Global Energy Perspectives

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Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-2

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2.2 Generation of electricity through nuclear power

Glossary to 2.2

Term	Description
BWR	Boiling Water Reactor
BGE	Federal Company for the Final Disposal (of Nuclear Waste)
BGR	Federal Institute for Geosciences and Natural Resources
CNNC	China National Nuclear Corporation
FBR	Fast Breeder Reactor
Land requirements electricity generat	Under land requirements, Our World in Data considered the land use for the plant itself during operation, the land used for mining the materials to build the plant, the mining of energy sources used either directly (i.e. coal, oil, gas or Uranium used in the supply chains) or indirectly (the energy sources used to produce the materials), the connection to the electricity grid and the land use for the disposal of the waste produced.
FNR	Fast Neutron Reactor
GCR	Gas Cooled Reactor
GW(h)	$10^{9.}$ W (h)
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NPCIL	Nuclear Power Cooperation of India Limited
PWR	Pressurised Water Reactor
USGS	United States Geological Survey
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association

2.2.1 Introduction

Electricity generation from nuclear energy has increased globally by a factor of almost 100 in the last 60 years and amounted to about 2,800 TWh in 2021 (see Figure 39).

In 2021, nuclear power thus covered about 10 % of global electricity demand. In its 'Stated Policies Scenario' in the World Energy Outlook 2021, the IEA assumes a growth in installed nuclear power capacity of over 26 % between 2020 and 2050 to 525 GW.[58]

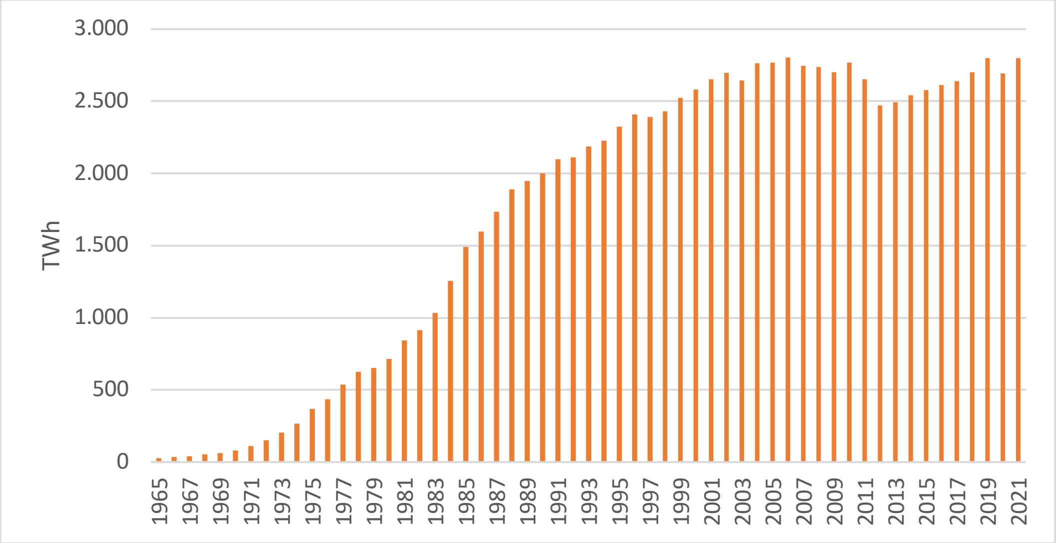

Figure 39: Electricity generation from nuclear energy[59]

In 2022, the USA had the largest nominal capacity of nuclear fission reactors in operation, followed by France, China and Russia. In total, there is a capacity of 422 GW in Figure 40 but globally a total installed capacity of 439 GW was in operation in 2021.

Currently, around 60 nuclear energy reactors are being built in 15 countries, mainly in China, India and Russia. About 100 reactors with a total gross capacity of about 100 GW are commissioned or planned, and over 300 more are proposed.[60] . A list of reactors under construction is given in the appendix in Table 4 . Most reactors are currently planned in Asia, where economies are growing fast and electricity demand is rising rapidly.

According to the World Nuclear Association, about two thirds of the world's Uranium production comes from mines in Kazakhstan, Canada and Australia [61]. According to the BGR, Kazakhstan, Australia and Namibia are the largest Uranium-producing countries, accounting for over 65 % of world production. [62]

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[58] to about 525 GW
[59] Cf. Our Word in Data (2022c) (Our World in Data, 2022)
[60] Cf. (World Nuclear Association, 2022 a)
[61] Cf. (World Nuclear Association, 2022 b)
[62] Cf. (BGR, 2021)

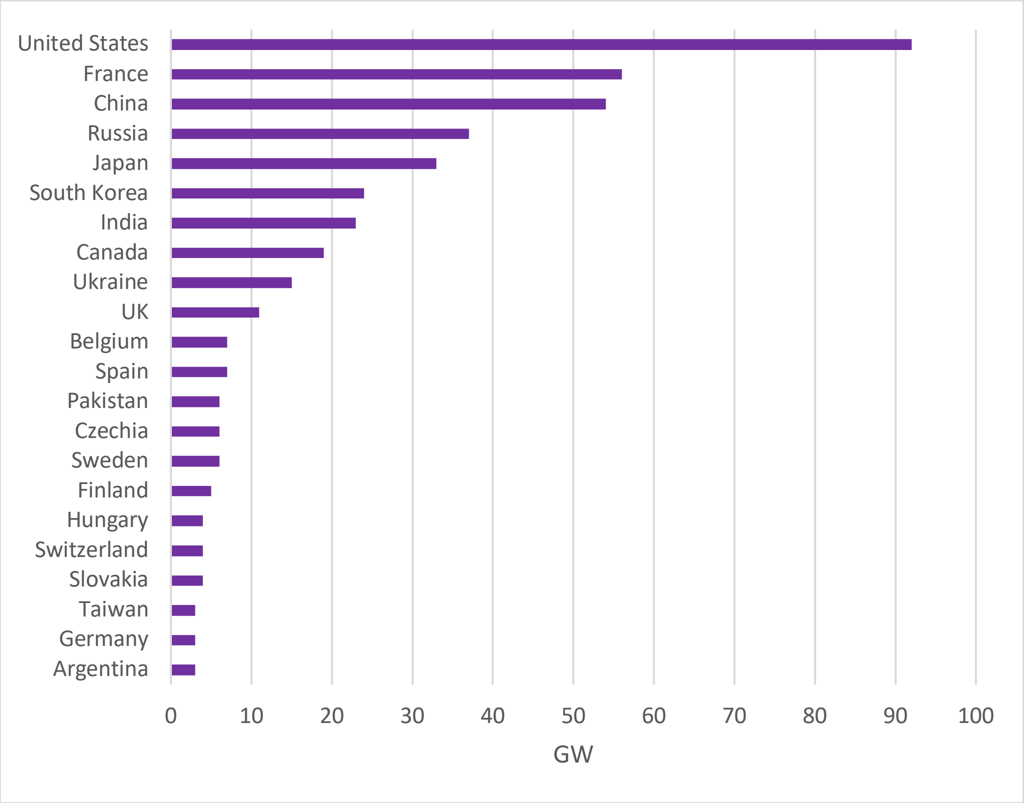

Figure 40: Installed capacity of nuclear power plants in various countries[63]

An increasing proportion of Uranium, now over 60 %, is recovered by in-situ leaching. With in-situ leaching (ISL), the ore is left in the ground and the minerals are brought to the surface by dissolving and pumping the solution, where the minerals can be extracted. Consequently, there is little damage to the surface and no tailings or waste rock. However, the ore body must be permeable to the fluids used and located so that groundwater outside the ore body is not contaminated.

The life-cycle greenhouse gas intensity of nuclear power is estimated at 34 - 60 gCO_2 e/kWh, far below that of coal-based baseload power plants (1,001 gCO_2 e/kWh). [64] Nuclear power plants consume 1,020 - 2,530 litres of water per MWh of electricity generated, depending on operating efficiency and site conditions. [64]

> Nuclear energy is the most land-efficient source of electricity generation (0.3 m^2 /MWh). It requires 50 times less land compared to coal and 18 to 27 times less land compared to solar energy, see Figure 44 in the appendix.[65]

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[63] Cf. (Statista, 2022) https://de.statista.com/statistik/daten/studie/152153/umfrage/anzahl-der-sich-in-betrieb-befindenden-atomkraftwerke-weltweit/

[64] Cf. (Center for Sustainable Systems, University of Michigan. 2021, 2021)

[65] Cf. (Our World in Data, 2022 a)

2.2.2 Overview nuclear reactors

A first to third generation nuclear fission reactor generates and controls the release of energy solely from the fission of Uranium-235 (U^{235}). The energy released from the continuous fission of the atoms of the fuel is used to generate steam indirectly and directly via cooling water circuits. The steam is used to drive the turbines that generate electricity (as in most fossil fuel power plants). Normally, Uranium oxide pellets are arranged in tubes to form fuel rods or held as spheres in the pebble bed reactor developed in Germany in the past (Thorium fuel). The rods are arranged in the reactor core to form fuel elements. In a PWR of the 1,000 MW class, there can be 51,000 fuel rods with over 18 million pellets.[66]

In a nuclear reactor, neutrons are needed to move from random nuclear fission to a controllable chain reaction in the reactor. For this purpose, it is necessary to control the speed of the neutrons so that they take effect in the correct cross-section for nuclear fission. To do this, various moderators are used to slow down the neutrons. Too little neutron moderation brings the fission process to a standstill.

