47202 Future Energy – Nuclear power

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Learning objectives

Upon successful completion of the course module, the student should be able to:

- Explain nuclear energetics and nuclear binding energies
- Describe neutron interactions and the fission process
- Explain fission reactor principles and design
- Describe the nuclear fuel cycle
- Discuss the role of nuclear power in the energy system

Nuclear power – prospects and controversies

Nuclear energy stems from fission or fusion of atomic nuclei. A defining characteristic of nuclear energy is its very high energy density, enticing both military and civilian applications. While nuclear and atomic radiation have been applied since early in the twentieth century – mainly for medical purposes – the first exploitation of the energy potential in nuclear fission was the development of atomic bomb during World War II. After the war, however, efforts started to harness the energy for peaceful purposes, specifically to provide propulsion for ships and for electricity generation.

It is easy to appreciate the potential for energy production: the energy released in fission reactions typically is measured in MeV, 10^6 times larger than energies associated with atomic or molecular reactions such as the combustion of fossil fuels. This implies that the amount of fuel required for electricity generation is reduced drastically when shifting from fossil fuels to uranium, with a reduced burden on mining and transport. Historically, the huge energy gain has also been argued to render the nuclear option substantially less expensive than other energy supply options.

At present, nuclear energy accounts for approximately 10% of the global electricity supply and in advanced economies, nuclear power contributes the largest low-carbon electricity generation. Some thirty countries have nuclear power plants with the nuclear share of the electricity generation ranging from more than 50% in several European countries down to a few percent in developing economies. In Europe, nuclear power accounts for approx. one quarter of the total electricity supply (Figure 1).

In a climate and environmental context, nuclear power has several merits making it a valuable and perhaps indispensable option for a clean energy transition. It is dispatchable providing baseload power and it may supplement variable renewable energy (VRE) generation; it is a reliable energy source, providing a security of energy supply and helps keeping power grids stable; and it has the potential for large-scale deployment to meet a growing energy demand. Due to the very high energy content associated with its uranium fuel, nuclear power has a minimal drain on natural resources, hence also minimal waste generation.

Nonetheless, concerns about safety, radioactive waste and proliferation associated with the nuclear fuel cycle remains, limiting the prospects for future deployment of nuclear energy in many countries. To address these issues of sustainability and to reduce growing costs of nuclear energy new nuclear technologies are pursued; in particular a next generation of nuclear fission reactors and/or thermonuclear fusion reactors, both aiming at reducing if not eliminating such concerns.

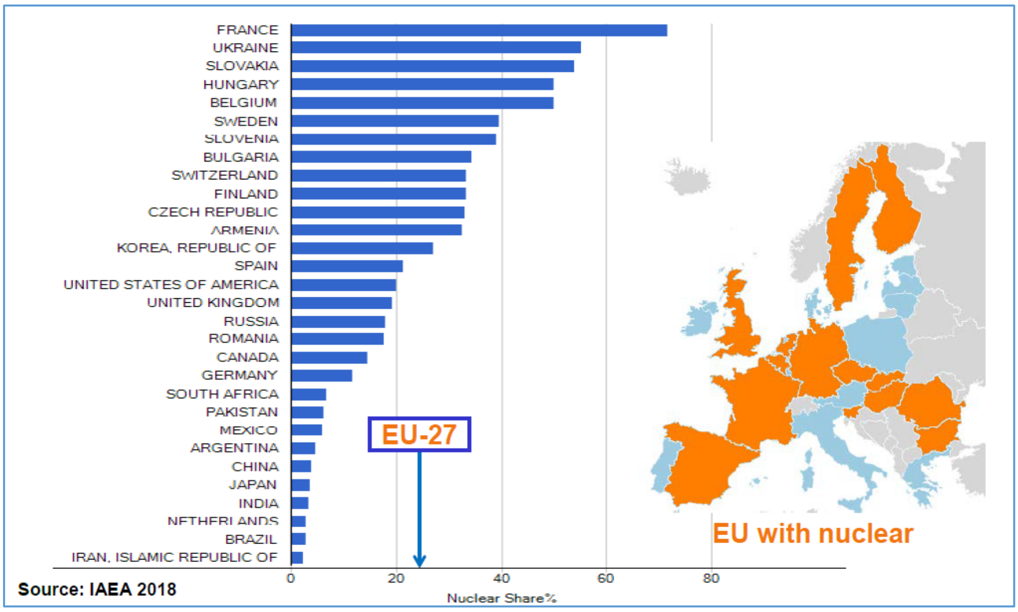

Figure 1. Nuclear share of electricity generation in 2017 (IAEA, 2018).

Nuclear reactions

Nuclear reactions underlie our very existence. The solar system originates from nuclear reactions through the nucleosynthesis forming all elements heavier than iron; nuclear fusion reactions power the Sun, and the mantle of the Earth itself is heated by radioactive decay of the very long-lived, predominantly heavy elements still present since the forming of the solar system some 10^9 years ago.

Nuclear power generation is based on controlled nuclear reactions; in fission reactions heavy atomic nuclei split into larger fragments while in fusion reactions light atomic nuclei merge into heavier elements. The energy potential in fission and fusion reactions can be understood from the nuclear binding energies, being the energy needed to separate the nucleons of the atomic nuclei.

Figure 2 shows the binding energy per nucleon for the stable elements including the very long-lived isotopes of uranium. The binding energy exhibits a maximum around A=60, with ^{56}Fe being the most stable element, and with both lighter and more heavy elements having smaller binding energies per nucleon. In fusion reactions, e.g. D+T → ^{4}He + n, and in fission reactions the excess binding energy is released, mostly in the form of kinetic energy of the reaction products (Table 1).

