11 Uranium and Nuclear Energy

The peaceful use of nuclear energy began in the 1950s with the assumption that it would make electricity abundantly available at low cost. However, mistrust of this energy technology has been salient from its beginnings. After the nuclear catastrophe of 1986 in Chernobyl, Ukraine, public acceptance of nuclear energy plummeted in industrial countries even though the Chernobyl reactor was of a very different design from those common in Western models. The following issues are addressed in this chapter:

– What are the risks of accidents in nuclear power plants from a technical perspective?
– What are the dimensions of potential damages?
– What type of risk assessment does the economic model lead to in the case of nuclear power?
– What insurance premiums are to be expected if nuclear risks are to be internalized?
– Are the risks of nuclear power plants insurable at all?

If a reassessment of nuclear power is taking place today, it is because greenhouse gas emissions and the need for an active climate protection policy combine with concerns regarding energy supply security. Such a reassessment gives rise to an additional set of questions:

– How long are uranium reserves expected to last?
– What are the costs of uranium fuels, and what are their major components?
– Is the industrial structure of the uranium market competitive or rather monopolistic?

Finally, there are issues such as the secure final disposal of radioactive waste as well the dangers of proliferation of nuclear fuels for military purposes. These

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aspects are touched on briefly in this chapter, while the comparative efficiency of nuclear power plants in electricity generation will be discussed in Sect. 12.2.

The variables and symbols used in this chapter are:

A	Activity of a radioactive substance
av	Pratt-Arrow measure of (absolute) risk aversion
D_k	Damage associated with damaging event k
D_{PSA}	Damage according to the probabilistic safety analysis (PSA)
$E[D]$	Expected overall damage (accident value)
μ	Expected loss at the individual level
N	Number of atoms not yet disintegrated/decayed
POP	Number of individuals exposed to an accident risk
R	Risk assessment
σ^2	Variance of damage
$T_{1/2}$	Half-life of radio activity
U	Utility
W	Wealth
w_k	Probability of occurrence of damage scenario k, per year

11.1 The Foundations of Nuclear Technology

The technical application of nuclear power is based on the discovery of Albert Einstein at the beginning of the twentieth century, stating that mass can be transformed into energy. Energy extraction from mass could 1 day become possible through the fusion of light atoms (for example, hydrogen) to heavier atoms (for example, helium). In contrast, contemporary nuclear power generation uses fission of rather heavy atoms (with an uneven number of neutrons) into lighter atoms. The most important milestones in the development of nuclear technology are listed in Table 11.1. The ‘Atoms for Peace’ speech of 1953 epitomizes the significant governmental support for nuclear technology. Initially motivated by military interests, later made available for civilian purposes, the large-scale application of light-water technology (which dominates the present electricity generation of nuclear power plants) would not have materialized.

In nuclear power plants, thermal energy produced by nuclear fission is used to activate a Carnot process (see Sect. 2.2.2). The most widespread commercial reactor type is the light-water reactor (LWR), which comes in two common variants. In the boiling water reactor, steam with a pressure of about 70 bar and a temperature of 290 °C is led directly to a steam turbine. Having done its work, the steam cools down to become water. In the pressurized water reactor, there are two cooling circuits, one of them separated from the nuclear reaction. A pressure of 150–160 bar in the primary cooling circuit prevents the vaporization of the water, which is conducted into a steam generator. There, it is cooled down before returning to the nuclear reactor. The steam generator produces saturated steam, which drives

Table 11.1 Milestones for the development of nuclear power

1896	Discovery of radioactivity by Antoine H. Becquerel
1897	Separation of radium from uranium by Marie and Pierre Curie
1938	Proof of the technical feasibility of nuclear fission by Otto Hahn and Fritz Strassmann
1941	First demonstration of the chain reaction by Enrico Fermi
1945	Dropping of atomic bombs on Hiroshima and Nagasaki (both in Japan)
	Development of the nuclear fusion bomb
1953	'Atoms for Peace' speech by President Dwight D. Eisenhower, who offered to share nuclear power technology with countries who are willing to abandon the development of nuclear weapons
1970	Non-proliferation treaty of nuclear weapons, monitored by the International Atomic Energy Agency (IAEA) in Vienna (Austria)
1979	Accident of the nuclear reactor Three Mile Island in Harrisburg (United States)
1986	Chernobyl catastrophe (Ukraine)
2011	Reactor accident in Fukushima (Japan)

a steam turbine for the generation of electricity in a secondary cooling circuit. This separation of the nuclear from the conventional cycle constitutes a safety feature.

About 90% of the 440 nuclear reactors in operation worldwide are of the LWR type. Installed capacities of a block vary between 300 and 1600 MW, compared to 8 MW of the wind turbine with the highest performance as of 2016. In many cases, several blocks are combined to form a nuclear site. Total installed net capacity of nuclear power plants reaches 370,000 MW worldwide, representing 14% of thermal power plant capacity. In 2014, nuclear power plants generated almost 2.6 mn MWh of electrical energy (16% of global power generation, with Europe accounting for 3.3 mn MWh). Particularly in the 1980s, electricity generation through nuclear power plants boomed in response to the two oil price shocks of 1973 and 1979. However, the Chernobyl accident of 1986 caused most Western countries to impose a moratorium or at least slow down on new power plant construction. Until recently, the increase in nuclear energy production since 1990 has been mainly the result of a more efficient operation of existing reactors in the United States and in Europe.

11.1.1 Radioactivity

The radioactivity of a substance is measured by the amount of radioactive decay per second (Becquerel). With N_t being the number of atoms not yet disintegrated, radioactivity A_t is equal to

$$A_t = \frac{\ln(2)}{T_{1/2}} \cdot N_t \tag{11.1}$$

with $T_{1/2}$ denoting the so-called half-life time at which the radioactivity of a substance is halved.

Three types of radioactivity can be distinguished.