There are the following types of nuclear fission reactors:

- *Light Water Reactor (LWR):* This is the most common type of nuclear fission reactor, mainly used in power generation. LWRs can be further distinguished as Pressurised Water Reactor (PWR) or Boiling Water Reactor (BWR) technologies, where light water serves as moderator and coolant.
- *Heavy Water Reactor (HWR*): This type of nuclear fission reactor uses heavy water as a moderator and coolant. [67] The reactors are often used in Canada (CANDU).
- *Gas Cooled Reactor (GCR)*: This type of nuclear fission reactor uses carbon dioxide as a coolant and carbon blocks as moderators. The reactors are mainly used in the UK.
- *Fast Breeder Reactor (FBR)*: This type of fission reactor is capable of producing more fuel than it consumes by converting Uranium^{238} into Plutonium^{239}. FBRs are mainly used in Japan and Russia, and also once in France. At present, the Russian breeder concept BREST seems to be the most advanced. At the Beloyarsk power plant, the waste from older-generation light-water reactors, which contain up to 96 % unused Uranium or Plutonium, and also the weapons-grade Plutonium earmarked for

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[66] Cf. (World Nuclear Association, 2022 c)

[67] Water with a high deuterium content

destruction under START[68], was used to generate electricity. Depending on the mode of operation, the fast breeder reactor can destroy or "breed" Plutonium.

- *Molten Salt Reactor (MSR)*: This type of nuclear fission reactor uses liquid salt at about 600 °C as a coolant and moderator. There are no fuel rods because the fuel is dissolved in the salt.[69] As the solution expands when overheated, the neutrons strike less fissile material and the chain reaction is reduced. This mechanism for achieving inherent safety is also used at Terrapower, the company founded by Bill Gates.
  MSR reactors are capable of reaching high temperatures and can be used to generate electricity, produce hydrogen and utilise waste materials. However, they are currently still in the development stage and are not yet used commercially. China has MSR plants using Thorium as fuel in trials since 2021.[70] The Norwegian shipbuilding company Ulstein recently presented a concept study for a civilian ship propulsion system.[71]
- *Dual Fluid Reactor (DFR):* the reactor, still in the planning stage, with a principle of cooling by liquid lead developed in Germany, should realise all expectations according to the description of its inventors[72] :
  - The DFR does not generate long-lived nuclear waste but dismantles existing nuclear waste.
  - Energy efficiency is expected to be about 100 times higher than electricity generation based on renewable energy, so that the generation cost of electricity in a 1.5 GW power plant could be 1 ¢/kWh.
  - The DFR is inherently safe.

Table 2 lists the global installed capacities of various types of nuclear fission reactors.

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[68] START: Strategic Arms Reduction Treaty of 1991, entered into force as START I in 1994, suspended by Putin in 2023

[69] Cf. Vahrenholt, 2023 p. 114

[70] ibid

[71] Cf. "Ulstein Thor": Powering battery-powered cruise ships with electricity from nuclear energy (cruisetricks.de)

[72] ibid

Table 2: Global fleet of nuclear fission reactors

Types of reactors	Number of reactors	Total output (GW)	Fuel rods
Pressurized water reactor (PWR)	307	294	enriched UO_2
Boiling water reactor (BWR)	61	62	enriched UO_2
Pressurised heavy water reactor (PHWR)	47	24	Natural UO_2
Light water graphite reactor (LWGR)	11	7,4	enriched UO_2
Advanced gas-cooled reactor (AGR)	8	4,7	Natural U (metal), enriched UO_2
Fast neutron reactor (FNR)	2	1,4	PuO_2 and enriched UO_2
High temper. gas-cooled reactor (HTGR)	1	0,2	enriched UO_2

2.2.2.1 Different types of nuclear reactors (SMR)

Nuclear fission can be considered a commercially mature technology, as the entire world reactor fleet is based on nuclear fission. The other nuclear technology for electricity generation that has been in international development for a long time with incipient successes in terms of technical feasibility (Wendelstein[73] and ITER[74]) is nuclear fusion.

The improvement of nuclear reactors for fission took place in several generations (Table 3). If the first generation was basically only the proof of concept for the generation of electricity but also for the breeding of nuclear weapons-grade Plutonium, a second generation had to be developed in order to build more economical and safer plants. In Germany, Obrigheim (1968) and Würgassen (1971) were the first reactors.[75] Reactors of this type still produce 85 % of the world's nuclear electricity today.[76]

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[73] Cf. Wendelstein 7-X nuclear fusion reactor: Next phase of experiments begins in Greifswald - n-tv.de

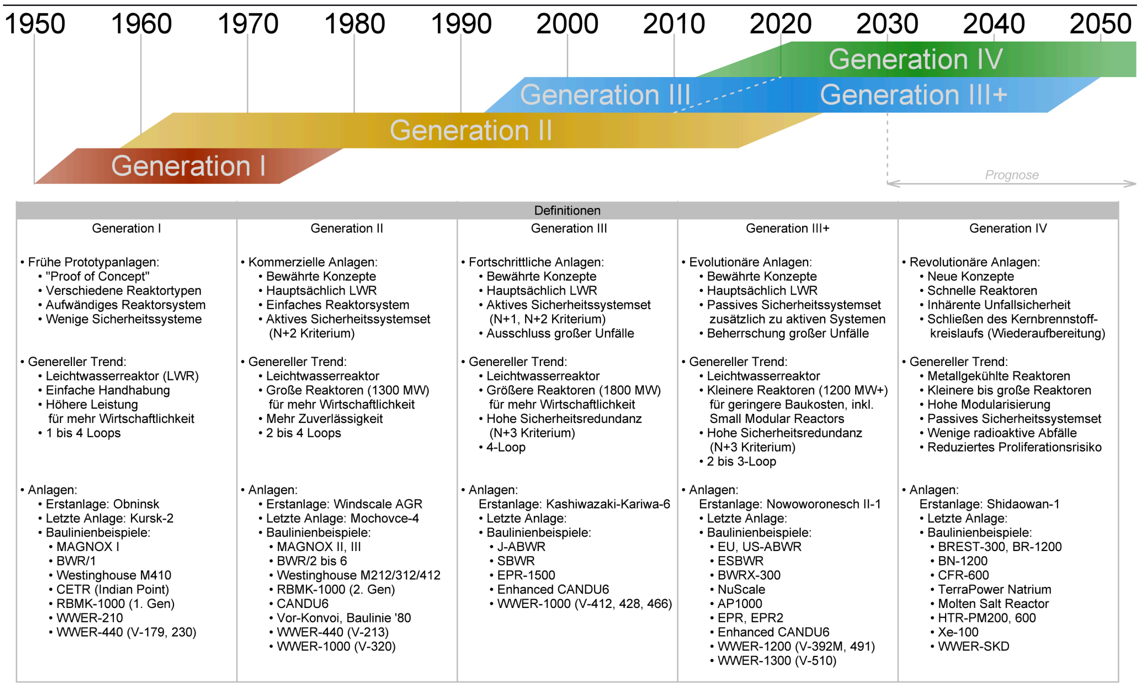
[74] Cf. ITER - the way to new energy

[75] Cf. Nucleopedia (n.d. a)

[76] ibid

Table 3: Generations of nuclear reactors

Source: https://de.nucleopedia.org/wiki/Datei:Reaktorgenerationen_Chart.svg



Definitionen				
Generation I	Generation II	Generation III	Generation III+	Generation IV
• Frühe Prototypanlagen: • "Proof of Concept" • Verschiedene Reaktortypen • Aufwändiges Reaktorsystem • Wenige Sicherheitssysteme	• Kommerzielle Anlagen: • Bewährte Konzepte • Hauptsächlich LWR • Einfaches Reaktorsystem • Aktives Sicherheitssystemset (N+2 Kriterium)	• Fortschrittliche Anlagen: • Bewährte Konzepte • Hauptsächlich LWR • Aktives Sicherheitssystemset (N+1, N+2 Kriterium) • Ausschluss großer Unfälle	• Evolutionäre Anlagen: • Bewährte Konzepte • Hauptsächlich LWR • Passives Sicherheitssystemset zusätzlich zu aktiven Systemen • Beherrschung großer Unfälle	• Revolutionäre Anlagen: • Neue Konzepte • Schnelle Reaktoren • Inhärente Unfallsicherheit • Schließen des Kernbrennstoffkreislaufs (Wiederaufbereitung)
• Genereller Trend: • Leichtwasserreaktor (LWR) • Einfache Handhabung • Höhere Leistung für mehr Wirtschaftlichkeit • 1 bis 4 Loops	• Genereller Trend: • Leichtwasserreaktor • Große Reaktoren (1300 MW) für mehr Wirtschaftlichkeit • Mehr Zuverlässigkeit • 2 bis 4 Loops	• Genereller Trend: • Leichtwasserreaktor • Größere Reaktoren (1800 MW) für mehr Wirtschaftlichkeit • Hohe Sicherheitsredundanz (N+3 Kriterium) • 4-Loop	• Genereller Trend: • Leichtwasserreaktor • Kleinere Reaktoren (1200 MW+) für geringere Baukosten, inkl. Small Modular Reactors • Hohe Sicherheitsredundanz (N+3 Kriterium) • 2 bis 3-Loop	• Genereller Trend: • Metallgekühlte Reaktoren • Kleinere bis große Reaktoren • Hohe Modularisierung • Passives Sicherheitssystemset • Wenige radioaktive Abfälle • Reduziertes Proliferationsrisiko
• Anlagen: • Erstanlage: Obninsk • Letzte Anlage: Kursk-2 • Baulinienbeispiele: • MAGNOX I • BWR/1 • Westinghouse M410 • CETR (Indian Point) • RBMK-1000 (1. Gen) • WWER-210 • WWER-440 (V-179, 230)	• Anlagen: • Erstanlage: Windscale AGR • Letzte Anlage: Mochovce-4 • Baulinienbeispiele: • MAGNOX II, III • BWR/2 bis 6 • Westinghouse M212/312/412 • RBMK-1000 (2. Gen) • CANDU6 • Vor-Konvoi, Baulinie '80 • WWER-440 (V-213) • WWER-1000 (V-320)	• Anlagen: Erstanlage: Kashiwazaki-Kariwa-6 • Letzte Anlage: • Baulinienbeispiele: • J-ABWR • SBWR • EPR-1500 • Enhanced CANDU6 • WWER-1000 (V-412, 428, 466)	• Anlagen: Erstanlage: Nowoworonesch II-1 • Letzte Anlage: • Baulinienbeispiele: • EU, US-ABWR • ESBWR • BWRX-300 • NuScale • AP1000 • EPR, EPR2 • Enhanced CANDU6 • WWER-1200 (V-392M, 491) • WWER-1300 (V-510)	• Anlagen: Erstanlage: Shidaowan-1 • Letzte Anlage: • Baulinienbeispiele: • BREST-300, BR-1200 • BN-1200 • CFR-600 • TerraPower Natrium • Molten Salt Reactor • HTR-PM200, 600 • Xe-100 • WWER-SKD