Table 1. Energy released in typical fission and fusion reactions

Fission reaction (^{235}U + n → ^{144}Ba + ^{90}Kr + 2n)	*Energy* (MeV)
Kinetic energy of fragments	165
Prompt neutrons	5
Prompt gamma radiation	7
Radioactive decay	25
Total	*202*
Fusion reaction (D + T → ^{4}He + n)	*Energy* (MeV)
Neutrons	14.1
Alphas	3.5
Total	*17.6*

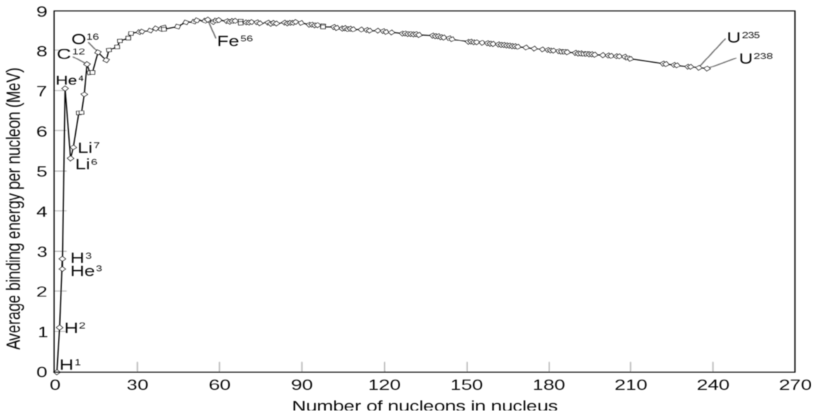

Figure 2. Nuclear binding energies for the stable elements.

Nuclear fission and chain reactions

The two naturally occurring isotopes of uranium, ^{235}U and ^{238}U, are both unstable but have very long half-lives, of the order of 10^9 years. The dominant radioactive decay of these heavy elements is by alpha emission; spontaneous fission of uranium may occur but is extremely rare with fission yields of the order of 10^{-6} relative to the alpha decay. Rather, for nuclear energy production we apply neutron-induced fission, initiated by the absorption of a slow neutron onto a uranium-235 nucleus,

$$^{235}\text{U} + \text{n (thermal)} \rightarrow {}^{236}\text{U} \rightarrow \text{X} + \text{Y} + \nu\text{n (fast)} + \text{Q} \quad (1)$$

with a Q-value of approx. 200 MeV. The two fission products, X and Y, are created in pairs over a large part of the atomic table, preserving the number of protons and neutrons in each fission reaction. The fission products are typically unstable, decaying further into stable elements through radioactive decay chains. In Table 1, the typical distribution of released energy among the different reactions products is shown for the fission and fusion processes. For fission, only about 85% of the energy release is prompt, while 10-15% of the energy is released at a later stage (seconds – days – years) at the time of the radioactive decay of the fission fragments.

In the fission reaction (1), a small number ν of fast neutrons, usually between 2 and 3, is liberated from the compound nucleus ^{236}U. For fission of ^{235}U, i.e. by absorption of a “thermalized” slow neutron, the average number of fast neutrons produced is ν=2.43. Due their short half-lives, free neutrons do not exist in nature; however the fission neutrons released allow for new fission reactions, *i.e.* for sustaining a nuclear chain reaction in which each fission may initiate new neutron-induced fission reactions in the uranium fuel.

In a nuclear reactor, the neutrons released in each fission reaction may either be absorbed in the fuel and induce new fission events, be absorbed in the fuel or in other material in the reactor core *without* causing fission, or may leak out of the reactor core containing the fuel. Hence, the evolution of a chain reaction is governed by the fate of the fission neutrons, *i.e.* by the number of neutrons released in each fission event and the probabilities for subsequent neutron-induced fission, absorption without fission, or leakage out of the reactor core.

This is parametrized by the effective multiplication factor k_{eff}, defined as the average number of direct fission events caused by neutrons released in an initial fission reaction, or

$$k_{\text{eff}} = \frac{\text{number of fissions in generation } i + 1}{\text{number of fissions in generation } i}$$

Depending on the value of the effective multiplication factor, the fission reactor is labelled subcritical ($k_{eff} < 1$), critical ($k_{eff} = 1$) or supercritical ($k_{eff} > 1$), and correspondingly the fission rate, hence reactor power will decrease exponentially, be steady, or grow exponentially.

Note that during startup of a fission reactor or ramping it to yield a higher energy output, k_{eff} should be larger than 1; once the desired reactor power level is reached k_{eff} is reduced to the value of 1. For safety reasons, however, with the exception of a few specially designed research reactors, the value of k_{eff} should always be limited to $k_{eff} < 1.001$.

The probability that a neutron will induce fission, or any other reaction, is described by the cross section σ [m^2], given by the ratio of the number of fission events (or other reactions) to the neutron flux. In Figure 3, the fission cross sections for neutrons incident on uranium (^{235}U and ^{238}U) and plutonium (^{239}Pu) are shown; note the strong dependence of the fission cross section as function of the neutron energy. The fission cross section for ^{238}U becomes negligible for neutron energies less than ≈ 1 MeV, while for ^{235}U and ^{239}Pu the cross sections increase with decreasing neutron energy. Hence, at thermal neutron energies, $E_n \approx 0.025$ eV, where the neutrons have been thermalized through collisions with the reactor core material, only the two odd-mass isotopes, *i.e.* the *fissile* isotopes ^{235}U and ^{239}Pu, contribute with fission reactions. At intermediate neutron energies, 1 eV < E_n < 1 keV, the cross sections are characterized by a large number of resonances.

The dominant isotope in nature, ^{238}U (99.3%), is not fissile but labeled *fertile*, as it may absorb a neutron and by double beta-decay transform to the fissile ^{239}Pu isotope:

$$^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}Np\ (\beta\text{-decay}) \rightarrow {}^{239}Pu\ (\beta\text{-decay}) \qquad (2)$$

Fast (neutron) fission in ^{238}U is possible, cf. Figure 3. A more likely process, however, is the neutron absorption in ^{238}U without fission.

