

Chapter 1

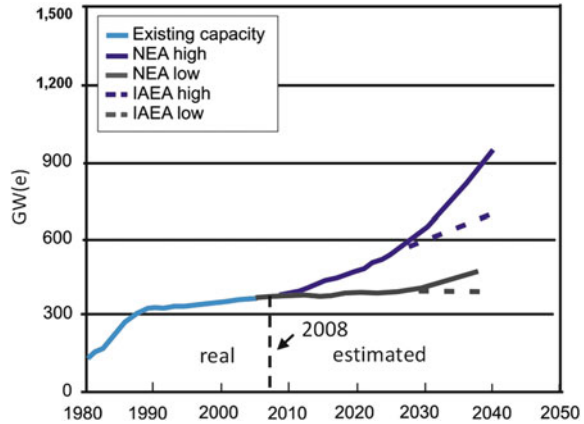
The Development of Nuclear Energy in the World

Abstract In 2011 there were about 436 commercial nuclear power reactors operating in the world with a total capacity of 370 GW(e). Nuclear energy supplied about 16% of the world electricity. The countries with the largest nuclear energy generating capacities were the USA, France, Japan, Russia, South Korea, UK, Canada, Ukraine, China, Spain. About 81% of the operating nuclear reactors were light water cooled and moderated reactors. About 11% were pressurized heavy water moderated reactors and about 3.4% graphite moderated and gas cooled reactors. Another about 4% light water cooled and graphite moderated reactors of the Chernobyl type were still operating in Russia. The remaining 0.6% were new prototype power reactors. Besides the use of nuclear power for electricity generation, wider application directly using the nuclear heat as process heat with temperatures of about 800°C (gas cooled reactors) is possible in future. In the past BN 350 situated on the shore of the Caspian Sea was already used as a dual purpose plant, supplying in addition to electricity (150 MW(e)) also fresh water (120,000 m³/d) by desalination. The economic advantages of nuclear power is based on the relatively low fuel cycle costs. However, nuclear power plants have capital costs higher than those of e.g. fossil fired power plants, but a much more pronounced cost degression for larger units. Nuclear power avoids to a large extent the emission of CO₂, SO₂, NO_x and also particulate emissions.

1.1 History of Development and Projections

The first nuclear power station for the generations of electricity with an output of 5 MW(e) for commercial use started to operate at Obninsk, Russia in 1954. It was a graphite moderated, light water cooled reactor. Only two years later, four 50 MW(e) graphite moderated and gas (carbon dioxide) cooled reactors started to operate at Calder Hall, UK. One year later the first electricity producing pressurized light water reactor (PWR) with 60 MW(e) began operation at Shippingport, USA. This initial phase was followed by a rapid growth of nuclear energy production in many countries.

Fig. 1.1 Global nuclear capacity in the OECD NEA and IAEA high and low scenarios [2, 3]



In 2011 there were 436 nuclear reactors operating in the world with a total capacity of 370 GW(e) [1]. Projections for the future development of nuclear energy on a global basis are made by the Nuclear Energy Agency (NEA) as shown in Fig. 1.1 up to the year 2030. A high growth and a low growth scenario are shown [2, 3]. These projections are in broad agreement with those from other international organizations, e.g. IAEA etc..

The future requirement of nuclear generating capacity strongly depends on the level of the future cumulative world energy requirement which, in turn, is determined very much by the growth of the world population and by economic developments in industrialized and developing countries.

The market share that nuclear power will be able to gain will depend on the economically available reserves of nuclear fuels, the reserves of the established sources of primary energy, i.e., coal, oil, natural gas and hydropower as well as on new technologies for the exploitation of renewable energies, especially wind, solar power and biomass. Finally, the rate at which nuclear power will be introduced will be determined also by the solution of the acceptance problems in the public, by the international non-proliferation policy and by associated political decisions.

This multitude of partly conflicting factors, some of which include major uncertainties and/or regional and national differences, makes it extremely difficult to forecast the expected future worldwide nuclear generating capacity.