– α radiation (helium nuclei): An α particle usually provides an amount of energy between 0.005 to 0.006 eV (electronvolt; 1 eV = $1.6 \cdot 10^{-19}$ J). This type of radiation is short-range only so it can easily be shielded, e.g. using a sheet of paper.
– β radiation (electrons): The energy of β particles lies in the range of 0.0001–0.002 eV and can be absorbed by a metal plate with a thickness of a few millimeters.
– γ radiation (photons, i.e. quants of electromagnetic radiation): γ radiation derives from the excess energy produced by nuclear decay in the fission processes (which also gives rise to α or β radiation). Its energy lies in the range of 0.0001 and 0.005 eV. Shielding from it is technically demanding and requires heavy materials such as lead or concrete.

To account for these differences, one distinguishes between the energy dose (Gray, Gy) and the radiation equivalent dose (Sievert, Sv). The latter attributes a weight of 1 to β and γ radiation but of 20 to α radiation in order to reflect its particular biological harmfulness. In Europe, average natural radiation exposure of the human body is around 0.002 Sv per year. In addition, medical exposure through x-ray diagnostics in particular amounts to the same magnitude (Table 11.2).

The energy of the emitted particles is absorbed by the surrounding matter. Thereby the atoms of these substances become ionized, causing a temperature increase. The ionization of living cells can change and even destroy them, resulting in radiation sickness. Inside the cell nucleus, radiation can also cause mutations and genetic damage.

With regard to the living body, a distinction is made between external and internal radiation. Internal radiation is particularly dangerous, because it is related to the absorption of radioactive substances by the organism and thus to a continuous exposure to radiation. The health impacts depend on the organ accumulating the radioactive substances and on the duration of exposure.

Human beings experience radiation sickness from a short-term equivalent dose of 0.5 Sv onwards, while cell mutations can already occur at a much lower value. The living organism has the ability to partly repair damages caused by radioactive radiation, provided overall radioactive exposure does not exceed certain limits. As

Table 11.2 Radioactivity units

Feature	Unit		Description
Activity Energy dose	Becquerel Gray	Bq Gy	1 decay per second Energy absorbed by matter (J/kg)
Equivalent dose	Sievert	Sv	Biologic impact of the energy absorbed by the matter (J/kg)
	Rem	= 0.01 Sv	Outdated unit

there is no possibility of determining these limits experimentally, one falls back on the assumption that natural radioactive radiation is tolerable, neglecting large geographical differences.

11.1.2 Uranium as the Dominant Fuel for Nuclear Power

Due to its easy fissionability, the uranium isotope ^{235}U is the most important nuclear fuel. The raw material is natural uranium ore, which consists of the isotope ^{238}U (99.29%) and the isotope ^{235}U (0.71%). The uranium isotope ^{235}U can be split into lighter atoms by bombarding it with slow and low-energy neutrons. Fission of one ^{235}U nucleus releases $3.2 \cdot 10^{-11}$ J of heat (a consequence of the so-called mass defect). With each fission, two or three new neutrons are created which induce the decay of further ^{235}U-nuclei in the guise of a chain reaction. With the help of moderators, the neutrons are slowed down. In the LWR, the moderator is natural water, which is also used for discharging the heat produced by nuclear fission from the reactor vessel.[1] The chain reaction is controlled and can be stopped using so-called control rods made of cadmium that partially absorb the neutrons.

Producing uranium fuel is technically complex and associated with risks of radiation. Uranium mining constitutes the first step of the production chain. The extracted uranium oxide (U_3O_8, so-called yellowcake) has a uranium concentration of 60–85%. To achieve the required degree of purity of 99.95%, the uranium ore is dissolved in nitric acid, filtered, treated with chemical solvents, and reconverted into uranium oxide.

In order to maintain the chain reaction in light-water reactors, concentration of ^{235}U isotopes in the nuclear fuel needs to be increased from 0.71% to 3 to 4%.[2] For this enrichment process, uranium oxide has to be converted into the gaseous uranium hexafluoride UF_6, which is channeled to gas centrifuges. At this point the separation of ^{235}U from 238 U isotopes proceeds by taking advantage of a difference in their molecular mass. It takes place in so-called separative work units (SWUs) and requires 50 kWh/kg of electricity. The enriched uranium hexafluoride is chemically reconverted into uranium oxide powder UO_2, to be processed to uranium fuel rods.

According to Table 11.3, the production cost of uranium fuel is 1880 USD/t UO_2 as of 2016. One kilogram uranium oxide powder UO_2 generates about 3400 GJ of heat (944.6 MWh heat), equivalent to about 315 MWh of electricity. Thus, the fuel cost of nuclear power amounts to 5.97 USD/MWh or 5.43 EUR/MWh, a rather low figure compared to fossil power plants (e.g. 40 EUR/MWh for gas-fired power plants).[3]

[1] Other possible moderators are heavy water D_2O or graphite ^{12}C; in this case, the chain reaction also proceeds using natural uranium.

[2] For nuclear weapons an enrichment level of >90% is necessary. Thus, weapons-grade material can be converted to nuclear fuel by blending it with depleted uranium.

[3] A currency exchange rate of 1.1 USD/EUR is assumed for 2016.

Table 11.3 Unit cost of uranium fuel production

Process	Quantity per kg fuel (kg)	Average price (USD/kg)	Average price (USD/tons UO_2)
U_3O_8 mining	8.9	97	862
Conversion	7.5	16	120
Enrichment	7.3 SWU[a]	82	599
Fuel assembly for production	1	300	300
Total			1880

[a]SWU: Separative work units; data source: WNA (2016)

11.1.3 Nuclear Waste

Table 11.4 provides an overview of the transformation of 100 t of uranium fuel during a 3-year period of use in a nuclear reactor. Only part of the isotope ^{235}U is split into lighter materials that can be used for generation. In addition, radioactive plutonium is produced from the isotope ^{238}U, which partly decays during the 3-year period, releasing heat.

Unlike the source material, used nuclear fuel is highly radioactive. It produces large amounts of residual heat (around 250 MW_{th} in a nuclear power plant of 1400 MW_{el} capacity) even after the reactor is turned off. This heat has to be dissipated to prevent destruction of the reactor containment, causing the release of radioactive material into the environment.

Usually, nuclear fuel rods are removed from the reactor after a 3-year period of use. At that time, the rods contain about 35 different chemical elements with about 300 radioactive isotopes. After their removal, the spent rods are first stored in a water basin for several decades before being transferred to a reprocessing facility or a final waste deposit. During interim storage, short-lived isotopes lose most of their radioactivity. In contrast, plutonium isotopes (so-called transuranium isotopes) with their long half-life represent a source of long-term nuclear radiation. Table 11.5 shows the time profiles of the respective sources of radioactivity.

