
Average	20	30

(b)

Figure 1.20 Results of prognosis on the worldwide demand of primary energy[11-14]

(a) Prognosis of world energy council (WEC); (b) Some results of prognosis of world demand on primary energy (average from many different prognoses)

1—other renewable sources; 2—nuclear energy; 3—coal; 4—oil; 5—natural gas; 6—hydro

In any case large investments in plants for production, conversion, transport and storage of energy supply systems are necessary. Immense efforts will be required to reach the goal indicated by Figure 1.20.

Especially if the share of renewable energy carriers shall be as large as planned today in some western countries, very large investments are necessary. As example the storage of electrical energy requires totally new concepts and large financial efforts.

Without a sufficient good and safe energy supply it will be difficult or even impossible to maintain peace and welfare in the world. There is another interesting aspect in the correlation between the specific numbers of end use of energy and gross national product (GNP).

Efforts for saving energy by optimization of processes and rational use of energy can reduce the specific values of consumption, as this has happened in the last decades. The strong coupling between GNP and primary energy supply can change in time by technical measures of rational use of energy and administrative measures in the different sectors of energy economy (Figure 1.21(a)). Large savings of primary energy were possible at rising values of GNP. The demand of electricity however retained a rising tendency. Similar developments of the influences of energy savings are known from many industrial processes and many countries. Figure 1.21 shows results for Germany together with variations of the oil price. Rising values of energy prices always have initiated strong efforts to save energy and to improve processes in all steps of the chain of energy conversion. As the oil price dropped again, the efforts as example in Germany were reduced. New aspects like realization of CO_2-poor or free technologies again favor rising efforts to develop new energy technologies.

In other countries like China, Russia, USA, similar developments of enlarging the energy efficiency took place (Figure 1.21(b)). The value stayed relatively constant in Germany in the two decades.

For the worldwide development, a view on the growth of population, energy demand and the development of the "gross national product" is necessary (Figure 1.21(c)). These large growth of values have to be discussed together with the development of CO_2 emission.

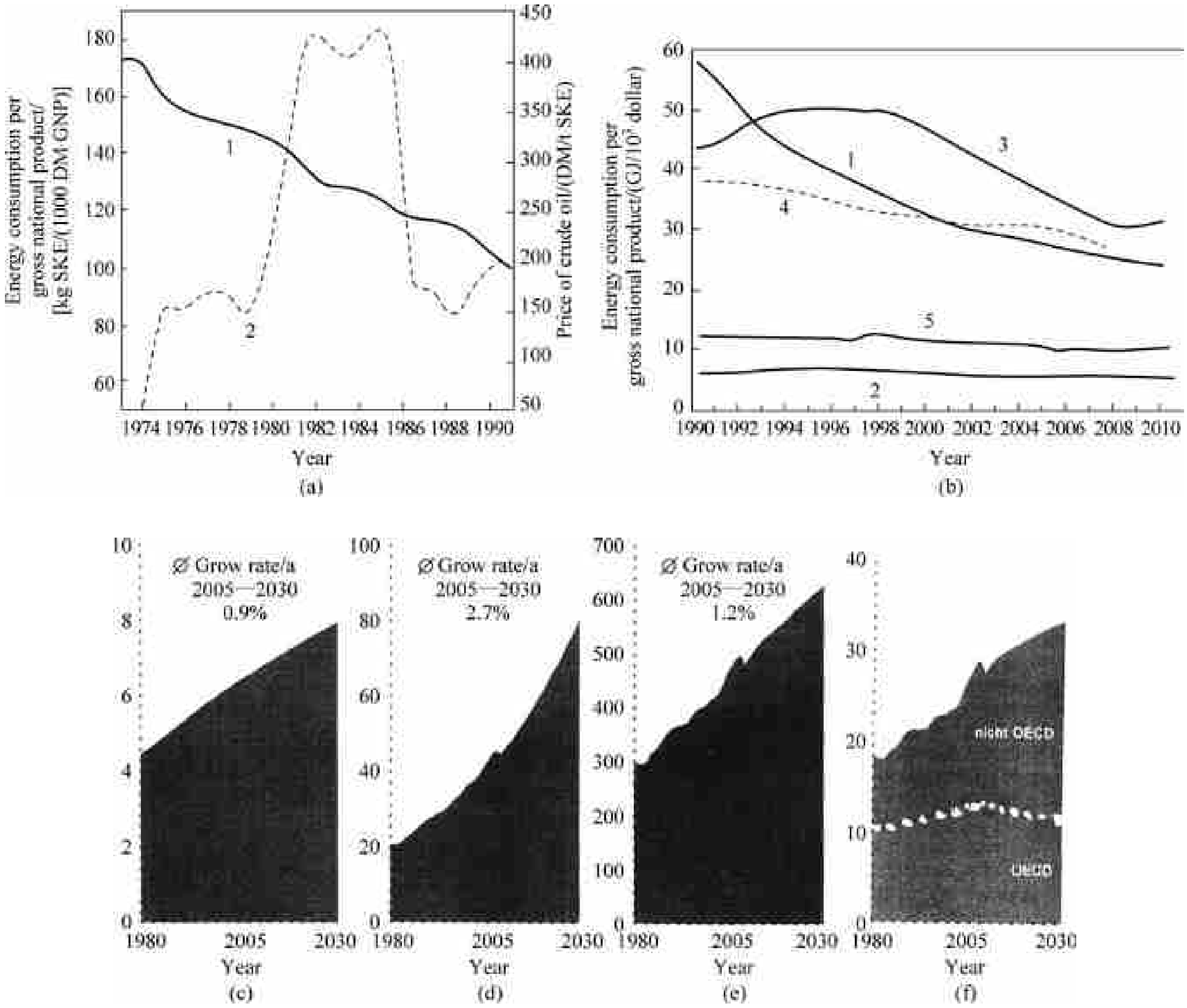


Figure 1.21 Aspects of developments in the energy economy

(a) Development of the energy consumption per Gross National Product (example: Germany) and price of crude oil; (b) Development of the energy consumption per Gross National Product in different countries; (c) World population (10^9 people); (d) Gross National Product (in 10^{12} US$ (2005)); (e) World energy supply (in billiards BTUs); (f) Worldwide CO_2 emission (10^9 t/a)

1—China; 2—Germany; 3—world; 4—former Soviet Union; 5—Africa

1.4 Energy reserves and resources

Worldwide large amounts of energy carriers are available for future use[15-19]. They are ordered in form of reserves and resources (Figure 1.22). The reserves cover those shares of energy carriers, which are already totally detected, developed and can be produced under actual economic conditions. The resources contain all amounts, which are expected from geological estimations. Today they are mostly not recoverable under economic conditions.

Included in these resources there are as example coals in large depth or gas and oil, which just could be produced under disadvantageous conditions. Change of costs and improvements of technology which just could be produced will allow in future partly to use these resources. Following this systematic in Figure 1.22 the values in Table 1.3 have to be discussed for the future worldwide energy supply during the next decades.

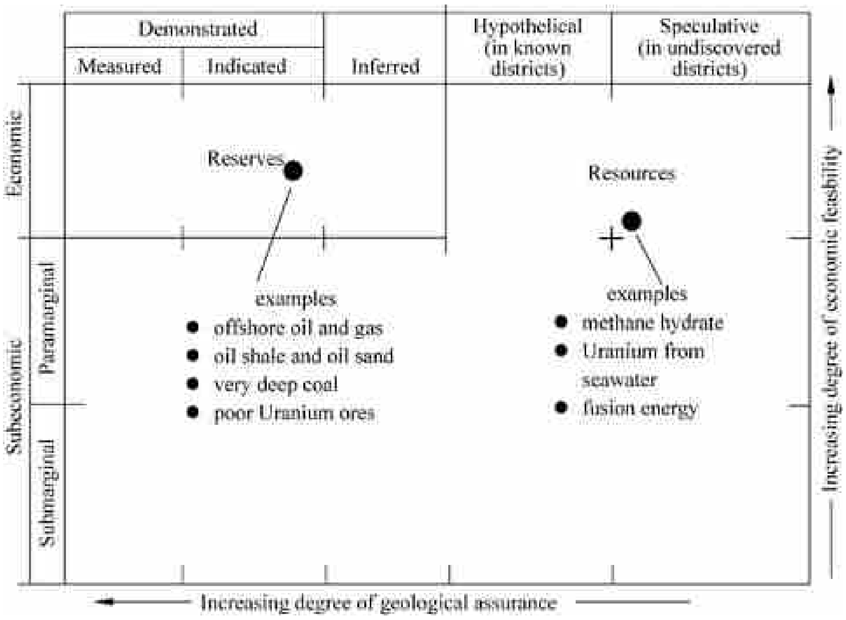


Figure 1.22 McKelvy diagram for the classification of energy reserves and resources[20]

Table 1.3 Reserves and resources of fossil energy carriers (HCU = Hard Coal Unit, 1t HCU = 0.67t oil)[21-28]

Energy carrier	Reserves/(10^9 t HCU)	Resources/(10^9 t HCU)	Remark
Crude oil	300	500	
Oil sand/oil shale	200	250	Just parts contained as resources
Natural gas	280	200	
Hard coal	800	4000	
Lignite	100	1000	

Especially the very large reserves and resources of coal initiate the development of many new technologies to use this energy carriers under optimized economical and environmental conditions. As example gasification and liquefaction of coal will become important in future.

Numbers especially about reserves are changing in time dependent on economical and environmental conditions. This can be explained on behalf of the example of oil (Figure 1.23). The estimations have been nearly doubled in the last 30 years because resources which were declared as reserves on the basis of rising oil price. Similar considerations are valid for the other primary energy carriers.

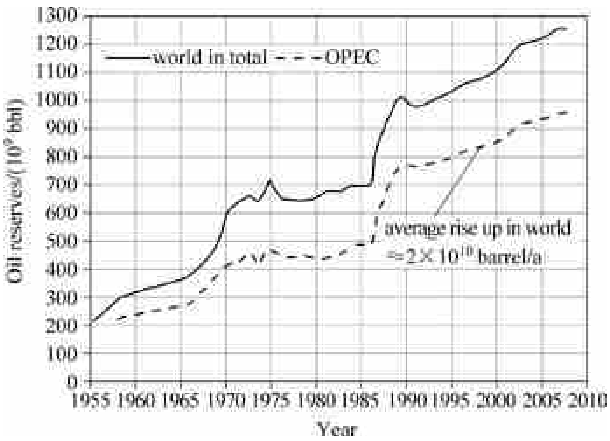


Figure 1.23 Development of estimations on oil reserves (economic producible, estimation of reserves in 2016: 1.5×10^{12} bbl) (1bbl = 160L)[22]

It can be estimated that in totally around 1.4×10^{12} t HCU fossil fuel are available worldwide in form of reserves. Assuming a today consumption of fossil fuel of 1.4×10^{10} t HCU/a, the reserves would be sufficient for 100 years. However there is no escalation of the consumption of fossil fuel included in this estimation. Considering fossil resources of nearly 6×10^{12} t HCU fossil fuel could be an option for several 100 years. However in this case it is expected that the emission of CO_2 will limit the consumption of these total resources.

The changes of estimation of reserves of all fossil fuels dependent from time, as shown in Figure 1.23 for oil, were large in the last decades. These expectations naturally influence the market and the oil prices. The prices of other energy carriers follow these tendencies.

Similar considerations on economic conditions to use different categories of fuel are representative for the uranium reserves as example (Table 1.4). As shown there is a distribution of the uranium reserves dependent on their production costs corresponding to the McKelvey-diagram. The today known and safe reserves of 4.6×10^6 t Uranium correspond to an energy of 9×10^{10} t HCU, if they are applied in light water reactors.

Table 1.4 Categories of costs of nuclear fuels[25]

Category	<40 dollar/kg	<80 dollar/kg	<130 dollar/kg	<250 dollar/kg
Known and production reserves Uranium	1.73×10^6 t	2.5×10^6 t	3.2×10^6 t	
Estimated add. reserves Uranium	1×10^6 t	1×10^6 t	1.4×10^6 t	
Estimated resources Uranium				5×10^7 t
Estimated resources Thorium				5×10^7 t

Natural Uranium can be valuated corresponding to the relation:

$$1\text{t U} \triangleq 2\times10^4\text{ t HCU (without breeding effect)}$$

Today $7\times10^6\sim10^7$ t of Uranium can be declared as reserves. This corresponds to an energy value of $1.4\times10^{11}\sim2\times10^{11}$ t HCU. In the future breeding processes will become important. In this case, U 238 is converted into the fissionable Pu 239.

1t U then would correspond to about 10^6 t HCU including theoretical numbers for breeding. The energetic value of Thorium is the same, if breeding into U 233 is included.

Uranium reserves with small content of uranium are available, but they are today not of economic interest. Granit as example contains 26mg/L U, shale material partly contains 150mg/L and phosphate around 100mg/L. In some cases these reserves could become interesting at an earlier time, because other materials could be produced as byproducts.

In case of breeding, naturally the value of fissile material using these special reserves is much higher as mentioned before. A practical breeding effect with a factor of 20 is estimated as feasible.

Furthermore Thorium is available with similar values of reserves and resources like Uranium. Using breeding process the generation of U 233 is possible, which is a similar usable nuclear fuel like the fissionable U 235. By this way the availability of nuclear fuel can be doubled. Principally the seawater contains large amount of Uranium (around 3mg U/m^3 water) and this is an unlimited source of energy. Several methods used to produce Uranium from sea water are valuated as feasible, however the production costs are estimated to be much too high today.

It is well known that breeding effects can allow a higher output of energy. However the factor of usage of Uranium depends from the cost of reprocessing and the price of Uranium on the world market. A dynamic optimization regarding this question is necessary and delivers different answers depending on the boundary conditions of the energy market of the future.

A very helpful measure in the energy economy is the range of an energy carrier. One distinct between a static and a dynamic range. The dynamic range can include different developments and changes. The static value is defined by the relation

$$R_{\text{stat}} = M/\dot{M}$$

Here M is the total available amount of a specific energy carrier and $\dot{M}$ is the actual worldwide consumption. As example, one gets for the static range of crude oil: $\dot{M} \approx 5 \times 10^9$ t/a, $M = 2 \times 10^{11}$ t, $R_{\text{stat}} = 40$ years, if the well-known economic reserves are taken into consideration.

The dynamic range includes the fact that the yearly worldwide consumption is rising up with a rate σ (%/a). This tendency is caused by the rising world population and the larger specific consumption. In this case, applying an escalation rate q one gets after n years:

$$M = \dot{M} \cdot (1 + q + q^2 + \cdots + q^n) = \dot{M} \cdot \frac{1 - q^{n+1}}{1 - q}, \quad q = 1 + \sigma/100$$

The dynamic range follows then as

$$R_{\text{dyn}} = n = \left[1 + \frac{M}{\dot{M}}(q - 1)\right] \Big/ \ln q - 1$$

If as example a today estimated fossil reserve of $M = 1.5 \times 10^{12}$ t HCU is considered and an actual worldwide consumption of $\dot{M} = 1.4 \times 10^{10}$ t HCU/a is assumed, one gets a number of $R_{\text{dyn}} = 70$ years, assuming an escalation rate of 2% per year. This escalation rate would include mainly the rise of population worldwide, which today is nearly 2%/a. The numbers of the today worldwide production, the reserves and the resources show the dominant role of coal (Table 1.3). Coal would be a solution for the energy supply of the world for some hundred years.

There is a third possibility to define a time, which is characteristic for the range of an energy carrier. It is the so called exhaustion time, which indicates a time when the energy carrier has been consumed to a special rest value. This method allows to the same time to estimate the consumption of the energy carrier in time.

The actual production P of an energy carrier can be connected to the cumulated already produced energy E_c by the relation

$$E_c(t) = \int_0^t P(t')\,dt', \quad P(t) = \frac{dE_c}{dt}$$

Furthermore, it can be assumed that the actual production P will be proportional to the amount of already produced cumulated energy E_c and the still possible production $(E_\infty - E_c)/E_\infty$.

$$P = \alpha \cdot E_c \cdot \frac{E_\infty - E_c}{E_\infty}$$

E_∞ corresponds to the totally available amount of the energy carrier. These assumptions are feasible because production P will be proportional to the investment already done (plants, underground pits, open pits, material processing plants, transportation systems), which are proportional to the amount of energy already produced (E_c). On the other hand, the production will be stopped long before exhaustion occurs, when the possible quantity of production $(E_\infty - E_c)$ becomes small. As a result, the differential equation

$$\frac{dE_c}{dt} = \alpha \cdot E_c \cdot \left(1 - \frac{E_c}{E_\infty}\right)$$

has to be solved with the boundary condition

$$t = 0, \quad E_c = E_c^0$$

The solution is

$$E_c(t) = E_\infty \cdot \exp(\alpha \cdot t) \Big/ \left[\frac{E_\infty}{E_c^0} - 1 + \exp(\alpha \cdot t)\right]$$

The production P is calculated as follows:

$$P(t)=\frac{dE_c}{dt}=E_\infty\cdot\left(\frac{E_\infty}{E_c^0}-1\right)\cdot\alpha\cdot\exp(\alpha\cdot t)\Big/\left[\frac{E_\infty}{E_c^0}-1+\exp(\alpha\cdot t)\right]^2$$

Because for $t=0$, $P=P_0$ is known, the production at the starting point of the consideration determines α

$$P_0=\alpha\cdot E_c^0\cdot\left(1-\frac{E_c^0}{E_\infty}\right)$$

$$\alpha=\frac{P_0}{E_c^0}\cdot\frac{1}{1-\frac{E_c^0}{E_\infty}}$$

The determination of limits ($t\to\infty$) delivers $E_c=E_\infty$ as defined before.

It is interesting to determine the time of the maximal production. From

$$\frac{dP}{dt}=0,\quad t=t_{max}$$

one gets the result

$$t_{max}=\frac{E_c^0}{P_0}\cdot\left(1-\frac{E_c^0}{E_\infty}\right)\cdot\ln\left(\frac{E_\infty}{E_c^0}-1\right)$$

The maximal value of production following this model is connected to the resources E_∞, the actual production P_0 and the cumulated production E_c^0 at the starting point of consideration:

$$P_{max}=P_0\cdot\frac{1}{4}\cdot\frac{E_\infty^2}{E_c^0}\cdot\frac{1}{1-\frac{E_c^0}{E_\infty}}$$

Based on the considerations explained before, an exhaustion time of an energy carrier can be defined as example by a condition like $E_c/E_\infty=0.9$, which seems to be a reasonable measure. The time T^*, at which 90% of the energy would be consumed then can be defined by

$$T^*(90\%)=\frac{E_c^0}{P_0}\cdot\left(1-\frac{E_c^0}{E_\infty}\right)\cdot\ln\left[q\cdot\left(\frac{E_\infty}{E_c^0}-1\right)\right]$$

The valuation of this type of equations delivers T^*-values for coal as example between 170 and 200 years for reserves of 1.5×10^{12} to 2.5×10^{12} t HCU. Figure 1.24 shows possible time dependencies of coal production depending on time and height of reserves. Aspects like limitation of use of coal because of CO_2-questions are not included in this consideration.

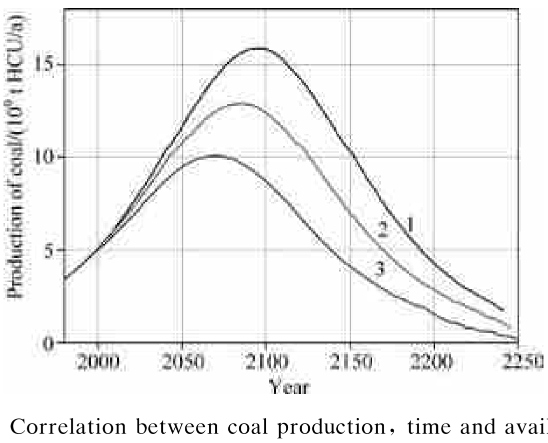


Figure 1.24 Correlation between coal production, time and available reserves

1—2.5×10^{12} t HCU; 2—2×10^{12} t HCU; 3—1.5×10^{12} t HCU

The role of fossil energy will stay important in the next decades. Following many estimations nuclear energy and renewables will become more important. Naturally the aspects of CO_2 emission and waste management will influence these expectations. Prognosis carried out by different institutions for the world energy supply assumes shares of around 50% of the total demand in 2030. The other 50% would be delivered by nuclear energy and renewables. The height of the share of renewables depends on technical progress and innovations especially in the field of storage of energy.