1.2 Status of Nuclear Energy Generation in 2008

Nuclear energy supplied about 16% of the world electricity in 2011 [1]. The countries that have built up the largest nuclear energy generating capacities are shown in Fig. 1.2. The countries with the highest number of nuclear power reactors were the USA, France, Japan, Russia, South Korea, UK, Canada, Ukraine, China, Sweden and Spain. In the rest of different countries 72 nuclear reactors were operating.

Fig. 1.2 Contributions to global nuclear generating capacity by country, 1957–2007 [2, 3]. Sources based on data taken from NEA (2006a) and NEA (2008a)

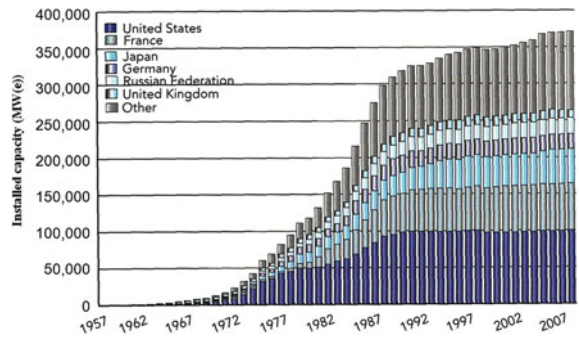


Table 1.1 Number of nuclear reactors and their share for electricity production [2, 4]

Country	Number of nuclear reactors	Share (%) for electricity production
USA	104	20
France	58	76
Japan	50	25
Russia	32	17
South Korea	20	36
Germany	9	16
United Kingdom	19	13
Canada	18	15
Ukraine	15	47
China	13	2
Sweden	10	42
Spain	8	18

Table 1.1 shows the number of nuclear reactors and their share (%) for electrical energy production.

The possibility of selecting different materials for moderating the energy of the fission neutrons in the reactor core as well as the different coolants used, lead to different types of nuclear power reactors. This is shown in Table 1.2. Light water cooled and moderated reactors (pressurized water reactors (PWRs) and boiling water reactors (BWRs) are dominating with 82%. Pressurized heavy water moderated and cooled reactors (PHWRs) follow with 10%. Graphite moderated and gas cooled reactors (GCRs) represent about 4%. Light water cooled graphite moderated reactors (LWGRs) (4%) were still operating in Russia around 2009.

Liquid metal cooled fast neutron reactors are developed for future application. They are the only type of reactors which can, by applying a breeding process, indirectly fission also the U-238 and Th-232 isotopes abundant in uranium and thorium ores.

In 2009 about 40 additional nuclear power reactors with a total capacity of 35 GW(e) were under construction. In addition many countries including China,

Table 1.2 Number and fraction of different nuclear reactors in the world [2, 3]

Type	Number of units	Fraction (%)
PWR	262	60.4
BWR	94	21.4
PHWR	44	10.0
GCR	18	4.1
LWGR	16	3.6
FBR	2	0.5
Total	436	100.0

India, Japan, South Korea, the Ukraine and Russia announced ambitious programs to expand nuclear energy capacities in the coming decades [2].

Nuclear power reactors are currently built mainly with an electricity generating capacity of 1,200–1,600 MW(e). They are erected in a construction period of about 60 months and are operating in the base load regime with an availability factor of 85–90%. Their operating life time has been increased from 35 years to about 60 years.

1.3 Technical Applications of Nuclear Fission Energy

1.3.1 Nuclear Power for Electricity and Process Heat Generation

The energy released in the nuclear fuel of the reactor core by the fission of uranium or plutonium nuclei mostly consists of kinetic energy of the fission products with the result that the nuclear fuel is heated. Consequently, the primary energy in nuclear fission is thermal energy (heat), which can be extracted from the reactor core by means of a coolant and used either directly as process heat or be converted into electricity by a thermodynamic water/steam process.

Nuclear power plants equipped with LWRs attain saturated steam conditions slightly below 300°C and approximately 70–78 bar (thermal efficiency: 33–36%). Power plants incorporating advanced types of reactors (advanced gas cooled reactors or liquid metal cooled fast neutron reactors) use superheated steam at slightly more than 500°C and 160 bar (thermal efficiency, approximately 40%).