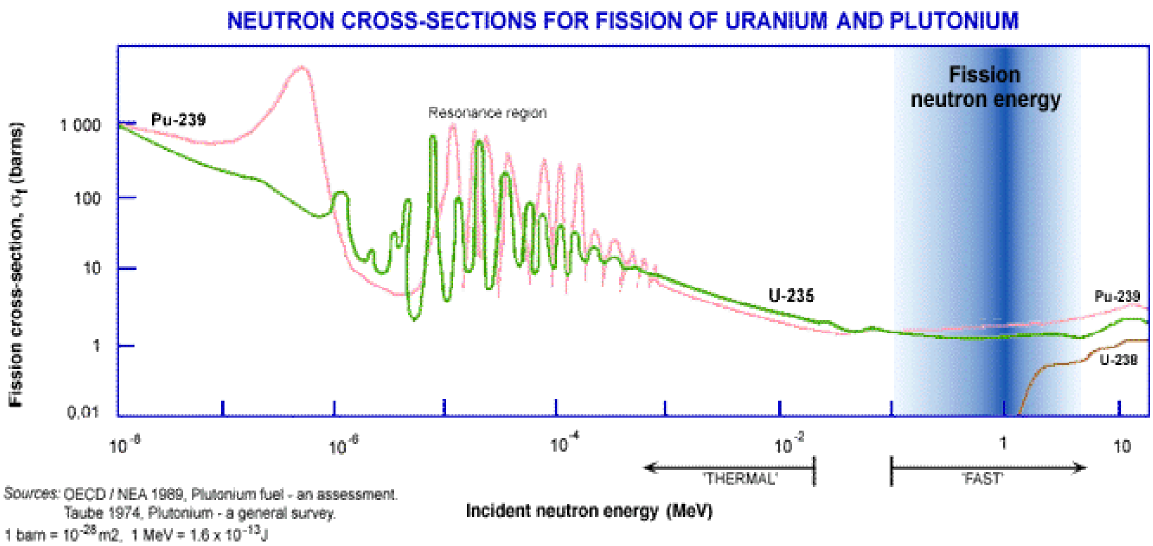

Figure 3. Fission cross section for ^{235}U, ^{238}U, and ^{239}Pu.

Nuclear reactors

Due to the very small fission cross section of ^{238}U a homogeneous reactor containing natural uranium only cannot sustain a chain reaction, as too many neutrons are absorbed in ^{238}U nuclei without causing fission. However, two alternative routes to criticality exist: i) by *enrichment*, which is increasing the relative content of ^{235}U in the uranium fuel, or ii) adding a *moderator* material to the reactor core that will slow the neutrons to thermal energies, thereby increasing the probability for fission in ^{235}U.

In a *thermal* reactor, e.g. a light water reactor (LWR) both methods are applied. The uranium fuel is typically enriched to 3-5% ^{235}U content, and water in the reactor core acts as a moderator; in a heterogeneous arrangement water flows through the solid fuel assemblies. The water acts both as a moderator slowing down the neutrons by elastic scattering and as a coolant, transferring heat to the conventional turbine-generator system. In a Boiling Water Reactor (BWR), steam is formed inside the reactor core directly feeding the steam turbines, and via a condenser, the water is pumped back into the reactor core. In a Pressurized Water Reactor (PWR), water passing the reactor core is kept at a very high pressure (~150 bar) in a primary loop while the heat is transferred to a secondary loop via heat exchangers (Figure 4).

In a *fast* reactor, the uranium is enriched even further to 10-20% and moderator materials are avoided, yielding a harder neutron spectrum. The benefit of a fast reactor is an improved neutron economy: fast neutron fission, i.e. fission by absorption of an energetic neutron (as opposed to fission by thermalized neutrons), will emit a larger number of neutrons, and furthermore, neutron absorption in a moderator material is avoided.

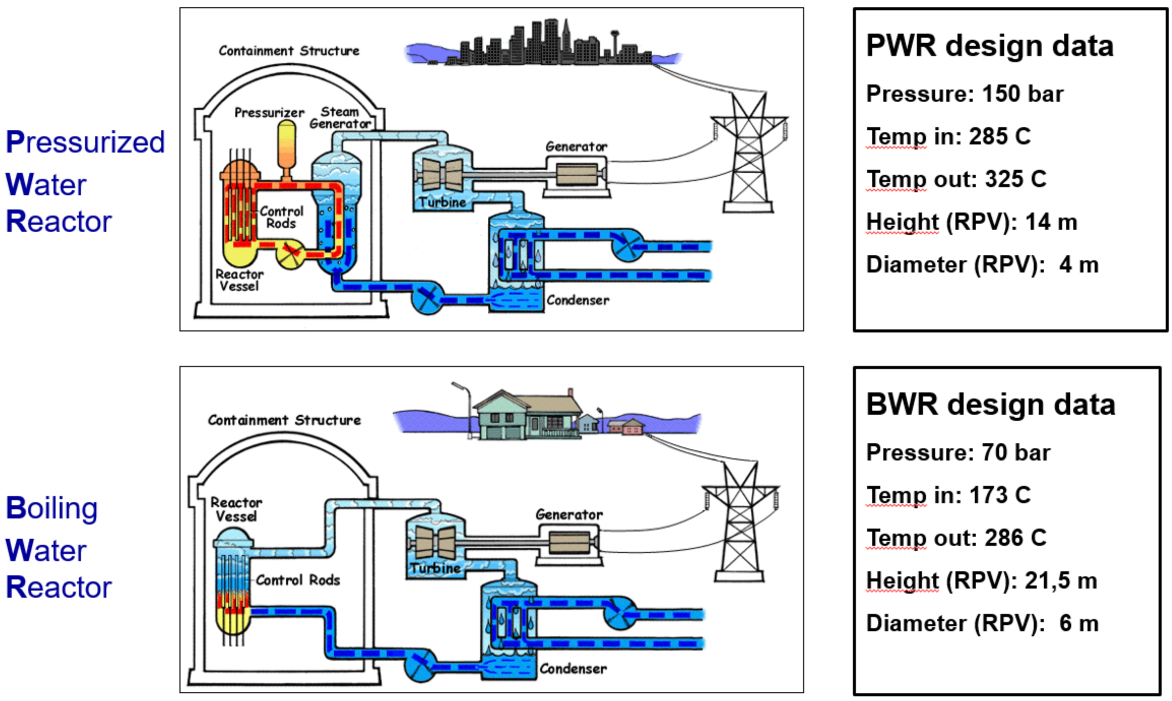

Figure 4. Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) layout.