A further very important topic is the worldwide distribution of reserves and resources. Table 1.5 gives an overview on the reserves, which are present on the different continents.

Table 1.5 Regional distribution of energy reserves[11-17]

Continent	Crude oil/(10^9 t HCU)	Natural gas/(10^9 t HCU)	Coal/(10^9 t HCU)
Asia + Middle East	150	90	190
Australia	1	40	80
Southern America	60	10	15
Africa	25	15	30
North America	40	10	250
Europe + Russia	25	60	300

Hard coal is distributed nearly equal in all continents worldwide. Crude oil today mainly is available in some parts of the world. Natural gas is available in all continents. The dependence of a country from energy import is a very important aspect of safe and reliable supply of energy economy. Especially there are cheap reserves of crude oil in the Near East (Arabia, Iran, Iraq), whereas Russia has large reserves of natural gas. China and USA have large reserves of hard coal too. Uranium is mainly available in Canada and Africa.

In the last time large reserves of gas have been mobilized in the USA by fracking methods. There are further countries, which plan to follow this concept of production of natural gas. For countries like Germany which don't have worth mentioning reserves on natural gas and oil imports are essential. Furthermore it is important to get the energy carriers from many different countries to reduce the dependencies and to realize a stable as possible supply. Figure 1.25 explains some aspects for Germany. The share of the energy by inland production dropped very much in the last decades, because the production of hard coal in Germany had stopped because of economical reasons (Figure 1.25). The import of oil and natural gas has been raised up and therefore today Germany depends on upto 70% from imports. Here oil and coal are imported from many countries, however for natural gas just some few exporting countries are available for Western Europe.

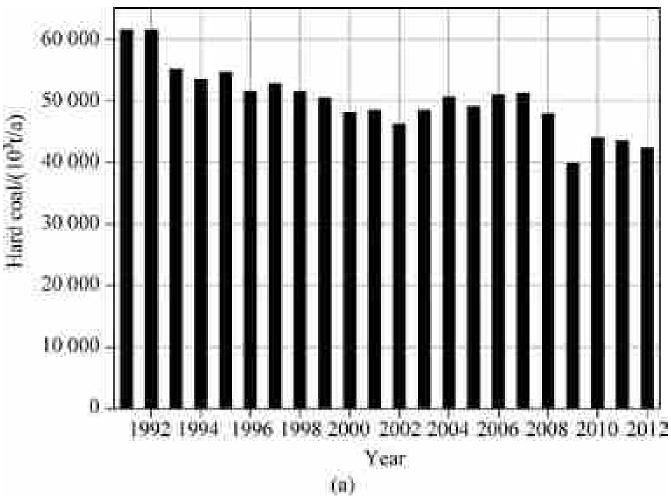


Figure 1.25 Energy imports: status in the past, today and expectations[29]

(a) Inland production and import (example: hard coal in Germany; in 2019 total consumption: 3.7×10^7 t coal/a; 100% import);

(b) Energy import in Germany (in the past and expectations)

Year	1990	2000	2010	2020
Total/%	50	65	70	75
Oil/%	90	92	93	94
Gas/%	80	82	85	90
Hard coal/%	20	50	70	80

(b)

Figure 1.25 (Continued)

The worldwide development of energy economy caused a special situation for the hard coal production in Germany. Imports from different countries became important for this sector of the energy economy, which originally was independent from foreign countries. The dependence of energy imports in Germany became even higher by this development and today amount to be above 70%. This is a danger for the safety of energy supply. The hard coal production has been totally finished in Germany in 2018.

1.5 Aspects of future worldwide energy supply

Assuming a future worldwide average fossil energy demand of around 20×10^{10} t HCU/a during the next decades, an estimated amount of fossil resources of energy of 3×10^{12} t HCU, which could be used principally in the future, would be sufficient for around 150 years. All known energy strategies include the massive use of fossil fuels in the future too and rising importance of renewables and nuclear energy. Following these strategies with the importance of fossil fuel, the rates of CO_2 emission however will still be high in the next decades. Therefore some very important questions of further research and development in the field of energy technology will require answers.

- Is the rising content of CO_2 in the atmosphere a problem or not?
- Can the nuclear fusion be realized as a usable energy source?
- Is the use of renewables corresponding to large shares of the world economy feasible?
- Can the safety of nuclear systems be improved to common accepted levels?
- Are solutions for final storage of CO_2 available?

The CO_2 emission is indeed a key question for the energy economy worldwide(Figure 1.26).

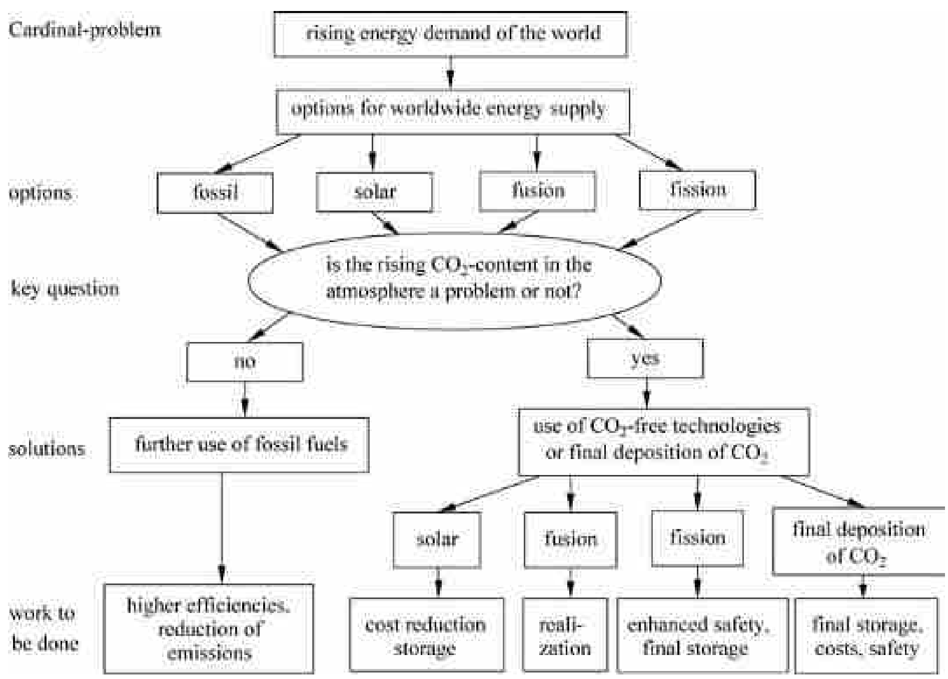


Figure 1.26 Worldwide options for future energy strategies: importance of the CO_2-question

Fusion is considered as an unlimited energy source, if it can be realized physically and technically. Furthermore in a far future, it has to be economically competitive to other than available energy sources. The development has taken and will take in the future a lot of time as shown in Table 1.6. As example, the time necessary between discovery of the fundamental effect of nuclear fission (1938) and the first large commercial power plants (Germany, PWR with 1200MW_{el}) was around 30 years. In case of fusion the time between the discovery of the first fusion reaction (1991 in the JET project) and maybe reactions in a self-sustaining plasma system will be already more than 30 years, if the ITER project[29] will be successful. The step to a technically continuously working system with heat transfer to power cycle will consume much more time than it was necessary in case of development of fission. Therefore the expectation is that fusion will not play a role for energy supply in the next decades.

Table 1.6 Time dependence of introduction of the fission energy and possible time schedules for the development of fusion energy

Step	Nuclear fission	Nuclear fusion
Proof of physical principle	1938 (Otto Hahn)	1991 (JET project)
Proof of chain reaction	1942 (Enrico Fermi)	2025 ? (ITER project)
Demonstration reactor	about 1950 (USA, LWR)	2035 ? (ITER, technical phase)
Commercial power plant	about 1970 (Germany, PWRBiblis)	2050(?) (first prototype)
Market introduction with significant shares in some countries	about 1980 (worldwide, LWR)	after 2060 (?) (commercial plant)
Worldwide application	future (innovative reactor)	?

The renewable energies must be used to a large extent if CO_2 emission shall be avoided. Regarding technology, wind energy convertors, solar thermal systems and photovoltaic cells for electricity production are available. Furthermore biomass conversion and hydropower are applicable worldwide. Today the production costs of renewable energies are relatively high compared to electricity production from coal and nuclear energy with the exception of hydropower. However for nearly all these energy systems, efficient and economic acceptable storage systems are necessary.

So far as the CO_2-question[30] caused by conversion of fuel is considered, the valuation shows that the burning of all fossil fuels produces different amount of CO_2 (Figure 1.27). Natural gas shows some advantages compared to oil fractions and coal. Lignite with a high water content shows the relatively highest specific CO_2-values during the burning process (Figure 1.27(b)). The burning of biomass produces CO_2 too, however the forming of biomass in the atmosphere by reactions including the catalytic action of green areas bounds CO_2 again.

$$xH_2O + yCO_2 + E_{solar} + (aNO_3 + bSO_4 + cPO_2) \longrightarrow C_nH_mO_r + H_2O + O_2 + \text{further products}$$

$$12H_2O + 6CO_2 + 2.8\text{MJ (solar energy)} \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

The production of oxygen by this reaction is fundamentally important for the life on earth. Therefore the conservation of green plants, trees and the extension of the areas for the photosynthesis is an extremely important topic connected to the energy economy.

Caused by these conversion processes until now, the worldwide CO_2 emission has been raised up till nearly 3.8×10^{10}t CO_2/a or around 4.9t CO_2/(a · person) assuming a world population of 7.8×10^9 people (status in 2020).

Fuel	Reaction	Heating value (lower)/ ($kW \cdot h_{th}/kg$)	Specific CO_2-emission /($kg\ CO_2/kg$)	Specific CO_2-emission /[$kgCO_2/(kW \cdot h_{th})$]	Remark
Hard coal	$C+O_2 \rightarrow CO_2$	8.6	3	0.35	80% C
Natural gas	$CH_4+2O_2 \rightarrow CO_2+2H_2O$	8.95	2.75	0.3	90% CH_4
Oil	$C_nH_m+\left(n+\frac{m}{4}\right)O_2 \rightarrow n\,CO_2+0.25mH_2O$	11.8	3	0.25	light fractions
Biomass	$C_xH_yO_z+\left(x+\frac{y}{4}-\frac{z}{2}\right)O_2 \rightarrow xCO_2+0.5y\,H_2O$	4.5	3.6	0.8	wood, dry
Hydrogen	$H_2+\frac{1}{2}O_2 \rightarrow H_2O$	3	—	—	—

(a)

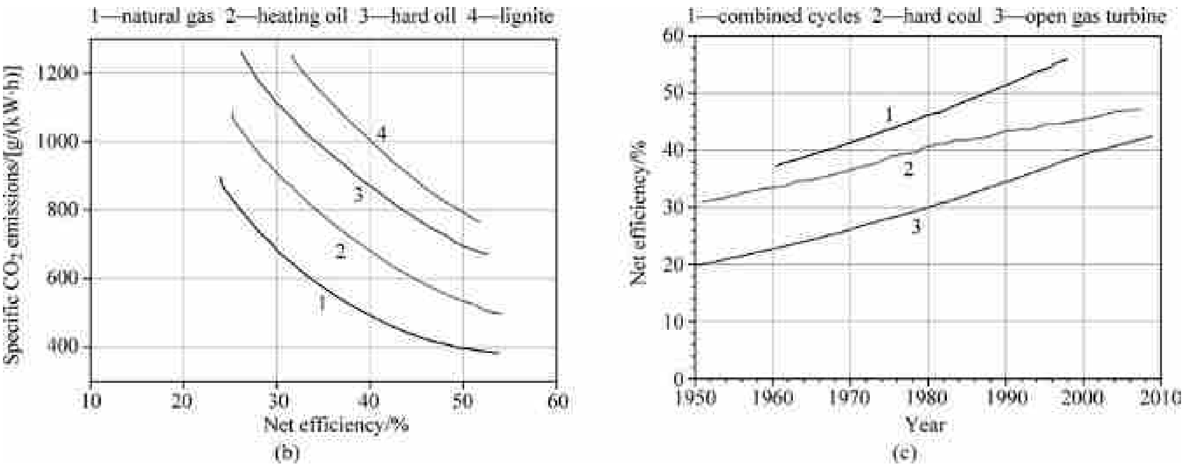
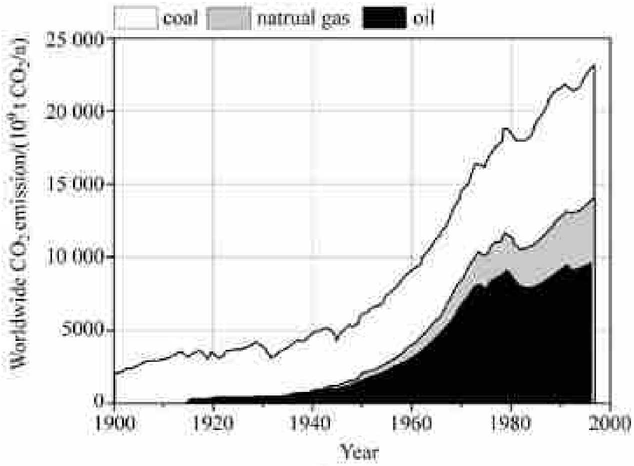


Figure 1.27 Data of burning fossil fuels in power plants

(a) Specific emission of CO_2 during burning processes of fuels: hydrogen for comparison; (b) Specific CO_2 emissions from power plants based on fossil fuels: dependence from net efficiency; (c) Development of efficiencies in the last decades of power plants based on use of fossil fuels

There are massive efforts of development, as example in the field of fossil fuelled power plants to reduce the specific CO_2 emission. However if a sequestration of CO_2 and a final storage should be realized in the future, the specific values given in Figure 1.27(b) will rise up again. The process steps of CO_2-separation, compression and transport to final storage require energy and reduce the net efficiency again. Partly values of reduction of 15%～25% (relatively) are expected. These values depend on the technical conditions and are found from optimization of the total chain of conversion including all steps. Some more details on these possibilities are explained in Chapter 14. Figure 1.28 contains some values, which characterize aspects of CO_2-emission worldwide.

The rise up in the worldwide emission of CO_2 corresponds to an average increasing rate of 3%/a. As a consequence, until now the CO_2 content of the atmosphere became larger and the expectation is that the temperature will rise up between 3℃ and 5℃ on the earth in the next 100 years. There is fear that intolerable consequences for the environment and human beings would occur. Figure 1.29 contains some information on necessary reduction of the emission of CO_2 in the world economy to stabilize the world climate.



(a)

Year	CO_2 emission / (10^9t/a)
2000	25
2005	30
2010	33
2015	35
2018	37

(b)

Country	Specific primary energy /[(tHCU/(person·a)]	Specific CO_2 emission /[(tCO_2/(person·a)]
India	0.8	2
Bangladesh	<0.3	<1
Indonesia	1	2.5
Japan	5	9.5
China	3.3	8
Germany	5.5	9
France	4.9	5
Sandi Arabia	11.3	18
Russia	6.5	10
United States	9.6	14.2
World average	2.3	4.7

(c)

Year	Specific CO_2 emission/ [t/(person·a)]
1980	≈1
1990	≈2.7
1995	≈3.7
2000	≈4
2010	≈5
2020	≈8

(d)

Year	Specific CO_2 emission/ [t/(person·a)]
2014	10
2030	≤5
2050	≤3

(e)

Figure 1.28 Some data on worldwide CO_2 emissions[28,30]

(a) Development of worldwide CO_2 emission dependent from type of fuel; (b) Development of worldwide CO_2 emission since 2000; (c) Specific CO_2 emission in different countries (t CO_2/(person · a)) (status 2019); (d) Specific CO_2 emissions in China (development); (e) Specific CO_2 emissions in Germany (planning of politics)

The curve for the rising values of CO_2 in the atmosphere can be explained qualitatively by the following estimation. For the content X_{CO_2} one can formulate the equation:

$$\frac{dX_{CO_2}}{dt} \approx \frac{\dot{M}_{CO_2}}{V} - (\alpha + \beta + \gamma) \cdot X_{CO_2}$$

$\dot{M}_{CO_2}$ is the yearly emission of CO_2, V is the volume of the atmosphere. α, β, γ characterize absorption of CO_2 in water (α), forming of new biomass (β) and other effects like disappearing out of

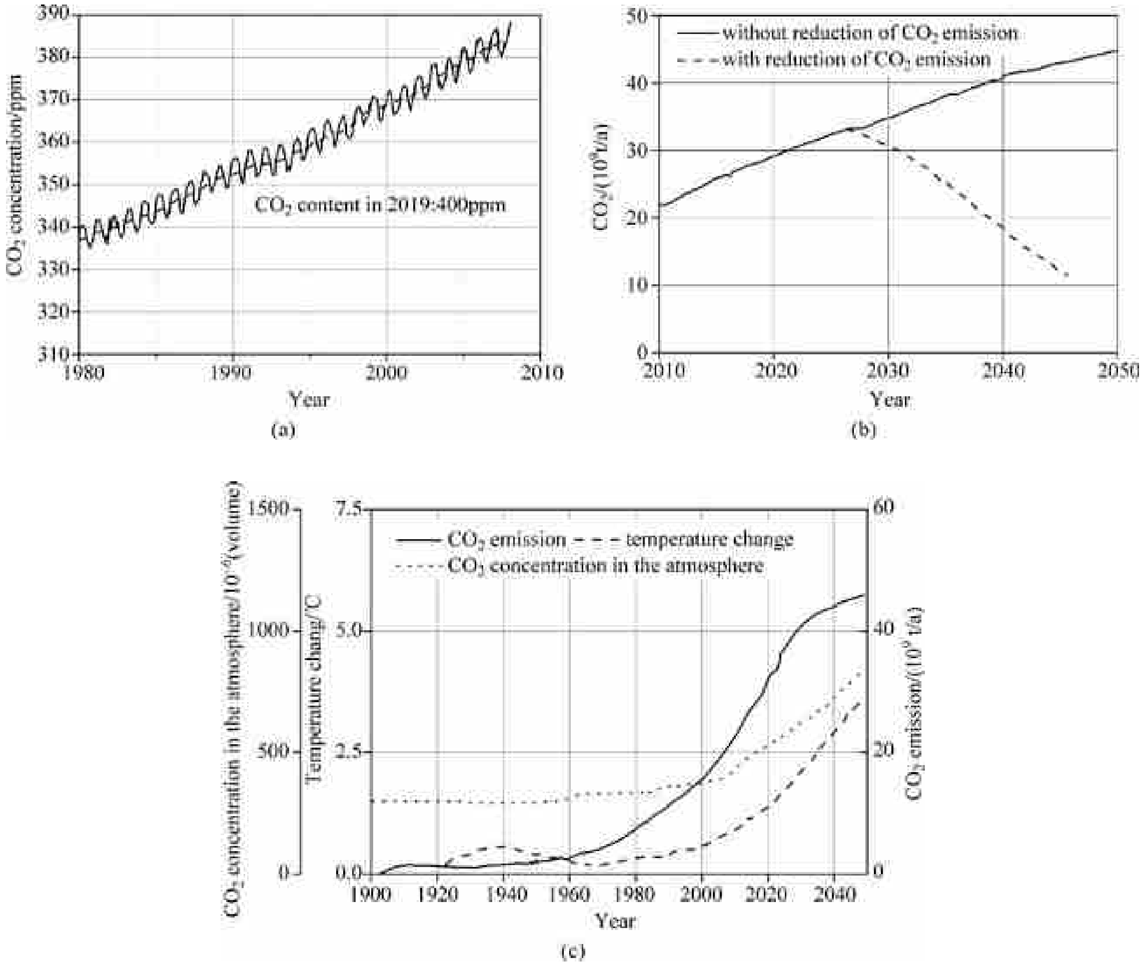


Figure 1.29 Aspects of necessary reduction of CO_2 emission to stabilize the climate[31-34]

(a) CO_2 concentration in the atmosphere[33]; (b) Necessary reduction of CO_2 to stabilize the CO_2-content of around 400mg/L in the atmosphere; (c) Rise of temperature as a consequence of content of CO_2 in the atmosphere

the atmosphere (γ). Applying some values like $\dot{M}_{CO_2} \approx 3\times 10^{10}$ t/a, $V \approx 10^9$ m^3 (assumption: distribution till 20km height in the air), one gets a slope of

$$\frac{dX_{CO_2}}{dt} \approx 2.5\times 10^{-6}/a \approx 2.5mg/L/a$$

A practical requirement resulting from the field of climate protection is to reduce the yearly CO_2 emission of the world energy economy. A value of around 15×10^{10}t CO_2/a or an average value of around 2 t CO_2/(person · a) in future seems to be a reasonable measure. Compared to the today situation worldwide, this includes very strong requirements for reduction in many industrialized countries. In some countries there is still some room to enlarge the specific emissions. For the world energy economy in totally this aspect of necessary reduction of CO_2 emission requires, that in 2040 already 70% of the primary energy must be produced CO_2-free. Figure 1.30 makes clear that this requirement would cause a total change of the structure of the world energy supply and the energy economy of countries like Germany.