The use of electricity for lighting, power and direct ohmic heating in industry, transport and private households has become widespread. The percentage fraction of electricity in the total consumption of final energy is likely to increase also in the future. In addition to direct ohmic heating, heating by means of electric heat pumps may well achieve growing importance in the future.

Besides the use of nuclear power for electricity generation, wider applications directly utilizing the heat are quite possible in the future, especially under the

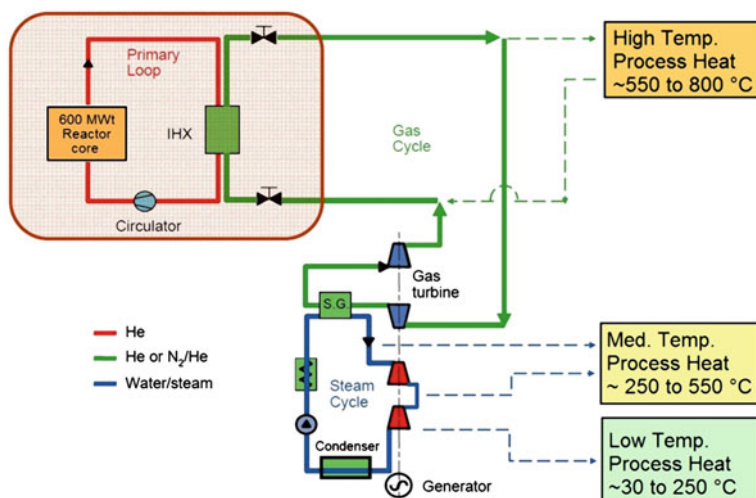


Fig. 1.3 Gas cooled nuclear power plant producing process heat and electricity [5]

incentive of finding substitutes for oil and natural gas as primary sources of energy for producing electricity and for transport purposes. In principle, the waste heat of nuclear power plants, as of coal fired power plants, can be exploited to supply district heat to cities or industrial regions. Optimum utilization of nuclear heat will be achieved in dual purpose nuclear power plants, in which the steam generated will first be partly expanded in turbines for electricity generation and then extracted either partly or entirely from the final turbine stage for purposes of heat supply (back pressure turbine process). The combined generation of power and heat in dual purpose nuclear power plants not only offers advantages in terms of energy (overall thermal efficiency, 75–85%), but is especially attractive also from an economic point of view. Figure 1.3 shows the basic flow sheet of a dual purpose gas cooled nuclear power plant producing process heat of different temperature levels and electricity.

Since nuclear power plants are built in large units for economic reasons, and since heat cannot be transported over long distances economically (the costs of the necessary distribution system decisively influence the costs of district heat), the use of nuclear power in combined dual purpose plants offers economic advantages only in areas of high and concentrated heat requirements [6].

A large part of industrial process heat is generated in the range of temperatures between 200 and 400°C, especially in chemical industries. For this application nuclear power from dual purpose power plants would constitute a solution. A special area of application of nuclear process heat is the generation of fresh water by sea water distillation. The world's fresh water requirement increases very much like the energy requirement. In many developing countries, the supply of fresh water by this technique will become a vital necessity. Since, for technical reasons, a steam quality not exceeding 150°C is sufficient for the desalination process, a combined dual pur-

pose system again would be most reasonable economically. The high capital outlay required for the power plant plus the distillation plant today still hampers the use of nuclear power for sea water desalination.

1.3.2 Nuclear Ship Propulsion

Nuclear reactors were used for ship propulsion initially to drive warships (submarines, aircraft carriers). Today's PWRs, which rank at the top in the list of reactor concepts, are a product of this marine reactor development in the fifties. In commercial shipping, nuclear propulsion has not been developed beyond a few demonstration projects.

The vessel to be mentioned first in this respect is the Russian icebreaker, N.S. "Lenin", which serves to keep the Western Arctic route open for the Soviet marine in winter. The N.S. "Lenin" was operated with three reactors in the period 1959–1966 and has been run on two improved reactors since 1970.