With uranium or thorium as fuel (the only two naturally occurring fissionable elements), three main fission processes exist, cf. Table 2. The simple uranium (^{235}U) fission process, which is the basis of most reactor operations, neutrons released in the fission reactions will either directly (i.e. as fast neutrons) or after thermalization induce new fission reactions in ^{235}U. In the plutonium cycle, fission neutrons will breed new fissile material by neutron absorption in ^{238}U, and induce new fission in the ^{239}Pu nuclei. Similarly, in the thorium fuel cycle fission neutrons are absorbed in ^{232}Th to produce the fissile ^{233}U following double beta decay of ^{233}Th.

Both the plutonium and the thorium fuel cycles require an excess number of neutrons in order both to induce fission and to breed new fissile material. In practice, depending on the fuel most reactor concepts rely on a combination of these processes. In a light water reactor, with fresh uranium fuel the initial fuel cycle will be the simple uranium (^{235}U) fission process. However, as the reactor starts producing Pu isotopes through neutron absorption in ^{238}U, the plutonium cycle will contribute more and eventually dominate the power production of the reactor.

Table 2. Fission processes

Uranium (^{235}U) burning	$n + {}^{235}U \rightarrow X + Y + \nu n$
Plutonium cycle	$n + {}^{238}U \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$ $n + {}^{239}Pu \rightarrow X + Y + \nu n$
Thorium cycle	$n + {}^{232}Th \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$ $n + {}^{233}U \rightarrow X + Y + \nu n$

Nuclear fuel cycle

In the nuclear fuel cycle, uranium raw material undergoes a range of processes, starting from mining and milling, conversion and enrichment, and fuel fabrication. During irradiation in the nuclear reactor, part of the fuel is consumed by fission while radioactive fission products and transuranic elements are formed in the fuel. The spent, highly radioactive fuel may be treated in a fuel conditioning plant, leaving it as waste, or it may be reprocessed for recycling of plutonium, un-used uranium and possibly other heavy transuranic elements, the Minor Actinides (MA).

Mining and milling. Uranium is a widespread mineral present in the crust of the Earth at an average concentration of 2.8 ppm. The largest uranium-producing mines are in Canada, Namibia, Australia and Kazakhstan (2019) and have uranium ore concentrations in excess of 1000 ppm. Milling and chemical processing of the uranium oxides is performed locally, producing yellow cake containing U_3O_8 at concentrations of 80-85%. Tailings from the mining and milling processes are left behind, containing radioactive materials from the decay chain of ^{238}U, including the ^{222}Rn gas, which may escape to the environment.

Enrichment. Natural uranium only contains 0.7% of the fissile isotope ^{235}U, while most power reactors require the concentrations of ^{235}U to be between 3% and 5%. The concentration of ^{235}U can be increased either by gaseous diffusion enrichment or by enrichment with gas centrifuges.

In both cases, uranium is first converted to a gas, UF_6. In the high-spin centrifuges, the 1% mass difference between the two uranium isotopes cause the uranium hexafluoride gas to separate into two streams, one containing a slightly higher concentration of ^{235}U. With thousands of centrifuges arranged in a cascade, the desired enrichment can be obtained. Similarly, in gaseous diffusion, the UF6 gas is forced to pass through a series of membranes and with the higher average speed of the lighter isotope, the gas molecules containing ^{235}U more readily passes through the porous medium.

Gaseous diffusion is rather energy intensive and is no longer used for commercial uranium enrichment. An alternative approach is laser separation, where ^{235}U is photo-ionized, utilizing a small isotopic shift in the atomic energy levels of the two uranium isotopes, and the isotopes are subsequently separated by an electric field. While laser separation techniques have been investigated for several decades, laser separation enrichment is still not applied on industrial scale.

Fuel fabrication and burnup. For light water reactors, standard fuel is fabricated in the form of ceramic (UO_2) uranium pellets, which are arranged in fuel assemblies. In a reactor of 1000 MW electrical power, the core will contain approx. 75 tons of uranium fuel. Starting from slightly enriched uranium, the high neutron flux will induce fission in ^{235}U but also neutron absorption in ^{238}U, thereby building up a plutonium inventory, and by sequential neutron absorption and beta decay, heavier transuranic elements as well. While some of the plutonium (about 50%) is consumed by fission in the reactor, the spent fuel would still contain plutonium, as well as un-used uranium and minor actinides.

Reprocessing. After irradiation two options exist. Either the highly radioactive spent fuel is treated as waste, to be transferred to a final disposal site, most likely a in an underground geological repository for indefinitely storage. Alternatively, plutonium, un-used uranium-235 and possibly the minor actinides are extracted chemically from the spent fuel at a reprocessing facility and re-used as nuclear fuel. The remainder material is vitrified, packed in steel canisters and to be transferred for final disposal.

In Europe, two large reprocessing facilities exist: At Sellafield in the United Kingdom and at La Hague in France. With current reactor technologies, only plutonium and un-used uranium (after enrichment) are recycled; the plutonium is mixed with uranium into mixed-oxide fuels (MOX) to substitute a fraction of the uranium fuel in light water power reactors.

A main advantage of recycling plutonium and possibly the minor actinides is the improved utilization of the fuel, but more importantly, better storage options for the spent fuel. While the spent fuel from the direct-disposal (once-through) option is highly radiotoxic, the toxicity decreases with time due to radioactive decay reaching the levels of the original uranium ore after maybe 10^5 or 10^6 years. Extracting plutonium and MA from the fuel before depositing will yield both a waste that is easier to handle (less heat production) and require shorter storage time before reaching the radiotoxicity level of natural uranium (Figure 5).