The third-generation reactors, which have been in operation since about 1996, can be described as state of the art. "Generation III is characterised by improved safety and economic efficiency, but not by sustainability with regard to the fuel cycle. Above all, the type of boiling water reactor - which is the second most common in operation worldwide after the pressurised water reactor - could be significantly simplified in its design and thus improved. Reactor representatives of the third generation are the ABWR (active in Japan), System 80+ (never sold that way, but incorporated into South Korean technology) and VVER-1200 (active in Russia and Belarus)."[75]

In Generation III+, passive safety has been significantly improved. The European Pressurised Water Reactor (EPR) is the most powerful reactor of this generation. Its development began as early as 1989 and aimed, among other things, to protect the groundwater from radioactivity by installing a reinforced concrete tank under the reactor pressure vessel and also to protect the power plant against aircraft crashes by means of a special containment.[77] The risk of a comprehensive core meltdown could be reduced from less than 1:100,000 to less than 1:1,000,000 by the design. However, the construction of the first two EPRs (FOAK projects), in Olkiluoto-3 (Finland) and Flamanville (France), turned into multi-billion dollar graves. Another two projects in China were much more successful. The reactor in Olkiluoto-3 had been

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[77] Cf. en.nucleopedia.org/wiki/Genaration_III

under construction since 2003 and, after extensive safety tests, went into commercial power operation by the operator TVO on 16 April 2023.

In some fourth-generation reactor concepts, very fast neutrons are used that are capable of making even non-fissile atomic nuclei fissile by neutron capture.[78] This process is called transmutation[79] . On the one hand, it has the advantage that the use of enriched U^{235} can be reduced and the proportion of U^{238} , which was not used for energy generation in reactors of the previous reactor types, is reduced. On the other hand, it also means that the proportion of highly radioactive waste is reduced and the storage times of the reactor waste can be reduced from one million years to "only" 500 years.[80]

This also means that fourth-generation reactors can be used to process highly radioactive residues from previous generations, to generate energy from them and to shorten final storage times.

2.2.2.2 Small Modular Reactors (SMR)

SMRs are typically smaller and less powerful than conventional nuclear power plants, with a capacity of less than 300 MW. They are intended to be safer than traditional nuclear power plants, with passive safety systems and inherent safety features of the reactor, such as lower power and lower operating pressure. SMRs require less frequent refuelling, only every 3 to 7 years, compared to every 1 to 2 years for conventional nuclear power plants.[81]

Both public and private entities are actively participating in efforts to bring SMR technology to commercial application before the end of this decade. Russia's Akademik Lomonosov Nuclear Power Plant, the world's first floating nuclear power plant, which began commercial operation in May 2020, generates energy from two 35 MW nuclear reactors. Other SMRs are under construction or in the licensing phase in Argentina, Canada, China, Russia, South Korea and the United States of America. More than 70 commercial SMR concepts (see Table 5 in the Annex) being developed around the world target different outputs and applications, such as electricity, hybrid energy systems, heating, water desalination and steam for industrial applications. Although SMR power plants have lower investment costs per unit, their economic competitiveness has yet to be proven in practice.

While land-based conventional nuclear power units produce up to 2 GW of electrical power, a typical ship or submarine propulsion reactor produces no more than a few hundred megawatts.

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[78] Cf. (Vahrenholt 2023), p. 113

[79] Cf. (Grytz, M. 2021)

[80] Cf. (Vahrenholt 2023), p. 113

[81] Cf. (IAEA, 2021 a)

Some Small Modular Reactors, are similar to marine propulsion reactors in terms of capacity and some design aspects, so nuclear marine propulsion is sometimes proposed as an additional market niche for SMRs. Naval reactors are operated with relatively low-enriched Uranium, which requires more frequent refuelling. Other reactors are operated with highly enriched Uranium, ranging from 20 % U-235 to over 96 % U-235, as used in American submarines.[82] The use of highly enriched fuel also increases the power density of the reactor and extends the useful life of the nuclear fuel, but it is more expensive and poses a greater proliferation risk than less highly enriched fuel.[83]

2.2.2.3 Thorium nuclear fission reactors

In a Thorium nuclear reactor, Thorium is first converted into a form that can be used as fuel. Uranium^{233} is produced by irradiating Thorium^{232} with neutrons. When Thorium^{232} absorbs a neutron, it becomes Thorium^{233}, which has a half-life of only 22 minutes. Thorium^{233} decays by beta decay into Protactinium^{233}, which beta decays to Uranium^{233} with a half-life of 27 days. Uranium^{233} is then used as fuel in the reactor.

Furthermore, Thorium is abundant in the earth's crust. Thorium deposits are mainly found in Australia, Brazil, India and the United States. India has the largest resources (850 kt), followed by Brazil (630 kt) and Australia and the United States (600 kt each).[84]

There have been many recent developments in the field of Thorium nuclear reactors. One of the most significant has been the development of molten salt reactors, which use a liquid fuel mixture containing Thorium and other elements. These reactors have the potential to be more efficient and safer than traditional nuclear reactors.[85] There are also some countries, including China and India, that are actively researching and developing Thorium nuclear technology.

2.2.2.4 Nuclear fusion

Nuclear fusion is the process in which two light atomic nuclei combine to form a single heavier one and release energy in the process, since the mass of the product is less than the mass of the initial particles and the difference is converted into energy according to $E=mc^2$. The mass defect only occurs in the fusion of very light elements and in the fission of heavy elements.

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[82] Cf. (Clay & Moltz, 2006)

[83] Cf. (Chunyan, Ma, & Hippel, 2008)

[84] Cf. (USGS, 2022)

[85] Cf. (World Nuclear Association, 2022 d)

Fusion reactions take place in a state of matter called plasma - a very hot, charged gas consisting of positive ions and freely moving electrons. In the sun, massive gravitational forces create the right conditions for fusion. The fusion fuel - various isotopes of hydrogen - must be heated to extremely high temperatures in the order of $5\cdot{}*10^7$ °C and kept stable under high pressure and strong external magnetic forces - i.e. confined densely enough and long enough for the nuclei to fuse. The goal of controlled fusion is "ignition", which occurs when enough fusion reactions take place so that the process is self-sustaining. In addition, the "ash" i.e. the product must be removed and fresh fuel added to continue the process. Once ignition is achieved, the net energy yield is about four times that of nuclear fission.[86] The different types of nuclear fusion reactors are as follows:

- *Tokamak*: This is the most advanced and most studied type of nuclear fusion reactor. It is a torus-shaped reactor that generates electrically charged plasma and keeps it away from the walls of the vessel with various strong magnetic fields.[87] ITER, the international company of 27 EU countries plus India, Japan, Korea, Russia and the United States operates an experimental reactor at Cadarache, France, designed to deliver 500 MW of fusion power with only 50 MW of added heating power. In November 2022, defects were found in the heat shields and vacuum vessel sectors, the repair of which necessitates a revision of the schedule delayed by COVID.[88]
- *Laser fusion reactor*: This type of nuclear fusion reactor uses lasers to apply the energy for nuclear fusion.

For more than 60 years, scientists have been working on one of the most difficult physics challenges of all time - harnessing nuclear fusion on Earth. On 5 December 2022, a series of lasers at the National Ignition Facility (NIF) fired 2.05 megajoules of energy at a tiny cylinder containing a pellet of frozen deuterium and tritium. [89] The pellet was compressed, producing temperatures and pressures strong enough to bring the isotopes to fusion. In a tiny fire that lasted less than a billionth of a second, the fusing atomic nuclei released 3.15 megajoules of energy - about 50 % more than had been used to heat the pellet. [90]

However, experts have stressed that while the results are an important proof of principle, the technology is still far from playing a significant role in energy supply.[91]

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[86] Massachusetts Institute of Technology

[87] Tokamak is an acronym from the Russian term for toroidal chamber with magnetic field

[88] Cf. https://www.iter.org/proj/inafewlines#1

[89] Deuterium and tritium are heavy isotopes of hydrogen

[90] Cf. (National Geographic, 2022)

[91] Cf. (Guardian, 2022)

2.2.3 Nuclear waste management

Another issue related to nuclear energy is the appropriate and safe handling and disposal of nuclear waste, which has raised public concern. The costs of handling and disposal are not found in the prime costs, but in the societal costs of nuclear energy, which are considered in chapter 2.2.4.