Over a period of eight years of operation, between 1962 and 1970, the American N.S. "Savannah" accumulated the necessary operating experience and was then decommissioned for cost reasons.

The N.S. "Otto Hahn", the German nuclear power research vessel, was operated between 1968 and early 1979 and, like the N.S. "Savannah", has produced excellent operating results. The Japanese N.S. "MUTSU" performed a similar trial phase of operation.

The market penetration of commercial vessels with nuclear propulsion systems is now mainly an economic question. In addition, the future of commercial nuclear shipping depends very much on the establishment of international agreements about port entry permits for the most important commercial ports in the world.

1.3.3 Nuclear High Temperature Process Heat

High temperature gas cooled reactors (HTGRs) can greatly expand the use of nuclear process heat. They attain coolant outlet temperatures of 700–950°C. In that range of temperature, especially processes of direct nuclear coal gasification are of interest in which the process heat required for conversion is supplied as nuclear heat from an HTGR in a temperature range up to 950°C.

1.3.4 Nuclear Power for Hydrogen Generation

Hydrogen as a future secondary fuel can make major contributions to the supply of energy in all areas of consumption of final energy. Nuclear power plants can produce

hydrogen both by electrolysis and by thermo-chemical water splitting processes at high temperatures. Hydrogen can be carried to load centres over long distances in pipelines of the type successfully applied today in the chemical industry. According to experience gathered in Europe, hydrogen can be stored, e.g., in underground cavities.

For water electrolysis, large electrolytic plants of several 100 MW(e) power will have to be developed in the future with low capital costs and high efficiencies for hydrogen generation. One main incentive in electrolysis processes may lie in the utilization of off-peak electricity, which means that the surplus electricity generated in nuclear power plants outside peak load times can be used to produce hydrogen.

The problems inherent in thermo-chemical water splitting processes today still lie in the choice and demonstration of economically viable processes. They can work successfully only in a range of temperatures offered at present by high temperature gas cooled reactors.

1.4 Economic Aspects of Nuclear Energy

The future of nuclear power decisively depends on its economic prospects. Economics in this case not only implies the operation of nuclear power plants, but also the facilities going with them to supply nuclear fuel and dispose of nuclear waste.

The economic advantage of nuclear power lies in its relatively low fuel costs, which means that, e.g., changes in the uranium price will only have moderate effects on the overall electricity generating costs of a nuclear power plant. This characteristic has a stabilizing influence on the energy market. On the other hand, nuclear power plants have capital costs clearly higher than those of fossil fired power plants. However, nuclear power plants have a much more pronounced cost degression for larger units.

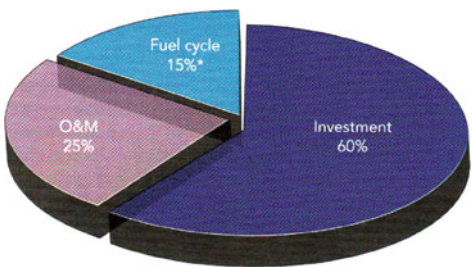
1.4.1 Electricity Generating Costs by Nuclear Power Reactors

The costs of generating electricity are determined as average cost values over the full life time of the nuclear plant and over the fuel cycle time periods of the fuel. They can be divided into three main components [7]:

- capital investment (construction costs and interest during the construction time),
- operation and maintenance cost (materials, man power and services, insurances, safety inspections and safeguards etc.),
- fuel cycle costs (uranium acquisition, conversion, enrichment, fuel fabrication, reprocessing and radioactive waste disposal).