This will be extremely difficult and expensive, because as example today Germany still depends to nearly 80% from fossil fuels.

The requirements to reduce specific CO_2 emission by saving energy and by substitution of fossil fuels by renewables or nuclear CO_2-free energy will be very important for countries, which today have still

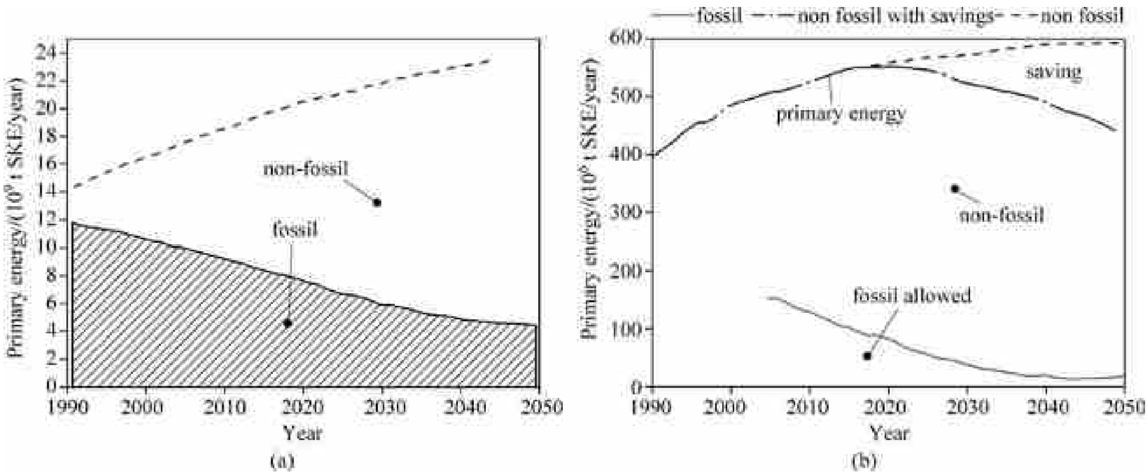


Figure 1.30 Allowed shares of fossil energy if the requirements of reduction of CO_2 emission to protect the climate shall be fulfilled

(a) Allowed fossil share of worldwide energy supply to limit CO_2 emission; (b) Allowed fossil share of energy supply in Germany to limit CO_2 emission

high values of specific emissions. USA, Canada, Russia and all European countries belong to this category.

The long term requirements for the energy economy are even more stringent, if the demands of the climate research shall be fulfilled. In Figure 1.28 (d) this was explained for the German situation. The energy economy has based until now mainly on the use of fossil fuels. Reaching a goal of as example 2 t CO_2/(person · a) means that just around 1.6×10^8 t CO_2/a will be allowed for emission. This is equivalent to 20% of the today usual values of yearly emission. Carbon containing energy carriers could just be used in the transportation sector and for chemicals, as example of plastics. In many countries the situation would be similar.

This strategy for the world energy economy causes immense efforts for systems of generation, transport, storage and rational use of energy. Renewables and nuclear energy must play an important role in the supply structures of the future to realize the goals and avoid large problems in the world because of shortage of energy supply.

The energy supply of the future has to be sustainable (Table 1.7). For the energy carriers this includes the following requirement.

Table 1.7 Aspects of sustainability

- Economic competitive
- Availability of fuel for very long time
- Safety of processes and waste management
- Application in all sectors of energy economy
- No misuse of materials (as example of fissile material)
- Realization of technologies worldwide
- Limitation of damaging consequences for the environment
- Guarantee of energy supply under all circumstances

So far as nuclear energy is considered, there is no doughty that it is and will be economically competitive in the future. However, nuclear technologies in the future must be realized with extreme high safety standards to be acceptable by people worldwide. In the sense of classification of accidents, severe accidents with high release rates of radioactive materials have to be avoided. This requirement will be valid not only for reactors, but also for all steps of waste management. More details are explained in Chapter 11. Because today the electricity production just covers around 30% of the energy market, nuclear energy must be made available for the energy economy in totally.

Special processes are necessary to reach this goal. Some processes are already fully developed as cogeneration, some are near the technical maturity, and some require still much work of development. The future application of nuclear energy for the non-electric market is the topic of nuclear process heat and will be discussed in this book in detail.

1.6 Aspects of nuclear energy for the future world energy economy

In totally for the future worldwide energy supply different options can be considered (Table 1.8). Partly they are solutions for all time, as solar energy, geothermal energy and nuclear fusion; partly they promise supply for some 100 till 1000 years, like nuclear fission systems.

Table 1.8 Options for a worldwide long duration energy supply

Option	Possible time duration	Status of development	Problems
Coal (expensive reserves include(d))	some 100 years	partly technical available	costs, CO_2 emissions, worldwide distribution
Oil (including oil sand/oil shale)	some 100 years	partly technical available	costs, CO_2 emissions, environment, worldwide distribution
Natural gas (off-shore include(d))	some 100 years	partly technical available	costs, CO_2 emissions, physical proof necessary
Nuclear fusion	solution for all time	not yet available	physical and technical realization, costs
Nuclear fission (poor Uranium ores, Thorium included, breeding)	some 1000 years	technical available	risks; environment; breeding + reprocessing necessary
Geothermal energy	solution for all time	partly technical available	costs; environment, worldwide distribution
Solar energy	solution for all time	technical available	costs; risks, partly environmental questions

The options have to be analyzed, compared and valuated under the following aspects:

- Availability of resources (physical);
- Availability of technologies (infrastructure);
- Safety of supply (physical and political);
- Safety during operation (extreme accidents exclude(d));
- Tolerable emissions (CO_2, radioactivity);
- Availability of acceptable final storage;
- Acceptable economical conditions (external costs include(d)).

There are some aspects, which characterize the importance of nuclear energy in general for the future of the world energy economy[35-39]. They are valuated as large advantages and until now support the worldwide activities to introduce this energy into the markets:

- A new energy carrier is available, which allows a very long time of use, if reprocessing and breeding are included. Inserting large amounts of poor ores worldwide, the time of use would be longer than 1000 years. Uranium gained from sea water today is not interesting at all from the economical standpoint. However it represents an option practical for all time (Table 1.9).
- The production cost of electricity and heat from nuclear power plants already today is lower compared to that on the basis of oil, coal or gas in many countries. This is true especially if large cost shares for transportation of fuel or electrical energy are included. It must be expected that

for future utilization, the additional costs for separation, transportation and final storage of CO_2 have to be added too. Then the economic advantages of nuclear energy become even larger.

Table 1.9 Resources and reserves of Uranium and ranges of the energy carrier[25]

Category	Reserves/(10^6 t)	Static range/years	Remark
Reserves of cost category<80 US$/kgU	3.8	54	Just 3%～5% of generation cost of electricity are caused by Uranium ore costs
Reserves of cost category between 80 and 130 US$/kg U	0.94	13	
Additional Uranium resources (more expensive til factor 5)	～20	280	Electricity generation costs become till 25% higher
Thorium resources	～20	280	Use in high converter reactors
Use of Uranium in breeder reactors	5～25	250～1000	Doubling of production cost of electricity; reprocessing is necessary
Uranium from sea water (<1000 US$/t U)	Practical unlimited	Practical unlimited	Generation costs of electricity are higher by a factor 3

- The production costs of electricity of nuclear plants are just weakly dependent from the price of uranium ore. Uranium, which is more expensive than that is used today, will stay economic attractive, because the price of uranium ore today causes just around 3%～5% of the total production costs of electricity.
- The costs of production of electricity from renewables (wind, solar, biomass) are relatively high too. The problems of storage and transport are not solved for this changing energy offer and this will cause additional high cost shares.

For the cost estimates, simple approximate equations can be applied. The last term covers the environmental damage or risks connected to the discussed energy technology:

$$X = X_{\text{capital}} + X_{\text{fuel}} + X_{\text{waste management}} + X_{\text{external}}$$

$$X = \frac{K_{\text{inv}} \cdot \bar{a}}{T} + \frac{K_{\text{fuel}}}{H_{\text{u}} \cdot \eta} + \sigma_{\text{WM}} \cdot K_{\text{WM}} + X_{\text{ext}}$$

The external costs today are not included in the usual cost estimations. In future however this will become necessary to allow reasonable comparisons.

The parameters in the simplified cost equations are defined as:

X——production costs of electricity;

K_{inv}——specific investment costs;

$\bar{a}$——capital factor (including depreciation, interest, insurance, taxes, operation);

T——hours of full power operation;

K_{fuel}——fuel costs;

H_{u}——heating value (or burn up);

η——efficiency;

σ_{WM}——specific number for waste production;

K_{WM}——specific waste management costs;

X_{ext}——external costs.

The following Table 1.10 gives an overview on some cost data, which could be relevant in western Europe countries. Furthermore some data are added for expected developments.

Table 1.10 Production costs of electricity (status 2010, German conditions)

Technology	Price of raw material	Production costs today/ [ct/(kW·h_{el})]	Production costs (future*)/ [ct/(kW·h_{el})]	Remark
Oil fired power plant	500 $ /t	10~15	till 17	CO_2-penalty included (future)
Coal fired power plants	100 $ /t	5~10	till 12	CO_2-penalty included (future)
Natural gas GUD-plant	400 $ /t	8~10	till 12	CO_2-penalty included (future)
Nuclear power plant	30 $ /lb U_3O_8	4~8	till 10	improved waste management included (future+)
Wind		6~15	10~15	on shore/off shore
Solar		20~40	15~20	without storage
Biomass		10~20	till 25	storage possible

* including estimated costs for CO_2-waste management; + including additional efforts for waste management for radioactive isotopes (example: partitioning).

Some more data characterizing the different technologies of power production are contained in Chapter 15. Data of costs of fuel supply or waste management are changing during the operation time of plants over 3 to 6 decades. Figure 1.31 (a) shows as example changes of prices of Uranium in the last years. These changes did not influence the production costs of electricity too much, as already explained. The consequences are more important for fossil fuels. Figure 1.31 (b) contains changes for oil, gas and coal. Especially the oil price showed very large change in the last years. This influenced the development and introduction of new technologies drastically. As example the development of nuclear process heat was financed by the state government in Germany with large amounts of money during the eighties because of the high prices of oil and natural gas to that time. In the last years the oil price has rised up again and the expectation is that this tendency will continue. New developments to realize plants with higher efficiencies and to realize new energy concepts become again interesting.

The situation of competition between different power plants and their economic conditions naturally depends from the country. Even today new light water reactors offer economic advantage compared to plants based on fossil fuels. In the mean time, the world market price of fossil fuels has risen up and this influences the economic conditions clearly.

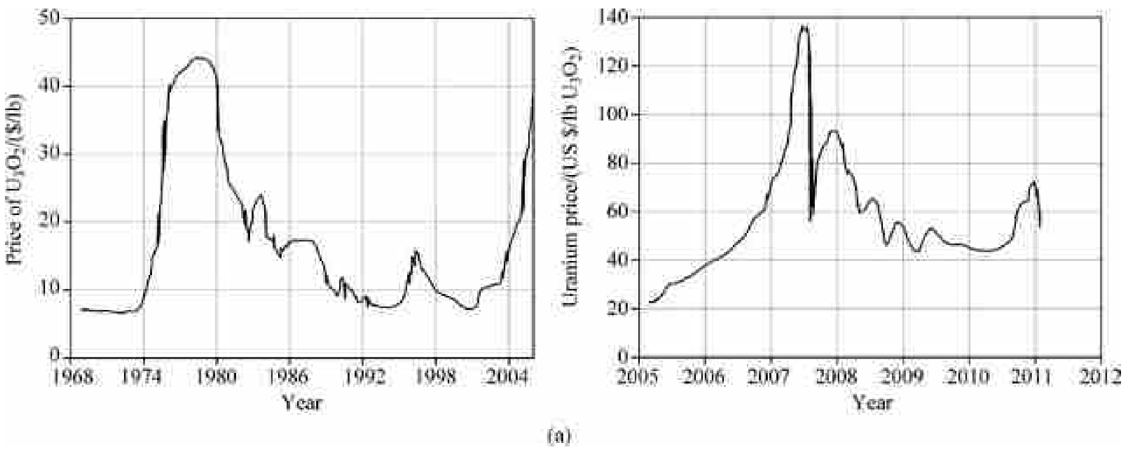


Figure 1.31 Changes of energy prices in the past[40]

(a) Development of Uranium ore prices between 1968 and 2011 ($ /bbl)[40]; (b) Development of prices of fossil fuel in the last decdes (example: conditions for the German energy market)[41]; (c) Development of oil price in the last years

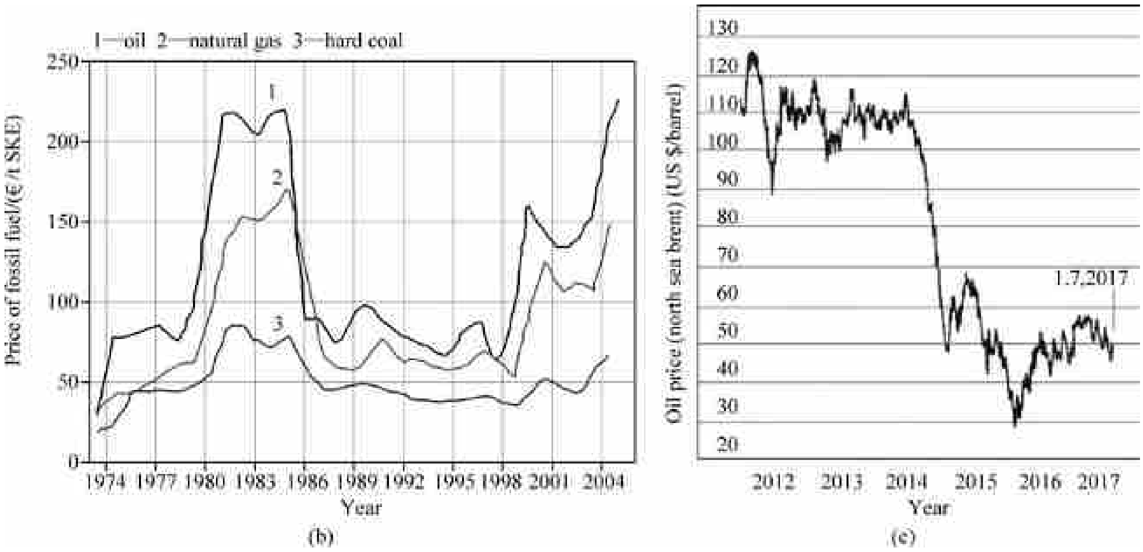
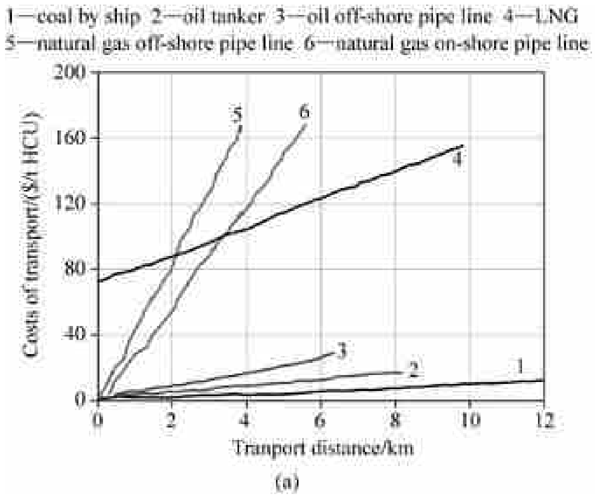


Figure 1.31 (Continued)

The influences of transport distances on cost structures (Figure 1.32(a)) have to be considered too, and it can be stated that natural gas and LNG cause much higher transport costs than coal and oil. The transport of coal by ship is relatively cheap compared to the transport costs by railways or cars on streets. The transport costs for Uranium can be practically neglected.

The production cost of electrical energy forms just one minor share in the price for electrical energy, which has to be payed by the consumer. Further shares are caused by transport, distribution and taxes. Figure 1.32(b) shows the conditions in Germany, as example for an average cost value of production of around 10ct/kW · h_{el}. The final price is nearly three times higher for the private consumer.



Share of costs	Characteristicvalue/ (ct/kW·h_{el})
Production (average)	10
Transport	6
Distribution	5
Taxes	10
Total	31

(b)

Figure 1.32 Aspects of total costs of energy supply

(a) Costs of energy transport for different energy carriers dependent from transport distance (t HCU = t hard coal unit); (b) Shares of total costs for electricity supply (example: Germany, private consumers)

In the future external costs have to be added to the normal production costs of energy. These additional costs either result from the valuation of damages in the environment, which really occur like by SO_2, NO_x, dust or heavy metals. On the other hand costs are valuated, which could result from severe accidents as example.

In case of today introduced light water reactors, these are usually costs which could be caused by the consequences of severe core melt accidents. In case of use of fossil fuels, these are costs of waste management to separate, transport and store carbon dioxide, if these processes are carried out. Alternatively costs for changes of climate and consequences have to be defined.

The term $X_{externl}$, which was contained in the equation given before covers for example the risks from severe nuclear accidents applying nuclear energy and can be expressed in the form

$$X_{external} = D \cdot P_D / (P_{el} \cdot T)$$

D is the damage expressed in money, P_D is the probability that the damage occurs. The waste management in case of fossil fueled plants can be valuated in similar form. For the sequestration of CO_2 one can write

$$X_{external} = \mu \cdot K_{CO_2}$$

This term describes additional costs, which are caused by separation, transport and final storage of CO_2. They could be added to the fuel costs or can be included in the product costs in future.

For a detailed comparison and valuation of the different systems of electricity supply, one has to find an optimum for the sum of production costs and external costs. The transportation and storage costs have to be included too. Figure 1.33 (a) indicates tendencies in qualitative form, if the effort for safety is chosen as variable.

Tendencies of changing energy prices and new requirements have to be included in life cycle cost analysis and are especially important if renewable energy systems are compared to those based on fossil or nuclear fuels. Figure 1.33(b) shows the principal aspects of this comparison. The time dependence of production cost of fossil plant is relatively strong. Nuclear plants are only weak dependent from ore costs. The costs of renewable systems will stay nearly constant over the whole operation time. These differences between nuclear and fossil heat generation as well as renewables favor the application of nuclear energy very much.

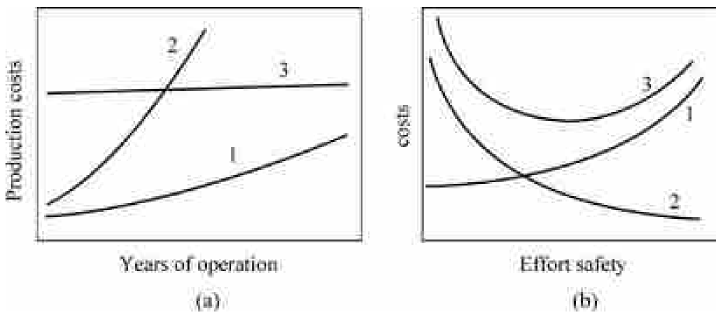


Figure 1.33 Aspects of costs of electricity production (qualitative figures, including storage)

(a) Development of production costs of electrical energy during the whole operation time of fossil, nuclear power plants and renewable plants

1—nuclear; 2—fossil; 3—renewable (qualitative explanation)

(b) Optimization between production costs and external costs

1—production cost; 2—external cost; 3—total cost

The possibility to store fuel and to realize some independency from changes of market conditions and energy prices is given in case of application of nuclear technologies. In Figure 1.34 a coal fired power plant and a today introduced light water reactor are compared regarding this question. The difference of masses on the side of supply and waste management is extremely large.