During the reprocessing of used nuclear fuel rods, plutonium and unspent uranium isotope 235 U are removed, to be used in the production of new fuel rods which are of the mixed oxide (MOX) type. As a consequence, radioactivity of the remaining nuclear waste diminishes over time, thus reducing the cost of final waste disposal. On the other hand, reprocessing poses considerable safety challenges. It is also much more expensive than the direct disposal of nuclear waste, even when crediting the nuclear fuel recycled. Therefore, direct disposal of nuclear waste is the preferred alternative in many countries.

For a classification of radioactive waste, besides radioactivity the heat arising from radioactive decay is also of importance. Given that the increase in temperature should not exceed 3 °C for geophysical reasons, about 95% of the volume of waste can be stored in a final deposit. This value includes waste associated with the later demolition of the power plant.

Table 11.4 Inventory of 100 tons uranium fuel after 3 years in a light-water reactor

Input	Reaction	Output (after 3 years)
3300 kg ^{235} U	(no reaction)	756 kg ^{235} U
	Capture of neutrons	458 kg ^{236} U
	Fission	2100 kg fission products
96,700 kg ^{238} U	(no reaction)	94,200 kg ^{238} U
	Breeding reaction	900 kg plutonium Pu
	Capture of neutrons, α, β decay	70 kg Np, Am, Cm
	Fission	1500 kg fission products of Pu

Source: Staub (1991)

Table 11.5 Radioactivity of 100 tons uranium fuel and waste

		Years after removal of waste from the nuclear reactor			
Isotope	Before usage	1	100	1000	100,000
	(10^{12} Bq, i.e. decays per second)				
Uranium ^{238}U	44	43	43	43	43
Uranium ^{235}U	10	2	2	2	2
Plutonium ^{238}Pu	–	430,000	190,000	0	0
Plutonium ^{239}Pu	–	40,000	40,000	40,000	2335
Plutonium ^{240}Pu	–	70,000	70,000	50,000	2
Plutonium ^{241}Pu	–	13,700,000	70,000	0	0
Plutonium ^{242}Pu	–	200	200	200	167
Krypton ^{85}Kr	–	20,400,000	30,000	0	0
Strontium ^{90}Sr	–	17,400,000	1600,000	0	0
Cesium ^{134}Cs	–	37,000,000	0	0	0
Cesium ^{137}Cs	–	30,200,000	3,100,000	0	0
Neptunium ^{237}Np	–	46	46	46	44
Americium ^{241}Am	–	44,400	38,200	2150	0
Americium ^{243}Am	–	1000	1000	828	0.08
Curium ^{245}Cm	–	1400	1400	1200	0.1

Source: Staub (1991)

However, the remaining 5% of radioactive substances (being isotopes) contain 99% of the radioactivity, calling for a staggered system of artificial and natural barriers in geologically suitable final deposits for highly radioactive waste. Exposure to radiation at the surface should not exceed the limit of 0.1–0.3 millisievert (10–30 millirem) per year. At present, no final storage facility satisfying this requirement is in operation anywhere around the globe, implying that the cost of storage can only be estimated. According to the World Nuclear Association, it is in the range of 1 EUR/MWh generated electricity (in the case of direct waste disposal) and 1.50 EUR/MWh (after reprocessing). At a maximum, this amounts to one-fourth of the production cost of uranium fuel.

To finance the final disposal of radioactive substances and the dismantling of nuclear power plants after their shutdown, plant operators often accrue reserves themselves or pay a certain amount of money per MWh to a public fund designed to cover the future cost of waste disposal and plant dismantling. National governments decide which of the two modalities applies, which differ in terms of their cost implications for nuclear power. Although this creates scope for distortion of competition in the energy industry, the European Commission has so far abstained from issuing a directive aiming at harmonization.

11.2 Uranium Market

The Nuclear Energy Agency of the OECD and the International Atomic Energy Agency (IAEA) of the United Nations publish a statistical compilation of global uranium reserves in biannual intervals, based on data provided by about 20 -uranium-producing countries (see Nuclear Energy Agency 2014). Taking into account that for a resource to become an economically relevant reserve, its sales price must at least cover the cost of extraction, several cost levels are distinguished. For instance, at a unit cost of 130 USD/kg U_3O_8 (a rather high value compared to extraction cost in 2016 according to Table 11.3), known uranium reserves are about 5.9 mn tons.

Global demand by nuclear power plants currently amounts to roughly 50,000 tons of natural uranium per year (see Table 11.6). If this figure is compared to recoverable uranium reserves, a static range of more than 100 years can be inferred.

Per MW of power plant capacity, the natural uranium requirement equals about 160 kg on average per year (compare this to the 250,000 tons of hard coal per MW and year required by a typical coal-fired plant). More advanced reactors are likely to have an even lower specific uranium requirement. The Swedish Oskarshamm·3 reactor with 1400 MW installed capacity may serve as an example. Following the repeal of the nuclear phase-out decision in Sweden, it was retrofitted to generate between 0.8 and 1.3 mn MWh electricity per ton of ^{235}U, depending on mode of operation. This means that its uranium requirement may be as low as 18 g/MWh, 30% below the global average cited in Table 11.6. This reduction results from an increase in thermal efficiency and a higher yield in ^{235}U-combustion, due to an enrichment of the uranium fuel to more than 4% ^{235}U.