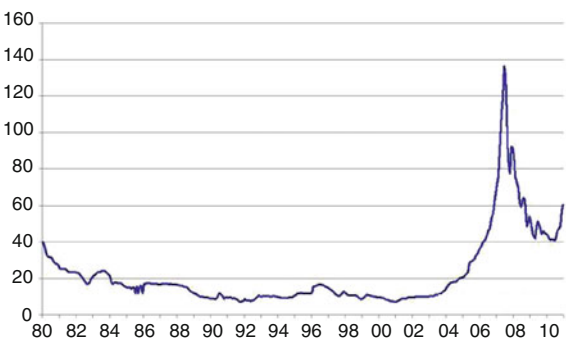
Figure 1.4 shows the cost structure of nuclear electricity generating costs. Nuclear power reactors typically have high investment costs of about 60%, maintenance cost

Fig. 1.4 Cost structure of nuclear electricity generation [2]. *Source* NEA and IAEA (2005)



*The cost of natural uranium typically represents only 5%.

Fig. 1.5 Uranium price development between 1976 and 2010 for uranium coming from different regions of the world [8]



of about 25% and fuel cycle costs of only about 15%. The costs of the uranium typically represent only about 5% of the total electricity generation costs [2].

Figure 1.5 shows the uranium market price development between the years 1976 and 2010. The uranium price development depends on a number of factors. The predominant factors are the uranium production and supply situation by the uranium mining industry and the demand of uranium by the nuclear power reactor industry.

1.4.2 Example for Projected Nuclear Electricity Generating Costs of a 1.6 GW(e) PWR

The OECD/NEA reported the following cost structure for a 1.6GW(e) PWR in 2007 (UK Department of Trade and Industry and Direction Générale de l’énergie et des matières premières of the (DTI) French Ministry of Economy) [2]:

Construction cost of the plant	2,500 US \$/kW(e)
Construction period	6 years
Plant availability factor	90%
Operation life time	60 years
Discount rate	10%

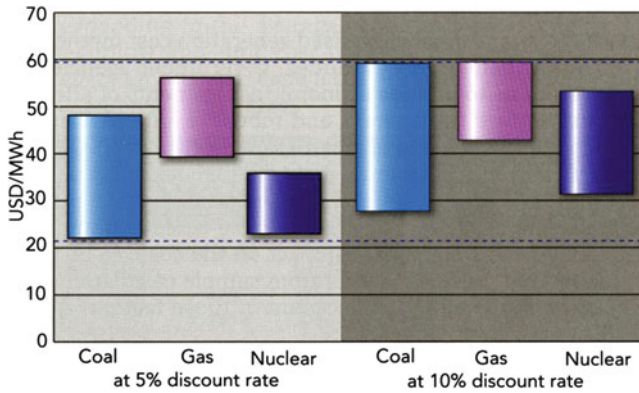


Fig. 1.6 Comparison of electricity generating costs for coal, gas and nuclear energy (for 5 and 10% discount rate) [2]

This leads to nuclear electricity generating costs of 6.2 US ¢/kWh. If a 30% cost overrun of construction cost would be assumed (DTI) these nuclear electricity generating costs could rise up to 8.8 US ¢/kWh. A lower discount rate of 5% instead of 10% would lower the nuclear electricity generating cost by about 30–35% [2]. The dependency on the discount rate is a characteristic of capital intensive technologies, such as nuclear power plants.

1.4.3 Cost Comparison for Nuclear Energy, Coal and Gas

Structures for construction costs, operation and maintenance, interest rates, taxes etc. are different in different countries. The OECD/NEA published in 2005 extensive studies and comparisons for electricity generation in different countries for the three main primary energies (coal, gas, nuclear). Figure 1.6 shows the results of this sensitivity study. The total electricity generation costs of three electricity generating base load plants (coal, gas and nuclear) with a 5 and 10% discount rate are compared. (The ranges shown do not contain the lowest and highest values obtained in these studies).

The nuclear energy cost ranges are in most cases lower than the competing plants using coal and gas. However, there are also cases for which coal can be as competitive as nuclear (5% discount rate case).

The cost projections given in Sect. 1.4.2 are somewhat higher, since they are based on higher construction cost.

