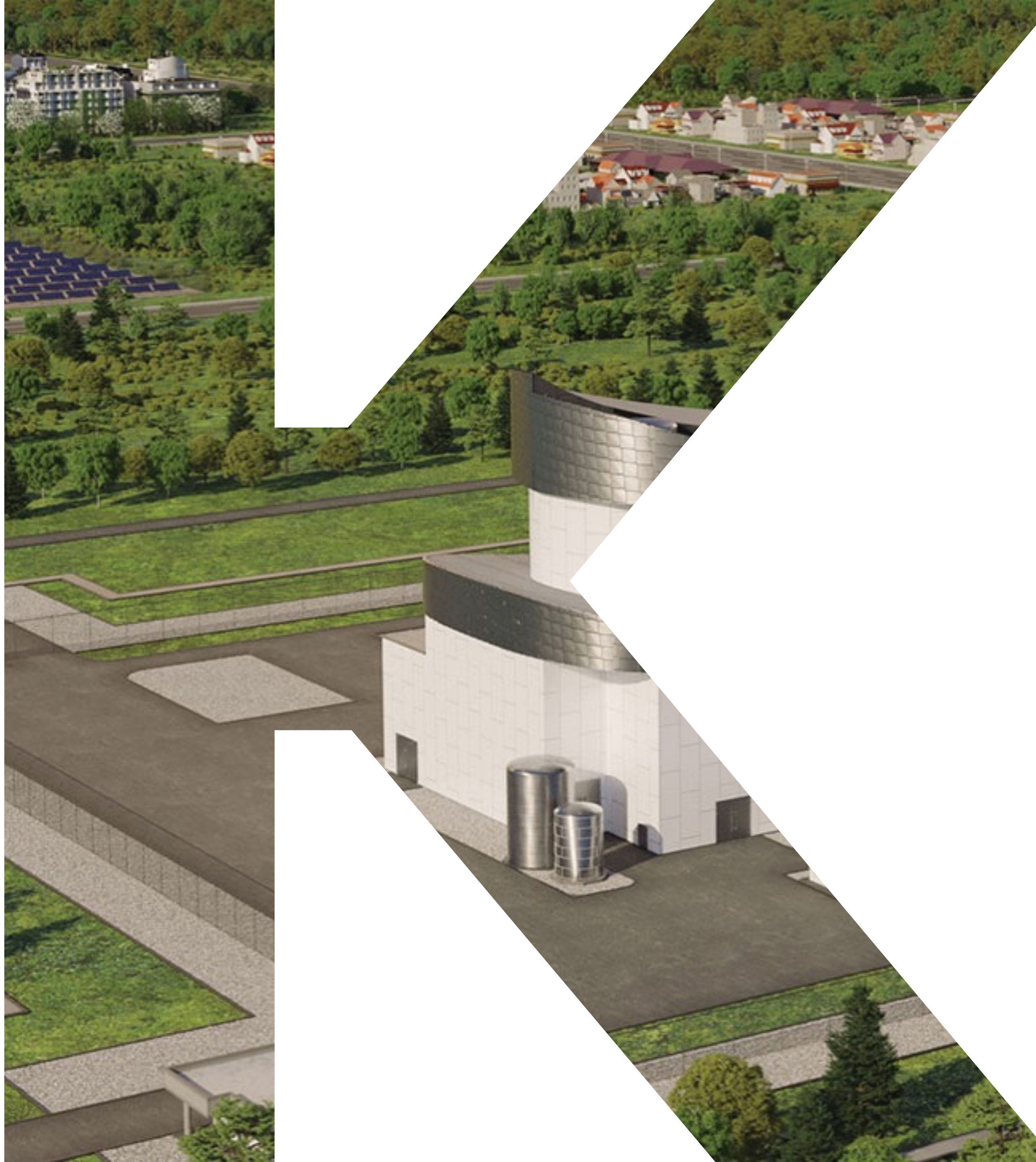
Nuclear small modular reactors (SMRs)

Holding disruptive hopes
December 2023

KEARNEY | Energy Transition Institute



Compiled by the Kearney Energy Transition Institute

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About the FactBook: Nuclear small modular reactors

The FactBook focuses on nuclear small modular reactors (SMR). It presents the key concepts of nuclear power technologies and their evolution. The factbook explores the diversity of SMR technologies, presenting their main characteristics, potential advantages and disadvantages, and potential applications. As an emerging technology, SMR competitivity is examined with the available data and the status of the market is summarized. Relevant regulations and public policies across the globe are presented, as well as the challenges faced from a regulatory, social acceptance, and waste management perspective.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

Authors

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Agenda

General abstract

Nuclear energy for electricity production has been used since the 1950s, reinforcing and giving stability to electrical grids, providing base-load power, and ensuring energy supply and security by diversifying the electricity mix. In some regions, its deployment has limited the use of fossil fuel for power production, while improving air quality and limiting regional acidification. **The nuclear power carbon footprint is among the lowest of all electricity sources**. These power plants are expensive to build, and once up and running, have predictable generating cost as well as low operating costs. Nuclear reactors have a relatively long operating life, ranging from 40 to 60 years.