Figure 11.1 compares the development of global military and civilian demand for uranium with that of global extraction. Between 1950 and 1970, production

Table 11.6 Global uranium demand for power generation in 2014

	Capacity	Energy
Global nuclear capacity	300,000 MW	1900 TWh
Specific ^{235}U demand	0.0124 tons/MW	1.95 tons/TWh
^{235}U demand	3700 tons/a	
Natural uranium demand	49,000 tons/a	
Specific natural uranium demand	0.16 tons/MW and a	26 g/MWh

Data source: Nuclear Energy Agency (2014)

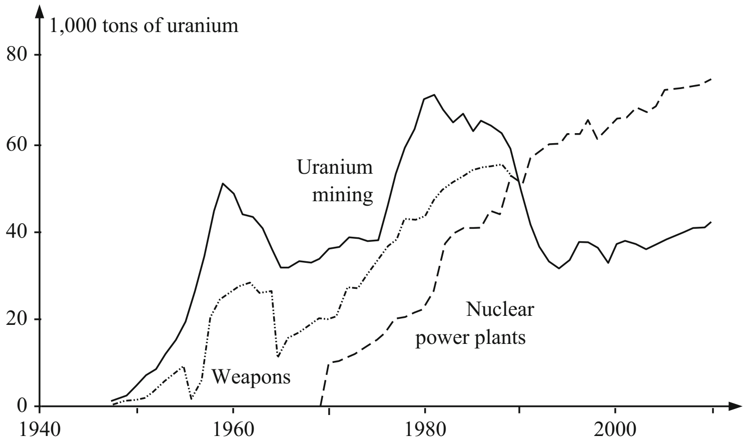


Fig. 11.1 Uranium supply and demand (source: Gerling et al. 2005)

consistently exceeded global demand, something one is unlikely to observe in a competitive market. A plausible explanation is governmental stockpiling for military purposes (note that the pertinent time series ends after 1990). Even with the advent of nuclear power plants in the late 1960s, excess production continued for two decades. Nevertheless, the price of natural uranium rose to more than 80 USD/kg during the second half of the 1970s due to expectations of a rapid expansion of global nuclear power capacities.[4] Again, governmental stockpiling played a role as well, by the U.S. Atomic Energy Commission who initially was the only supplier of enriched uranium in the western world. Westinghouse/Toshiba, the leading producer of nuclear power plants at the time, reinforced the price increase by purchasing uranium beyond its short-term requirements.

However, expectations of a bright future for nuclear power were dashed in 1979 when the accident at the pressurized water reactor of Three Mile Island (Pennsylvania, United States) occurred—with global uranium production reaching an all-time high just then. The drop in demand caused uranium production and price to fall, the latter to a level below 40 USD/kg. Pressure on price further intensified during the 1990s, when traders started selling Russian nuclear fuel on the world market. U.S. American and European restrictions of imports from Russia could not prevent a collapse to about 20 USD/kg, even though many uranium mines abandoned their production at the time. While weapons-grade uranium became available for civilian use, there was still a shortfall of uranium supply relative to current requirements of nuclear power plants.

Only after 2003 did this shortfall result in a hefty increase in the price of natural uranium. The price hike by a factor four is comparable to that in crude oil prices

[4] In U.S. statistics, the natural uranium price is specified in USD/lb (pound). A kilogram corresponds to a mass of 2.205 lb.

after 2000 (see Sect. 8.3). Reduced uranium exports of Russia and a series of accidents in uranium mines and processing plants contributed to this price explosion. While an acceleration of global uranium exploration and development has been observed lately, comparatively high prices are likely to persist because these investments take 5–7 years to affect production.

Uranium production is heavily concentrated regionally, with only five countries accounting for three-fourths of it, namely Canada (28%), Australia (23%), Kazakhstan (9%), Nigeria, and Russia (8% each). The United States, just like China, produce their own uranium oxide but need imports to meet their demand. France, Japan, Germany, and Great Britain are entirely dependent on imports.

Corporate concentration is marked as well, exceeding that in crude oil and coal markets. At the level of natural uranium extraction, the four largest companies currently have a joint market share of more than 60%. These are Cameco (Canada, 20%), Rio Tinto (Australia, 20%), Areva (France, 12%), and BHP Billiton (Australia and Great Britain, 9%).

At the level of uranium enrichment, the U.S. government allowed private possession of uranium only after 1968, and state monopolies have in fact persisted since then. The largest ones currently are the Russian TENEX (32% market share), the United States Enrichment Company (U.S. Department of Energy, 17%), and the French Areva (15%)—all government-controlled. Only the production of fuel rods has a competitive industry structure.

This heavy governmental involvement is the likely reason that with the exception of French Areva, there are no vertically integrated companies along the nuclear value chain in the western world. In fact, economic conditions (factor-specific assets, high transaction costs, and high supplier concentration) would favor such an industry structure (see Sects. 8.2.1 and 9.3.1). In spite of its consolidation during the 1990s, the industry is unlikely to become more vertically integrated in future in view of governmental reservations in particular against private uranium enrichment.

Operators of power plants are the customers of the producers of nuclear fuel. Even at a historically high price of 130 USD/kg natural uranium, their variable fuel costs are very low compared to coal-fired and gas-fired power plants (see Sect. 12.2.2). The cost of fuel being such a small part of the total, still higher uranium prices would not make them lose their competitiveness. In addition, most nuclear power plants are almost fully amortized, while fossil power plants are likely to be burdened by the cost of avoiding CO_2 emissions in the near future.

11.3 Risk Assessment of Nuclear Energy

Risks associated with nuclear power are of three types. First, abuse of nuclear fuels (enriched uranium, plutonium) for military and terrorist purposes needs to be prevented effectively. Second, secure final waste disposal of radioactive substances needs to be guaranteed for a long period of time. Third, incidents in nuclear power plants must not lead to the release of large quantities of radioactive substances.

All three risks are borne only in part by the operators of nuclear power plants—and ultimately by the consumers of electricity. Therefore, they constitute external effects of a stochastic nature. Economic efficiency in the management of such risks calls for an amount of preventive effort such that its certain marginal cost equals the expected value of marginal utility (for a discussion of this condition as well as ways to attain it, see Sect. 7.3), for example by imposing an internalization tax (so-called Pigou tax; see Fig. 7.4 in Sect. 7.3.1). However, such policy measures require knowledge of both the marginal cost and marginal utility schedules. Both of these schedules are extremely difficult to estimate.

While economists generally are in favor of internalization through price ('the polluter pays' principle), they tend to prefer legal rules and norms in this instance to deal with the risks cited above.