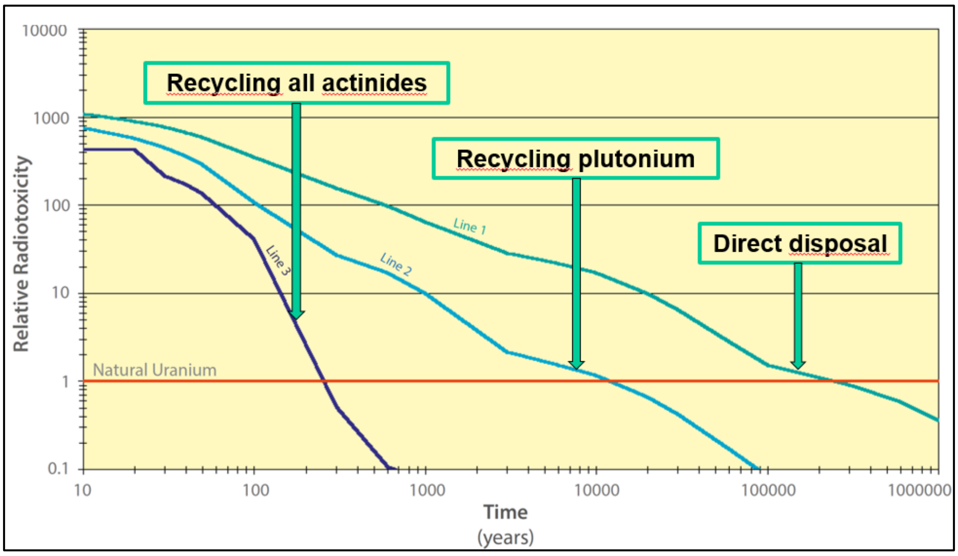

Figure 5. Radiotoxicity of spent nuclear fuel relative to natural uranium. IAEA Bulletin 55-3, 2014.

Waste management. Radioactive waste from the nuclear fuel cycle is characterized according to the activity concentration and the heat production from the waste. Exempt waste with very low activity levels can be disposed of, while low-, intermediate- and high-level waste containing higher acitivity levels and/or long-lived radionuclides in high concentrations should be stored as waste. Low- and intermediate level waste are usually placed in near-surface disposals, while deep geological disposal of high-level waste is recommended (IAEA, 2014), to keep the radioactive waste out of the natural environment for geological lifetimes. At present, no country has established a final repository for spent nuclear fuel or high-level waste.

Nuclear power in the energy system

Prospects for nuclear energy indicate a global growth, both in a current policy scenario based on planned constructions and closures of nuclear power plants and even further in the IEA Sustainable Development Scenario [ref]. Nuclear energy policies, however, remain uncertain in many countries as these are influenced by the need to ensure affordable and clean energy, by climate objectives and by public opinion, but also by costs estimates of nuclear energy, means for the integration of nuclear in electricity systems with a high share of variable renewable energy (VRE), and by concerns over safety and waste.

Resources. World total reserves of uranium are estimated at 6 million tons (at a price of up to USD 130/kg U), sufficient to cover NPP requirements for the next 90 years with current technology and consumption rate (WNA, 2020). Similar to other mineral resources, quantities are subject to market prices and costs of extraction, and further exploration and/or higher prices will increase the reserves. An increased consumption rate, e.g. due to an increased nuclear electricity share or possible other uses of nuclear energy, will lower the time span for using current reserves. In addition to the geological reserves, civil stockpiles of uranium and plutonium exist as well as military stockpiles arising from nuclear disarmament.

Current reactor technology is foremost based on LWRs, utilizing only 0.5% of the energy content in natural uranium. With fast reactor technologies, utilization will increase by two orders of magnitude, greatly extending the time span for using world uranium reserves (Figure 6). Furthermore, prospects for extracting uranium from seawater, at a rate where uranium is constantly replenished from the bedrock, will increase the uranium reserves manifold, in practice rendering nuclear energy renewable.

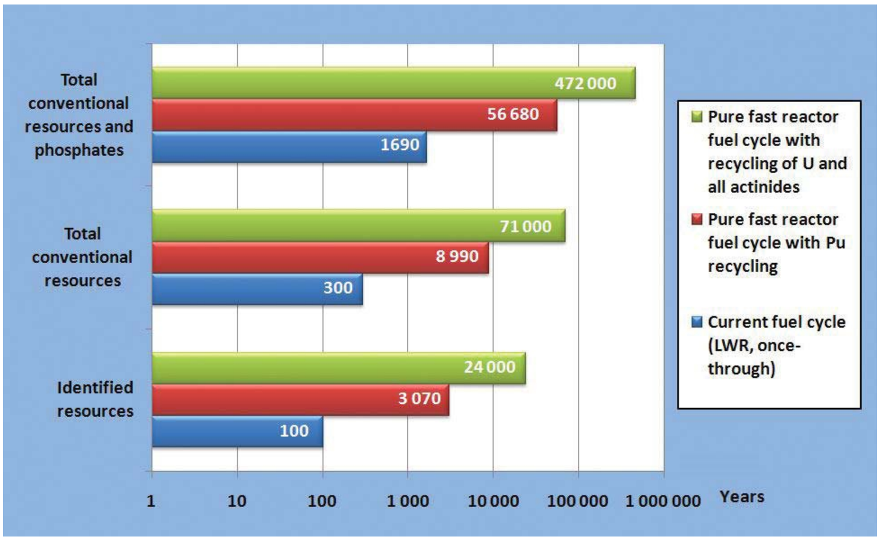

Figure 6. World uranium resources with current (once through) and with fast reactor technologies

Economy. Unlike variable renewable energy (VRE) sources, e.g. wind energy or photovoltaic cells, the cost of nuclear energy has not decreased over the last few decades. On the contrary, the cost of nuclear new builds has gone up in recent years, in particular in Europe and in the USA. This is attributed to a number of reasons, including the diminishing knowledge and experience in building nuclear power plants, construction delays caused by lengthy and complicated license processing and by increased and costly safety and security measures. Figure 7 shows the building "overnight" costs, *i.e.* independent on the actual construction time, for historical and for recent nuclear power plants (MIT, 2018).