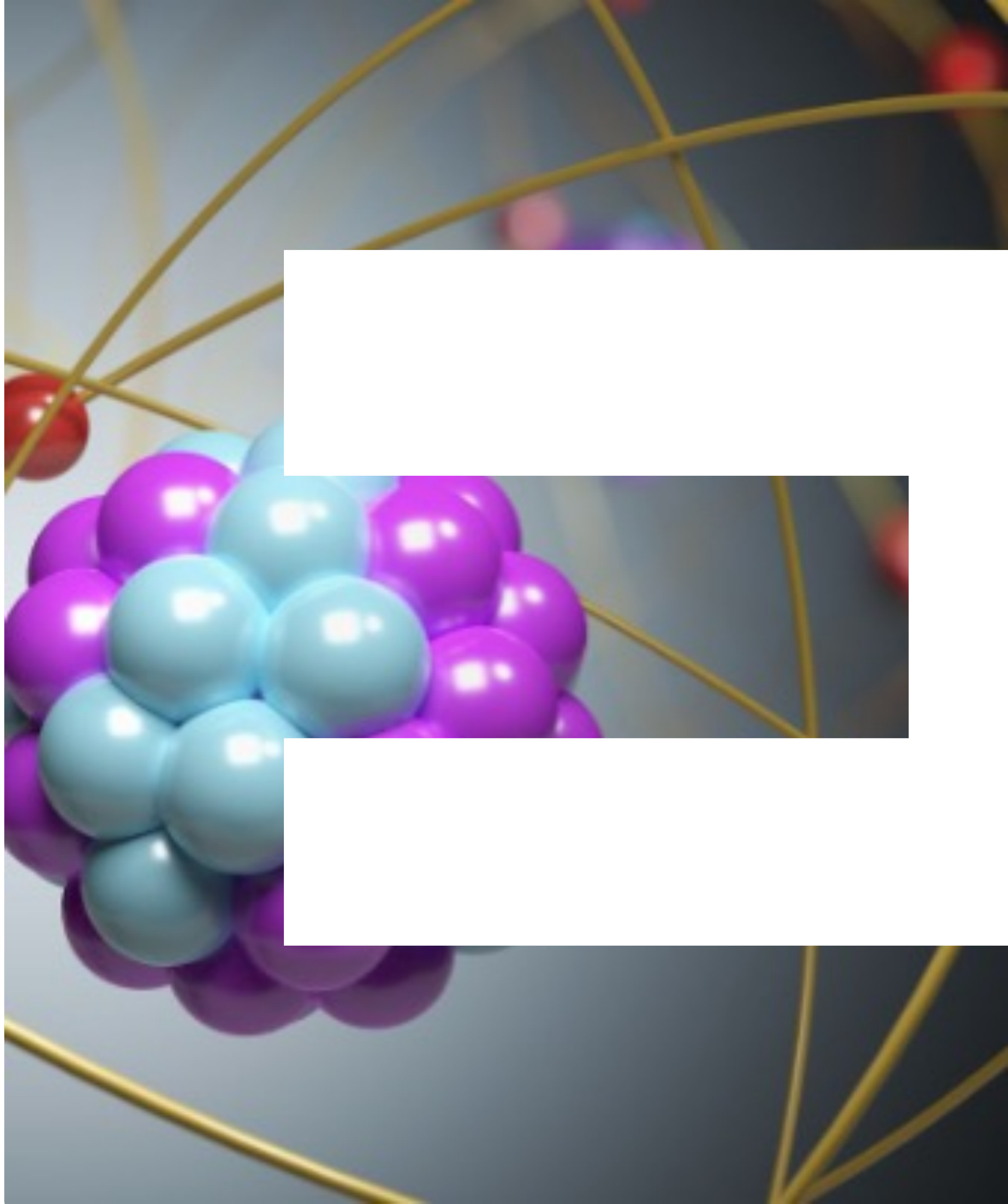
Between the 1970s and 2000s, nuclear power experienced accelerated growth despite the Three Mile Island accident—until the Chernobyl accident. Growth was slowed until the 2005s when a budding renaissance started, but that was affected by the Fukushima accident in the following decade. In recent years, with the energy transition and the need for climate mitigation solutions, nuclear power, as a low-carbon technology, has regained traction.

Nuclear energy use presents challenges including safety concerns, disposal of radioactive waste, high construction costs, and the potential for nuclear proliferation. Innovation of nuclear power has been driven by cost reduction, ease of deployment, and increased safety and security features. Among these innovations, nuclear small modular reactors (SMRs) have been designed as factory-built modules using traditional and novel reactor technologies.

This FactBook has been prepared to cover the topic of nuclear SMRs. SMRs have gained momentum because they provide a new perspective of deployment thanks to their modularity and potentially safer technologies. SMRs also have the potential to respond to other uses including thermal and off-grid applications.

As of today, only two SMRs are operational, and more than 60 projects are at different stages of design and construction. **There is limited information about this incipient sector, and commercial projects have not yet been built, thus reflected as an imbalance of subjects across the report**. Some topics were not covered as no representative data is available to date. Other topics, including waste management, licensability of projects, and economics, remain unknown and estimates are based on theoretical projections.

1. Nuclear physics for the layman



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Nuclear principles are fundamental for understanding nuclear reactions

Elements and isotopes. An atom is the smallest particle of any element that holds the characteristics of that element . The number of protons in an atom defines the identity of the element, but the number of neutrons can differ resulting in the existence of isotopes. The elements relevant to nuclear power production include plutonium (Pu), uranium (U), thorium (Th), cesium (Cs), and strontium (Sr). Each radioactive isotope has its own decay process and is measured with a time period referred to as half-life.

Nuclear energy principles. The protons and neutrons in the nucleus of an atom are held together by the strong nuclear force. Heavy nuclei can undergo fission, breaking up into lighter, more stable nuclei and releasing energy and neutrons. In nuclear reactors, a controlled nuclear fission chain reaction occurs, and energy is released in the form of heat and radiation.

An atom is the smallest particle of any element that holds the characteristics of that element

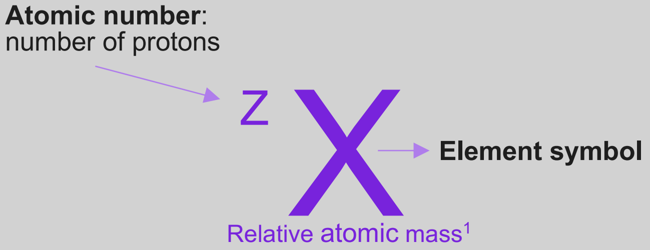
Atoms are constituted by a nucleus of protons and neutrons, and surrounding electrons

1.1 Nuclear elements and isotopes

Basic structure of matter

- All **matter** is **made up of atoms.**
- Any **material** that is composed **of only one type of atom** is called a chemical **element**—for example, hydrogen, carbon, and uranium.
- All the **atoms** of a **specific element** have the **same number of protons.**