There are several methods used to dispose of nuclear waste, including:

- *Surface storage (interim storage):* This method involves storing the waste in above-ground facilities, such as concrete or highly complex steel casks (e.g. CASTOR). The unprocessed spent fuel, or radioactive waste after reprocessing, is stored in a secure location, such as a military base or a research facility, until a permanent disposal method can be found, e.g. by transmutation in the future. This type of nuclear waste disposal in interim storage facilities is implemented in countries such as Germany, Finland, France, the Czech Republic, the USA and Sweden.[92]
- *Deep geological disposal:* This method involves placing the waste deep underground in a geologically stable location, such as a salt cavern or granite rock formation. The waste is placed in complex special containers, which are then sealed and sunk deep into the ground in prepared cavities. Disposing of nuclear waste in deep geological repositories is the safest way, WNA says. Between 1954 and 2016, about 390 kt of "spent fuel" (highly radioactive) was generated. Two-thirds of this is in disposal and the rest has been reprocessed. [93]
  A nuclear fission power plant with the capacity of 1 GW generates about 30 t of spent nuclear fuel per year and, according to common opinion, should not be further processed/reprocessed as "spent fuel", i.e. it should be temporarily and then directly disposed of.[94] [95] However, the fourth generation reactors will probably revise this opinion.
- The first deep geological repository: In the Onkalo repository near Olkiluoto in Finland, nuclear waste of about 6.5 kt, which will accumulate over 100 years, will be stored stably 425 m underground for the next 10,000 years. The Onkalo facility is the result of almost 20 years of work and over this period the storage facility could cost an estimated 3.5 billion euros. [96] However, there are also experts who do not consider the new storage facility for nuclear waste disposal to be safe, as Finland is lifting as a whole due to

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[92] Cf. (World Nuclear Association, 2021)
[93] Cf. (IAEA, 2022 a)
[94] Cf. (Mohammed, Alwaeli, & Mannheim, 2022)
[95] Cf. (IAEA, 2000)
[96] Cf. (NS Energy, 2022)

the disappearing load of the ice sheet from the Ice Age, and with it the dumped radioactive waste.

- Internationally, the final disposal of radioactive waste is still a politically unsolved problem. However, the development of fourth-generation reactors is giving the debate a twist, as the radioactive "waste" is another source of energy for the reactors and the inherent safety of the power plants is significantly improved.

  In Germany, a multi-stage, democratically legitimised procedure is underway to find a site for the final repository with the best possible safety for the period of one million years. [97] The procedure was originally supposed to be completed by 2031. Internal documents of the BGE show that the procedure is not expected to be completed until 2046 at the earliest.

2.2.4 Financial aspects of nuclear energy

2.2.4.1 Investment and operating costs

Efforts to improve the safety of nuclear power plants are naturally reflected in construction costs. The construction of a core catcher, which safely catches the core of a reactor in the event of a core meltdown[98] , increased the construction costs in Olkiluoto /Finland)[99] among many other technical high safety features and project delays to 11 billion euros and in the double unit at Hinkley Point in England to 27 billion euros. [100]

According to some estimates, the investment costs for building a new nuclear power plant can vary between 4,000 and 12,000 USD/kW installed capacity. [101] [102] These costs include the cost of the reactor itself as well as site preparation, infrastructure and other related expenses.

The operating costs for a nuclear power plant can also vary significantly depending on factors such as fuel costs, maintenance and decommissioning. Some estimates say that the average operating cost for a nuclear power plant can vary from 30 to 60 USD/MWh of electricity produced, which casts doubt on the claim that nuclear power is cheap energy production. It is difficult to give average global investment and operating costs for nuclear fission reactors, as these costs can vary significantly depending on many factors, such as the type of reactor,

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[97] Cf. https://de.wikipedia.org/wiki/Endlagersuche_in_Deutschland

[98] Nuclear meltdowns have occurred at Harrisburg (1979), Chernobyl (1986) and Fukushima (2011)

[99] Construction of the reactor in Olkiluoto (EPR type) began in 2003 and has been on line since 16 April 2023; as construction proved more complex than planned, see https://www.mdr.de/wissen/vierte-generation-atomkraft-reaktor-klimawandel-100.html

[100] Cf. (Vahrenholt, 2023), p. 111

[101] Cf. (Söder, 2019)

[102] Cf. (Lazard, 2020)

location, regulatory environment, disposal costs and financing terms. With possible operating times of more than thirty years[103] , however, it is clear that the massive capital costs are put into perspective, and a cost-effective, virtually CO_2 -free, large-scale, 24/7 over 365-day load-stable power generation source is available here.

The approval process for the construction of power plants in Germany will follow a "major approval procedure". The duration and outcome of the procedure depend on how the local public reacts to the construction project, whether written objections are made or expert opinions against the construction are prepared. Approval procedures can drag on for several years in this way.

2.2.4.2 How much CO_2 is produced in the production of nuclear power and what does it cost?

There are different figures for this, depending on whether the calculation was made by anti-nuclear or pro-nuclear activists. The IPCC report of 2014 names an emission range of 3.7 to 110 g CO_2 e/kWh.[104] According to a study by the WISE organisation, the CO_2 emission is 117 g CO_2 /kWh over the entire life cycle of a nuclear power plant, if the significant emissions during construction and demolition of the plant are taken into account.[105] It is therefore certainly not correct to claim that no CO_2 is released during electricity production with nuclear power. But the emissions are significantly lower than, for example, generation with natural gas (approx. 442 g CO_2 e/kWh) or hard coal (approx. 864 g CO_2 e/kWh).[106]

In Germany, electricity generation through nuclear power has been subsidised for decades to the tune of around EUR 287 billion (purchasing power of 2019), according to conservative calculations and excluding the expenditure of the former GDR.[107] This corresponds to an amount of 4.6 Ct/kWh, of which 2.4, Ct/kWh is not included in the electricity price.[107]

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[103] The average age of the 173 European reactors is 34.5 years, cf. https://www.grs.de/de/aktuelles/kernenergie-weltweit-2022

[104] Cf. IPCC (2014)

[105] Cf. WISE (2017)

[106] Cf. Deutsche Welle (2021)

[107] Cf. FÖS (2020)

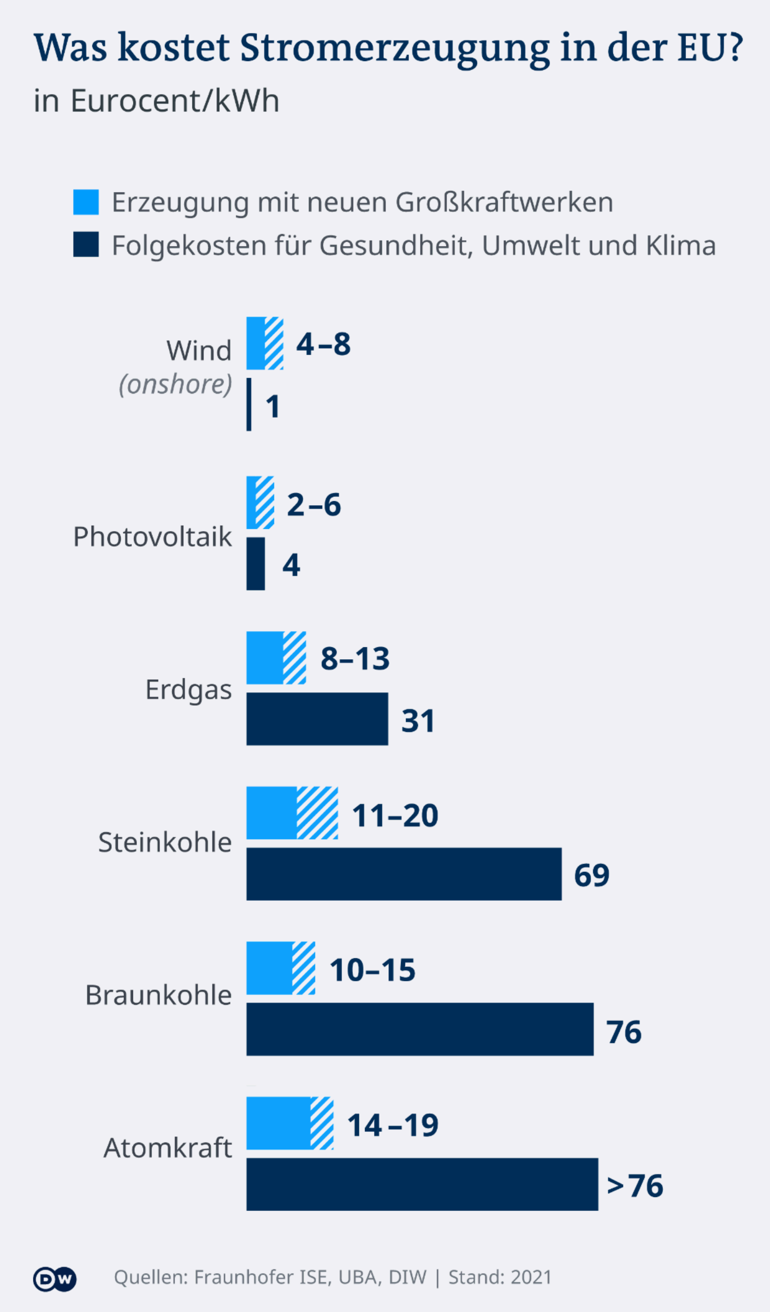

Figure 41: Cost of nuclear power generation in the EU;

Source: Deutsche Welle (2021)

With regard to the costs of nuclear electricity, a distinction must be made between the costs that the consumer has to bear directly and that he sees on his electricity bill, and the costs that arise from the impairment of his health and the consequential costs that are not added to his electricity bill. Figure 41 illustrates that nuclear power is not cheap, as already noted, because not only does generation cost about the same as with hard coal and lignite, but the overall societal follow-up costs, taking health, climate and the environment into account, are higher than with any other type of energy generation.