From the standpoint of technology and economy for coal and natural gas power plants, a storage of fuel would be practically impossible over a very long time period. For nuclear power plants, the fuel for some years could be stored and later used. The financial effort would be small in comparison to the fossil fuelled alternatives.

- Especially the final storage of CO_2 as well as the transport from the plant to the storage are very

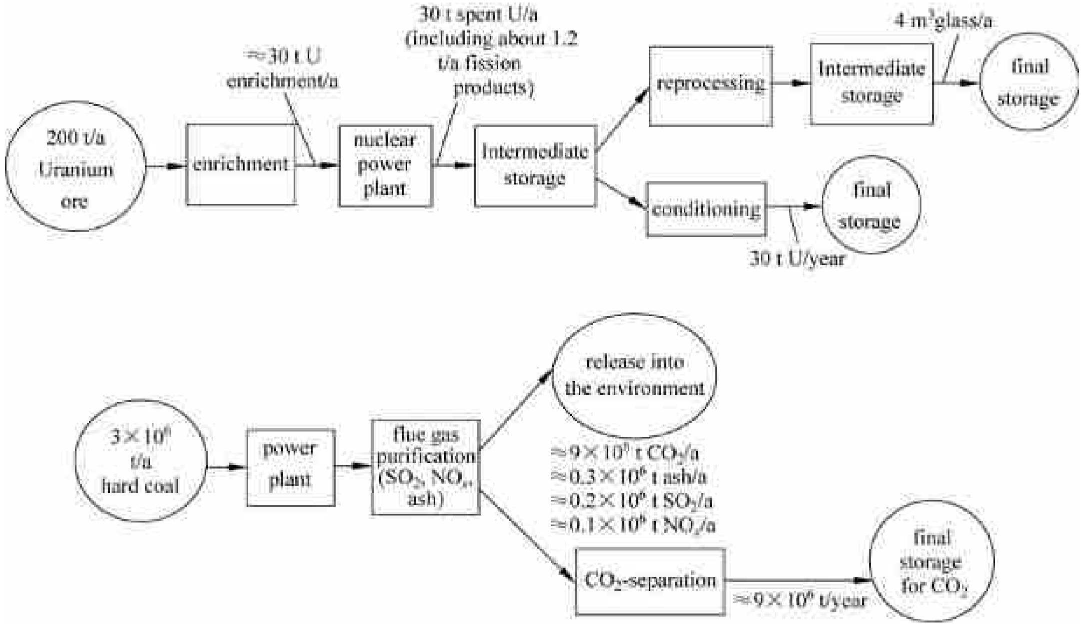


Figure 1.34 Comparison of masses of supply and emissions in case of coal fired power plant (P_{el} = 1300MW, τ = 8000h/a) and nuclear power plant (LWR, P_{el} = 1300MW, τ = 8000h/a)

problematic because of the large masses per year and the necessary volume. It should be mentioned here that the storage of 1t CO_2 in deep underground cavities needs a volume of around $2m^3$ (at a temperature of 30℃ and a pressure of 75bar).

- For many countries the siting of power plants causes problems, especially if the distance for transportation of fuel from the source to the plant is large. Figure 1.35 shows one example for energy transport over very long distances: this is a gas fired power plant in Western Europe supplied by gas from Russia.

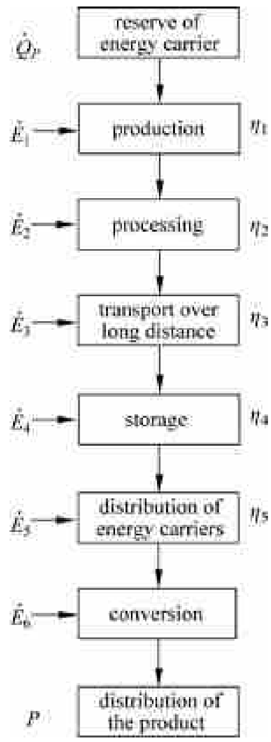


Figure 1.35 Aspects of siting of fossil power plants relative to the sources of primary energy

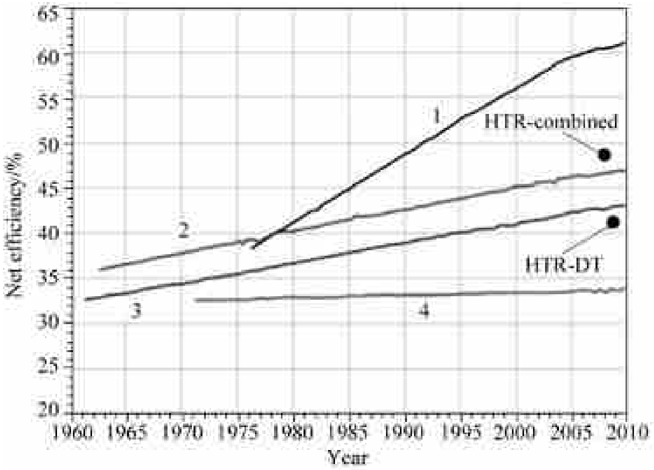
Chain of energy transport

- Large transportation distances for energy carriers have to be overcome. Large distances cause high investment costs for the infrastructure and therefore high transportation costs. In case of nuclear power plants, the masses which must be transported are very small and sites for plants can be selected corresponding to the needs of the consumers. Furthermore for cases of large transportation distances, the necessary energetic input has to be considered. In some cases, release of other climate relevant gases like CH_4 can play a role. As example production and transport of natural gas from Siberia in Russia to Western Europe and China can cause additional emissions of greenhouse gases, which are much more relevant for changes of climate than CO_2 (factor more than 20 for CH_4 compared to CO_2). For the use factor of primary energy one gets for the total chain:

$$\eta = P / \dot{Q}_P = \prod_{i=1}^{6} \eta_i$$

This factor depends clearly on the conditions of energy transport and conversions in the different stages of this chain.

- Further important parameters connected with the choice of the site of a power plant are the possibility of cooling and the standards of safety. The use of dry air cooling towers or the application of cogeneration as example with HTR promises advantages regarding the question of cooling. Choosing a site near the consumers of electricity or heat extreme requirements of safety have to be fulfilled. New concepts with a maximum of features of inherent safety favor this possibility of siting. In Western Europe, as example partly the transportation costs for electricity are higher than the generation costs of nuclear power plants.
- High temperature reactors open the field to apply improved processes to produce electrical energy (Figure 1.36).



(a)

Technology	Characteristic efficiencies η/%
LWR	33~34
Hard coal	40~45
Hard coal*	35~40
Lignite	38~43
Lignite*	30~33
Open gas turbine	35~38
Combined cycle (GT)	58~60
Combined cycle (GT)*	54~56

(b)

Figure 1.36 Development of efficiencies of power plants during the last decades (example: Germany) (HTR-DT: stream turbine application; HTR-comb: combined cycle)

1—natural gas with combined cycle; 2—hard coal with steam cycle; 3—lignite with steam cycle; 4—nuclear energy with LWR; HTR-combined: HTR with combined cycle; HTR-DT: HTR with steam cycle; *: with CO_2-waste management

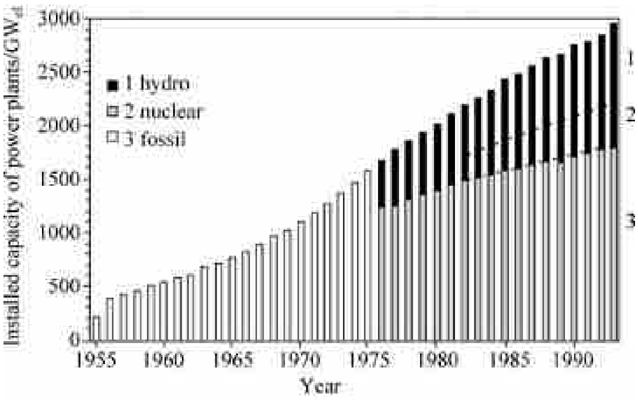
As is well known the efficiency of the mostly applied light water reactors is around 33%. Higher efficiencies enable a better use of fuel and reduce the amount of high level waste relatively to the produced electrical energy. Special solutions for the HTR can allow to apply combined cycles in the future (see Chapter 3).

- The development of nuclear technology was accompanied with large progress in the field of many technologies, which have accelerated developments and progress in other branches very much.

Especially procedures of quality management and safety valuation were applied in quite different branches. Characteristic examples, which used progress with very good success were technologies of process engineering or the production and operation of air planes.

1.7 Nuclear energy for the market of electrical energy

The installation of nuclear power plants worldwide and thereby the introduction into the market has happened relatively fast in the first decades. Just in the years since 1986 (accident in Chernobyl/UdSSR), the development of nuclear capacities was slowed down, because the acceptance of this new technology by the population became smaller in some countries, as example in Europe. Furthermore the economic conditions compared to other primary energy carriers like natural gas have changed partly in several regions of the world. Actually (2017) the growing rate of nuclear capacities worldwide is in the order of 1%/year. Figure 1.37 shows the development of capacities in the last decades.



(a)

Year	Total installed power/GW$_{el}$	Installed nuclear power/GW$_{el}$
2000	3200	350
2005	3400	370
2010	3600	375
2015	3800	390
2017	4000	394
2019	5000	402

(b)

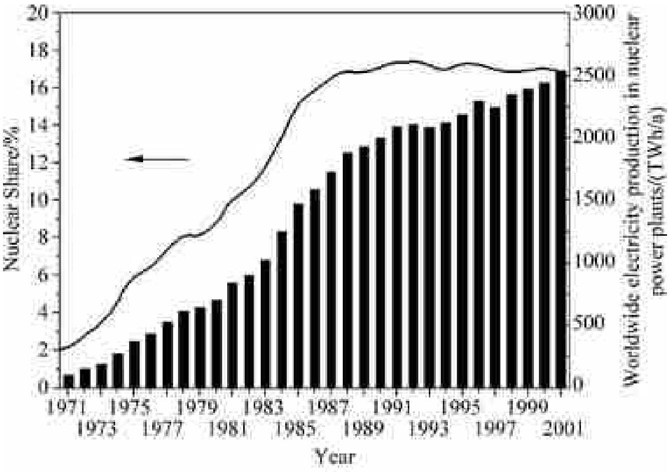
Figure 1.37 Total worldwide installed capacity of power plants for electricity production[40]

(a) Development till 1994; (b) Development from 2000 to 2021

Corresponding to the data in Figure 1.37 today for 7.8×10^9 people in the world a capacity of around 5000GW$_{el}$ is installed. Naturally the numbers for capacities will contain some uncertainties in several countries.

Nearly 8% of the capacities are nuclear power reactors in the today established world energy economy.

In 2019, 456 large nuclear power plants with a total capacity of 400GW$_{el}$ were installed and in operation. Furthermore 60 new plants are in construction. The nuclear power plants produced around 2500TW · h$_{el}$/a in 2019. This corresponded to a share of nearly 11% of the total worldwide production of electrical energy. Figure 1.38 shows the development of the production of electrical energy in nuclear power plants in the past and the share of nuclear energy on the total worldwide production. The reduction of share of nuclear energy in the last decade is caused by the rapid enlargement of power plants based on coal, natural gas and the addition of large capacities of renewable energy carriers in many countries in the world.



(a)

Year	Total production of electrical energy/(TW·h$_{el}$/a)	Nuclear production of eleterical energy/(TW·h$_{el}$/a)
2000	15 000	2407
2005	17 000	2640
2010	19 000	2725
2015	22 500	2330
2019	27 000	2660

(b)

Figure 1.38 Development of the world wide electricity production in nuclear power plants[40]

(a) Production and nuclear have till the year 2001; (b) Development from 2000 to 2018

The reduction of production of the year 2010 was caused by reactions on the accident in Fukushima (2011). In Japan as example nuclear power reactors were out of operation for sometime, in Germany 7 nuclear power reactors were taken out of operation finally.

In some countries the dependence from nuclear energy is already very strong as indicated in Table 1.11.

Table 1.11 Importance of nuclear energy in some countries (2013)[6]

Country	Installed nuclear capacity/GW	Total production of electricity/(TW · h/a)	Share of nuclear energy/%
France	66	570	78
Russia	25	1046	18
China	13	5300	2.5
USA	106	4300	19
Japan	46	1015	18
Germany*	12	610	20
India	6	1770	5
World	392	22 000	13

* after the accident in Fukushima in Germany the nuclear power was reduced from about 20GW$_{el}$ to 12GW$_{el}$.

Especially France is nearly totally dependent on nuclear energy, because more than 75% are produced by this energy carrier. The dependence from nuclear energy today is rising up in some countries like China, India and Russia. Furthermore many old nuclear power plants in different countries need revival. Partly the lifetime of existing power plants is extended. In some countries operation times of 60 years have been licensed. In other counties, like Germany, the lifetime of nuclear power plants was limited under the influences of the catastrophic accident in Fukushima/Japan in 2011. Worldwide there is the expectation that the capacity of nuclear power plants could be doubled in the next two decades.

There are some aspects, which are disadvantageous connected with the use and further introduction of nuclear energy or which require progress in the future.

- A suited infrastructure containing competent construction companies, licensing bodies, advisers, governmental organizations and operating companies has to be available or established. This is still difficult today in some countries. Especially the independence of supervision and licensing is an important boundary condition to realize high safety standards.
- Release rates of radioactive substances in normal operation have to be limited. This requires high efforts. However much progress was possible in the past (Figure 1.39). The release values normally reached just some percent of the licensed limits. Further improvements in the future are possible. From the technical standpoint an even more effective retention would be possible.

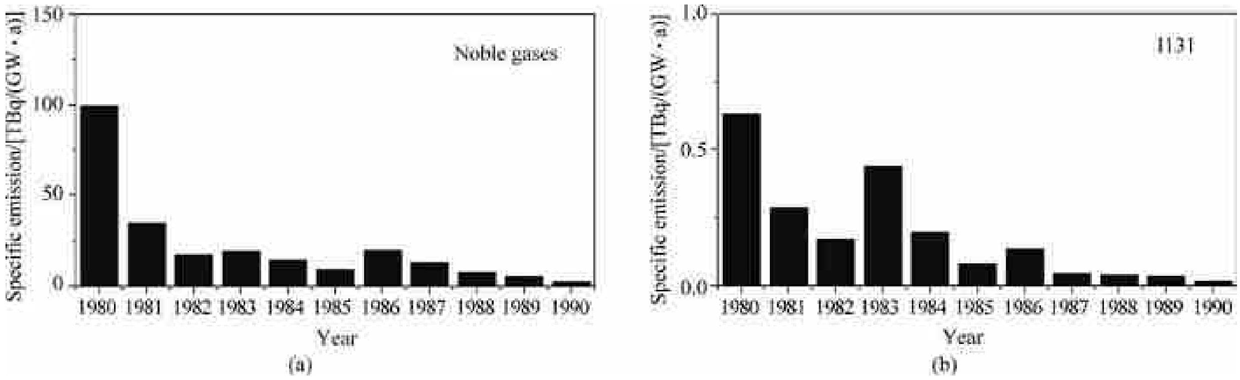


Figure 1.39 Reduction of emissions (related to electricity production) during normal operation from nuclear power plants(example: LWR in Germany; release via stack)[41]
(a) Noble gases; (b) I131

This aspect needs optimization of the effort (Figure 1.40 (a)). In any case the share of nuclear power plants on the radiological burden of population caused by emissions during normal operation, is small compared to other sources as shown here for the example of Germany (Figure 1.40(b)).

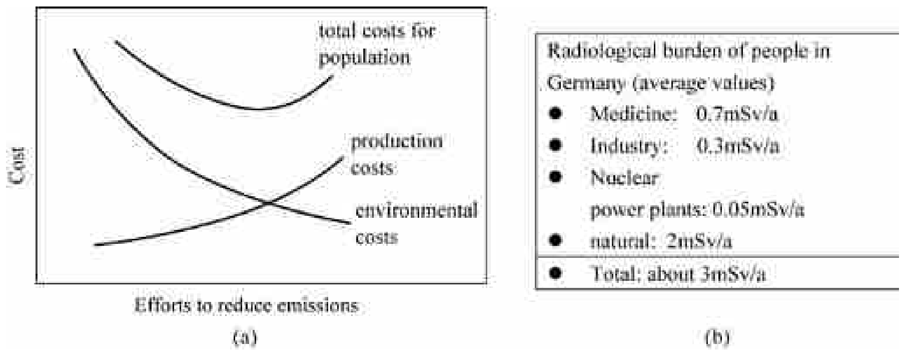


Figure 1.40 Aspects of plant design regarding optimization of efforts to reduce emissions of radioactive substance during normal operation
(a) Consideration on efforts to reduce emissions during normal operation; (b) Shares of radiological burden of population (example: Germany)

- In future nuclear power plants severe accidents with the release of large amounts of radioactive substances have to be excluded. Events like in Chernobyl (Figure 1.41) or in Fukushima (Figure 1.42) must be avoided by a suitable design of the plants. Especially the long time contamination of land must be ruled out.
- As the measurements show, in the neighborhood of Chernobyl even today after more than three decades since the accident has happened, nearly 10 000km^2 are very highly contaminated and people had to be resettled from these areas. In larger distances further areas of more than 50 000km^2 are still contaminated with isotopes in such height, that special limitations for food

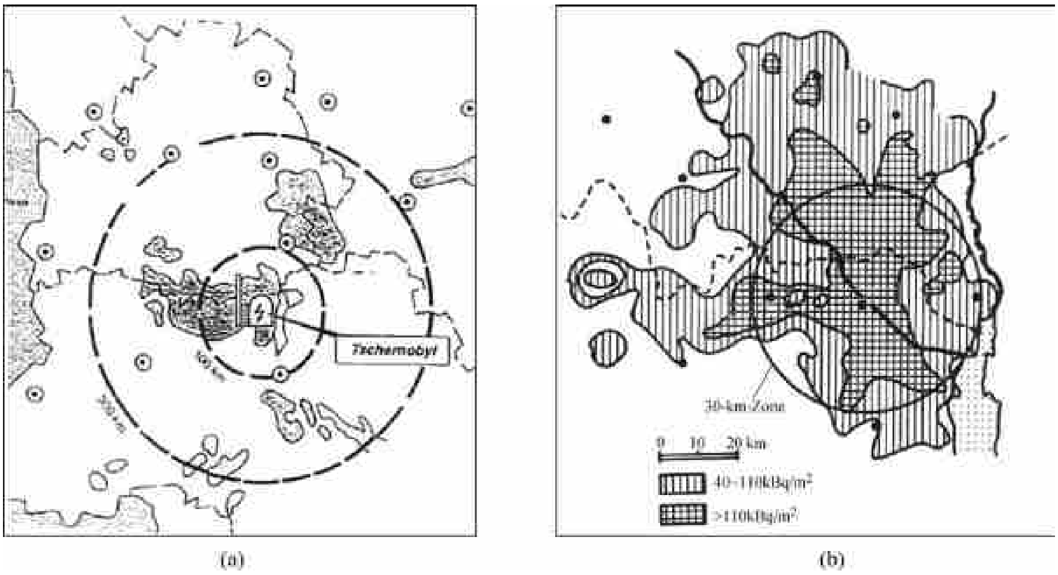


Figure 1.41 Contamination of land after the catastrophic accident in Chernobyl (UdSSR, 1986)[42]

(a) Ce 137; (b) St 90

and drinking water are necessary. After the accident in Fukushima, similar sizes of areas had to be evacuated to protect the population. Decontamination is necessary in an area of more than 10 000km. However, no early fatalities occurred because the population has been evacuated directly after the accident.