Nuclear notation
Used in the periodic table



Atomic number: number of protons

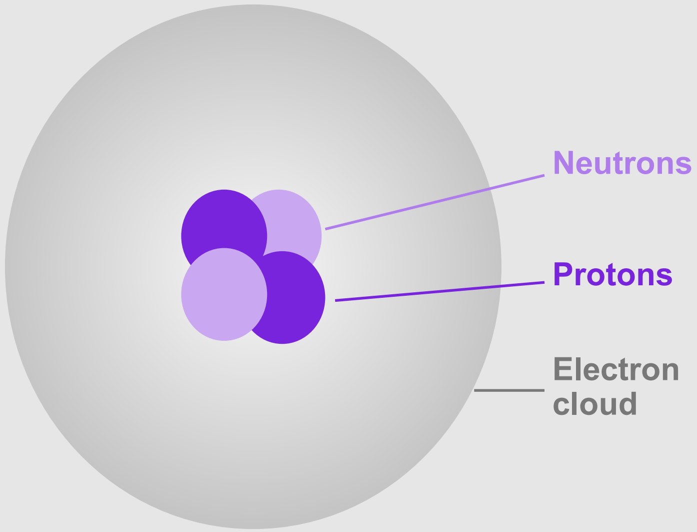
Z X

Element symbol

Relative atomic mass[1]

Mass number: number of protons and neutrons

Simplified diagram of an atom



- Protons and neutrons make up the **nucleus** of an atom.
- All **protons** are **identical** to each other, and all **neutrons** are identical to each other.
- **Protons** have a **positive** electrical charge.
- **Neutrons** have **no** electrical **charge**.
- **Electrons** are **negatively** charged subatomic particles that are as negative as protons are positive.
- The **number** of **protons** and **neutrons** in the nucleus gives the **atoms** their **specific characteristics**.
- The **number** of **protons** in an **atom** is **equal to** the number of **electrons** in it.
- The **mass of an electron** is **negligible** when **compared to** the mass of a **proton** or a **neutron**.

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[1] The relative atomic mass corresponds to the weighted average of the masses of the isotopes of an element compared to 1/12 of the mass of the carbon-12 atom.

Sources: Iowa State University, Center for Non-Destructive Evaluation, Atomic Elements; adapted from Britannica; CERN's website, Subatomic Particles; Kearney Energy Transition Institute analysis

The number of protons defines the identity of an element, but the number of neutrons can differ resulting in the existence of isotopes

Isotopes are fundamental for understanding nuclear reactions.

Isotopes may present different physical properties even though they are a unique element, chemically speaking.

1.1 Nuclear elements and isotopes

What are isotopes?

The atoms of each chemical **element** have a defining number of protons and electrons, but the quantity of **neutrons can vary**. **Isotopes** are variants of an element that **differ** on the **number of neutrons** they possess.

Types of isotopes

There are **two categories** of isotopes: stable and unstable or radioactive.

Stable isotopes do not emit radiation and can be **present in nature**—for example, carbon-12 and oxygen-16.

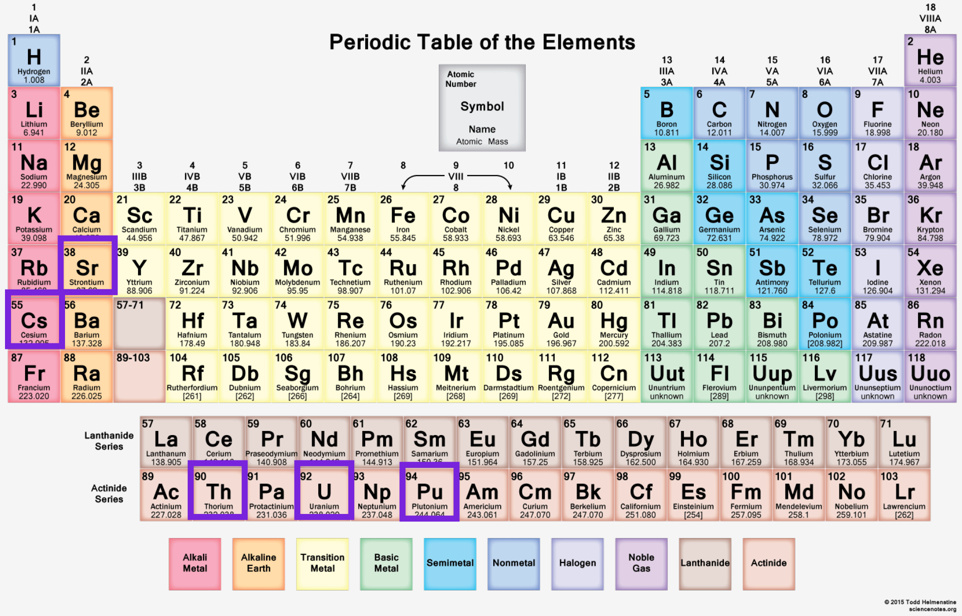
Unstable isotopes have **too many or too few neutrons** to maintain their stability, so they **decay** and produce radiation (in the form of alpha, beta, or gamma rays). Through this phenomenon, they **regain stability** either by rearranging the nucleus or by ejecting the excess number of neutrons or protons (for example, carbon-14, uranium-236). These isotopes can be produced in nuclear reactors or in cyclotrons.[1]

Elements for nuclear power

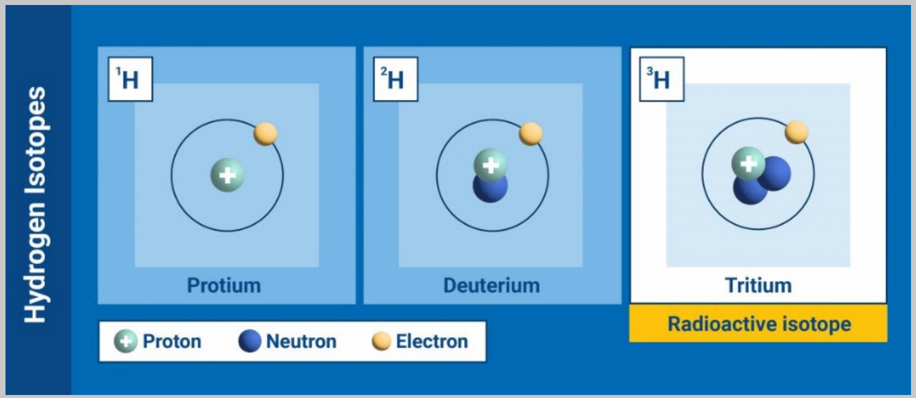
The elements relevant to nuclear power production include **plutonium (Pu), uranium (U), thorium (Th).**

Periodic table of elements

Elements relevant to nuclear power production



Example : Hydrogen isotopes



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[1] A cyclotron, also known as a particle accelerator, propels a beam of charged particles (protons) in a circular path.