Table 1.3 Average CO₂ emissions by energy source (kg CO₂/kWh) [2, 9, 10]

Energy chain	Average CO ₂ emissions
Lignite	1.2
Hard coal	1.07
Oil	0.9
Natural gas (combined cycle)	0.4
Solar PV	0.060
Wind (offshore)	0.014
Wind (onshore)	0.011
Nuclear	0.008
Hydro	0.005

1.5 Comparison of Environmental Impacts of Nuclear Energy

1.5.1 Carbon Dioxide Emissions

Nuclear power avoids to a large extent the emission of CO₂ during electricity generation. Table 1.3 shows the CO₂ emissions in kg CO₂ per kWh electricity generation for different energy sources. The data were determined as average values on a full life-cycle basis (construction, operation, decommissioning) of the power plants [2, 9, 10]. Each of the time periods for construction, operation and decommissioning produces its own CO₂ emissions since their realization consumes energy.

Lignite and hard coal have the highest CO₂ emissions per kWh during operation of these plants for energy production followed by oil and gas. Plans for coal fired plants to sequester the CO₂ from the flue gas and store it underground can lower these CO₂ emissions by about 80%.

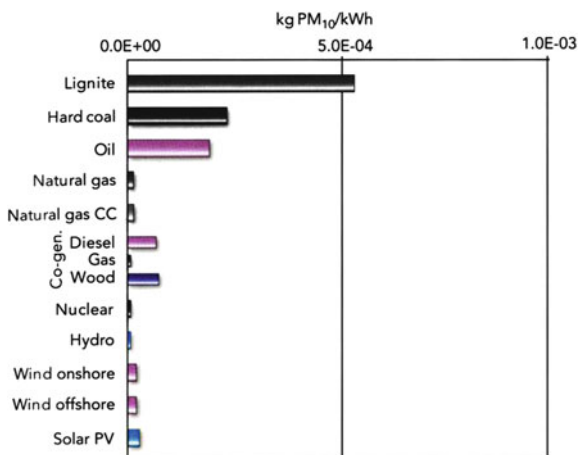
Nuclear power together with hydro power, wind and solar power have the lowest CO₂ emissions. CO₂ emissions are only produced during their construction and decommissioning phases. According to OECD/NEA nuclear power has already avoided between 1971 and 2004 more than 20% of the CO₂ which would have been emitted otherwise [2].

1.5.2 Particulate Emissions

Particulate emissions refer to aerosol particles (solid or liquid) in the atmosphere. Power stations and other industrial processes or diesel engines are the main sources of particulate emissions. Particles smaller than 10 microns (PM₁₀) are responsible for health damage (lung diseases). Figure 1.7 shows the life-cycle releases of particulates (PM₁₀) in kg/kWh for selected energy chains. Lignite, hard coal and oil are mainly responsible for the highest particulate emissions followed by Diesel engines and wood burning.

Natural gas, wind, solar, hydro and nuclear power show the best performance for the emissions of particulate matter (PM₁₀).

Fig. 1.7 Particulate emissions by energy sources (kg PM₁₀/kWh) (OECD-NEA) [2, 9, 10]



1.5.3 SO₂ Emissions

For fossil fuel (lignite, hard coal, oil) power plants the SO₂ emissions depend on the sulphur content of the fuel. Figure 1.8 shows the SO₂ emissions for different energy chains on a life-cycle basis in kg SO₂/kWh. Lignite, hard coal and heavy oil have the highest SO₂ emission. Again natural gas, solar, wind, hydro and nuclear power have the lowest SO₂ emissions.

1.5.4 NO_x Emissions

Figure 1.9 shows the NO_x emissions on a life-cycle basis for the different energy chains. The high temperature of the combustion process with air for the fossil fuel is mainly responsible for the high NO_x emissions of lignite, hard coal, oil and natural gas. Again hydro, wind and nuclear power have the lowest NO_x emissions.

1.5.5 Radioactive Gas and Liquid Emission

The above mentioned emissions do not cover the emission of radioactive substances, e.g. hard coal contains uranium and thorium and their daughter products on a ppm level.