- Theft and abuse of nuclear fuels (enriched uranium, plutonium) for military and terrorist purposes: To decrease this risk, a surveillance system for nuclear power, enrichment, and reprocessing plants was created by the International Atomic Energy Agency IAEA. However, only countries who have ratified the Treaty on the Nonproliferation of Nuclear Weapons of 1970 submit themselves to this surveillance. Furthermore, even after ratification some countries have been conducting fairly advanced clandestine nuclear weapon programs. This demonstrates that fully-fledged surveillance is not possible in the long run. Finally, nongovernmental organizations increasingly possess both the financial means and knowledge necessary to acquire and use nuclear weaponry. The proliferation of nuclear weapons is thus difficult to prevent in the long run, calling for the consideration of additional instruments in security policy. However, this issue is hardly related to the civilian use of nuclear power; indeed, countries without commercial nuclear power have been able to acquire nuclear weapons in the past. Thus, even a global phasing-out of nuclear power would not entirely eliminate the risk of proliferation.
- Final disposal of radioactive waste from nuclear power plants: Spent fuel remains highly radioactive over a period of 100,000 years (see Sect. 11.1.3, particularly Table 11.5). There are technical procedures and geological deposits that prevent release of radioactivity into the biosphere even beyond periods that humans are able to foresee. However, if a discharge of radioactivity should occur far in future, neither plant operators, nor insurance companies, nor governments can be held liable. A possible solution could be the conversion of radioactive waste into less dangerous substances through irradiation with neutrons and protons (so-called artificial nuclear transmutation). However, at present not even commercial pilot projects are under way anywhere in the world.
- Incidents in nuclear power plants: This risk category constitutes a different case. The peaceful use of nuclear power is based on the precondition that the release of radioactive substances is limited to an amount corresponding to the natural level of radioactivity. Permanent adherence to this precondition can be verified during the life of a nuclear power plant; given normal operation, it is satisfied. However, a severe incident can lead to the release of very large quantities of radioactive

substance. There are mechanic and electric systems designed to prevent this. While they are characterized by a great deal of redundancy, they may fail with a very small probability. The following section is devoted to the estimation of this probability.

11.3.1 Probabilistic Safety Analysis of Nuclear Power Plants

Probabilistic safety analysis (PSA) is a procedure to determine the annual probability with which a particular system may fail. In the case of a nuclear power plant, the system should prevent the release of the plant's radioactive inventory (the so-called source term). PSA also seeks to quantify the corresponding damages in monetary units.[5] This method, originally developed by Rasmussen et al. (1975), has become the most common procedure to calculate the operational risk of nuclear power plants (U.S. Nuclear Regulatory Commission 1991).

The results of a probabilistic safety analysis are k loss scenarios with their estimated annual probabilities of occurrence w_k and the respective damages D_k. For the case of the nuclear power plant Mühleberg in Switzerland, seven loss scenarios with an increasing source term are distinguished in Table 11.7.

The so-called expected loss is given by

$$E[D] = \sum_k D_k \cdot w_k. \tag{11.2}$$

Expected loss $E[D]$ is a measure of financial risk commonly used in insurance; in the present context, it indicates the safety-related risk of a nuclear power plant. It is

Table 11.7 Accident scenarios for the Mühleberg nuclear power plant (Switzerland)

Source term (% of inventory)	Damage D_k (mn EUR)	Modeled frequency per year w_k	
		Given low release rates	Given high release rates
0	0	0.999992	0.9.99868
0.0005	4	$5.00 \cdot 10^{-6}$	$1.00 \cdot 10^{-4}$
0.5	4353	$1.00 \cdot 10^{-6}$	$2.00 \cdot 10^{-5}$
5.0	91,905	$1.30 \cdot 10^{-6}$	$6.67 \cdot 10^{-6}$
15.0	178,965	$4.00 \cdot 10^{-8}$	$3.33 \cdot 10^{-6}$
30.0	417,555	$1.00 \cdot 10^{-8}$	$1.00 \cdot 10^{-6}$
70.0	765,794	0	$1.00 \cdot 10^{-6}$
$E[D_{PSA}]$ (mn EUR)		0.135	2.480
Standard deviation (mn EUR)		118	961

Data source: Ott and Masuhr (1994, p. 83ff)

[5] This means that a value needs to be assigned to a (statistical) human life (see Sect. 7.4).

plant-specific, depending on reactor type, safety technology employed, and reactor site (because of weather conditions and population density in its vicinity). Since radioactive inventory increases with plant capacity, $E[D]$ is usually related to the annual amount of electricity generated, a very large quantity. For this reason, the values shown in Table 11.8 are just fractions of U.S. cents per kWh.

These values (see Table 11.8) are often used as a measure of the external cost of operation imposed on society by nuclear power plants because most of the damage is suffered by individuals who have no economic relationship with the plant. They are so small that the internalization of these stochastic externalities through a Pigou tax (see Sect. 7.3.1) would not affect the competitiveness of nuclear power vis-à-vis other power generation technologies.

For many engineers and physicists associated with nuclear technology, the lack of acceptance of nuclear energy-related risks by large parts of the population seems irrational. They turn to psychologists, sociologists, political scientists, and philosophers with the request to scientifically analyze the seemingly irrational behavior of specific social groups. However, this request emanates from a neglect of standard economic theory. For simplicity, let damage be measured in terms of the number of premature deaths D occurring with probability w. There is a choice between technologies which differ with regard to these two parameters. One of them is a coal-fired plant that causes 20 premature deaths due to air pollution with probability $w = 0.05$, resulting in $E[D] = 1$ (the actual probability is much closer to $w = 1.00$, but this would complicate calculations). Another is the LWR; with probability $w = 10^{-5}$, it causes the death of 100,000 persons, resulting also in $E[D] = 1$ (both values are on the high side but simplify calculations). Now engineers and physicists associated with nuclear technology typically argue that the two technologies (and in fact all technologies and their combinations with the same expected loss of $E[D] = 1$) should be viewed as equivalent. In Fig. 11.2, they are all on the same hyperbolic locus (note that $w \cdot D = 1$ implies $w = 1/D$), constituting the feasibility frontier. Coal-based generation is represented by point C, the nuclear alternative, by point N.