Sources: IAEA, What are isotopes; US DOE, DOE Explains...Isotopes; Australia ANSTO, Radioisotopes; Orano, Isotopes: what to remember; Kearney Energy Transition Institute analysis

The most prevalent isotopes in nuclear power production have different fundamental characteristics

Each isotope has a unique decay process and is measured with a time period called the half-life.

The half-life is the time it takes for half of the unstable atoms to undergo radioactive decay.

1.1 Nuclear elements and isotopes

Most prevalent isotopes for nuclear power

Uranium isotopes

Uranium has three naturally occurring isotopes: U-238 (the most stable and abundant one), U-235, and U-234. All but 0.7% of naturally occurring uranium is U-238. **U-235** is the only isotope that **is fissile.** Some isotopes are produced artificially in fission reactors (for example U-232 and U-236).

92
U
238.024

Naturally occurring isotopes of uranium

Uranium 234: 92 protons + 142 neutrons (0.006%)
Uranium 235: 92 protons + 143 neutrons (0.719%)
Uranium 238: 92 protons + 146 neutrons (99.275%)

Other isotopes used for nuclear power

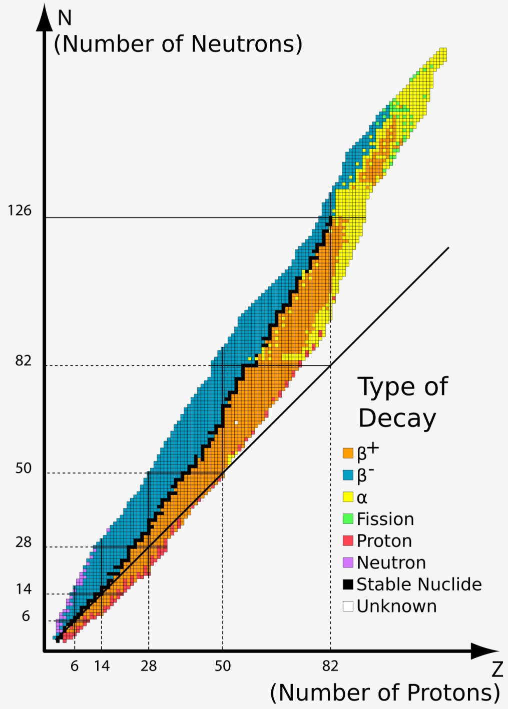
Alternative isotopes are used for nuclear power production, including:

- **Plutonium (Pu-239)** is produced by breeding it from U-238. U-238 becomes U-239 after capturing a neutron, then converts to neptunium (Np-239) by losing an electron, then Np-239 loses an electron and transforms into Pu-239.
- **Thorium (Th-232)** is not intrinsically fissile but is fertile and when absorbing a neutron transforms to U-233.

Fissile vs. fertile atoms

- **Fissile nuclei** are those in which striking **low-energy** (slow, thermal) **neutrons** can **trigger fission** readily and consistently. Examples are **U-235**, **U-233,** and **Pu-239**.
- **Fertile nuclei** are not fissile themselves, but they **can capture a neutron** and **transform into a fissile nucleus**, either directly or after one or more beta decays. For instance, **U-238** that becomes Pu-239, and **Th-232** that becomes U-233.

Radioisotopes radioactive decay



- Only a few isotopes of each element are stable nuclides.
- For light atoms, stability is achieved when the number of protons and neutrons is equal or similar.
- Heavy atoms are stabilized with more neutrons than protons.

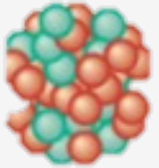
Sources: Australia ANSTO, Radioisotopes; Orano, Isotopes: what to remember; All about plutonium; Science notes, Periodic table; IRSN; Britannica; Kearney Energy Transition Institute analysis

Nuclear binding energy holds together the nucleus of an atom, and it is proportional to the mass difference between the nucleus and the sum of the nucleons[1]

At the nuclear level, energy is released by fusing into larger more stable nuclei (fusion) or by breaking up in smaller more stable nuclei (fission)

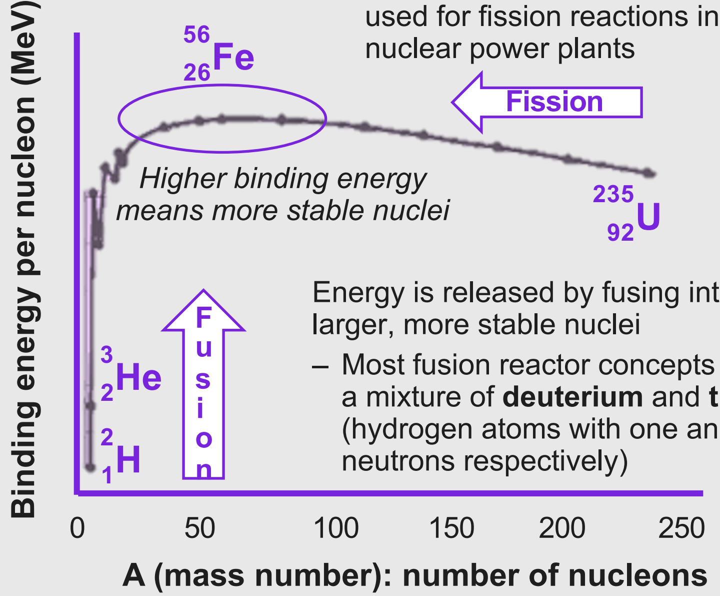
1.2 Nuclear energy principles

Nuclei are made up of **protons and neutrons held together by the strong nuclear force** that compensates the repelling Coulomb force due to the positive charge of the protons.



Nuclear binding energy

- The mass of a nucleus is always less than the sum of the masses of the protons and neutrons (except for hydrogen that has only one proton).
- The difference in mass, or mass defect, is a measure of the nuclear binding energy which holds the nucleus together and can be calculated by Einstein’s formula.
- The average binding energy per nucleon is a function of the atomic number of the nucleus. This is highest for atoms with atomic numbers around 50, so these are most stable.
- Breaking up large atoms to smaller ones (fission) or joining smaller ones to larger ones (fusion), therefore releases binding energy.