In case of nuclear energy the whole nuclear fuel cycle starting from uranium mining and conversion to fuel fabrication, nuclear energy production in fission reactors, fuel reprocessing and refabrication as well fuel waste disposal must be considered. During uranium mining and milling, radium and radon will be released or

Fig. 1.8 SO₂ emissions by energy source (kg SO₂/kWh) (OECD-NEA) [2, 9, 10]

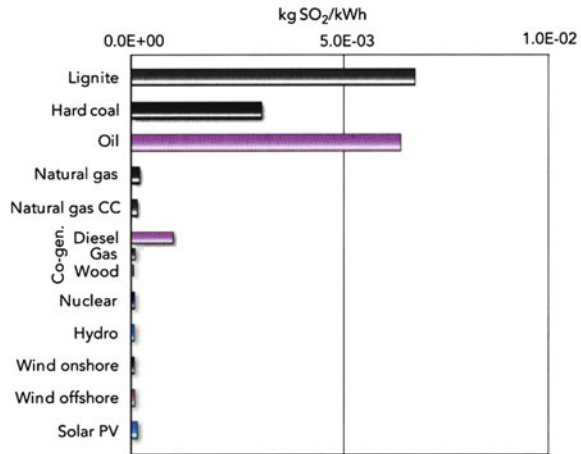
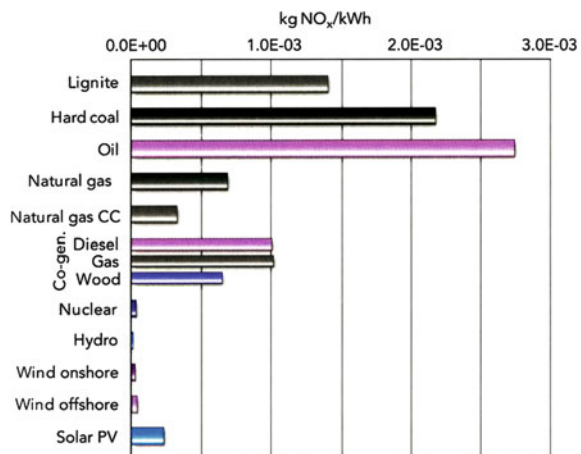


Fig. 1.9 NO_x-emissions by energy source (kg NO_x/kWh) (OECD-NEA) [2, 9, 10]



emitted. The tails from mining and milling must be covered by a layer of several meters of sand to prevent radon emission. Uranium mining and milling cause similar collective global radioactivity exposure as nuclear fission reactors (Chap. 10) [2].

Uranium enrichment and fuel fabrication plants have much lower radioactivity releases to the environment than nuclear fission reactors (Chap. 10). The radioactivity release of nuclear fission reactors and of spent fuel reprocessing plants are given in Chap. 10. These radioactive substances released into the air or water typically lead to radioactivity exposures of the public which are about 1% of the natural background radiation levels (Chap. 10) [2].

Both the operational and potential accidental radioactivity exposures to the environment will be discussed in detail in Chaps. 10 and 11.

1.6 Sustainability of Nuclear Energy

The definition of sustainability of energy-systems was published by the Brundtland Commission of the World Commission for Environment and Development of the United Nations [11]. This can be cast into the following requirements for energy [12]:

- No short time depletion of resources.
This can assured by the large scale introduction of the FBR technology and the utilization of U-238 and Th-232 ores for many thousands of years as mentioned in Sects. 1.2 and 2.2.1 and presented in detail in Chap. 6.
- Extremely low emission of noxious or radioactive substances.
This was shown in Sect. 1.5 and will be presented in more detail in Chap. 10.
- Extremely low risk for the population and environment.
The extremely low risk of nuclear energy technology in comparison to other energy technologies will be presented and discussed in Chap. 11. The transformation of the very long term risk of nuclear waste disposal into a few thousands years problem by partitioning and transmutation or destruction of long-lived radiotoxic nuclides will be discussed in Chaps. 7 and 9.
- The economical competitiveness of nuclear energy was shown in Sect. 1.4.

It will be shown in the subsequent sections that nuclear energy can satisfy the requirements for sustainability of the Brundtland Commission of the United Nations.

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