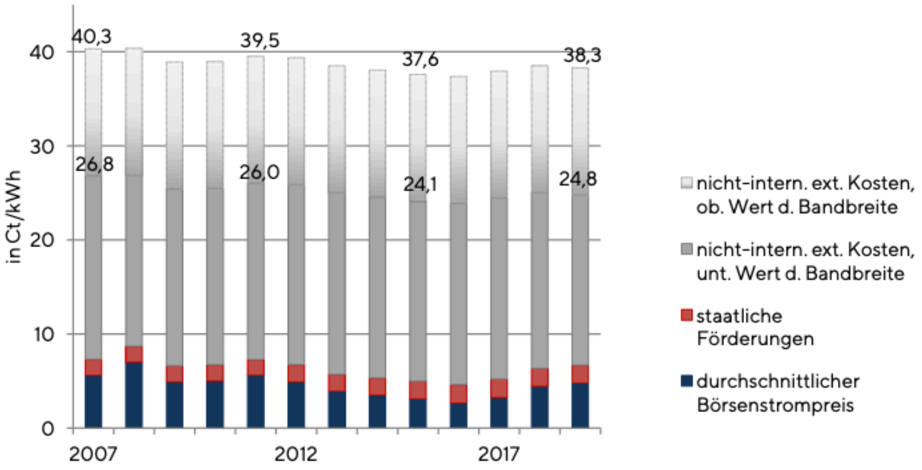

Figure 42: Total societal costs of electricity generation from nuclear energy from 2007 to 2019

Source: FÖS (2020)

The Forum Ökologisch-Soziale Marktwirtschaft (FÖS) calculated the hidden costs of the overall social costs of electricity generation from state subsidies (financial aid and tax concessions) and external costs alone in the years 2007 to 2019 at an average of 25 Ct/kWh to 39 Ct/kWh (see Figure 42 and Figure 43). This amounts to EUR 348 to 533 billion for this relatively short period. Due to a lack of data at other times, the societal costs cannot be fully and accurately determined. Societal costs can also be determined for the other types of energy production (see Figure 43). Nevertheless, the figures are sufficient to conclude, after analysing the costs of different energy sources, that nuclear energy is associated with the highest overall societal costs and will continue to cause high costs in the future, which are difficult to estimate, due to the high risks of this technology.[108]

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[108] Cf. infographic: Follow-up costs of nuclear power highest | Statista, https://de.statista.com/infografik/27231/kosten-der-stromerzeugung-in-deutschland-nach-energietraeger/

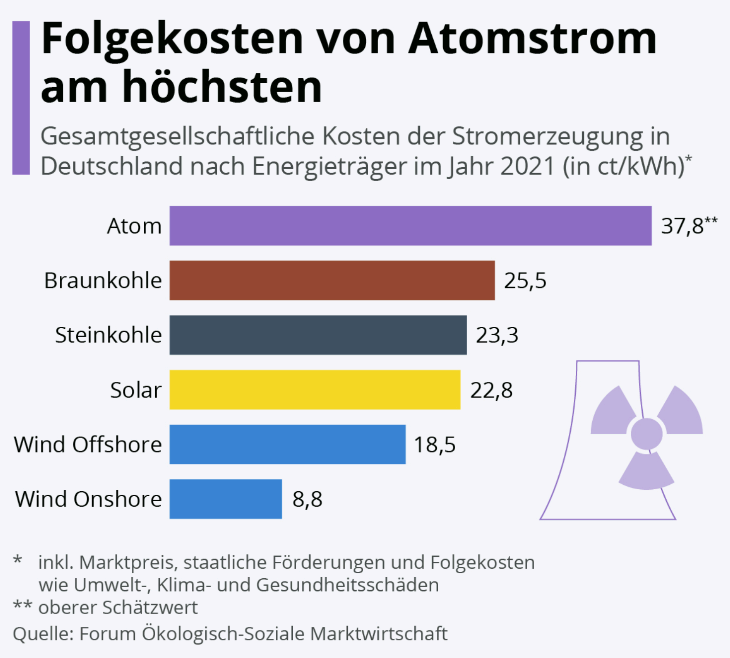

Figure 43: Total social costs of electricity generation by energy source

Source; Statista[108]

2.2.4.3 State and private investors

There are many private companies and public institutions that have actively invested in nuclear power generation. The US government has invested in nuclear energy by funding the Department of Energy, which provides money for research and development in nuclear energy. The German government did the same.

Examples:

- Electricité de France (EdF) is a utility company that operates a fleet of 58 nuclear reactors in France. In a 2022 statement, the French Ministry of Finance announced that it had offered €9.7 billion, or €12 per share, to buy the remaining 16 % stake in EDF.[109] Once the transaction is completed, the state will fully nationalise EdF and become the sole owner of the company.
- China National Nuclear Corporation (CNNC) is a state-owned utility in China that has invested in nuclear energy and operates a number of nuclear power plants in the country.

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[109] Cf. (Power Technology, 2022)

- TerraPower is a private nuclear energy company funded by Bill Gates and other private investors. It has raised $750 million to develop advanced Thorium nuclear reactors to serve as an alternative to light water reactors.[110]
- NuScale Power is a private developer of Small Modular Reactor funded by the private equity firms like Enerbility, Samsung C&T Corporation, JGC Holdings Corporation, Japan Bank for International Cooperation and Enercon Services.[111]

2.2.5 Health and environmental risks

In the history of nuclear energy, there have been some accidents in which radioactive material has leaked, people have been harmed and the environment has been damaged. Nevertheless, nuclear energy has one of the lowest levels of fatalities per electricity generated (30 to 90 per PWh) in the entire spectrum of power plants.[112]

The negative attitude towards nuclear energy among the German population was essentially shaped by dramatic accidents in Chernobyl (1986) and Fukoshima Daiichi (2011). The latter even initiated Germany's final withdrawal from nuclear energy in a knee-jerk reaction, although a more accurate assessment of the causes leading to the disasters should have recognised that such accidents could not have happened in Germany. [113]

The International Nuclear and Radiological Event Scale (INES) was introduced by the IAEA in 1990 to enable rapid transmission of safety-related information in the event of nuclear accidents.[114] The scale is designed as a logarithmic scale, each ascending level representing an accident that is about ten times as severe as one in the previous level. Level 0 is classified as a deviation, levels 1 to 3 are classified as incidents and malfunctions, and levels 4 to 7 are classified as accidents. The reportable levels of events are evaluated according to three aspects:

- Effects on people and the environment
- Impairments of radiological barriers and monitoring measures
- Impairment of safety precautions

On 11 March 2011, after a major earthquake, a 15-metre tsunami knocked out power and cooling to three reactors at Fukushima Daiichi, causing a nuclear accident. The accident was

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[110] Cf. (CNBC, 2022)
[111] Cf. (NuScale, 2022)
[112] Cf. (Statista, 2021) https://www.statista.com/statistics/494425/death-rate-worldwide-by-energy-source/ , (Our World in Data, 2022 b)
[113] Cf. (Vahrenholt 2023), p. 107
[114] Cf. (Wikipedia, 2022) https://en.wikipedia.org/wiki/International_Nuclear_Event_Scale

rated level 7 on the International Nuclear and Radiological Event Scale. Official figures show that there were 2,313 disaster-related deaths among evacuees in Fukushima Prefecture.[115] All four reactors at the nuclear power plant, with a total capacity of 2.7 GW, were shut down due to damage in the accident.

The Chernobyl accident in 1986 was the result of a faulty reactor design operated with inadequately trained personnel. The resulting steam explosion and fires released at least 5 % of the radioactive reactor core into the environment, depositing radioactive material in many parts of Europe. Two workers at the Chernobyl nuclear power plant died as a result of the explosion, and another 28 people died within a few weeks as a result of acute radiation syndrome. This accident was classified at level 7 on the INES scale. The classification of other nuclear accidents on the INES scale as well as the description of different levels are shown in Figure 44: Land requirements for various types of electricity generation

Figure 44 in the appendix.

Regardless of how the Uranium is extracted from the rock, radioactive waste remains from the extraction processes. For example, the solid radioactive waste left over from milling is called *tailings* and the liquid waste from in-situ extraction is called *raffinates.*[116] Uranium mining produces tailings that are usually "disposed of" in near-surface deposits near the mine. These tailings pose serious environmental and health risks in the form of radon emissions and the escape of heavy metals and arsenic into groundwater. [117] In the past, these risks were politically addressed in many countries around the world because they disproportionately affected low-income populations and minorities. For example, from 1944 to 1986, the United States mined 4 Mt of Uranium ore, leaving 500 abandoned mines in Navajo territory.[118] During this time, rates of lung cancer and other diseases increased dramatically among Navajo living near the mines.[119]

In addition, several studies, including from Japan's Kyoto University and India's Jadavpur University, have confirmed radioactive pollution of the air, water and soil in the village of Jadugoda, India, where Uranium has been mined in open-pit operations since 1967.[120] An independent nuclear scientist has documented cases of congenital malformations, infertility, cancer, respiratory problems and miscarriages in Jadugoda.

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[115] Cf. (World Nuclear Assocition, 2022 e)
[116] Cf. (EPA, 2022)
[117] Uranium decays naturally to radon gas
[118] Cf. (Longstaff, 2017)
[119] Cf. (Arnold, 2014)
[120] Cf. (Alzjazeera, 2014)

A safer, more transparent and environmentally friendly extraction of Uranium would be necessary to enable the protection of the human rights of indigenous peoples and a more equitable use of nuclear energy in developing countries. The use of robots could avoid the work of humans in mines that are harmful to health, while drones could monitor the spread of substances that are harmful to the environment and health. According to GlobalData, robotic technology is essential for any mining company that wants to be competitive in the future.[121] The future goals of mining companies - safety, productivity and sustainability - can all be supported by the use of robots.