Energy is released by breaking up into smaller, more stable nuclei

- **Uranium** and **plutonium** are most used for fission reactions in nuclear power plants

Energy is released by fusing into larger, more stable nuclei

- Most fusion reactor concepts will use a mixture of **deuterium** and **tritium** (hydrogen atoms with one and two neutrons respectively)

Nuclear binding energy = Δmc^2

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[1] Nucleons are the particles that make up the nucleus of an atom: protons and neutrons.

Sources: IAEA; C. McCombie personal communication; Kearney Energy Transition Institute analysis

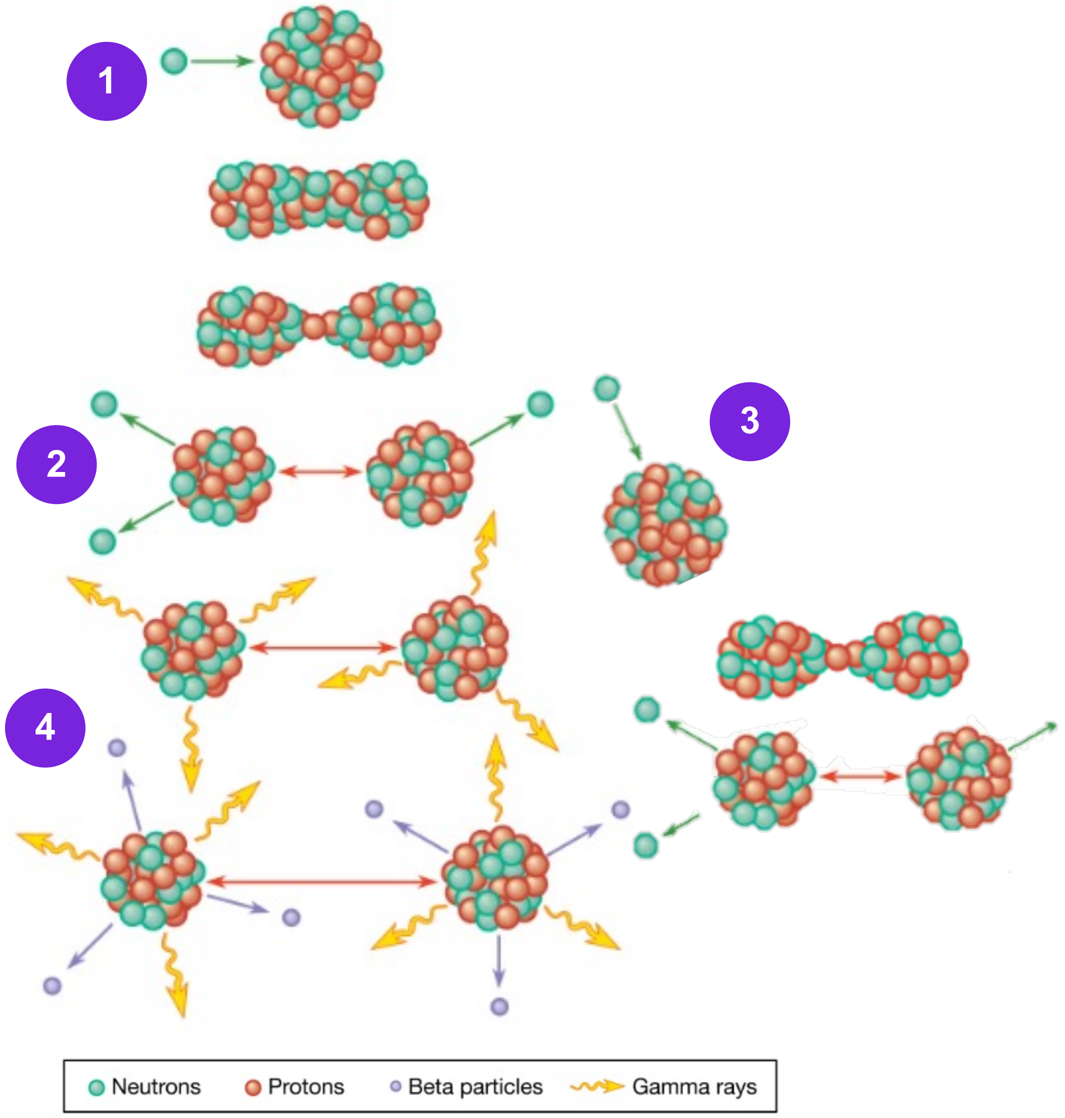
In nuclear fission, a neutron collides with the nucleus of a fissile atom (e.g., uranium-235) and splits it, releasing a large amount of energy in the form of heat and radiation

All nuclear power plants today use nuclear fission to produce energy.

How fission works?

1. A neutron is fired at an atom. Under the proper circumstances, the atom captures the neutron and becomes unstable.
2. Then it fissions into two lighter, more stable atoms, releasing additional neutrons.
3. Some of these neutrons then hit other nuclei, causing them to fission and release more neutrons (starting a chain reaction).
4. Most of the energy released goes into kinetic energy of the fission products, while some is retained because the fission products are in an excited state. The excess energy is then lost by radioactive decay in the form of gamma rays and beta particles (over a variable period ranging from seconds to years).

Sequence of events of a fission chain reaction



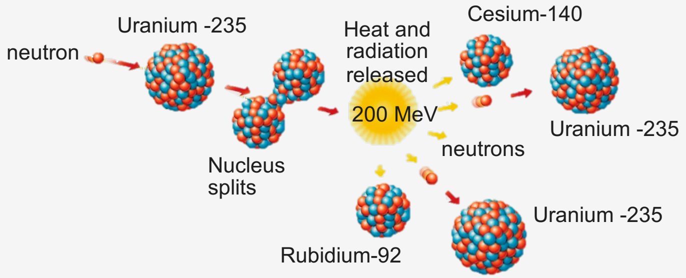
Sources: EIA, adapted from Britannica, World Nuclear Association; C. McCombie personal communication; Kearney Energy Transition Institute analysis

The outcome of the interaction between a heavy atom and an incident neutron depends on the nature of the atom and on the velocity of the neutron, and is probabilistic