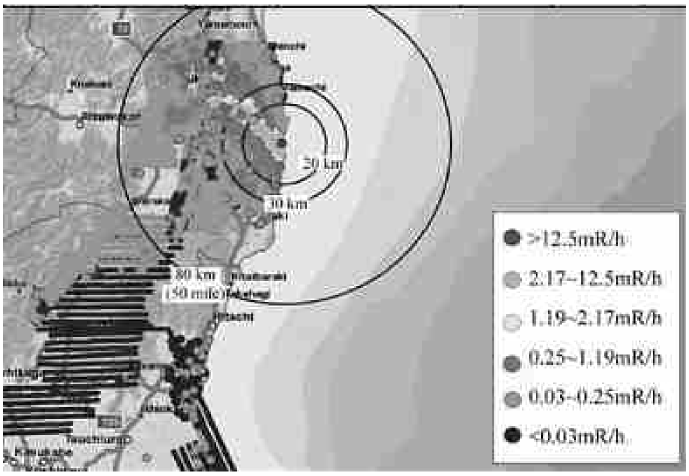


Figure 1.42 Contamination of land after the catastrophic accident in Fukushima (Japan, 2011)[43]

- Activity and decay heat stay relevant for radioactive waste for a very long time (Figure 1.43). The final waste disposal must be realized without the danger of large release from these deposits. In case of reprocessing, the amounts of masses which have to be brought to the final storage are very small ($4m^3$ glass/year for a LWR plant with a power of $1300MW_{el}$).

The release of fission products from final storage systems has been analyzed for the relevant geological systems in different countries. The accident, which was assumed in all these cases, is the massive ingress of water. Over a long time by the corrosive attack of water, thick walled storage vessels for spent fuel elements will be damaged. Finally fission products can be leached out from the fuel and transported from the storage region through different layers of covering rock and soil structures. On the surface of the earth then doses for people can occur. Figure 1.44(a) shows results for different materials in many countries, which consider the direct final storage of spent fuel elements. Similar considerations and estimations were carried out for the storage of glass coquilles from reprocessing(Figure 1.44(b)).

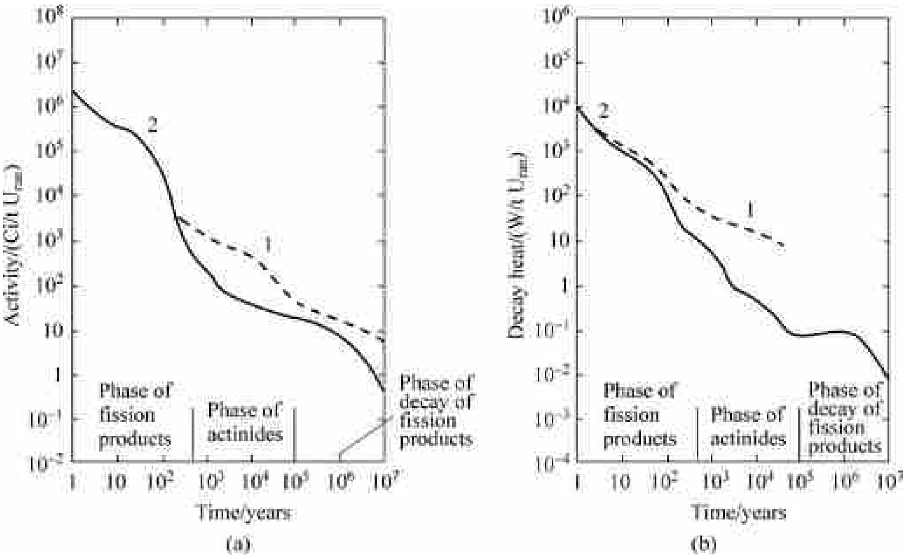


Figure 1.43 Conditions of radioactive waste during intermediate and final storage

(a) Activity dependent from time; (b) Decay heat dependent from time

1—spent fuel elements; 2—glass coquilles after reprocessing[44]

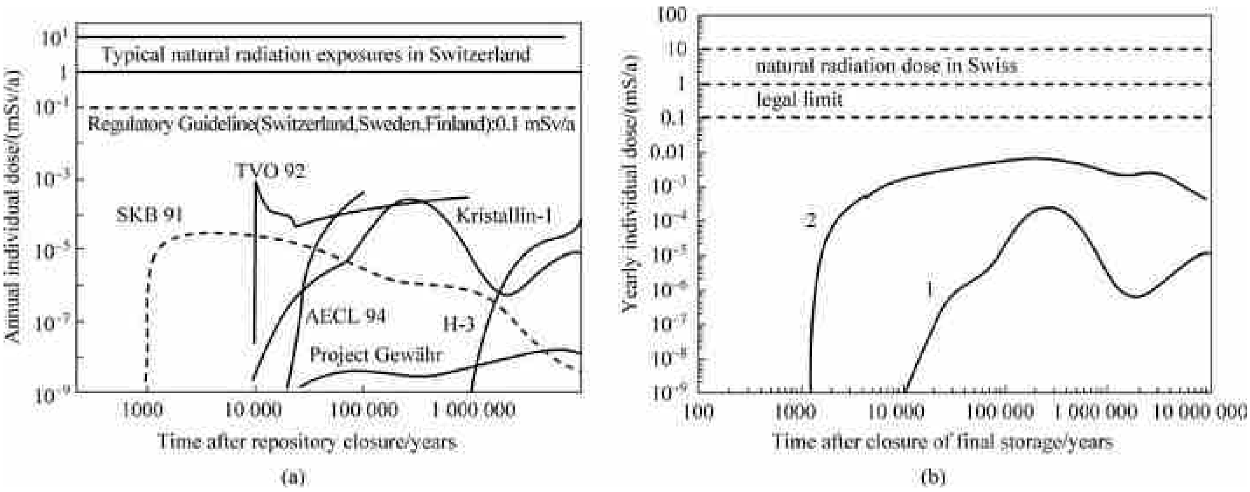


Figure 1.44 Expected radiological burden from radioactive waste[45-46]

(a) Direct final storage of spent fuel elements (SKB91 (Sweden); TVO92 (Finland); AECL 94 (Canada); H-3 (Japan); Kristallin-1 (Switzerland); Project Gewähr (Switzerland)); (b) Final storage of glass coquilles loaded with fission products and small amounts of Plutonium and minor actinides

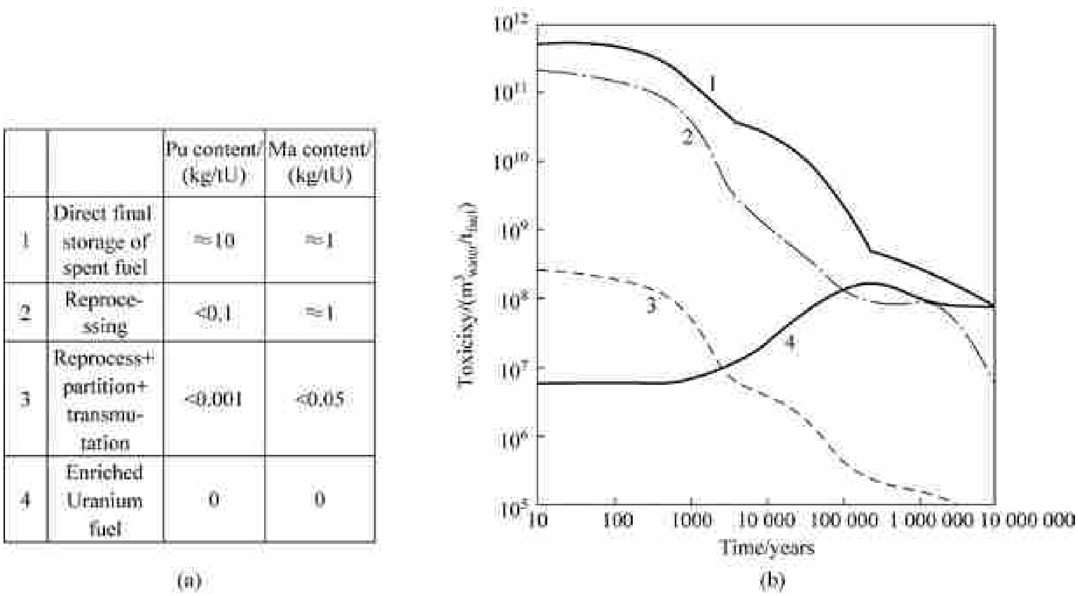
1—storage of glass coquilles; 2—accident: massive water ingress(a factor 100 higher than normal)

Analyses of accident in final storage systems show that the doses for the population are much smaller than limits set by the regulation authorities (example: Swiss).

The risks from power plants are significant higher than that from processes in the fuel cycle. Further improvements are possible by partitioning and transmutation (Figure 1.45). This figure explains that in case of final storage of glass coquilles, a section with the radiotoxicity of the Uranium, which was inserted to produce the waste, occurs after around 50 000years. If partition and transmutation are added in future, the section will be after around 1000 years.

Similar tendencies of curves as in Figure 1.45(b) are obtained, if the radiotoxicity is expressed in $Sv/(GW_{el} \cdot a)$, i.e. related to the produced electrical energy.

It becomes clear that in case 1, the direct final storage of spent fuel elements, the section of the curve with that of the Uranium just happens after around 10^7 years. The reason is the high content of Plutonium and minor actinides in the final storage. If the normal reprocessing is carried out, the



		Pu content/(kg/tU)	Ma content/(kg/tU)
1	Direct final storage of spent fuel	≈10	≈1
2	Reprocessing	<0.1	≈1
3	Reprocess+ partition+ transmutation	<0.001	<0.05
4	Enriched Uranium fuel	0	0

Figure 1.45 Toxicity of radioactive waste (PWR, burn up: 35GWd/t)

(a) Characteristics for three different waste management strategies (curve 4: toxicity of 1t enriched Uranium (3.4% U235, 0.24% U234));

(b) Toxicity of waste dependent from storage time (expressed by the necessary volume of water per ton of heavy metal to realize free limits)

Plutonium is already reduced by a factor larger than 100, however the minor actinides stay in the waste. Therefore the section occurs behind a time of 50 000 years. Just if by additional processes of partitioning and transmutation the Plutonium content and the mass of minor actinides in the waste are reduced, the section of the curve with the original inserted fuel is at a time of around 1000 till 2000 years after the start of the phase of final storage. Further progress of waste processing is possible.

The non-proliferation of fissile material has to be guaranteed worldwide. This requires strong international control of inventories and mass flows of those materials. Maybe one needs a control system for highly radioactive materials in the future too, to avoid misuse, as example by terroristic attack.

Summarizing aspects that have been discussed before, some general statements can be made, which are convincing arguments for the worldwide ongoing activities to make nuclear energy to a long term important source for the energy supply in the future (Table 1.12).

Table 1.12 Aspects which favor the introduction of nuclear energy

- Nuclear energy is an additional energy source for worldwide use
- Production costs of nuclear energy today already are lower than those of the most competing energy carriers
- In future with rising energy costs nuclear energy is only very weak dependent from rising costs of Uranium ore; this is quite different compared to plants using fossil fuel
- Use of nuclear energy allows to store raw-materials for a long time
- The fossil resources and reserves are spared by the introduction of nuclear energy
- High converters and breeding systems make nuclear energy an option of more than 1000 years
- Principally the final deposit of nuclear waste is much easier than that of CO_2; the amount of mass is smaller by a factor of 10^6; fission products decay, CO_2 stays for all time
- The realization of nuclear plants is possible in aride areas because of efficient use of air cooling towers
- Small plants can be realized to apply cogeneration processes near areas of consumption
- Process heat applications allow the reduction of CO_2 emission
- High temperature process heat applications open a totally new market for nuclear energy
- The use of nuclear energy enables a higher degree of safety of energy supply
- The development of nuclear technologies accelerates technological developments in other fields too

It will be necessary to carry out a successful development of the processes, which are explained in the next chapters. A main precondition to realize these advantages is a convincing safety concept, which is proven and accepted by the public.

1.8 Some aspects regarding the application of nuclear energy in the non-electric energy market

Until now nuclear energy mainly has been applied to produce electrical energy. However, it is well known that electrical energy just covers a smaller share of the energy market. The structure of the energy market in an industrialized country is shown in Figure 1.46.

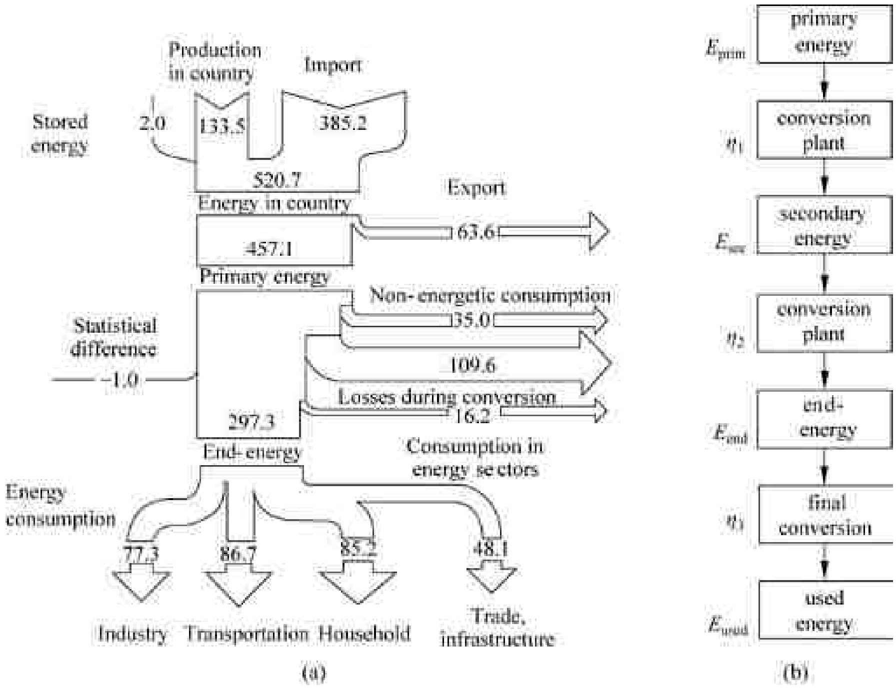


Figure 1.46 Energy conversion in the energy economy of a country

(a) Energy balance of an industrialized country (example: Germany, 2010; numbers in t HCU; primary energy: 5.207×10^8 t HCU/a; secondary energy: 2.973×10^8 t HCU/a)[47]; (b) Chain of energy conversion

With regard to the figure shown before, one can state that the end-energy is used in industry for household, trade and transportation. Starting from the primary energy (100%) around 57% are available as end energy for the supply in these different sectors of energy economy. The difference between primary energy and end-energy is caused by conversion and transportation in different stages of the total chain. A total efficiency of the chain can be defined by the relation

$$\eta_{tot} = \frac{E_{end}}{E_{prim}} = \prod_i \eta_i = \eta_1 \cdot \eta_2 \cdot \eta_3$$

Partly chains of energy conversion occur with more stages and values for η_i.

Losses for conversion from primary energy into secondary energy occur in refineries, power plants, coking processes, during the use as raw material for production processes. The end-energy is used in the different sectors, applying specific process efficiencies. The shares for the different sectors shown here are relevant for an industrialized country like Germany (2010):

- Industry (26%);
- Transportation (29.2%);
- Household (28.6%);

• Trade, commerce, infrastructure (16.2%)。

The energy supply of countries can change strongly during time, as indicated in Figure 1.47 for the energy economy of Germany. A major change was caused by the penetration of oil and natural gas into the market since 1960. Nuclear energy started to play a role after 1980. A special change happened in the energy economy after 1990, as the reunion of western and eastern Germany took place. The importance of lignite, which was mainly relevant for eastern Germany, was reduced because of environmental aspects. Renewable energy started to become important after 1995 because of large subventions.

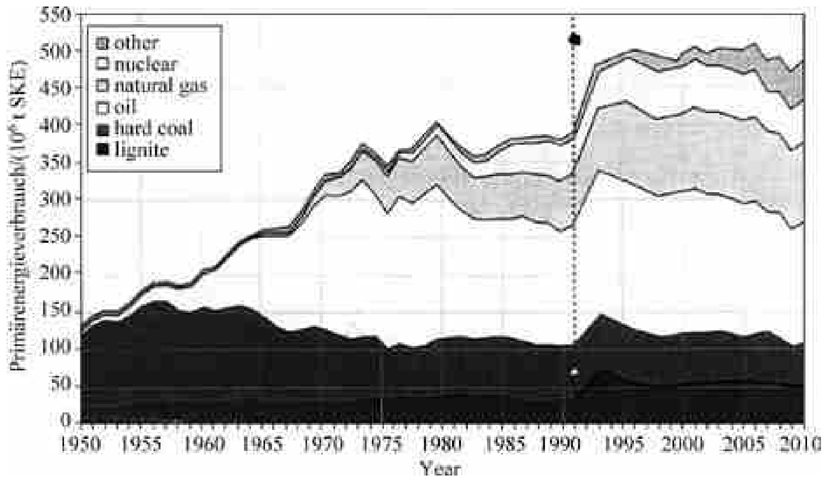


Figure 1.47 Development of the energy economy and change of importance of primary energy carriers (example: Germany)[47]
● includes the countries of former German Democratic Republic (DDR)

A characteristic distribution of different types of end-energy carriers (oil products, gases, electrical energy, liquid fuels, district heat) is given in Figure 1. 48. This distribution is the basis for considerations on application of nuclear process heat. During the use of the secondary energy in the different sectors, further losses occur and partly just a small part of the original applied primary energy is used as the final energy requirement.

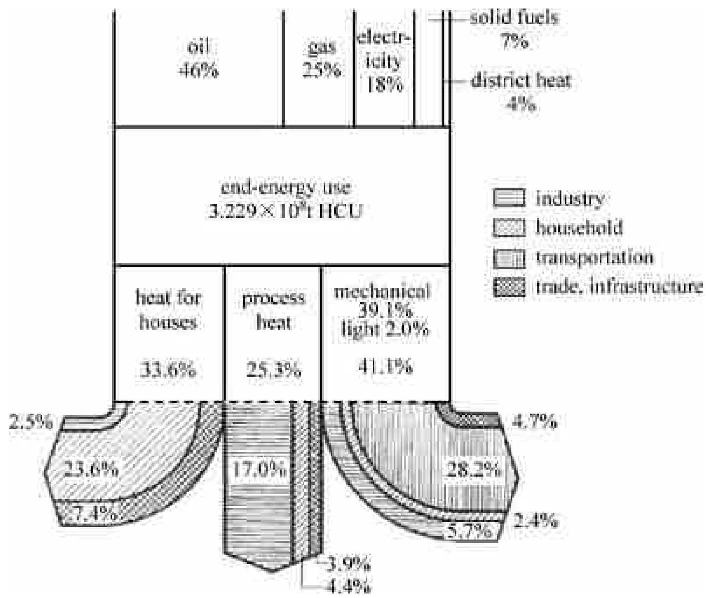


Figure 1.48 Structure of the end-energy consumption in an industrialized country (example: Germany, 1998)[47]

The market for heat and transportation energy is large, and therefore many considerations were carried out to apply nuclear energy in this sectors too[28-33]. Some examples of delivery of heat from nuclear reactors, which are still in operation or have been in operation, are contained in Table 1.13. These were mainly low temperature process heat applications. The plants had to follow special licensing processes and had to fulfill high safety requirements.

Table 1.13 Some example of application of nuclear process heat[35]

Name of plant	Country	Type of reactor	Power of plant/MW_{el}	Power of process heat delivery/MW_{th}	Start of delivery	Remark*
Calder Hall	Großbritannien	Magnox	4×4	15(75)•	1956—1959	
St. Petersburg	Russia	LWGR	40×1000	4×80	1973/1976,1979/1981	
Biliblno	Russia	LWGR	4×12	4×29	1974—1976	
Kola	Russia	PWR	4×440	146(46)	1973—1985	
Südukraine	Ukraine	PWR	2×1000	446(102)	1983/1985	
Saporosche	Ukraine	PWR	2×1000	1165(104)	1985/1986	
Schewtschenko	Kasachstan	FBR	⩽150	⩽300*	1973	Desalination
Kosloduy	Bulgariay	PWR	4×440	230	1974—1989	
Bonunice	Slowakei	PWR	4×440	240(90)	1979—1985 (1986)	
Paks	Ungary	PWR	4×440	55(43)	1983—1987 (1977)	
Bruce A	Canada	CANDU	4×904	350(813)	1976—1978 (1978/1988)	
Beznau	Swiss	PWR	2×364	80(50)	1979 (1979)	Steam for industry
Gösgen	Swiss	PWR	970	54(24)	1972 (1983)	Steam for industry
Stade	Germany	PWR	672	40(40)		Steam for industry

* mainly district heat; • in parenthesis: till 1990 realized power; LWGR: RBMK-plants; FBR: fast breeder reactor.

In Germany, additionally there was a project to deliver process steam and electricity in a large chemical complex by two pressurized water reactors with large power (2000MW_{th} each). These plans, which have been worked out in detail were not realized because the license process in a dense populated area became very difficult. As example a burst protection for the primary enclosure was required. It was planned in detail.