Nuclear power plants are characterized by having large construction costs and low operational costs; two thirds of the Levelized Cost of Electricity (LCOE) are typically related to the construction costs while 20 % of the overall costs are for operation and maintenance. Fuel costs as well as back end costs (decommissioning and waste management) are minor.

Figure 8 shows the projected LCOE for low-carbon technologies in USA and in Europe including nuclear new build and lifetime extension of existing nuclear power units. Note that the LCOE concept does not include grid and system costs required for balancing the energy source. Hence, energy investment decisions will need to consider the specifics of the energy system, and may favor energy sources of higher LCOE. In particular, the value of dispatchable energy sources is usually higher than the value of the non-dispatchable sources.

While nuclear energy may have a higher LCOE than intermittent energy sources (VRE), deep decarbonization of the electricity sector will be considerably more costly without nuclear than when including nuclear energy (MIT, 2018; IPCC, 2014).

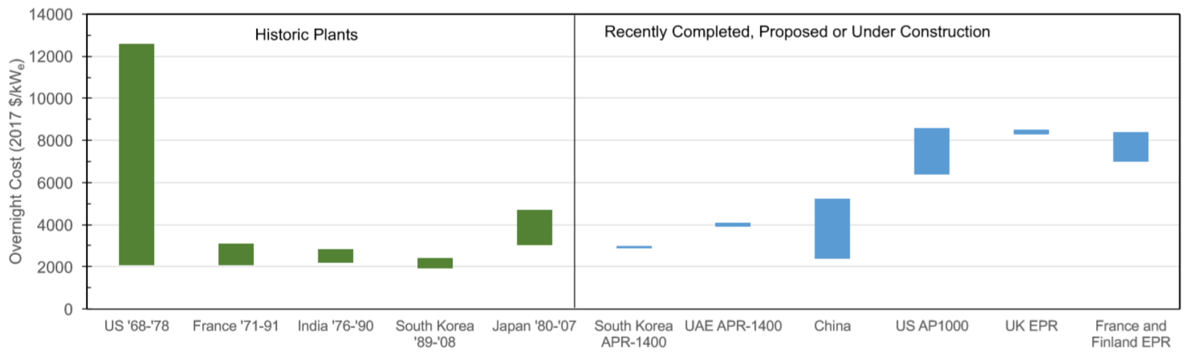

Figure 7. LWR construction costs around the world (MIT, 2018).

Electrical power generation. Due to the cost characteristics of nuclear with high fixed costs and low variable costs, nuclear energy is preferably used as a base load option for electricity generation. However, nuclear reactors may operate in load-following modes, as required from either having a high nuclear share of the electricity generation (France) in order to follow daily or seasonal variations, or to balance intermittent output from VRE (e.g. Germany), and to maintain grid voltage and stability. An example of load-following operation of nuclear power plants is shown in Figure 9.

The ability to ramp a nuclear reactor depends both on the type of reactor and on the power level at which the reactor is operated. For a large range of power levels, a LWR typically allows for ramping the power level at a rate of 5% per minute or even faster when the reactor is operated at close to the maximum power level. Small power levels below 20% should be avoided due neutron poisoning effects (xenon poisoning), that would inhibit ramping of the reactor.

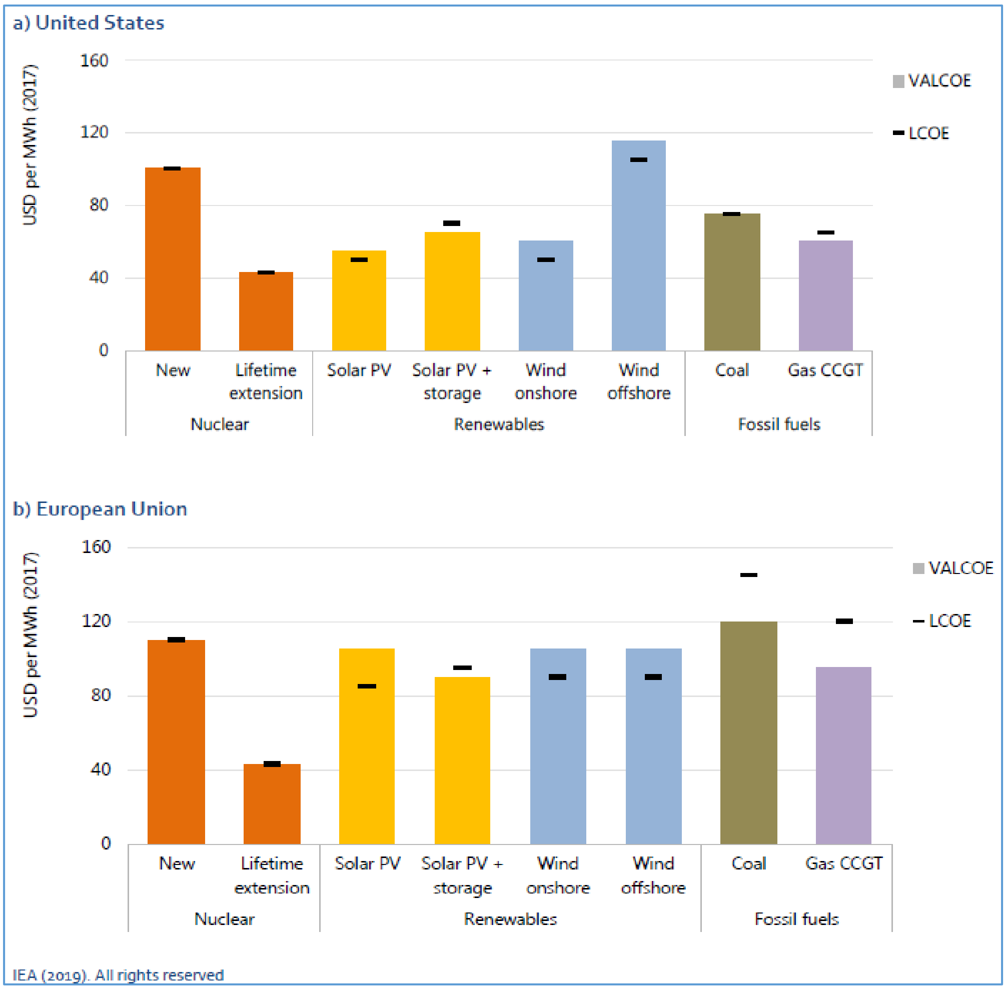

Figure 8. Projected LCOE and value-adjusted LCOE (VALCOE) for low-carbon technologies for year 2040 (IEA, 2019).