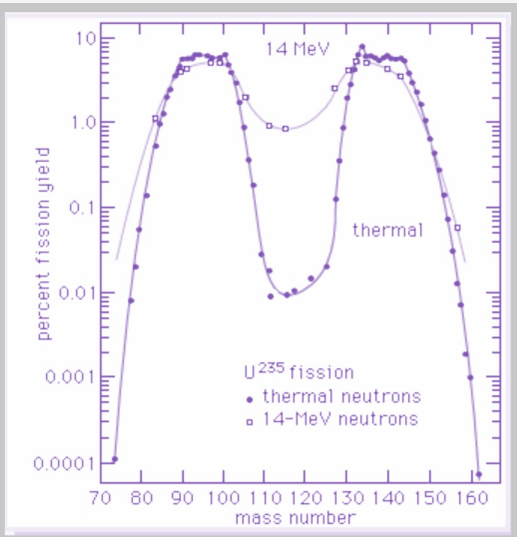
Nuclear fission of U-235 when it absorbs a neutron

When **uranium-235** is hit with a neutron, it captures it to form an unstable intermediate (U-236), which quickly undergoes fission. This reaction can produce a large range of fission products:

- As an example of a fission reaction, U-235 can break into **cesium-140** and **rubidium-92** along with **2 neutrons** and **releasing energy, about ~200 MeV.**



$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{55}^{140}Cs + {}_{37}^{94}Rb + 2{}_{0}^{1}n + \sim 200\ MeV $$



In reality, the **distribution of the fission products** (using thermal neutrons) forms a well-known **double-humped curve**, with a **high prevalence** of nuclides whose **mass numbers** are **between 95 and 135.**
Cs-137 and **Sr-90** are examples of **high yield products.**

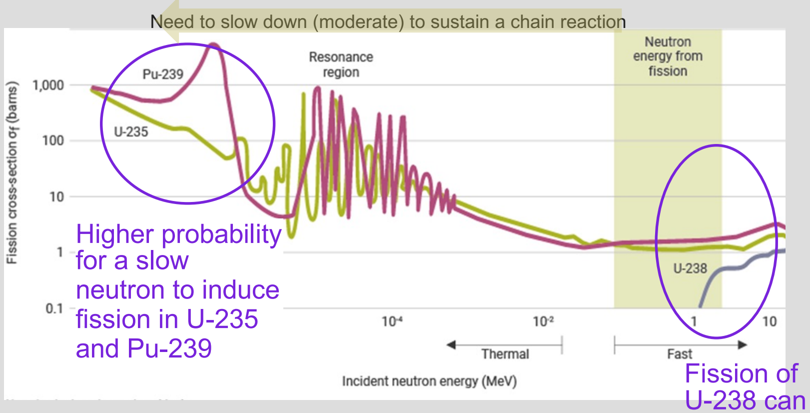
Neutron cross-sections

A neutron passing near to a heavy nucleus may or may not induce fission. **Whether capture of the neutron and fission takes place is probabilistic and depends on the velocity (energy) of the incident neutron and on the nucleus involved.** The probability is measured by the cross section.

Low-energy (slow, or thermal) neutrons may cause fission in isotopes of uranium and plutonium whose nuclei contain odd numbers of neutrons (*e.g.,* U-233, U-235, and Pu-239). These are called fissile nuclei.

- Newly-created fission neutrons are moving at about 7% of the speed of light (~21,000 km/s).
- These neutrons must be slowed down (at about eight times the speed of sound ~2,700 m/s) to increase the fission cross section and sustain a chain reaction.

On the other hand, U-238, the most abundant uranium isotope, is not fissile but it can undergo fission if the incident neutrons have energy above 1 MeV because it is fertile; i.e., it can be converted into fissile Pu-239 by neutron absorption and beta decay.



Higher probability for a slow neutron to induce fission in U-235 and Pu-239

Fission of U-238 can happen

Notes: MeV is a million electron-volt and corresponds to the kinetic energy acquired by a particle with one electron charge in passing through a potential difference of one million volts in a vacuum.
Sources: EIA; Britannica; World Nuclear Association; Kearney Energy Transition Institute analysis

1.2 Nuclear energy principles

2. Putting the atom to use

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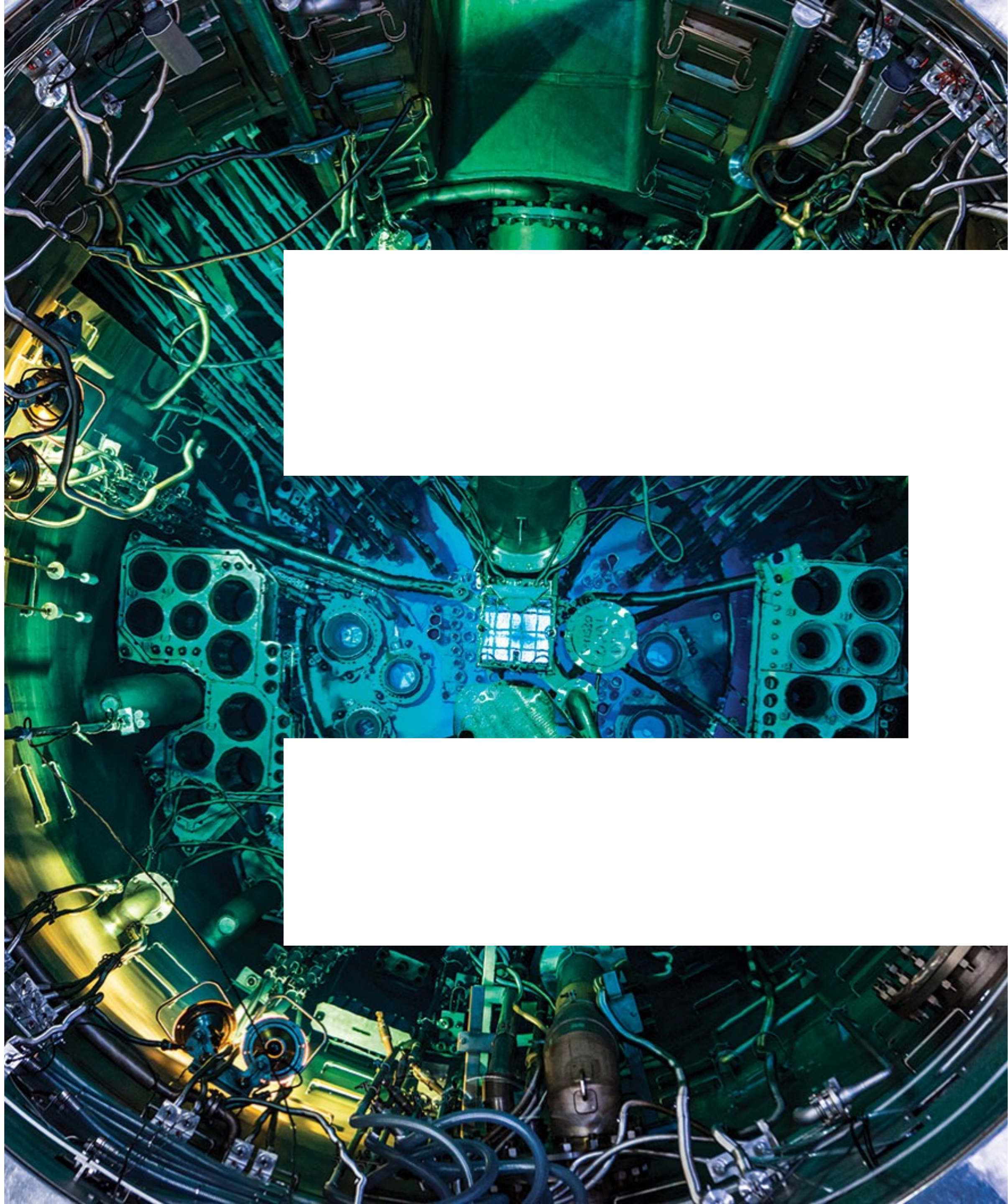