2.2.6 Development relevance and geopolitics

The IAEA has established rules of conduct to ensure global safety in the use of nuclear energy. The Code of Conduct is a recognised, non-legally binding international instrument that has the political support of more than 130 member states. [122][123] The Guidance *on the Import and Export of Radioactive Sources* complements the Code and is intended to ensure an appropriate transfer of responsibility when a radioactive source is moved from one state to another. [124]The Guidance *on the Management of Disused Radioactive* Sources provides further guidance on the establishment of a national policy and strategy for the *management* of disused radioactive sources and the implementation of management options such as recycling and reuse, long-term storage pending disposal and return to a supplier.[125]

In the European Union, nuclear safety involves a wide range of activities such as ensuring proper operating conditions for nuclear power plants and preventing accidents and mitigating their consequences. With the amendment of the Nuclear Safety Directive (*2014/87/Euratom*), the EU has significantly strengthened its leadership role in nuclear safety worldwide.[126]

In India, activities related to the establishment and use of nuclear facilities and the use of radioactive sources are carried out under the provisions of the *Atomic Energy Act, 1962*. The environmental protection aspects are governed by the *Environmental Protection Act, 1986. The* provisions for radiation protection aspects are laid down in the *Radiation Protection Rules, 1962*. The safety aspects of mining and processing of so-called Prescribed Substances are governed by the *Mines Prescribed Substance Rules, 1984*. Safe disposal of waste is ensured

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[121] Cf. (GlobalData Thematic Research & MiningTechnology, 2022)
[122] Cf. (IAEA, 2018)
[123] Cf. (IAEA, 2022 b)
[124] Cf. (IAEA, 2018)
[125] Cf. (IAEA, 2018)
[126] Cf. (European Union, 2015)

through the implementation of the *Atomic Energy Safe Disposal of Radioactive Waste Rules, 1987.*

2.2.6.1 Peaceful use of nuclear energy

Technology exchange and cooperation between nations can also involve the development of nuclear power and nuclear research in developing countries. For example, the Rooppur project in Bangladesh is the first initiative under an Indo-Russian agreement to implement nuclear power projects in third countries.[127]

India's NPCIL will play a key role in the construction of a nuclear power plant on foreign soil, as it is to supply equipment and materials for the plant being built by Russia in Bangladesh. Rosatom has also started construction of two nuclear power plants in Hungary in 2022.[128]

Russia is considered the world market leader for the export of nuclear power plants. The state-owned company Rosatom has started building 19 nuclear reactors between 2012 and 2021, 15 of them abroad.[129] This is far more than the next major nuclear power plant developers China, France and South Korea are realising. Although China started building 29 reactors in the same period, only two of them were commissioned abroad. France started building two reactors abroad and South Korea four.

About 40 % of the world's refined Uranium comes from Russia.[130] There are at least 50 countries that have some form of nuclear cooperation with Russia. Rosatom is also a leader in enriching Uranium, offering about 46 % of the world's enriched Uranium on the world market. At the same time, China's CNNC share of the global market of 18 % in 2018 will increase to 28 % in 2030.

Such dependence on a handful of suppliers can be detrimental to the world's energy security, and dependencies can be exploited for geopolitical purposes, as the world is experiencing with Russia's invasion of Ukraine.

2.2.6.2 Military use of nuclear energy

Nine countries, namely the United States, Russia, France, China, the United Kingdom, Pakistan, India, Israel and North Korea, possess nuclear weapons[131]. In total, the world's nuclear

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[127] Cf. (Economic Times, 2018)
[128] Cf. (Euronews, 2022)
[129] Cf. (REFRL, 2022)
[130] Cf. (REFRL, 2022)
[131] Cf. Statista (2022a) https://www.statista.com/statistics/264435/number-of-nuclear-warheads-world-wide/#:~:text=As%20a%20weapon%20of%20mass,the%20United%20States%20and%20Russia.

arsenal amounts to about 13,000 weapons, which is less than the 60,000 weapons that existed during the Cold War.[132] A majority of these weapons are under the control of the USA and Russia - 5,400 and 6,000 weapons respectively.

The main weapons material is highly enriched Uranium, which contains at least 20 % Uranium-235 (U^{235}) and usually about 90 % U^{235} . Highly enriched Uranium can be mixed with low U^{235} Uranium to produce low enriched Uranium with less than 5 % U^{235} as fuel for nuclear power plants. It is mixed with depleted Uranium (predominantly U^{238}), natural Uranium (0.7 % U^{235}) or partially enriched Uranium. Highly enriched Uranium in the weapons and other military stockpiles of the USA and Russia amounts to about 1.5 kt, according to the 2017 World Nuclear Association report.[133]

The US-Russian pledges to convert nuclear weapons into fuel for power generation became known as the "Megatons to Megawatts" programme. Between the years 1993 and 2013, 500 tonnes of highly enriched Uranium were to be converted by Russia into low enriched Uranium to be purchased by the US for use in nuclear power plants.[134] Furthermore, weapons-grade Plutonium consists of more than 93 % Pu^{239} and can be used as fuel for power generation like reactor-grade Plutonium. However, this potential remains limited for technical and economic reasons.

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[132] Cf. (Union of Concerned Scientist USA, 2022)
[133] Cf. (World Nuclear Association, 2017)
[134] Cf. (World Nuclear Association, 2017)

Appendix to 2.2

Table 4: List of nuclear fission power plants under construction

Launch ye	Location	Reactor	Model	Gross GWe
2022	Belarus, BNPP	Ostrovets 2	VVER-1200	1,2
2022	China, CGN	Fangchenggang 3	Hualong One	1,2
2022	Russia, Rosenergoatom	Kursk II-1	VVER-TOI	1,3
2022	Slovakia, SE	Mochovce 3	VVER-440	0,5
2023	Bangladesh	Rooppur 1	VVER-1200	1,2
2023	China, CGN	Fangchenggang 4	Hualong One	1,2
2023	China, CNNC	Xiapu 1	CFR600	0,6
2023	France, EDF	Flamanville 3	EPR	1,7
2023	India, NPCIL	Kakrapar 4	PHWR-700	0,7
2023	India, NPCIL	Kalpakkam PFBR	FBR	0,5
2023	India, NPCIL	Kudankulam 3	VVER-1000	1,0
2023	India, NPCIL	Kudankulam 4	VVER-1000	1,0
2023	India, NPCIL	Rajasthan 7	PHWR-700	0,7
2023	India, NPCIL	Rajasthan 8	PHWR-700	0,7
2023	Korea, KHNP	Shin Hanul 2	APR1400	1,4
2023	Korea, KHNP	Shin Kori 5	APR1400	1,4
2023	Russia, Rosenergoatom	Kursk II-2	VVER-TOI	1,3
2023	Slovakia, SE	Mochovce 4	VVER-440	0,5
2023	Turkey	Akkuyu 1	VVER-1200	1,2
2023	UAE, ENEC	Barakah 4	APR1400	1,4
2023	USA, Southern	Vogtle 3	AP1000	1,3
2023	USA, Southern	Vogtle 4	AP1000	1,3
2024	Bangladesh	Rooppur 2	VVER-1200	1,2
2024	China, SPIC & Huaneng	Shidaowan 1	CAP1400	1,5

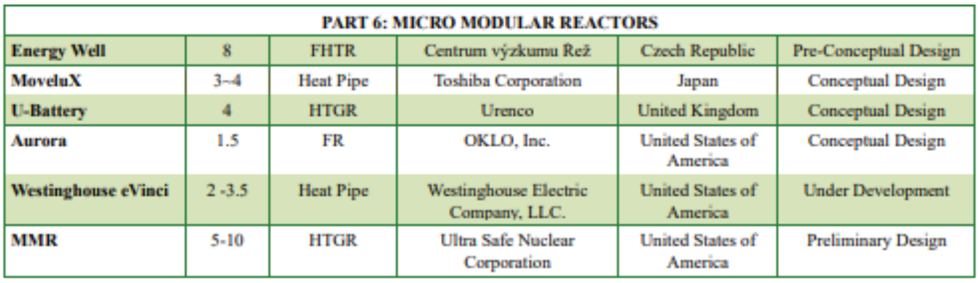
2024	China, Guodian & CNNC	Zhangzhou 1	Hualong One	1,2
2024	Iran	Bushehr 2	VVER-1000	1,1
2024	Korea, KHNP	Shin Kori 6	APR1400	1,4
2024	Turkey	Akkuyu 2	VVER-1200	1,2
2025	China, SPIC & Huaneng	Shidaowan 2	CAP1400	1,5
2025	China, CGN	Taipingling 1	Hualong One	1,2
2025	China, Guodian & CNNC	Zhangzhou 2	Hualong One	1,2
2025	Turkey	Akkuyu 3	VVER-1200	1,2
2026	China, CGN	Cangnan/San'ao 1	Hualong One	1,2
2026	China, Huaneng & CNNC	Changjiang 3	Hualong One	1,2
2026	China, CNNC	Changjiang SMR 1	ACP100	0,1
2026	China, CGN	Taipingling 2	Hualong One	1,2
2026	China, CNNC	Tianwan 7	VVER-1200	1,2
2026	China, CNNC	Xiapu 2	CFR600	0,6
2026	India, NPCIL	Kudankulam 5	VVER-1000	1,0
2026	Russia, Rosatom	BREST-OD-300	BREST-300	0,3
2026	Turkey	Akkuyu 4	VVER-1200	1,2
2027	Argentina, CNEA	Carem	Carem25	0,0
2027	China, CGN	Cangnan/San'ao 2	Hualong One	1,2
2027	China, CNNC	Sanmen 3	CAP1000	1,3
2027	China, CNNC	Tianwan 8	VVER-1200	1,2
2027	China, CNNC & Datang	Xudabao 3	VVER-1200	1,2
2027	China, Huaneng & CNNC	Changjiang 4	Hualong One	1,2
2027	India, NPCIL	Kudankulam 6	VVER-1000	1,0
2027	UK, EDF	Hinkley Point C1	EPR	1,7
2028	Brazil, Eletrobrás	Angra 3	Pre-convoy	1,4
2028	China, CGN	Lufeng 5	Hualong One	1,2