The energy demand of the different sectors sets special conditions: in the transportation sector, liquid fuel is still dominant; in the household sector mainly low temperature heat is necessary; and in the industry, heat on different temperature levels is applied (Figure 1.49).

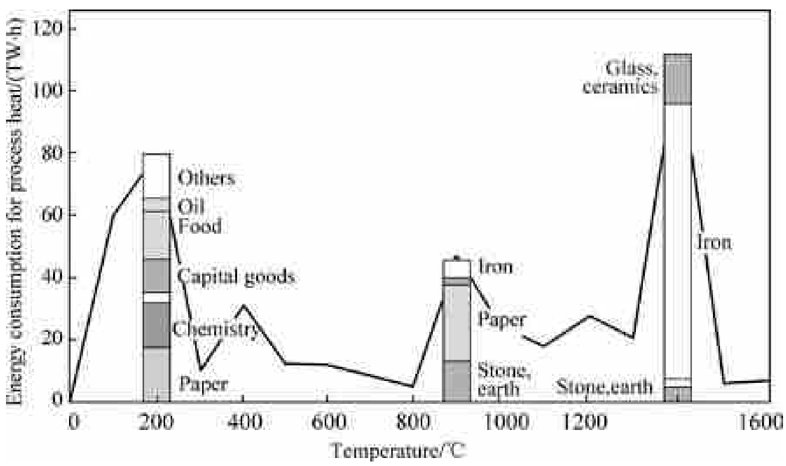


Figure 1.49 Process heat spectrum in the industries as a function of process temperature in Germany as of 1996[48]

The figure for the industrial demands indicates that there is a large market with a temperature level till around 250℃ and then a smaller market for temperature between 250℃ and 800℃. A large market exists for process temperature between 900℃ and 1600℃.

Nuclear process heat can be applied to processes with around 900℃ considering today available or foreseeable technologies. However these heat sources have to fulfill several conditions:

- Avoiding of contamination of products and additional radiological burden of population;
- Economically competitive to other solutions;
- Acceptable by public; exclusion of severe accidents by an extremely high level of safety;
- The capacity of the heat sources should be compatible to the capacity of processes, therefore limitation of power and application of a modular concept of reactors to get as high as possible availability;
- Special new questions of coupling nuclear heat source and chemical processes have to be solved: realization of intermediate heat exchanger circuits; limitation of permeation of Tritium and hydrogen; handling of process gases in the neighborhood of nuclear plants.

There are some general reasons, which make nuclear process heat attractive for the future energy economy, e.g. energy for heat supply and transportation. The heat supply is relevant for house heating and industrial processes. For the future enhanced importance of nuclear energy, generally the following aspects are discussed (Table 1.14). The production of liquid fuels could open a new additional market for nuclear energy. Especially the possible independence from fossil fuels in the sector of transportation is a promising option for the far future.

Table 1.14 Special aspects of work regarding nuclear process heat

• Fossil fuel is substituted and the production of CO_2 is avoided. This allows a saving of reserves of fossil fuels and reduces the requirements regarding CO_2-waste management. It is thought that in future the separation, transport and final storage of CO_2 costs much money, if it will be possible at all
• The production of nuclear heat allows to realize lower costs than costs from burning fossil fuel like oil or gas. The production cost of nuclear energy just weakly depend from rising prices of primary energy, in this case from the Uranium ore price. Because this share is just in the order of some percent of production costs, in future even poor Uranium ores with much higher production costs and prices can be used
• Nuclear process heat promises more independence from sensitive world markets of energy (oil, liquid gas, natural gas). For many production processes this can be a very important factor of site selection
• Nuclear technologies are complex and can strengthen the industry in a country in other different fields

The aspect of lower costs of nuclear heat is a major argument for future energy strategies to use this form of energy. Comparison of heat costs delivers a figure like that given in Table 1.15, where costs of production from oil are compared to values relevant for nuclear energy. Today the nuclear heat costs are smaller than the costs from systems burning of oil. The competition to coal is very different in worldwide comparison.

Table 1.15 Some estimations on production cost for heat from oil and nuclear reactors

Energy carrier	Specific investment cost/($/kW·$h_{th}$)	Fuel costs /(ct/kW·h_{th})	Costs of waste management /(ct/kW·h_{th})	Total costs of heat /(ct/kW_{th})	Remark
Nuclear	1500	0.5	0.3	3[3]	values for LWR
Oil	500	6[1]	1.5[2]	7.5	CO_2 separation

1: oil price: 100$/barrel; 2: cost of CO_2 separation and waste management: 60$/t CO_2; 3: depreciation time of LWR: 40 years.

Table 1.15 contains the production costs of heat of light water reactors. It is assumed that the results for full developed and commercially introduced HTR plants would be similar. The heat production of older LWR plants, which have been built as example in the eighties are in the order of

1.5 to 2ct/kW • h_{th}. Oil prices have changed very much in the past as already was explained in Figure 1.31. For the future rising oil prices are expected, because sources like oil shale and oil sand will have to contribute to the supply.

A characteristic example for the possible future importance of nuclear process heat is the supply of the transportation sector. Figure 1.50 shows the past development of the world oil market and future possible changes.

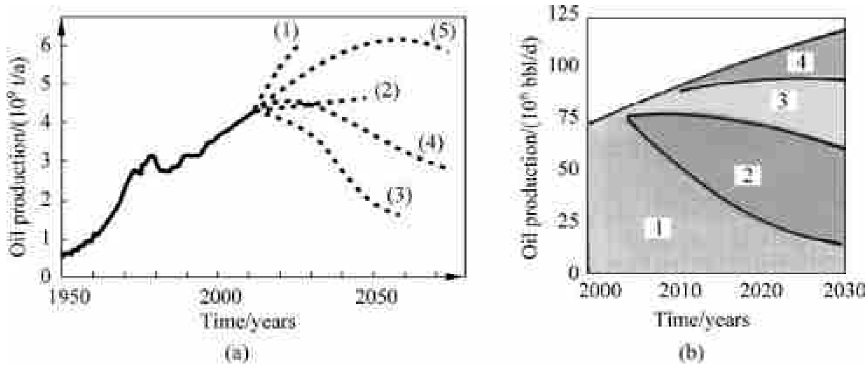


Figure 1.50 Estimations on the future development of the world oil market[49]

(a) Estimation on oil supply

1—US Department of Energy, 1999; 2—world energy conference, 1999, conventional and unconventional oils; 3—Campell, 1997, only convent oils (2.5×10^{11} t); 4—Shell study, 1995, convent and unconvent oils (6×10^{11} t); 5—Shell study, 1998, convent and unconvent oils (8×10^{11} t)

(b) Estimation on oil supply

1—existing capacities; 2—use of known reserves; 3—non-conventional oils; 4—use of new discoveries

Assuming the today consumption of around 5×10^9 t oil/a and an available amount of relatively cheap oil in the order of 200×10^9 t oil, the static range would result as 40 years. Including an escalation rate of 2%/a, this time span is reduced to around 30 years.

The consumption of oil for the transportation sector has reached a saturation in some countries, as example in Western Europe or the United States. There are other countries, in which now the demand on liquid hydrocarbons for this purpose rises up very much, as example in China (Figure 1.51). In many other countries, this tendency is expected for the future too. As a result the demand on oil or substitutes for this energy carrier will show rising tendency in the next decades. The general accepted estimation is that in 20 years, around 50% of the oil necessary for the world market have to be produced by unconventional methods. The success of the discovery of new oil reserves became smaller in the last years.

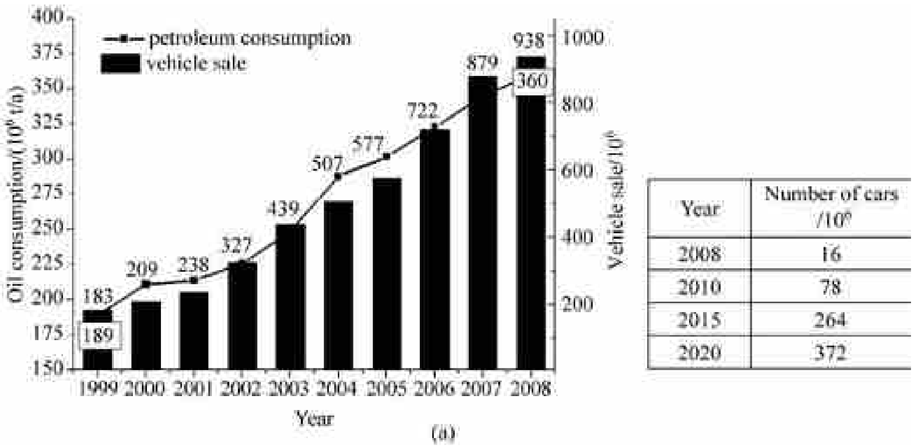
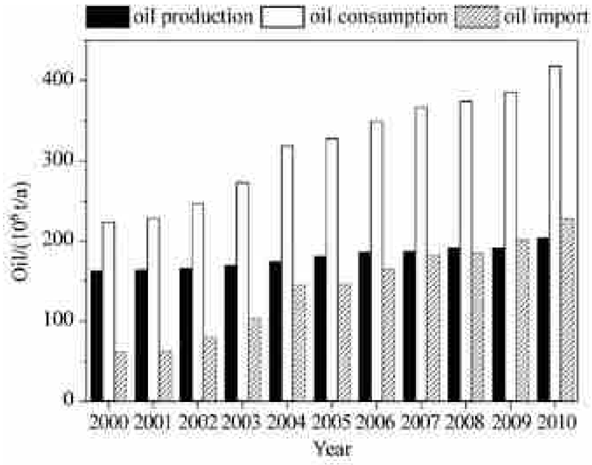


Figure 1.51 Some data of the transportation sector in China[50]

(a) Correlation between number of vehicle sale and oil consumption; (b) Oil production, consumption and import



Year	Oil consumption per year and expectation/(10^6 t/a)
2010	439
2015	543
2020	650
2030	690

(b)

Figure 1.51 (Continued)

Already in the year 2014 China had to import around 35% of the demand of oil. The production of additional oil by enhanced methods of recovery and the retorting of oil shale and oil sand will shift this time schedule by some decades. It is clear however, that for a long time worldwide strategy of supply, different other options have to be considered and soon as possible realized. Some alternatives to supply the transportation sector with energy are shown in Table 1.16.

Including oil resources, which today are still declared as unconventional (oil sand, oil shale), the world energy market can expect a supply of around $6\times10^{11}\sim8\times10^{11}$ t of oil. Corresponding to the today consumption, this results in a static range of more than 100 years. Assuming an escalation rate of around 2%/a with a saturation of nearly 10^{10} t/a for the consumption, the dynamic range will be reduced to 70 years. In any case new options for the supply of the transportation sector have to be developed for the far future. An important and interesting question is what about the use of electrical energy in the transportation sector. The development of efficient and cheap storage system is the key question for this application.

All processes mentioned in Table 1.16 are suited to produce energy carriers for the transportation sector. The processes need energy for the conversion. As explained in Chapter 2 in more detail, the processes mostly require around 50% of the feed as process heat. This can be substituted by nuclear energy. The substitution allows the reduction of CO_2 emission and promises economic advantages.

Table 1.16 Some options to fulfill the worldwide rising demand of the transportation sector

- Rising the output of refineries by addition of all thermal energy from other heat sources
- Oil production by enhanced methods (steam flooding)
- Oil production from oil shale and oil sand by retorting processes and following upgrading to light liquid products
- Liquid gases for transportation purposes
- Production of energy alcohols (methanol, ethanol) from natural gas, biomasses or coal
- Production of gasoline from coal
- Methanol from H_2 and CO_2-offgases
- Hydrogen production and use in gaseous or liquid form

An indication for this aspect was given in Table 1.15, where the oil price was compared with the production cost of nuclear heat. Here mainly the heat costs of light water reactors are mentioned, but the heat cost of modular HTR should not differ too much. The economic advantages of substitution of oil by nuclear energy becomes clear. If penalties for CO_2 separation, transport and final storage are added, the differences become even larger. More details of economic analysis are contained in Chapter 15. In future the ratio of H/C in fuels will become larger (Figure 1.52). Many technologies are well known to realize this goal.

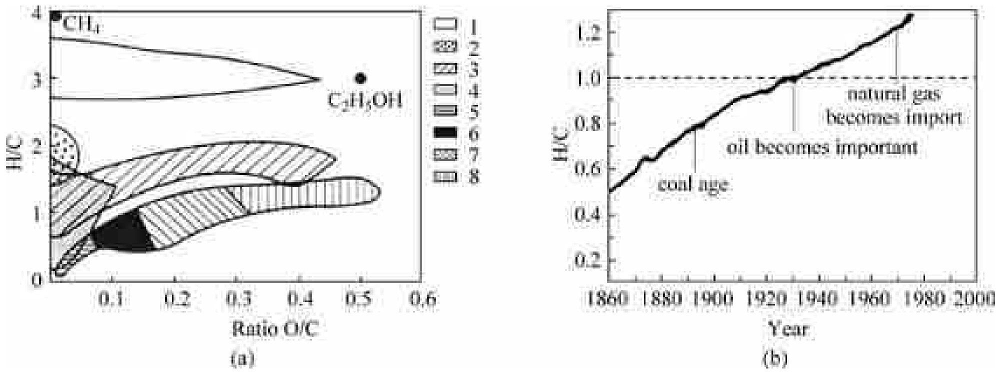


Figure 1.52 Aspects of the ratio H/C of fossil fuels

(a) Correlation between H/C and O/C; (b) Change of the ratio H/C of fuels mixture in the energy economy dependent from time

1—natural gas; 2—oil; 3—oil shale; 4—asphalt; 5—hard coal (anthracite); 6—hard coal (different types); 7—ignite; 8—peat

The technologies to convert C-containing substances into light hydrocarbons are hydrotreating, retorting processes or gasification of C-containing fuels with steam or hydrogen. Further processes to produce liquid fuels are methanol synthesis, Fischer-Tropsch-synthesis or principally coal hydrogenation (Figure 1.53).

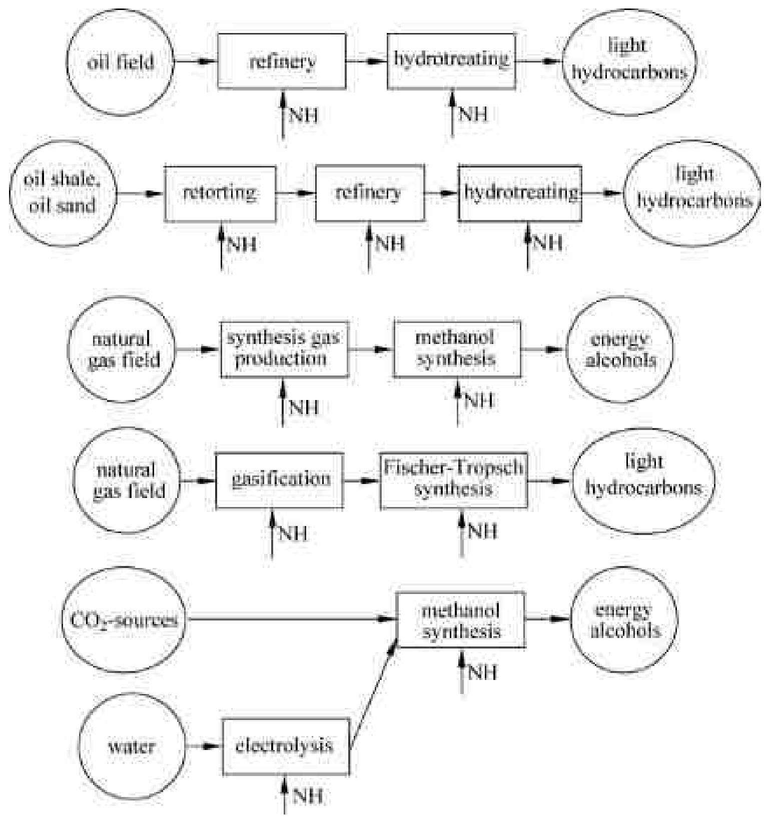


Figure 1.53 Some future process combinations, which can produce light hydrocarbons for the transportation sector (NH = nuclear heat)

All processes market here are well known from the developments of the past. Major improvements in the future can be: saving of carbon, reduction of CO_2 emission, reduction of production costs.

Regarding these requirements, combinations between nuclear energy and renewable energy carriers like biomass can get large importance in the future system of energy supply too. A proposal for this concept is contained in Chapter 2.

1.9 Some further aspects of future energy supply

Future energy supply systems, which should have importance for long time periods, have to fulfill requirements of sustainability[51-53]:

- They must be technically feasible;
- Energy reserves and resources need to be saved;
- The environment must be protected;
- Economical requirements have to be fulfilled;
- The technologies must be available worldwide to people.

Suited concepts have to be analyzed, valuated and finally realized. Some explanations regarding these aspects are given in Figure 1.54.

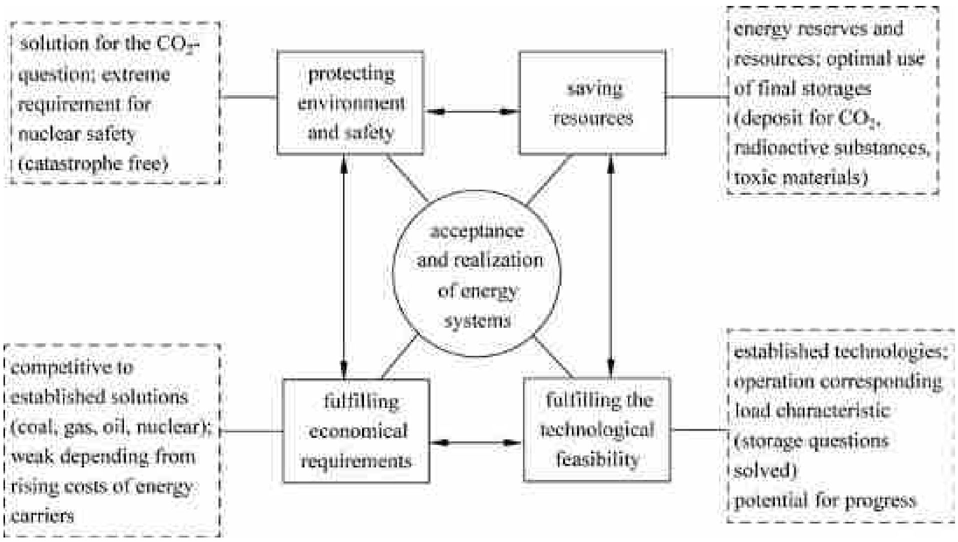


Figure 1.54 Some aspects of acceptance and requirements for future energy systems

In the field of nuclear energy application, some of the topics indicated in the figure like extreme safety considerations or aspects of waste management were underestimated in the past. They are now moving into the focus of the international discussions and politics. Similar considerations now are related to the question of CO_2 emissions and final deposit of this waste of fossil fuel technology. The reason is that consequences of the emissions of CO_2 in normal operation of plants or the release of fission products during severe accidents can have consequences for the whole world or neighbor countries. Principally all systems need optimization of the effort, which is necessary to protect people and the environment.

Two examples may characterize this important topic of energy economy. One relevant example from power plant technology is the cleaning of the off-gases from the burning process of coal. The degrees of desulfurization of flue gases, which contain SO_2, NO_x and dust are well-known parameters in the field of environmental protection. An optimal value of the effort in the field of tension between economy and environmental requirements have to be found, and in the last decades strong regulations for SO_2 emissions from power plants and from industry have been introduced (example: Germany). The valuation of this question can be carried out on hand of existing data. For the total costs connected to the cleaning systems and for environmental damages from SO_2 one gets with e as the effort for SO_2 removal:

$$E_{\text{tot}}(e) \approx E_{\text{prod}}(e) + E_{\text{envir}}(e) \approx c_1 + c_2 \cdot e + c_3 \cdot \frac{1}{e + c_4}$$

Here it is assumed that the production costs for electricity rise up linearly with the effect. On the other hand, the environmental cost drop with rising effort and reduced emission. A minimum of costs follows from the relation

$$\partial E_{tot}/\partial e = 0; \quad \partial^2 E_{tot}/\partial e^2 > 0; \quad e(\text{optim.}) \approx \sqrt{c_3/c_2} - c_4$$

The total costs for the community should show a minimum (Figure 1.55). The government today usually sets a limit e'. In older times a value e^* maybe was relevant. There are mainly technical limits, which will restrict the effort to specific values.