The development of nuclear energy started some 100 years ago, and today plays a key role in the fight against climate change

Nuclear applications. Nuclear power has a broad range of applications, ranging from energy related purposes such as electricity and heat to agricultural, medical, military or water uses.

Nuclear power reactors. In a nuclear power plant, the heat energy released by a fission chain reaction is partially converted into electricity. The most important and defining components of a nuclear reactor are the fuel, moderator, coolant, and control rods. According to the choice of these elements, reactors can be classified into a number of technologies, of which water-cooled reactors are widely deployed at a commercial scale while the other technologies using different coolants are at earlier phases of development.

History of nuclear power. The foundations for harnessing nuclear energy were laid at the beginning of the 20th century. The first commercial Nuclear Power Plants (NPPs) were built in the 1950s and their adoption expanded through the United States and Europe for several decades. However, the competition from cheap fossil fuels and a number of nuclear accidents including Chernobyl led by the mid-1990s to a stagnation period worldwide (exception Asia) with the share of nuclear in global electricity generation declining. A budding renaissance brought about by rising fossil fuel prices was slowed after the Fukushima accident in 2011. The incipient interest in decarbonizing the energy sector could propel a nuclear renaissance, with most projects being developed in Asia and a renewed interest from European and North American countries (22 countries pledged to triple nuclear capacity during COP28).

Nuclear fuel cycle. The most dominant one is the uranium fuel cycle. The nuclear fuel cycle includes the stages of fuel fabrication (including mining, conversion, and enrichment), use, and waste management. The latter involves temporary storage and long-term disposal solutions, and in some cases the reprocessing and recycling of spent fuel. Many companies partake in the fuel cycle, some of which are specialized in one instance while others are active in several of them. Uranium has always been the most used nuclear fuel, but some research projects are focused on looking for alternatives.

Present and future of the nuclear sector. The United States, France, and China account for more than 50% of global nuclear installed capacity, while Germany, has shutdown all their nuclear power plants. Worldwide, the nuclear fleet is ageing, with more than 70% of NPPs being over 30 years old. According to the IEA's NZE scenario, nuclear primary energy consumption should double by 2050, so the installed capacity is expected to increase to accompany the growth in demand. Fifty-nine nuclear reactors are under construction as of May 2023, but even more will be necessary.

Nuclear power plants have a wide range of applications

Electricity generation

- Nuclear plants’ **main function is to provide reliable baseload power to the electricity grid,** but their output can also be modified to meet fluctuating grid demands.
- Nuclear power plants have some of the **highest capacity factor** among electric power sources and require less maintenance and are designed to operate for longer stretches before refueling.
- Nuclear is a **significant part (~10%)** of the world electricity mix and after hydropower, it is the world's **second largest source of low-carbon power.**

However, **non-electric applications powered by nuclear energy** offer potential solutions to decarbonize a number of sectors and end uses. There is a strong interest in the development of new and emerging applications of nuclear technologies across the globe.

Non-exhaustive

Non–electric applications

Hydrogen

- Nuclear power can be used to **produce low-carbon hydrogen** via several processes:
- Low-temperature electrolysis by using nuclear electricity
- Steam electrolysis by using nuclear heat and electricity
- Thermochemical process by using nuclear heat at above 600°C

Process heat for industry

- High-temperature heat from nuclear plants **can be transformative in decarbonizing hard-to-abate sectors (e.g: steel making)**.

District heating

- Nuclear plants are a **proven source of heat for urban district heating** that have operated successfully in Russia, several East European countries, Switzerland, and Sweden.
- More recently, China started a trial of the country’s first commercial nuclear heating project in 2020.

Marine propulsion

- Nuclear power is particularly suitable for **vessels that need to be at sea for long periods without refueling, or for powerful submarine propulsion.**
- The majority of the approximately 140 ships powered by small nuclear reactors are submarines, but also include icebreakers and aircraft carriers.

Desalination

- Nuclear energy is already being used for **desalination of brackish or sea water.** The feasibility of integrated nuclear desalination plants has been proven with more than 150 reactor-years of experience, chiefly in Kazakhstan, India, and Japan.
- In addition, the treatment of urban wastewater is increasingly being undertaken as well.

Miscellaneous industrial uses

- Other potential non-electric uses include synthetic fuels and chemicals production, cooling and refrigeration, and cogeneration applications.

Sources: UNECE technology brief (Nuclear); World Nuclear Association; Kearney Energy Transition Institute analysis

Besides energy purposes, nuclear science and technologies are used across multiple sectors including military applications

Other uses include radioactive material-based designs of many common consumer products (such as smoke detectors, watches and clocks, and non-stick materials), detection and analysis of pollutants through radioisotopes, industrial tracing and inspection using radioactive material, etc.