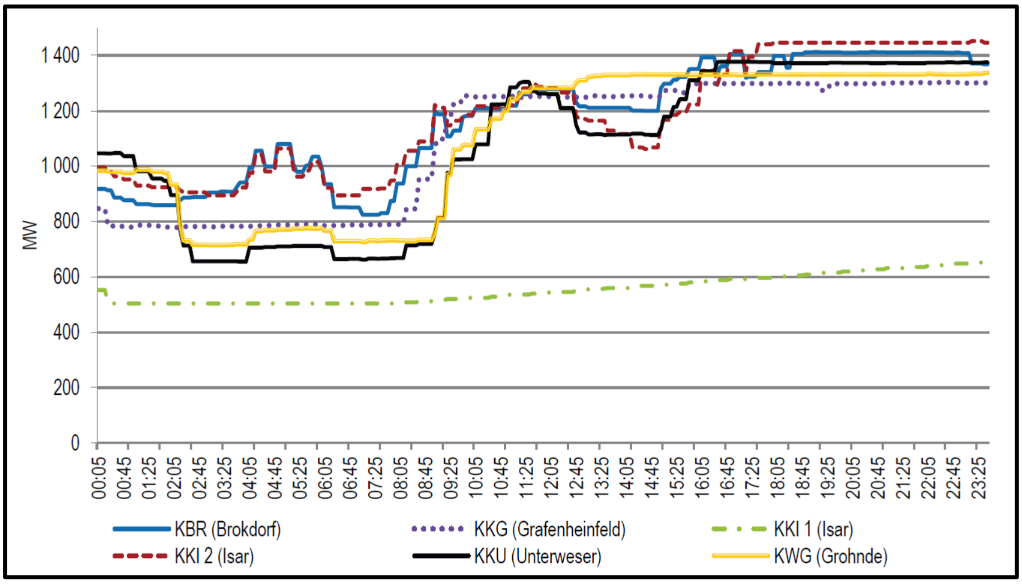

Figure 9. Electricity production at German nuclear power plants during a 24 hour period (NEA 2011).

Non-electricity applications. While nuclear energy is used mostly for electricity production, other applications of nuclear energy exist. These include ship propulsion (submarines and ice breakers), district heating (only supplied from a few power reactors today), and desalination for freshwater supply. Future deployment of high temperature reactors will allow for a range of industrial applications of process heat, including heat for the petro-chemical industry and for production of synthetic fuels for the transport sector.

Research reactors do not generate electricity. However, they play an important role in the production of medical isotopes, in particular ^{99m}Tc (from the decay of ^{99}Mo), which is used extensively in nuclear medicine. Furthermore, research reactors are used for reactor physics studies and as a neutron source for material science and material testing as well as for education and training.

Safety. Of primary concern for the nuclear power sector is safety issues and the risk for accidents at which radioactive material is dispersed into the environment. From a physics point of view, two initiating events, possibly leading to a major accident may occur: i) criticality accidents (Chernobyl), in which the reactor becomes supercritical leading to a possible large power excursion, and ii) loss-of-coolant accidents (Three Mile Island), in which the means for cooling the reactor after shutdown are lost.

To prevent such accidents, nuclear reactors are designed both with limited capabilities for reaching a supercritical state and with a large degree of redundancy in auxiliary cooling systems. In addition, reactors are designed with a series of protective barriers, defense-in-depth, to prevent radioactive material from reaching the environment should an accident happen nonetheless.

The Fukushima accident in 2011, at which four reactors at the Fukushima Daiichi NPP experienced a (partial) meltdown was a loss-of-coolant accident. The initial earthquake caused the power plant, along with other nuclear power plants in Japan, to scram with a loss of primary power, but left the reactors in a safe state. However, the tsunami that followed approximately one hour later wiped out the emergency cooling systems (generators and pumps) and destroyed much of the infrastructure surrounding the plant, inhibiting an effective emergency management. As a result, in a sequence of events radioactive material was released to the atmosphere, contaminating large areas of land around the power plant.

In the aftermath of the Fukushima accident, nuclear power plants in Europe and elsewhere have undergone extensive “stress tests”, to examine their capacity for withstanding loss of power and external cooling due to e.g. earthquakes and flooding events; no NPP was closed based on these tests. Current reactor designs, Generation III or III+ reactors, are incorporating passive safety systems, e.g. for emergency cooling, that will function without human intervention or external power supply.

Technology outlook

The next generation of nuclear fission reactors being developed today are collectively known as Generation IV reactors (Figure 10). These reactors, and their associated fuel cycles aim for improved sustainability, meeting specific sustainability, economic, safety and non-proliferation goals. While a very large (>100) number of reactor designs have been proposed, these are commonly grouped into six reactor concepts: the Super-Critical Water Reactor (SCWR), Sodium-cooled Fast Reactor (SFR), Gas-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), Very-High Temperature Reactor (VHTR), and the Molten Salt Reactor (MSR).