Yet people have preferences regarding the choice of technology. Let there be just two types of people, I and II. Their preferences are depicted by indifference curves, along which expected utility is constant. The direction of preference is indicated by arrows which point to the origin since ($w = 0$, $D = 0$) constitutes the

Table 11.8 Expected loss of nuclear power plants

Author	Year	Expected loss(U.S. cents/kWh)
Friedrich/Voss	1993	0.006–0.041 (Germany)
Ott/Masuhr	1994	0.0007–0.12 (Switzerland)
CEPN	1994	0.00018–0.013 (France)
PSI/ERI	1994	0.0012 (Mühleberg, Switzerland)
PSI/ERI	1994	0.0014 (Peach Bottom, United States)
PSI/ERI	1994	0.0069 (Zion, United States)

Data source: ExternE (2003)

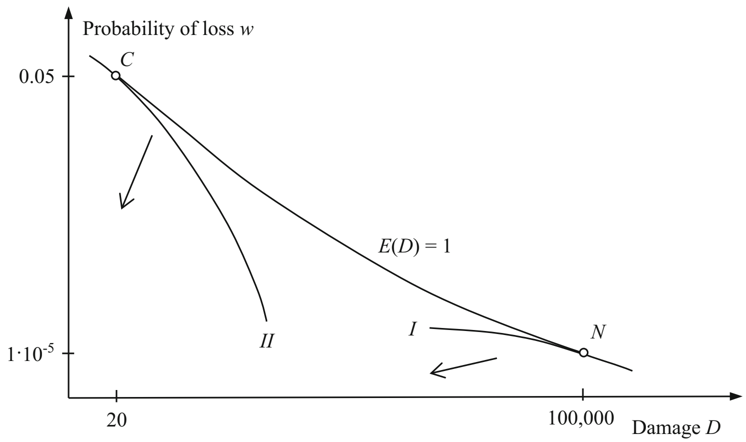


Fig. 11.2 The feasibility locus $E[D] = 1$ and two indifference curves

best imaginable situation for both types. This implies that for type *I*, the tangency point *N* is the optimal choice, involving exclusive reliance on nuclear power but no use of coal. For type *II* however, generation of electricity should optimally be by coal only.

Neither type *I* nor type *II* is irrational. The concavity of their indifference curves (more easily discernible for type *I*) indicates that when they have to accept a higher number of deaths, they both need to be compensated by an increasingly marked reduction in the probability of occurrence—a very intuitive assumption. However, type *I* would be willing to trade off a small decrease in the number of deaths *D* in return for a very small increase in the probability *w* only. For instance, he or she may have most relatives and friends living in the vicinity of the power plant, creating a particular interest in the survival of relatively few individuals. By way of contrast, type *II* would be willing to trade off the same decrease in the number of deaths *D* against a substantial increase in *w*. This type may have relatives and friends living spread out all over the world; only his or her survival is at stake. Note that sociological surveys are unlikely to identify the difference between the two types because they fail to confront respondents with the trade-off involved. If asked, "Do you find an energy-generating technology that may kill 100,000 people acceptable?", they will of course say 'No'. They may respond differently if made aware that the alternative is a technology that kills 20 people with a much higher probability (in reality, almost with certainty).

11.3.2 Risk Assessment According to the (μ, σ^2) Criterion

From an economic point of view, an internalization tax equal to the value of the expected loss as given by Eq. (11.2) would not bring about the welfare maximum in relation to the use of nuclear power. Recall that the appropriate condition states that the marginal cost of effort undertaken for risk prevention should be equal to its marginal utility in terms of risks reduction. However, marginal cost of effort is not directly related to expected loss while marginal utility is a subjective quantity. If a market for the prevention of nuclear risk existed (including the purchase of insurance coverage by private households), one would know that buyers' marginal utility is at least as high as the observed market price. Equivalently, their marginal willingness to pay (WTP) would be at least as high as the market price. Since no such market exists, one has to look for other ways to measure WTP.

A first approach is the so-called (μ, σ^2)-criterion which is popular for describing the behavior of risk-averse investors in capital markets. Its mathematical formulation can be traced back to Pratt (1964) and Arrow (1974) and amounts to a version of expected utility theory (see Sect. 3.5). According to it, the willingness of person i to pay for risk avoidance (denoted by R_i) is given by the expected loss μ_i the person is exposed to plus a surcharge that depends on the variance ${\sigma_i}^2$ of the possible loss and the individual's degree of subjective risk aversion av_i,

$$R_i = \mu_i + \frac{av_i(W_i)}{2} \cdot \sigma_i^2 \quad \text{with} \quad av_i(W_i) = -\frac{U_i''(W_i)}{U_i'(W_i)}. \tag{11.3}$$

The so-called coefficient of absolute risk aversion av_i depends on $U'_i(W_i)$, the curvature of the individual's risk utility function $U_i(W_i)$ which is a function of assets at risk W_i. In the context of the risks associated with nuclear power, willingness to pay of course importantly reflects concerns for health and survival. However, note that these concerns can be integrated by making the $U_i(W_i)$ function dependent on the state of health, see Zweifel and Eisen (2012). For marginal utility, one has $U'_i(W_i) > 0$, while the second derivative $U''_i(W_i)$ depends on the individual's risk preference. If $U''_i(W_i) > 0$, the individual is risk-seeking, if $U''_i(W_i) = 0$, he or she is risk-neutral. However, for a risk-averse individual, the second derivation is negative,

$$U_i''(W_i) < 0. \tag{11.4}$$

This implies that the person values a loss of assets more heavily than an equally probable gain of the same amount. From Eq. (11.3), one therefore has $av_i(W_i) > 0$ given risk aversion but $av_i(W) = 0$ given risk neutrality.

At the macroeconomic level, willingness to pay for the avoidance of nuclear risk R corresponds to individual values R_i summed up over the population POP exposed to the risk,

$$R = \sum_{i=1}^{POP} \mu_i + \sum_{i=1}^{POP} \frac{av_i(W_i)}{2} \cdot \sigma_i^2. \tag{11.5}$$

In the following, all persons POP are assumed to be exposed to the same loss with expected value μ and same variance σ^2 and to exhibit the same degree of risk aversion $av(W) > 0$. Thus, Eq. (11.5) reduces to

$$R = POP \cdot \mu + POP \cdot \frac{av(W)}{2} \cdot \sigma^2. \tag{11.6}$$

Although commonly used in transitions from the microeconomic to the macroeconomic level, assumptions of this type are admittedly not very realistic. In fact, they cut the social evaluation problem down to the willingness to pay of a representative individual for the avoidance of risk. However, such simplifications are helpful as a first step to estimate the magnitude of an aggregate willingness to pay value.