2028	China, CNNC & Datang	Xudabao 4	VVER-1200	1,2
2028	Egypt, NPPA	El Dabaa 1	VVER-1200	1,2
2028	UK, EDF	Hinkley Point C2	EPR	1,7
2030	Egypt, NPPA	El Dabaa 2	VVER-1200	1,2

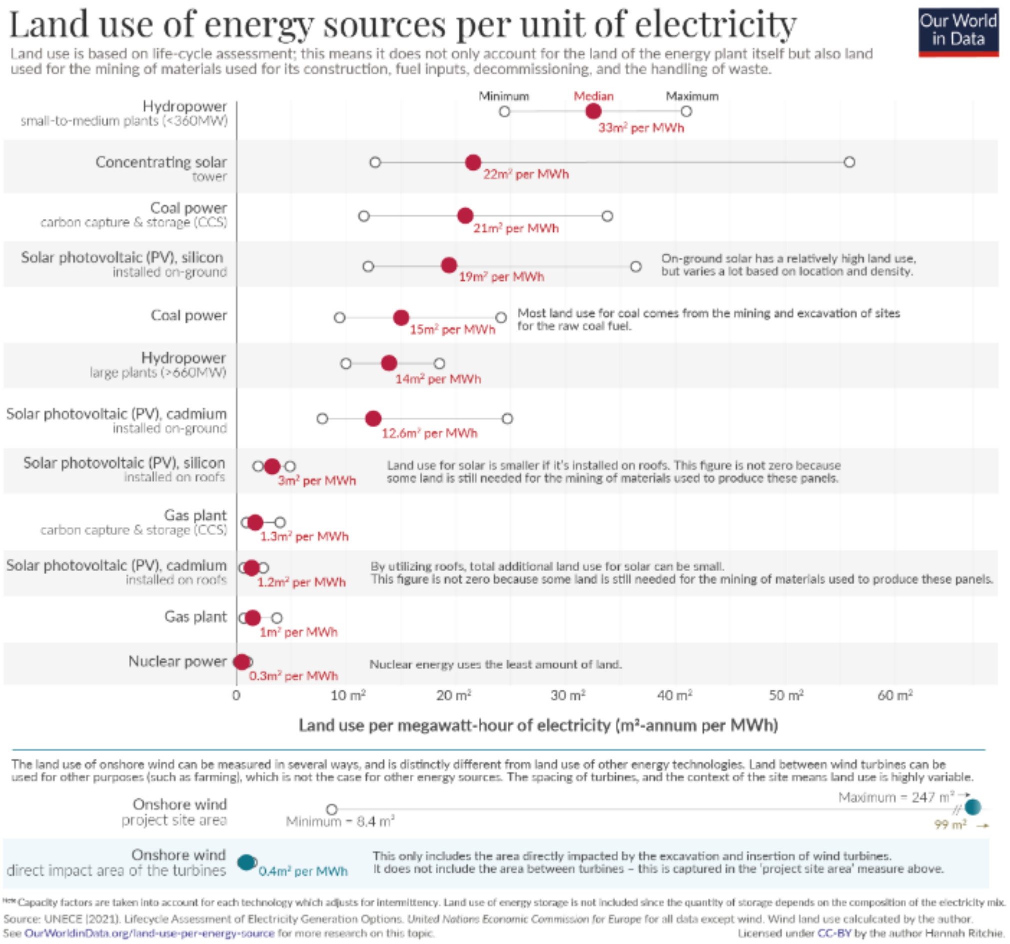
Table 5: List of Small Modular Reactors under construction worldwide

Design	Output MW(e)	Type	Designers	Country	Status
PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Detailed Design
CANDU SMR	300	PHWR	Candu Energy Inc (SNC-Lavalin Group)	Canada	Conceptual Design
CAP200	200	PWR	SNERDI/SPIC	China	Conceptual Design
DHR400	400 MW(t)	LWR (pool type)	CNNC	China	Basic Design
HAPPY200	200 MW(t)	PWR	SPIC	China	Detailed Design
TEPLATOR™	50 MW(t)	HWR	UWB Pilsen & CIIRC CTU	Czech Republic	Conceptual Design
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Basic Design
DMS	300	BWR	Hitachi-GE Nuclear Energy	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea, and Saudi Arabia	Certified Design
RITM-200	2 × 53	PWR	JSC "Afrikantov OKBM"	Russian Federation	Under Development
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
KARAT-45	45 - 50	BWR	NIKIET	Russian Federation	Conceptual Design
KARAT-100	100	BWR	NIKIET	Russian Federation	Conceptual Design
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
UK SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual Design
NuScale	12 × 60	PWR	NuScale Power Inc.	United States of America	Under Regulatory Review
BWRX-300	270 - 290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America, Japan	Pre-licensing
SMR-160	160	PWR	Holtec International	United States of America	Preliminary Design
W-SMR	225	PWR	Westinghouse Electric Company, LLC	United States of America	Conceptual Design
mPower	2 × 195	PWR	BWX Technologies, Inc	United States of America	Conceptual Design
PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
KLT-40S	2 × 35	PWR in Floating NPP	JSC Afrikantov OKBM	Russian Federation	In Operation
RITM-200M	2 × 50	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Under Development
ACPR50S	50	PWR in FNPP	CGNPC	China	Conceptual Design
ABV-6E	6-9	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Final design
VBER-300	325	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Licensing Stage

SHELF	6.6	PWR in Immersed NPP	NIKIET	Russian Federation	Detailed Design
PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
StarCore	14/20/60	HTGR	StarCore Nuclear	Canada/UK/US	Pre-Conceptual Design
GTHTR300	100 - 300	HTGR	JAEA	Japan	Pre-licensing
GT-MHR	288	HTGR	JSC Afrikantov OKBM	Russian Federation	Preliminary Design
MHR-T	4 × 205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic Design
SC-HTGR	272	HTGR	Framatome, Inc.	United States of America	Conceptual Design
HTR-10	2.5	HTGR	INET, Tsinghua University	China	Operational
HTTR-30	30 (t)	HTGR	JAEA	Japan	Operational
RDE	3	HTGR	BATAN	Indonesia	Conceptual Design
PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
ARC-100	100	Liquid Sodium	ARC Nuclear Canada, Inc.	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
microURANUS	20	LBR	UNIST	Korea, Republic of	Pre-Conceptual Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	LMFR	LeadCold	Sweden	Conceptual Design
EM^2	265	GMFR	General Atomics	United States of America	Conceptual Design
Westinghouse LFR	450	LMFR	Westinghouse Electric Company, LLC.	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
PART 5: MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor - Wasteburner	300	MSR	Moltex Energy	United Kingdom / Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual Design
Mk1 PB-FHR	100	FHR	University of California at Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50 - 1200	MSR	Elysium Industries	USA and Canada	Conceptual Design



PART 6: MICRO MODULAR REACTORS					
Energy Well	8	FHTR	Centrum výzkumu Řež	Czech Republic	Pre-Conceptual Design
MoveluX	3~4	Heat Pipe	Toshiba Corporation	Japan	Conceptual Design
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual Design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual Design
Westinghouse eVinci	2 -3.5	Heat Pipe	Westinghouse Electric Company, LLC.	United States of America	Under Development
MMR	5-10	HTGR	Ultra Safe Nuclear Corporation	United States of America	Preliminary Design



Land use of energy sources per unit of electricity

Land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste.

On-ground solar has a relatively high land use, but varies a lot based on location and density.

Most land use for coal comes from the mining and excavation of sites for the raw coal fuel.

Land use for solar is smaller if it's installed on roofs. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

By utilizing roofs, total additional land use for solar can be small. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

Nuclear energy uses the least amount of land.

The land use of onshore wind can be measured in several ways, and is distinctly different from land use of other energy technologies. Land between wind turbines can be used for other purposes (such as farming), which is not the case for other energy sources. The spacing of turbines, and the context of the site means land use is highly variable.

This only includes the area directly impacted by the excavation and insertion of wind turbines. It does not include the area between turbines – this is captured in the 'project site area' measure above.

Note Capacity factors are taken into account for each technology which adjusts for intermittency. Land use of energy storage is not included since the quantity of storage depends on the composition of the electricity mix.
Source: UNECE (2021). Lifecycle Assessment of Electricity Generation Options. *United Nations Economic Commission for Europe* for all data except wind. Wind land use calculated by the author.
See OurWorldinData.org/land-use-per-energy-source for more research on this topic. Licensed under CC-BY by the author Hannah Ritchie.