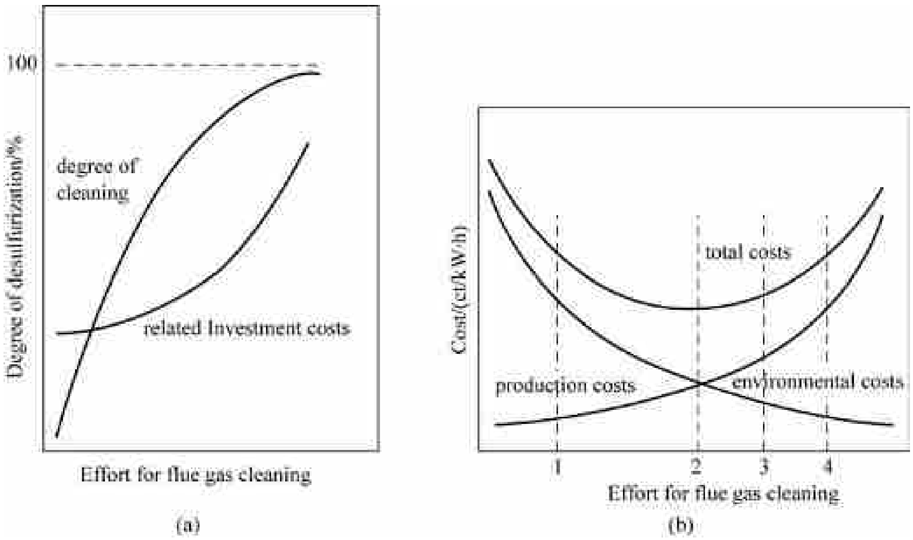


Figure 1.55 Considerations on the optimization of the effort for flue gas cleaning (example: fossil power plants; SO_2, NO_x, dust-removal) (e = degree of removal of SO_2, NO_x, dust, e' corresponds to technical limit)

(a) Degree of desulfurization and related investment costs dependent from effort (qualitative); (b) Estimation of cost structures: optimization between production costs and environmental costs

1—value, which was realized in the past; 2—optimal value (actual); 3—legally prescribed value; 4—corresponding possibly future requirement

Corresponding to the progress of technology of removal of SO_2 as example the emission of this substance has been reduced drastically in the past (German conditions). Parallel to this technical development and initiating this tendency the regulations for power plants and industrial heat sources had been changed (Table 1.17).

Table 1.17 Aspects of emisions from coal fired power plants and other sources[54]

Year	Limits for SO_2 emission/ (mg/m^3 flue gas)
till 1980	850
1982	650
today	400

(a)

Substance	Limits for emissions/ (mg/m^3 flue gas)
Dust	50
NO_x	200
CO	250
HCl	100
HF	15

(b)

Emission	Dimension	Value(1980)	Value(2000)
Dust	$g/(kW \cdot h_{el})$	0.7	0.2
SO_2	$g/(kW \cdot h_{el})$	6	1
NO_x	$g/(kW \cdot h_{el})$	3	1
CO_2	$kg/(kW \cdot h_{el})$	0.8	0.75

(c)

Year	SO_2 emission/(10^6 t/a)
1990	25
2000	10
2010	5

(d)

(a) Regulations on emissions (example: SO_2-limits in Germany); (b) Regulations on emissions (example: different limits in Germany); (c) Specific emissions from hard coal fired power plants (example: Germany); (d) SO_2-emissions in the European Union (27 states)

A further characteristic example for this type of optimizations and finding compromises may be taken from the development of nuclear technologies. The effort e to limit the release of radioactivity into the environment causes surely higher investment and production cost on the one hand and by this measure the damage cost of the environment is reduced in case of severe accidents. One major activity in the field of light water reactors in the last decades was to reduce the core melt probability, and as a consequence to reduce the probability that large amount of radioactive substances could be released to the environment (Figure 1.56). The tendency of this development, which is a consequence of technical improvements of the systems, is shown in Figure 1.57.

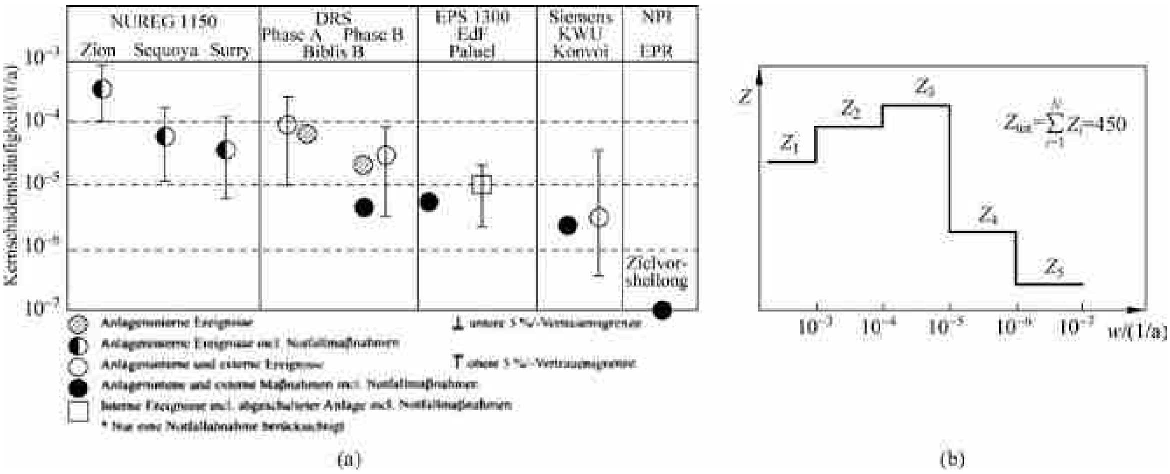


Figure 1.56 Aspects of core melt probability of LWR

(a) Some results of core melt probabilities of LWR from different risk studies[55]; (b) Qualitative picture of the number of worldwide operating nuclear power plants with specific melt probability w

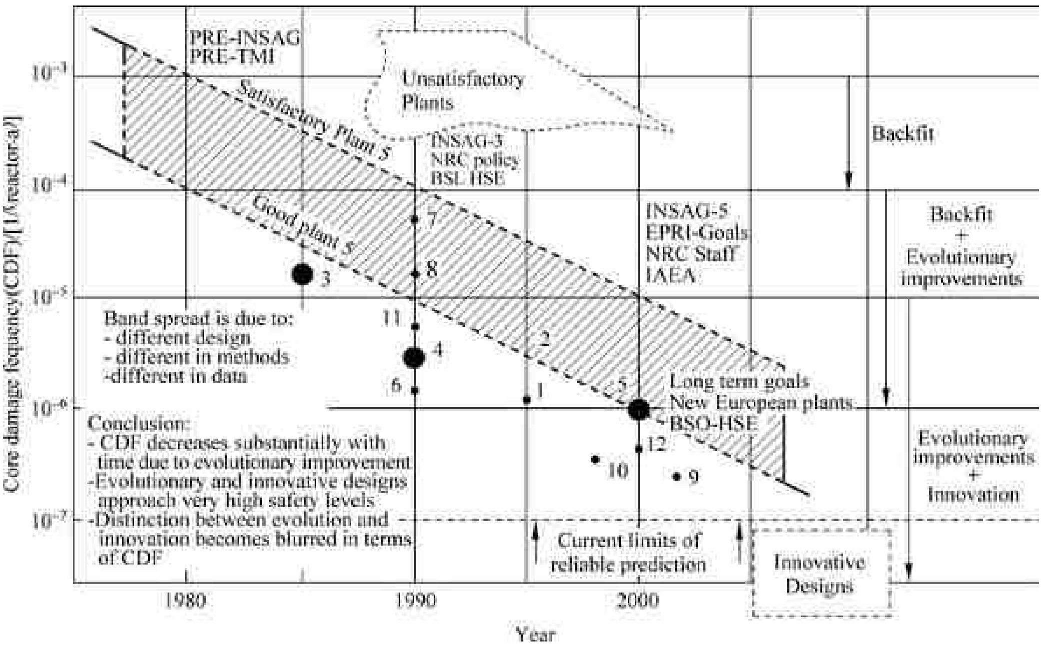


Figure 1.57 Development of core melt probability: influence of technical improvements[56]

Some examples: 1—Sizewell B; 2—N-4; 3—Biblis; 4—Konvoi; 5—EPR; 6—P-Bottom(not directly comparable); 7—Zion; 8—Surry; 9—AP 600; 10—ABWR; 11—Candu; 12—Sys80+

Naturally the 450 large nuclear power plants, which today are operated worldwide and connected to the grids, follow quite different standards of safety. This is already caused by the age of the plants. The probability that a severe accident in the world can happen might be destinated by the plants with the largest probabilities. Strong impacts from the outside, like by terroristic attack or caused by air plane crash, can change this valuation totally. Then the today usual probabilistic valuation, which results in relatively small frequencies for strong core damage and large release rates, can not play the same role as today in the licensing process and in the debate about acceptance of nuclear technologies. The severe accident in Fukushima (2011) and the discussion on consequence of terroristic attack after the catastrophic event in New York (2001) have changed the valuations following probabilistic analysis worldwide.

There is much progress in the field of reactor safety. As Figure 1.57 explains the value of core melt probability has been reduced by two decades in the last 30 years. Despite of this development old plants are still in operation and contribute to the total risk worldwide. Characteristic efforts for the new generation of nuclear reactors are improved concepts for decay heat removal, for a core catcher or for future advanced reactor containments. This very interesting topic is explained on the example of the development of the LWR-containment until now and further improvements. Figure 1.58 shows some options for this important last barrier in the LWR-technology to retain radioactive substances in the plant.

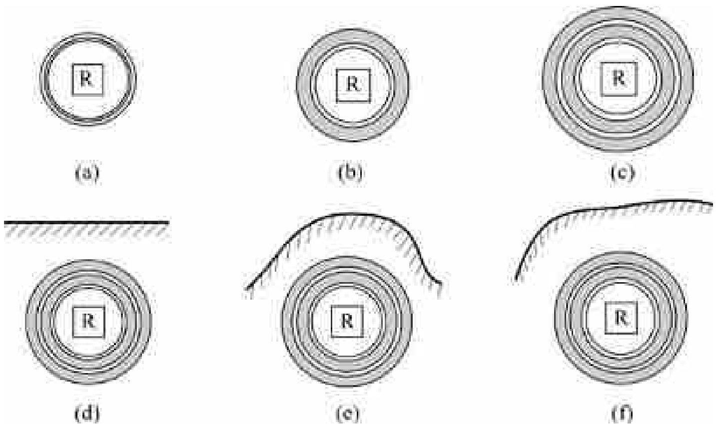


Figure 1.58 Rising efforts for reactor safety (example: improvements of the LWR-containment)

(a) Steel shell with thin wall of concrete (≤0.5m), arrangement above ground; (b) Steel shell with thicker concrete wall (≤1m for older plants; 2m for younge plants), arrangement above ground; (c) Steel shell with doubled concrete wall (≈2m), arrangement above ground; (d) Underground arrangement; (e) Underground arrangement with protecting hill; (f) Arrangement in cavern in rocks

Very old plants had just a steel shell to contain the released radioactive material together with coolant at a reasonable pressure (at around 5bar). Containments of many reactors operating today have an additional concrete shell, which in most cases has a wall thickness of around 1m. The maximal pressure is similar to the value mentioned before. The wall thickness is not sufficient to protect the primary system against the crash of large air planes. Some few plants have been realized with a wall thickness of 2m for the containment. Therefore they offer protection against the crash of military planes. Today reactor concepts for LWR are under construction, which use two concrete shells and promise higher safety by improved fission product retention and enlarged physical protection. In the future underground arrangement of reactor containments can help to get safety even against extreme strong impacts from the outside.

Additionally to the improvements indicated in Figure 1.57, as a further measure the containment got a depressurization system in the last years and in some plants already N_2 filling in normal operation with respect to possible hydrogen explosion was realized. The addition of a storage building for fission products for the case of extreme accidents would be a further possibility to improve the safety (Figure 1.59). Similar aspects of optimization of the efforts regarding the process itself and the safety behavior of the total plant can be discussed for nuclear process heat applications too (Chapter 11). Especially the connection between a nuclear plant and a chemical facility causes this type of questions to find optimal combinations and parameters for the concepts.

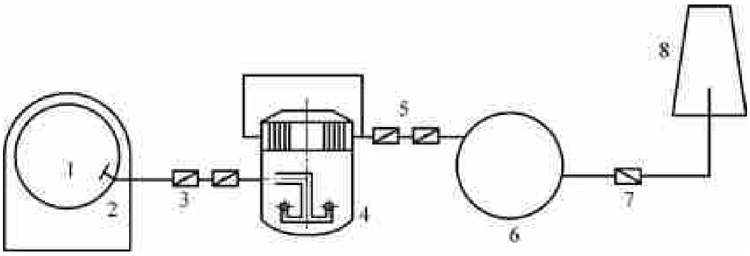


Figure 1.59 Improved containment with the addition of an intermediate storage for radioactive substances, occurring after severe accidents

1—containment or inner concrete cell (in modular HTR); 2—outer reactor building; 3—selfacting closure system for inner cell; 4—washing pool and filtering system; 5—selfacting closure system; 6—intermediate storage for gas (with fission products); 7—valve to depressurize the storage; 8—stack

The question, which risks are tolerated by the population and accepted by the politics, is different and the answers are different in countries which use nuclear energy.

There is an old proposal made by Farmer[57] and this was for many years a basis for risk studies and valuation of the result of this analysis. The release of I 131 ($T_{1/2}$ = 8 days) was used as measure for the burden of the population after an accident. Following curve in Figure 1.60(a) as example the release of more than 10 000 Ci I 131 should have a probability smaller than 10^{-4} per year, which means it should be a seldom event. By this method it was possible to define regions with acceptable and not acceptable consequences on the basis of the amount of the released radioactive substances. It was possible to estimate doses for the population. Figure 1.60 (b) shows an example, worked out in Canada for the CANDU systems. Here the whole body dose is chosen for the consequences. The application of a total dose of 10^2 Sv to a group of persons can be correlated theoretically with around 20 fatalities. Based on this principal model of valuation of risks, there are many proposal in the field of risk analysis to establish a scheme for general use. Figure 1.60 (c) contains some numbers, which characterize the risk of daily life. In any case these types of regulations are decisions by politics based on acceptance by the society.

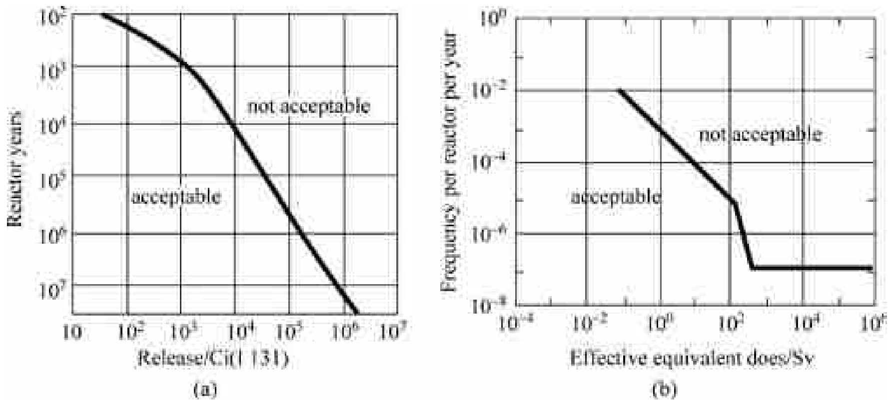
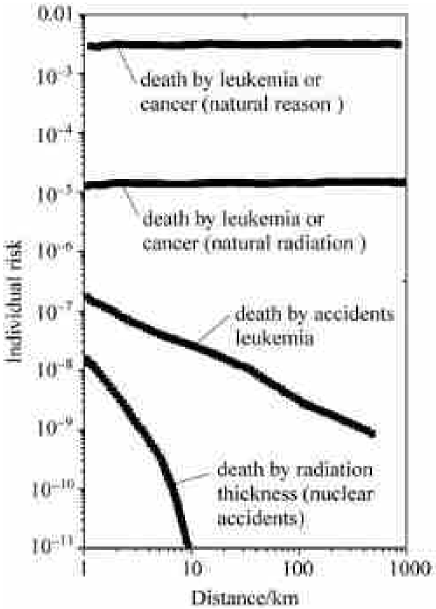


Figure 1.60 Aspects of risk acceptance by the population

(a) Curve of Farmer for risk acceptance[57]; (b) Curve worked out in Canada for valuation of risks by nuclear power plants[58]; (c) Individual risk dependent from distance (example: Germany): death by cancer; (d) Risks for death by different reasons (example: USA, 1970)[60]

(leukemi(a) 1—natural reasons; 2—natural radiation; 3—all accidents; 4—nuclear accidents)[59]



(c)

Type of casualty	Total number /(1/a)	Individual risk for persons/ [1/(a·person)]
road traffic	55 791	1/4000
falls	17 827	1/10 000
fire	7 451	1/25 000
drowning	6 181	1/30 000
fire arms	2 309	1/100 000
air traffic	1 778	1/10 000
falling object	1 271	1/160 000
electric shock	1 148	1/160 000
lightning	160	1/2 000 000
tornados	91	1/2 500 000
hurricanes	93	1/2 500 000
casualty total	111 992	1/1 600
nuclear accidents (100 plants	0	1/300 000 000

(d)

Figure 1.60 (Continued)

1.10 Some aspects of process analysis in the field of energy technology

All processes, which are discussed in the following chapters are complex and in most cases a plant consists of different combined sections. This requires as example to work out detailed mass and energy balances. The following Table 1.18 contains some forms of energy and exergy, which have to be considered in these analysis.

Table 1.18 Forms of energy and corresponding exergy

Form of energy	Energy	Exergy
kinetic energy	$E=\frac{1}{2}m(v^2-v_u^2)$	$E_{ex}=E$
potential energy	$E=mg(z-z_u)$	$E_{ex}=E$
work (without change of volume)	$E=W_{techn}$	$E_{ex}=E$
work (with change of volume)	$E=W_{12}$	$E_{ex}=W_{12}-p_u(V_1-V_2)$
inner energy (closed system)	$E=U$	$E_{ex}=U-U_u-T_u(S-S_u)+p_u(V-V_u)$
flow of enthalpy	$E=H$	$E_{ex}=H-H_u-T_u(S-S_u)$
heat	$E=Q=mcT$	$E_{ex}=Q\frac{T-T_u}{T}$
reaction enthalpy	$E=-\Delta\overline{H}_R$	$E_{ex}=-\Delta\overline{H}_R-T_u(\overline{S}-\overline{S}_u)$
chemical energy	$E=H_u$	$E_{ex}\approx H_u$
electrical energy	$E=UI$	$E_{ex}=E$
nuclear energy	$E=m\cdot c^2$	$E_{ex}=E\cdot(1-T_u/T)$

In the course of a process analysis, the boundaries for the balances have to be defined. These can include the whole process, parts of the plant or groups of components or single component. The mass and energy balances can cover chemical or nuclear reactions too[61-66].

Figure 1.61 indicates a model, in which time dependent mass and energy streams enter the balance volume. This volume can be a component, a region of a plant or a total plant.

For the change of mass and energy in the balance region one gets

$$\frac{dm}{dt}=\sum_i(\dot{m}_i)_{in}-\sum_j(\dot{m}_j)_{out}+w\cdot V$$

$$\frac{dE}{dt} = \sum_i (\dot{E}_i)_{in} - \sum_j (\dot{E}_j)_{out} + \dot{H}_w$$

w characterizes changes of composition by chemical reactions, V is the volume of the system in which the reaction takes place. $\dot{H}_w$ characterizes internal conversion processes, the term $\dot{E}$ contains enthalpies, mechanical heat and other forms of energy.

In case of nuclear reactions like fission or radioactive decay, the connection between energy and mass corresponding to Einstein's equation

$$\Delta E = \Delta m \cdot c^2, \quad 1 \text{ atomic mass unit} \triangleq 931\text{MeV},$$

$$1\text{amu} = \frac{1}{12} m(^{12}_{6}\text{C})$$

has to be included. c is the velocity of light ($c = 300\ 000$km/s).