For an empirical implementation of Eq. (11.6), a value for the coefficient of absolute risk aversion $av(W)$ characterizing a society is needed. One way to infer a society's degree of risk aversion is to analyze the share of its assets it chooses to insure. This was done by Szipiro (1986) for a number of industrial countries.[6] Applying his estimate to the Swiss population, Zweifel and Nocera (1994) derived $av(W)$ to be between $5 \cdot 10^{-5}$ and $7 \cdot 10^{-5}$ per CHF. Using the 1994 conversion rate of 1.61 CHF/EUR, one obtains an interval for $av(W)$ of

$$8.1 \times 10^{-5} \text{per EUR} < av(W) < 11.3 \cdot 10^{-5} \text{ per EUR} \tag{11.7}$$

Although these are very small values, when multiplied with the variance of aggregate loss (which is huge), the surcharge over expected loss $POP \cdot \mu$ in Eq. (11.6) becomes sizable. Therefore, the view of engineers and physicists that expected loss is sufficient for assessing the risk of energy-related technologies is refuted (see Sect. 11.3.1).

This insight can be deepened by taking up the notion, touched upon in Sect. 11.3.1, that people do not care about their own health and survival only but also about that of relatives and friends. The results of the probabilistic safety analysis applied to the Swiss nuclear power plant Mühleberg (see Table 11.7) may serve as the point of departure. By dividing expected loss $E[D]$ by the number of persons POP exposed to the risk, one obtains an estimate of expected loss at the individual level,

$$\mu_i = \frac{E[D]}{POP}. \tag{11.8}$$

Now assume that people not only consider their own expected loss μ_i, but also that of 100 other persons μ_j, with $j \neq i$ (e.g. relatives, neighbors, friends, colleagues). Let their risk utility function be of the logarithmic type (it qualifies

[6]From an ethical point of view, one could argue that the use of market results is inadmissible when dealing with human life and health. This issue is discussed in Sect. 7.4.

because $U'_i(W_i) > 0$ and $U''_i(W_i) < 0$). After taking into account altruism, expected loss $\mu_{i,alt}$ thus becomes

$$\mu i, alt = (1 + \ln(100)) \cdot \frac{E[D]}{POP} = 5.6 \cdot \mu i. \tag{11.9}$$

In total, the individual evaluation of the damage increases by the factor 5.6 in contrast to calculations with the formulas (11.2) or (11.7).

Finally, the variance of potential damages σ^2 needs to be estimated. At the individual level, it is given by

$$\sigma i^2 = \sum_k \left(\frac{D_k - E[D]}{POP} \right)^2 \cdot w_k. \tag{11.10}$$

To take into account altruism again, it has to be scaled up by the factor $(1+\ln(100))^2 = 5.6^2$ to become

$$\sigma i, alt^2 = 5.6^2 \cdot \sum_k \left(\frac{D_k - E[D]}{POP} \right)^2 \cdot w_k. \tag{11.11}$$

Returning to aggregate values, one sees that Eq. (11.6) needs to be modified by simply inserting the factors 5.6 and 5.6^2, respectively, resulting in

$$R = 5.6 \cdot \mu + 5.6^2 \cdot \frac{av(W)}{2} \cdot \sigma^2. \tag{11.12}$$

Using the interval (11.7) for $av(W)$ and the Mühleberg data for low and high release rates (see Table 11.7), respectively, one obtains willingness-to-pay values between 3.3 mn and 247.0 mn EUR per year.

Up until now the fact has been ignored that nuclear contamination persists over long periods (at least many decades) when estimating willingness to pay (even though probabilities w_k are given as frequencies per year). However, due to the long-term impact of nuclear contamination, insurance companies do not need to provide the entire sum of total remuneration payments immediately. Instead, they can distribute remuneration payments over a relatively long period (following the distribution of damages over time). Assuming a uniform distribution of damage over a period of 30 years, the variance of potential damages σ^2 becomes

$$\widehat{\sigma}^2 = \sum_k \left(\frac{D_k}{30} - \frac{E[D]}{30} \right)^2 \cdot 30 \cdot w_k = \frac{1}{30} \cdot \sigma^2. \tag{11.13}$$

In contrast to variance σ^2, average aggregate damage μ remains constant. Therefore, the estimation for the aggregate willingness to pay R (Eq. (11.12)) can be adjusted using Eq. (11.13) to become

$$\widehat{R} = 5.6 \cdot \mu + 5.6^2 \cdot \frac{av(W)}{2} \cdot \frac{\sigma^2}{30}. \tag{11.14}$$

In 1994, the Swiss population was about 7 mn. Using the data for the Mühleberg plant provided in Table 11.7 and applying Eq. (11.14), one can estimate adjusted aggregate willingness to pay,

$$0.8 \text{ mn EUR/a} < \widehat{R} < 21.7 \text{ mn EUR/a}. \tag{11.15}$$

Dividing these figures by the annual electricity production in the Mühleberg plant (about 2500 mn kWh), willingness to pay is bounded by 0.0003 and 0.0087 EUR/kWh. To the extent that financial reserves of plant operators are insufficient for the payment of possible nuclear damages, these figures also represent the external cost of nuclear power. With figures this low, the introduction of internalization taxes would not affect the competitiveness of nuclear power.[7]

Even though estimated external effects can be internalized through taxes on nuclear power, the population still rejects nuclear energy in many cases. An explanation of this could lie in an incorrect estimation of willingness to pay using the (μ, σ^2)-criterion which assumes variance of damage to be finite. It is questionable whether this assumption is correct when assessing risks associated with the current generation of nuclear plants. However, this might change with improvements of the safety technology in future reactor generations.