Figure 44: Land requirements for various types of electricity generation[135]

Figure 44: Various nuclear accidents on INES scale (next page)

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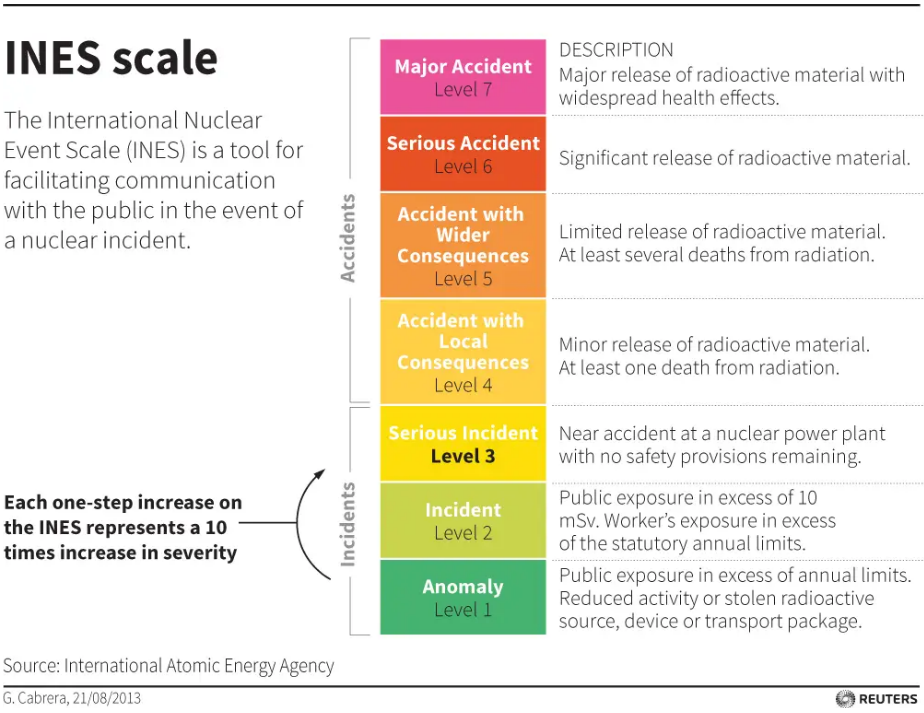
[135] (Our World in Data, 2022 a)



INES scale

The International Nuclear Event Scale (INES) is a tool for facilitating communication with the public in the event of a nuclear incident.

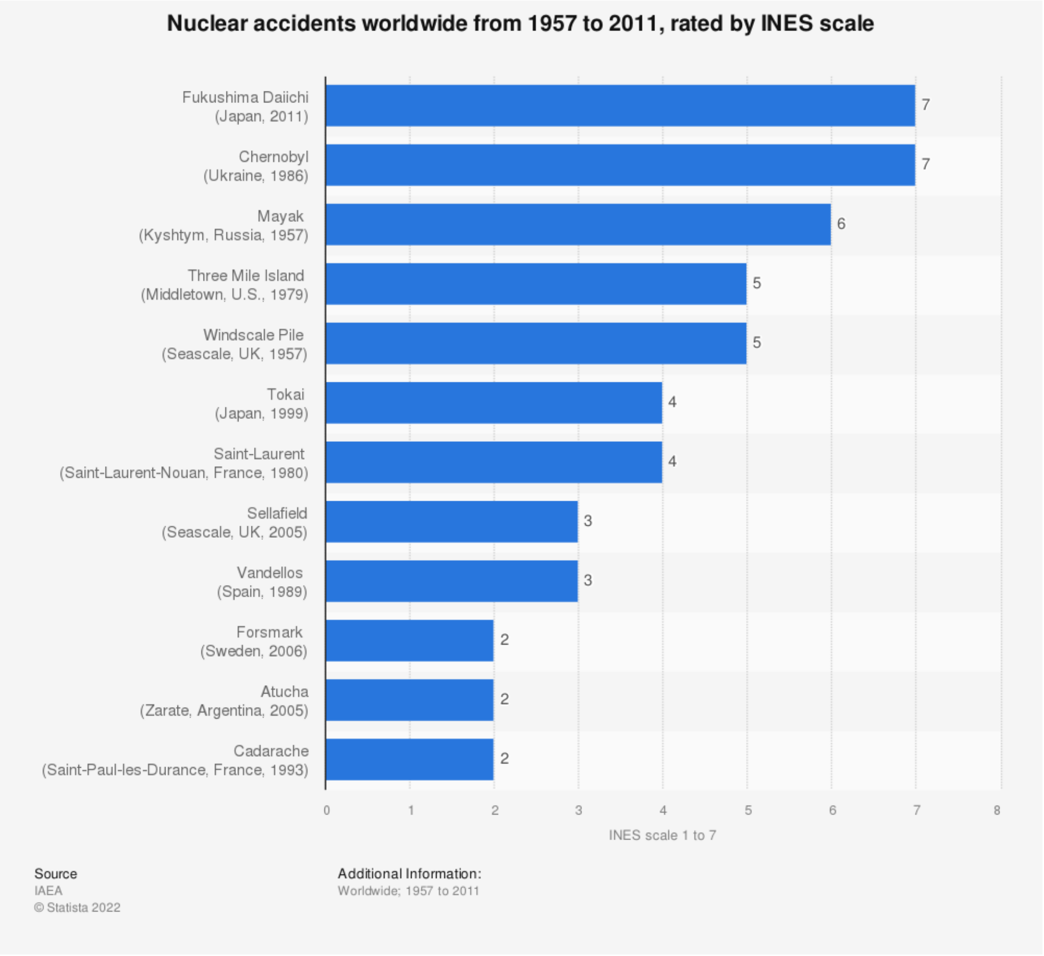
	Level	DESCRIPTION
Accidents	**Major Accident** Level 7	Major release of radioactive material with widespread health effects.
	Serious Accident Level 6	Significant release of radioactive material.
	Accident with Wider Consequences Level 5	Limited release of radioactive material. At least several deaths from radiation.
	Accident with Local Consequences Level 4	Minor release of radioactive material. At least one death from radiation.
Incidents	**Serious Incident** Level 3	Near accident at a nuclear power plant with no safety provisions remaining.
	Incident Level 2	Public exposure in excess of 10 mSv. Worker's exposure in excess of the statutory annual limits.
	Anomaly Level 1	Public exposure in excess of annual limits. Reduced activity or stolen radioactive source, device or transport package.

Each one-step increase on the INES represents a 10 times increase in severity

Source: International Atomic Energy Agency

G. Cabrera, 21/08/2013

REUTERS



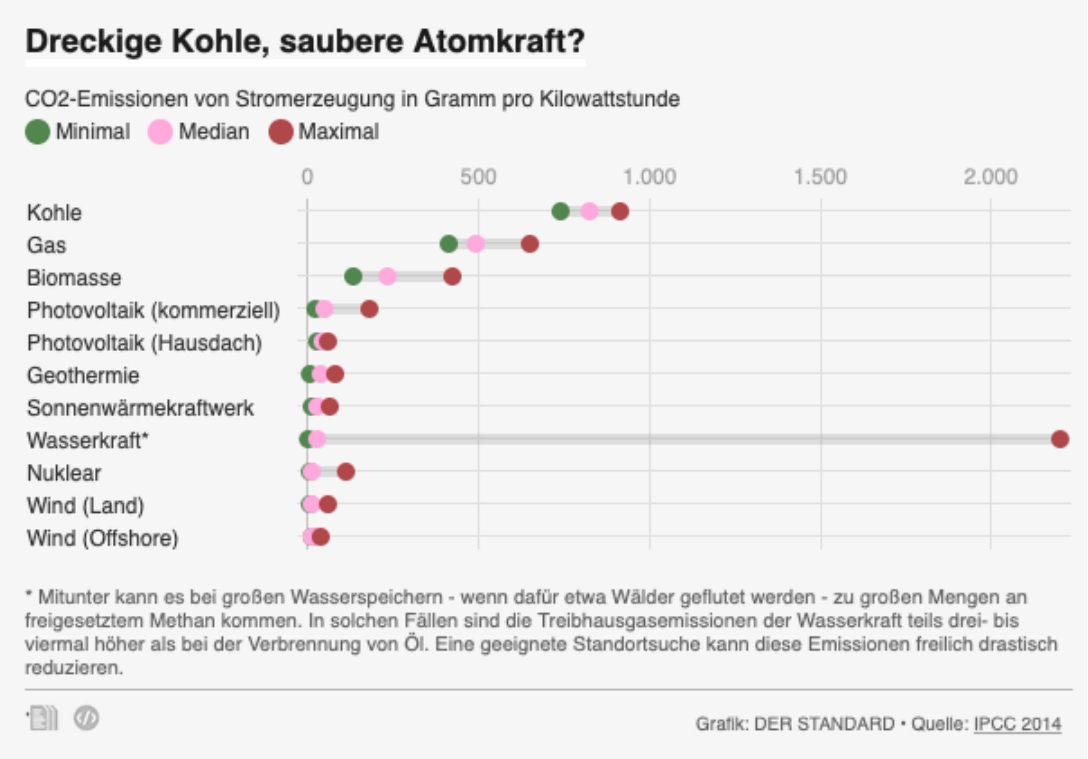
Nuclear accidents worldwide from 1957 to 2011, rated by INES scale

Source
IAEA
© Statista 2022

Additional Information:
Worldwide; 1957 to 2011

Figure 45: World nuclear accidents ordered by INES scale;

Source: Statista (2022b)



Dreckige Kohle, saubere Atomkraft?

CO2-Emissionen von Stromerzeugung in Gramm pro Kilowattstunde

* Mitunter kann es bei großen Wasserspeichern - wenn dafür etwa Wälder geflutet werden - zu großen Mengen an freigesetztem Methan kommen. In solchen Fällen sind die Treibhausgasemissionen der Wasserkraft teils drei- bis viermal höher als bei der Verbrennung von Öl. Eine geeignete Standortsuche kann diese Emissionen freilich drastisch reduzieren.

Grafik: DER STANDARD • Quelle: IPCC 2014

Figure 46: Dirty coal, clean nuclear power;

Source: IPCC Report (2014)