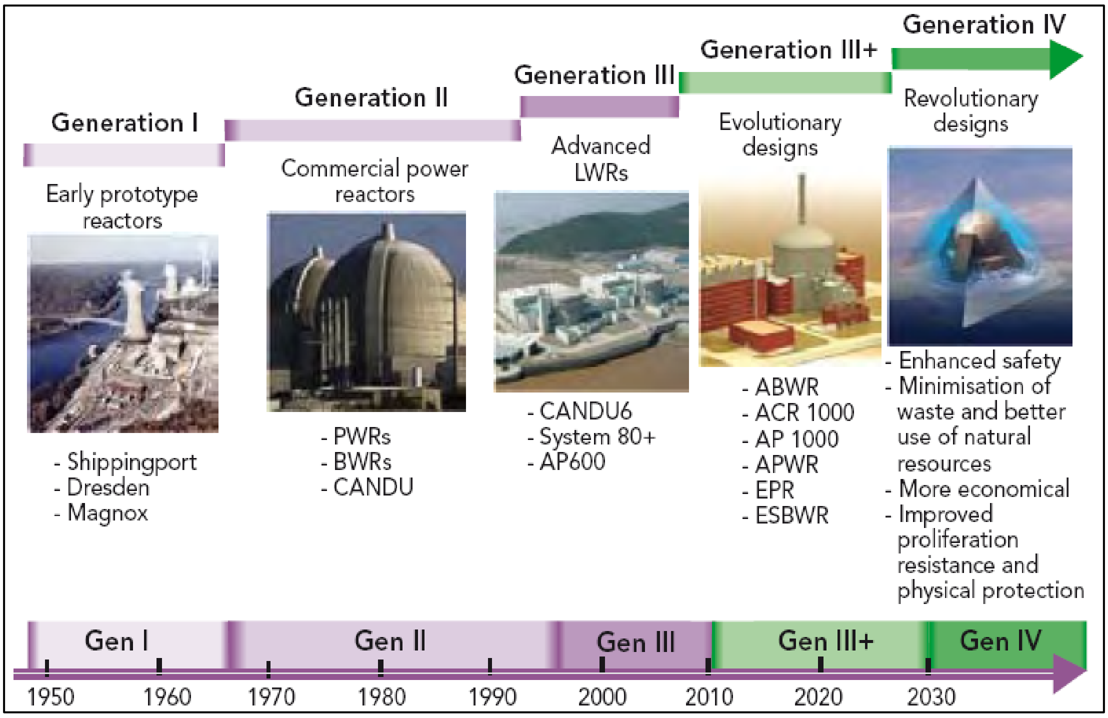

Figure 10. Generation I-IV nuclear fission reactors.

High temperature reactors

Almost all proposed reactor designs operate at higher temperatures, ranging from 400°C up to almost 1000°C, much higher than the operating temperature of ~280°C for LWR designs. The higher operating temperature will allow for a higher thermal efficiency, *i.e.* a higher electricity output, but equally important it may provide process heat for the petro-chemical industry and other heat-demanding industrial applications. Above 600°C and 800°C, process heat will allow for efficient electrolysis and thermolysis, respectively, e.g. to provide synthetic fuels for the transport sector.

Fast reactors. The lead, lead-bismuth, or sodium-cooled fast reactors operate with a fast neutron spectrum. This allows for a much better fuel utilization, up a factor of 50-200 compared to present day LWRs, by efficiently employing the Pu-cycle in the reactor operation (Table 3). From a sustainability point of view, this would reduce demand on uranium and would considerably shorten required cooling time for the high-level waste.

Prototype fast reactors are, or have been in operation in France (Phenix and Superphenix, sodium-cooled fast reactors), in Russia (BN800, sodium-cooled fast reactor) and elsewhere, but these reactors have not yet seen commercial deployment.

The molten salt reactor (MSR), which has gained renewed interest in many countries, in its main design version has the uranium or thorium fuel dissolved in a liquid salt, which also provide heat transfer via a secondary loop to the turbine-generator system. It operates at low (atmospheric) pressure and the liquid fuel facilitates on-line refueling as well as fission product removal. Hence, the MSR is of a fundamentally different design than the solid-fueled reactors, with a potential gain in both safety and economy. The MSR can operate both with a fast neutron spectrum and with a thermal/epithermal spectrum.

Subcritical reactors. An accelerator-driven reactor system may provide an excess neutron flux from proton-induced spallation processes inside the reactor. This will allow for operating a reactor in a sub-critical mode, thereby reducing the risk of criticality accidents. This reactor type is of particular interest for transmutation of minor actinides, hence for improving fuel utilization.

A prototype subcritical reactor, MYRRHA, is prepared for construction in Belgium.

SMRs. A small modular reactor (SMR) is a reactor unit, of any design, which has an electricity output of less than 300 MW. The small modular design allows for series-construction with the main manufacturing and assembly carried out at a central facility, e.g. a shipyard, thereby reducing building costs and the overall LCOE. The small unit size will allow for deploying NPPs at locations with smaller needs for electrical capacity or at places, where it is difficult to build large infrastructure.

An example of an SMR is the Russian floating nuclear power plant, Akademik Lomonosov, having two 70 MWe PWRs installed on a barge. It was commissioned in 2020 in the Chukotka region in the Russian Far East. The floating NPP will be transported back to a central service facility for refueling and eventually for decommissioning. This concept of operation and decommissioning, including taking care of the spent fuel, will ease exporting nuclear power technologies to third countries.

Fusion. In a very different approach from fission, nuclear power may be based on the fusion of light elements. In fusion, the thermonuclear reactions take place in a reactor at low pressure but at very high temperature, of the order of 10^{10} K, ten times higher than the temperature in the center of the Sun. At these high temperatures, the hydrogen fuel (deuterium and/or tritium) is in the form of a plasma. The plasma and the relevant conditions for fusion can be maintained by magnetic confinement (Tokamak or stellarator design), or by inertial confinement by means of laser heating and compression of fuel particles.

A prototype thermonuclear reactor, ITER, is being constructed in France, based on the Tokamak magnetic confinement design. While still far away from commercial matureness, prospect are that a prototype fusion power reactor can be developed within 20-30 years.

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