11.3.3 Risk Assessment Based on Stated Preferences

The (μ, σ^2)-criterion presented in the previous section constitutes an attempt to base risk assessment as far as possible on objective quantities. However, in the determination of willingness to pay (WTP) for risk reduction, $av(W)$ enters, a subjective parameter. Moreover, values of $av(W)$ derived from e.g. insurance data may not be applicable to the present context, where not only survival but also the health of relatives and friends are at stake. In this situation, determining WTP through experiments may be worthwhile. A popular alternative is the discrete choice experiment, in which participants repeatedly choose between two alternatives, one of them typically the status quo. The status quo is described by a set of attributes, while the alternative features attribute levels that vary in the course of the experiment. If one of these attributes is the price to be paid, WTP values for the other attributes (and hence for the alternative as a whole) can be inferred using econometric methods. Admittedly, discrete choice experiments measure only stated preferences rather than preferences revealed through actual choices in markets.

[7] Since 2003, electricity consumers in Germany and Austria connected to a low-voltage grid have been paying an environmental tax of about 0.021 EUR/kWh, which however does not differentiate between power plant types, and thus lacks an incentive effect.

However, a market for nuclear risk reduction (e.g. insurance against risks of nuclear power) does not exist for private households.

A discrete choice experiment designed to measure WTP for a reduction of financial risk emanating from nuclear power was conducted by Schneider and Zweifel (2004), involving 500 Swiss participants. In accordance with the theory of consumer demand developed by Lancaster (1966), the product ‘electricity’ was described by five attributes,

– Financial damage per household in case of a severe accident;
– Problem of final nuclear waste disposal solved/not solved;
– Average number of power interruptions per year;
– Coverage ratio of liability insurance to be purchased by nuclear plant operators for payment of damages to households;
– Price of electricity at the household level.

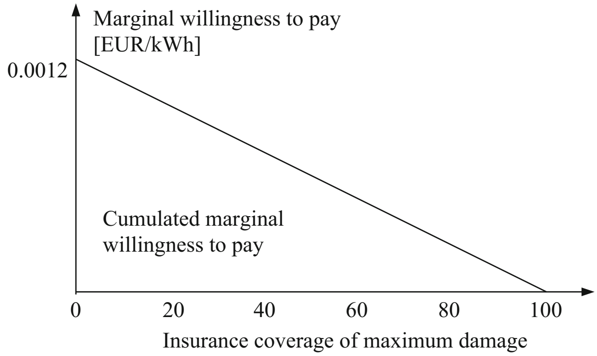
The damage probability does not appear as an attribute here; this is supposed to prevent the danger of inconsistent statements made by the participants. In many former experimental designs, it was noticed that the interviewees gave inconsistent answers when probabilities changed (the so-called Allais paradox).

As is well known, the slope of an indifference curve indicates how much the individual considered is willing to sacrifice of one good (attribute, respectively) in return for obtaining one unit of the other. In the present context, the slope of the indifference curve through the status quo shows how much disposable income (through paying a higher price for electricity) a respondent is willing to sacrifice in return for a higher degree of financial protection through a higher coverage ratio in plant operators’ liability insurance. Therefore, respondents’ repeated choices between the status quo and an alternative permit the experimenter to identify their indifference curves and with them, their marginal WTP in the neighborhood of the status quo.

Schneider and Zweifel (2004) estimated a value of 0.0012 EUR/kWh as the marginal WTP of the Swiss population for an increase of liability coverage from 0.55 bn EUR (the status quo) to 1.2 bn EUR per nuclear plant. They also found that marginal WTP decreased with the coverage ratio, as predicted by economic theory (see Fig. 11.3, with a linearized function for simplicity). Moreover, it reached zero at 100% coverage, which is intuitive because there is no financial risk anymore at that point. Most importantly, cumulated marginal WTP between 0.55 and 1.2 bn EUR clearly exceeded the estimated cost of a corresponding extension of liability coverage. Marginal utility can therefore be said to be at least as high as marginal cost, justifying the extra preventive effort from an efficiency perspective.

Maximum damage has been estimated to reach (and even exceed) 100 bn EUR. Using this value, one obtains willingness to pay of 0.092 EUR/kWh for the increase of liability coverage from 0.55 to 1.2 bn EUR as the integral of the marginal WTP schedule (see Eq. (11.16)),

Fig. 11.3 Willingness to pay for reducing exposure to nuclear risks (Switzerland, 2003)



$$0.0012 \cdot (100 - 0.55)/(1.2 - 0.55) \cdot 0.5 = 0.092 \text{ EUR/kWh}. \tag{11.16}$$

This is a lot more than the 0.0087 EUR/kWh derived from the (μ, σ^2)-criterion. If nuclear power plants had to pay an internalization tax of this magnitude, they would not be competitive anymore on the market for electricity generation. Yet Schneider and Zweifel (2004) cite an estimate according to which additional insurance coverage up to even more than 1.2 bn EUR could cost as little as 0.007 EUR/kWh. Still, the result of this discrete choice experiment reflects the prevalent non-acceptance of nuclear energy, at least in Switzerland.

At the same time, the experiment provides evidence that 100% liability coverage does not represent the optimum amount of internalization when it comes to the risks of nuclear power.[8] For efficiency, insurance coverage should be such that its marginal cost (the additional insurance premium) equals to marginal willingness to pay. According to the authors, this equality would be reached through a fivefold increase of coverage, from 0.55 bn to 2.75 bn EUR.

In some countries, liability insurance coverage is not provided by insurance companies but mutually by nuclear plant operators. In the United States in particular, there is the so-called joint and several liability rule which mandates all operators to contribute to the payment of damages caused by one of them. In Germany, nuclear liability has three layers which in combination approximate the optimal amount of coverage as calculated by Schneider and Zweifel (2004):

– Private liability insurance (limit of 260 mn EUR per accident);
– Joint and several liability among plant operators (2244 bn EUR of liquid assets);
– Liability of plant owners including their holding companies with their total assets (amount unknown but huge).

Yet in spite of such an extremely high degree of coverage, acceptance of nuclear power in Germany is limited, evidenced by its government's decision to exit from

[8]The bankruptcy risk of a company with limited liability is not fully borne by its owners but in part also by society.

nuclear (as part of the so-called *Energiewende*) in response to the Fukushima accident of 2011 in Japan. Clearly, acceptance cannot be attained by internalization of the risks associated with nuclear power alone. In the end, the crucial factor will be the population's belief whether or not security of electricity supply and mitigation of greenhouse gas emissions can be achieved without nuclear power plants.

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