For many applications energetic and exergetic efficiencies based on a model as shown in Figure 1.62 are defined.

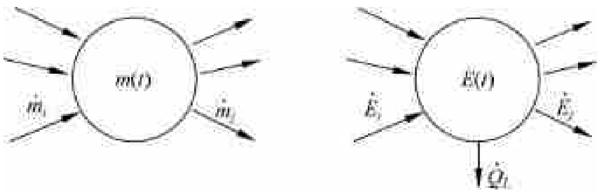


Figure 1.61 Concept of mass and energy balance

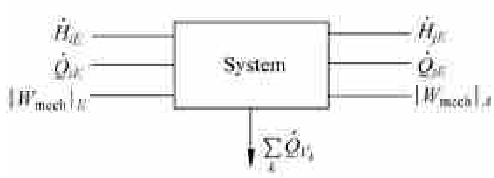


Figure 1.62 Model for the definition of efficiencies

The energetic efficiency can be expressed in general form by the equation

$$\eta = \text{energetic benefit/energetic expense}$$

$$\eta = \frac{\sum_j \dot{H}_{jA} + \sum_j \dot{Q}_{jA} + |W_{mech}|_A}{\sum_i \dot{H}_{iE} + \sum_i \dot{Q}_{iE} + |W_{mech}|_E} = 1 - \frac{\sum_k \dot{Q}_{V_k}}{\sum_i \dot{H}_{iE} + \sum_i \dot{Q}_{iE} + |W_{mech}|_E}$$

In case of thermodynamic cycles this equation is simplified in the form:

$$\eta_{th} = \frac{|W_{mech}|}{\sum_i \dot{Q}_{iE}}$$

Including all efficiencies of the total chain of energy conversion in a power plant, one obtains a product for the total efficiency of a process.

$$\eta_{tot} = \eta_{th} \cdot \prod_i \eta_i$$

Here the η_i-values characterize efficiencies of the steam generator, the turbine, the electrical generator, losses of the components of the steam cycle and expenses for the own consumption of a plant. Similar efficiencies have to be defined in a process heat plant, which contains a chain of process steps too. Often exergetic efficiencies have to be defined, in which the thermodynamic worth of energy is included.

$$\eta_{exerg.} = \frac{|W_{mech}| + \dot{Q}_A \cdot (1 - T_{env}/T)}{\sum_i \dot{Q}_{iE}}$$

Here an amount of heat $\dot{Q}_A$, which leaves the process, is valuated corresponding to the temperature of the heat. The factor is the Carnot factor and indicates which efficiency to use the heat could be possible from the thermodynamic standpoint. This type of valuations become important for processes, which deliver several products. Cogeneration is a very important example.

In the course of process analysis it is often necessary to compare different technologies as far as total energetic valuation is considered. Energy is necessary to construct the plants and to fabricate the necessary materials, and to supply the fuel during operation. After the operation lifetime of the plant energy has to be inserted for decommissioning. Some notations and definitions are helpful to characterize plants:

- Energy expense for construction of the plant (EE_c): these are expenses of construction of the plant including all energy expenses for fabrication of materials, fabrication, mounting and transport of components. Direct energy investment at the site of the plant, indirect energy investment for the production of materials have to be included.

$$EE_c = \int_0^\tau P^*(t)\,dt + \sum_i m_i\sigma_i + \int_0^\tau \dot{Q}(t)\,dt + \int_0^\tau P^{**}(t)\,dt$$

$\int_0^\tau P^*(t)\,dt$ ——electrical energy used directly at the site of the plant;

$\int_0^\tau \dot{Q}(t)\,dt$ ——heat energy used directly at the site of the plant (oil, gas, coal, steam);

m_i——amount of materials for fabrication of components (steel, concrete, copper, aluminum, plastics);

σ_i——specific numbers of energy consumption to produce the materials (electrical energy, oil, gas, coal calculated as primary energy);

$\int_0^\tau P^{**}(t)\,dt$ ——electrical energy used indirectly in the factories to produce the components.

The time schedules for the construction partly are long and reach some years.

- Equivalent of primary energy: the amount of primary energy which is necessary for the production of one unit secondary energy (1kW·h (electrical) means 2.5~3kW·h (thermal) in case of nuclear or fossil power plants, 1kW·h_{el} corresponds with 1.3~1.5kW·h_{th} in case of hydropower). In general form is:

$$E(\text{primary} \triangleq \text{thermal}) \approx E(\text{electrical})/\eta$$

- Time of energetic amortization of a plant (T_A): time of operation of a plant which is necessary to produce the amount of primary energy which has been used to construct the plant (Figure 1.63).

$$EE_c = \int_0^{T_A} P(t)\,dt \cdot \frac{1}{\eta} \approx P_0 \cdot T_A/\eta$$

In principal the following model can be applied (Figure 1.63). A time T_A can be calculated from the balance.

- Exploitation factor related to the construction of the plant (EF_c): the factor EF_c is important for the calculation of the time which is necessary to recover the energetic investments for the construction of the plant (Figure 1.64).

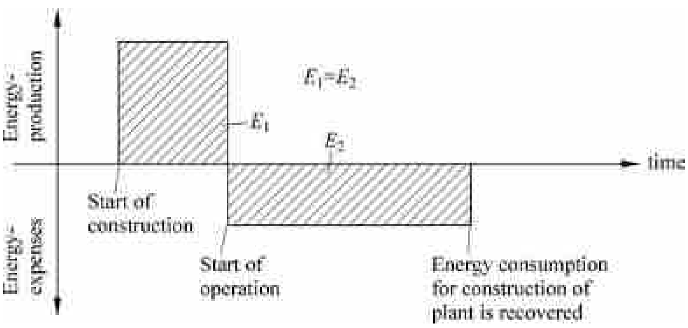


Figure 1.63 Model to define a time of energetic amortization

Figure 1.64 Model for the definition of the exploitation factor

$$EF_c = \frac{\text{netto production during lifetime of plant}}{\text{energy consumption for construction of plant}}, \quad EF_c = \frac{N \cdot P_0 \cdot T}{EE_c}$$

N corresponds to the number of years of operation of the plant, P_0 is the nominal power of the plant, T is the time of full load operation during one year. For the special case $EF_c = 1$, one obtains

$$EF_c = 1 \longrightarrow EE_c = P_0 \cdot T_A$$

T_A is the static time of energetic amortization for the plant.

- Exploitation factor related to the total lifetime of the plant (EF_L) is a further definition, which is helpful to characterize energetic demands during the whole life of the plant (Figure 1.65).

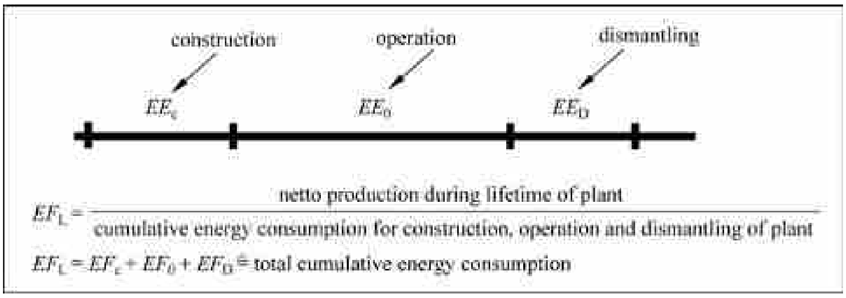


Figure 1.65 Model for description of the plant life

Inserting some relations used before one gets

$$EF_L = \frac{N \cdot P_0 \cdot T}{EE_T} = \frac{N \cdot P_0 \cdot T}{EE_c} \cdot \frac{1}{1 + \frac{EE_0}{EE_c} + \frac{EE_D}{EE_c}} = EF_c \cdot \frac{1}{1 + \alpha + \beta}$$

α = factor energy for operation related to energy for construction

β = factor energy for dismantling related to energy for construction

- The substitution factor (SF) is important to valuate processes, if different fuels can be applied. The substitution factor SF is the ratio between the primary energy consumption which can be substituted and the primary energy consumption.

$$SF = \frac{\text{difference between netto energy production (primary equivalent) and cumulative energy consumption}}{\text{cumulative energy consumption}}$$

$$SF = \frac{N \cdot P_0 \cdot T \cdot \frac{1}{\eta} - EE_T}{EE_T} = \frac{N \cdot P_0 \cdot T}{\eta \cdot EE_T} - 1 = EF_c \cdot \frac{1}{\eta} \cdot \frac{EE_c}{EE_T} - 1$$

The cumulative energy EE_0 during the operation of the plant requires the valuation of different energy carriers. Fossil fuels are taken into account with their lower heating values; regenerative primary energy sources and nuclear fuels with their conversion factors.

The factor SF allows as example an answer to the question, if a regenerative energy system produces more energy than it consumes. $SF > 0$ fulfills the condition that there is a contribution to the saving of fossil resources.

- The grade of substitution (SG) allows an overview on the influence of substitution over the whole life of the plant:

$$SG = \frac{\text{netto energy production (primary energy equivalent)} - \text{cumulative energy for plant}}{\text{netto energy production of plant}}$$

$$SG = \frac{N \cdot P_0 \cdot T \cdot \frac{1}{\eta} - EE_T}{N \cdot P_0 \cdot T} = \frac{1}{\eta} - \frac{EE_T}{N \cdot P_0 \cdot T} = \frac{1}{\eta} - \frac{1}{EF_L}$$

The grade of substitution corresponds to the ratio of the primary energy consumption which is consumed and the energy production.

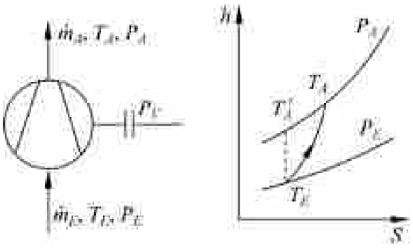
In the process analysis[63-66] many process units or components have to be analyzed (Table 1.19).

For each component balances for mass and energy can be estimated on the basis of available data of working media. Characteristic parameters of technology can be sampled. Steam turbines are parts of all processes and shall be elected here as an example.

Some examples of components, which are necessary in all processes are described in simplified form in Figure 1.66, Figure 1.67 and Figure 1.68.

Table 1.19 Overview on process units and special components of process heat plants

Components of processes (units)	Special process heat components
• heat exchangers • chemical reactors • pumps • compressors • steam turbine • pipes • valves • storages • columns • cooling towers • drives • control units	• core region • hot gas duct • steam generator • gasifier • reformer • waste heat utilization • gas purification • steam turbine cycle • gas turbine process • burning chamber • gas separation unit • electrolysis plant • synthesis plants • diesel engines



mass balance

$$\dot{m}_E = \dot{m}_A = \dot{m}$$

energy balance

$$\dot{m}_E h_E + P_V = \dot{m}_A h_A$$

exergy balance

$$\dot{m} e_E + P_V = \dot{m} e_A - \Delta \dot{E}_V$$

thermodynamic relation

$$ds = c_p \frac{dT}{T} - R\frac{dp}{p}$$

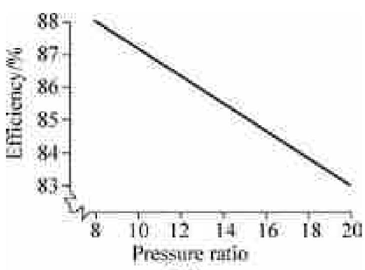
$$dh = c_p dT$$

$$T_{A'} = T_E \left(\frac{p_A}{p_E}\right)^{\frac{\kappa-1}{\kappa}} \quad \text{(ideal)}$$

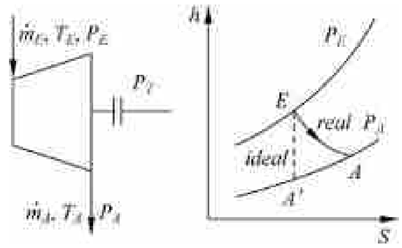
$$T_A = T_E \left\{1 + \frac{1}{\eta_V}\left[\left(\frac{p_A}{p_E}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]\right\} \quad \text{(real)}$$

inner efficiency

$$\eta_V = \frac{T_{A'} - T_E}{T_A - T_E}$$



(a)



mass balance

$$\dot{m}_E = \dot{m}_A = \dot{m}$$

energy balance

$$\dot{m}_E h_E = \dot{m}_A h_A + P_T$$

exergy balance

$$\dot{m} e_E = \dot{m} e_A + P_T + \Delta \dot{E}_V$$

thermodynamic relation

$$ds = c_p \frac{dT}{T} - R\frac{dp}{p}$$

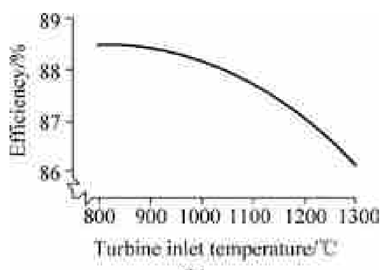
$$dh = c_p dT$$

$$T_{A'} = T_E \left(\frac{p_A}{p_E}\right)^{\frac{\kappa-1}{\kappa}}$$

$$T_A = T_E \left[1 - \eta_T + \eta_T \left(\frac{p_A}{p_E}\right)^{\frac{\kappa-1}{\kappa}}\right]$$

inner efficiency

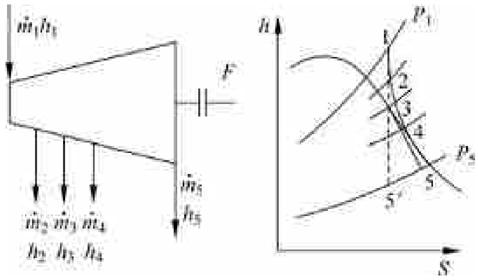
$$\eta_T = \frac{T_E - T_A}{T_E - T_{A'}}$$



(b)

Figure 1.66 Simplified description of important process unit

(a) Compressor; (b) Gas turbine



mass balance

$$\dot{m}_1 = \sum_{i=2}^{5} \dot{m}_i$$

energy balance

$$\dot{m}_1 h_1 = \sum_{i=2}^{5} \dot{m}_i h_i + P_T + \sum_j \dot{Q}_{V_j}$$

exergy balance

$$\dot{m}_1 e_1 = \sum_{i=2}^{5} \dot{m}_i e_i + P_T + \Delta \dot{E}_V$$

thermodynamic relation

$$h = h(s,p,T),\ s = s(T,p)$$

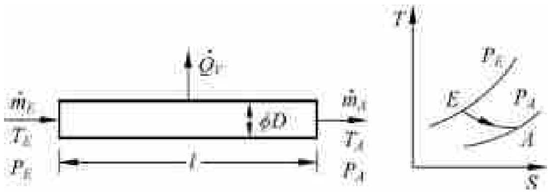
inner efficiency

$$\eta_i = \frac{h_1 - h_5}{h_1 - h_{5'}}$$

$= f$(application, p, T, P, technical concept, age, operation conditions)

values of η_i: 0.8～0.9

(a)



mass balance

$$\dot{m}_E = \dot{m}_A = \dot{m} = \rho v A = \rho v \frac{\pi}{4} D^2$$

energy balance

$$\dot{H}_E + \dot{W}_{\text{pot } E} + \dot{W}_{\text{kin } E} = \dot{H}_A + \dot{W}_{\text{pot } A} + \dot{W}_{\text{kin } A} + \dot{Q}_V$$

$$\dot{m}h_E + \dot{m}gz_E + \frac{\dot{m}}{2}v_E^2 = \dot{m}h_A + \dot{m}gz_A + \frac{\dot{m}}{2}v_A^2 + \dot{Q}_V$$

exergy balance

$$\dot{m}e_E + \dot{m}gz_E + \frac{\dot{m}}{2}v_E^2 = \dot{m}e_A + \dot{m}gz_A + \frac{\dot{m}}{2}v_A^2 + \Delta\dot{E}_V$$

pressure loss

incompressible media

$$\Delta p = \left(\frac{\lambda}{D} l + \sum_i \xi_i\right) \frac{\rho}{2} v^2$$

compressible media

$$\Delta p = p_E \left[1 - \sqrt{1 - \frac{\rho_E v_E^2 \lambda l (1+\alpha) T_m}{p_E D T_E}}\right]$$

T_m = middle temperature, $\alpha = D \sum_i \xi_i / (\lambda l)$, $\lambda = f(Re)$

pump power

incompressible media

$$P = \dot{m} \frac{\Delta p}{\rho \eta_P}$$

compressible media

$$P = \frac{\dot{m} c_p}{\eta_P} T_E \left[\left(\frac{p_A}{p_E}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]$$

heat loss

$$\dot{Q}_V = \dot{m} c_p (T - T_u) \left[\exp\left(\frac{kA}{\dot{m} c_p}\right) - 1\right]$$

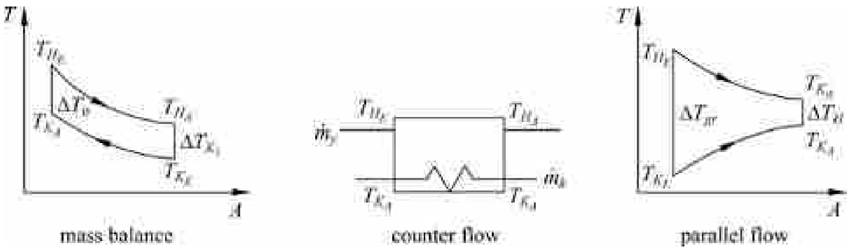
(b)

Figure 1.67 Simplified description of important process unit

(a) Steam turbine; (b) Pipe

Gas turbines, compressors, steam turbines or pipes are applied in all plants and shall be discussed here in more detail using some characteristic balances and valuations.

Naturally, firstly the parameters of the working fluid have to be sampled as a basis for all calculations. Technical examples from many fields of technology are helpful to analyze those components and work out technical concepts in detail.



$$\dot m_{H_E} = \dot m_{H_A} = \dot m_H$$

$$\dot m_{K_E} = \dot m_{K_A} = \dot m_K$$

energy balance

$$\dot m_H (h_{H_E} - h_{H_A}) = \dot m_K (h_{K_A} - h_{K_E})$$

exergy balance

$$\dot m (e_{H_E} - e_{H_A}) = \dot m_K (e_{K_A} - e_{K_E}) + \Delta \dot E_V$$

characteristic equations

$$\dot C_H = \dot m_H c_{pH}, \quad \dot C_K = \dot m_K c_{pK}$$

$$T_{H_A} = T_{H_E} - \phi (T_{H_E} - T_{K_E})$$

$$T_{K_A} = T_{K_E} - \phi \frac{\dot C_H}{\dot C_K} (T_{H_E} - T_{K_E})$$

$$\phi = \frac{1 - \exp\left[-\left(1 - \frac{\dot C_H}{\dot C_K}\right)\frac{kA}{\dot C_H}\right]}{1 - \frac{\dot C_H}{\dot C_K}\exp\left[-\left(1 - \frac{\dot C_H}{\dot C_K}\right)\frac{kA}{\dot C_H}\right]} \qquad \text{counter flow}$$

$$\phi^* = \frac{1 - \exp\left[-\left(1 + \frac{\dot C_H}{\dot C_K}\right)\frac{kA}{\dot C_H}\right]}{1 + \frac{\dot C_H}{\dot C_K}} \qquad \text{parallel flow}$$

characteristic values for heat transfer coefficients

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{1}{\lambda / s} + \frac{1}{\alpha_2} \qquad \text{(for flat geometry)}$$

Medium in tubes (1)	Medium outside tubes (2)	Value α_1/ [W/(m² · K)]	Value α_2/ [W/(m² · K)]	Value k/ [W/(m² · K)]
air	flue gas*	20	20	10～15
water	air*	1000	20	10～15
oil	water	1000	500	100～300
water	water	2000	500	500～1000
water	steam (condense(d))	2000	10 000	2000～3000

equation for dimensioning of heat exchanger

$$\dot Q = \dot m_H c_{pH} (T_{H_E} - T_{H_A}) = \dot m_K c_{pK} (T_{K_A} - T_{K_E})$$

$$\dot Q = kA \Delta T_{\log}, \quad \Delta T_{\log} = \frac{\Delta T_{gr} - \Delta T_{kl}}{\ln(\Delta T_{gr} / \Delta T_{kl})}$$

Figure 1.68 Equations characteristic for heat exchangers

*: normal pressure

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