Agricultural

Ionizing techniques used in food and agriculture industries include:

- Insect pest control through different techniques using ionizing radiation (sterile insect technique or inherited sterility)
- Food irradiation which allows maintaining food quality, reduces bacterial contamination, and slows down spoilage through ionizing radiation
- Livestock and plant breeding and reproduction with isotopic techniques

Medical

Nuclear techniques are used in medicine and nutrition:

- Cancer diagnosis (x and gamma rays) and treatment (radiotherapy, brachytherapy, radiopharmaceutical therapy)
- Assessment of undernutrition, body composition, or the effect of the surrounding conditions/toxic elements in the body, through the use of stable isotopes

Military

Nuclear power is used for military purposes:

- Nuclear reactors are used as propulsion engines for submarines, aircraft carriers.
- Nuclear bombs include the hydrogen bomb (fusion bomb), the plutonium bomb, and the uranium bomb (both fission bombs)

Space

Nuclear energy can power space exploration:

- Radioisotope power systems operate continuously over long-duration deep-space missions spanning decades without any maintenance and are capable of producing heat and electricity under harsh conditions.
- Nuclear thermal propulsion (NTP) systems could significantly reduce travel times and carry greater payloads than today’s top chemical rockets.

Water

Nuclear techniques provide important analytical tools in the management and conservation of existing water resources:

- Isotope hydrology techniques enable accurate tracing and measurement of the extent of underground water resources.
- Neutron probes can measure soil moisture accurately, enabling better management of land affected by salinity for irrigation purposes.

Sources: IAEA, Nuclear technology and Applications; World Nuclear Association; Kearney Energy Transition Institute analysis

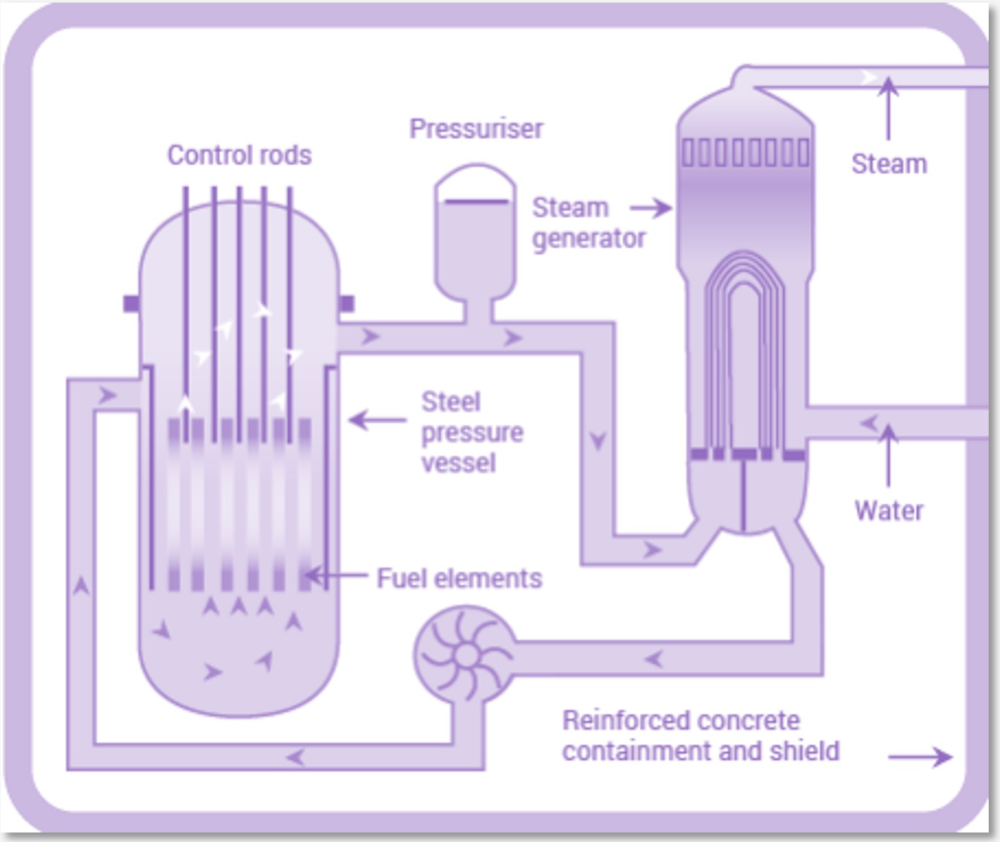
Nuclear reactor designs share several components given common principles for electricity generation via nuclear energy

Definitions of nuclear reactors' key components

Non-exhaustive

Component	Description	Options in reactor designs
Fuel	Fissile material that generates the energy in a sustainable chain reaction; usually encapsulated in fuel elements with specific geometry to favor the balance of neutrons within the core	– Enriched uranium – Natural uranium – Thorium – Plutonium
Moderator	Material used to slow down neutrons released from fission to energy levels that increase the cross-sections	– Light water (H_2O) – Heavy water (D_2O) – Graphite
Control rods or blades	Neutron-absorbing material inserted or withdrawn from the core to control the reaction, or to halt it	– Boron – Cadmium – Hafnium
Coolant	Fluid circulating through the core to extract the energy from it and transfer it to the steam generator; in some reactor types it is also the moderator	– Light water – Heavy water – Gas (CO_2, Helium) – Molten salts – Liquid metals[1]
Pressure vessel/tubes	Containment for the reactor core and moderator/coolant	– Vessel or pressure resistant tubes

Schematic principle of a PWR



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[1] Alternatives in some fast breeder reactor designs

Sources: World Nuclear Association; Kearney Energy Transition Institute analysis

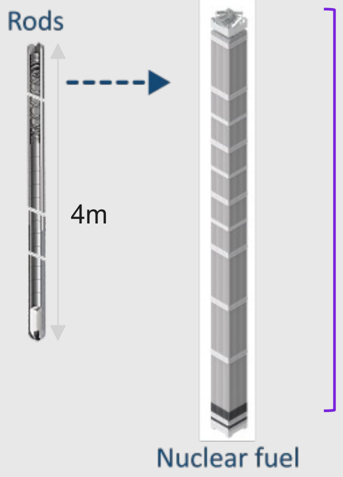
A fission nuclear power reactor generates large amounts of heat part of which can be converted into power through a turbine-generator system

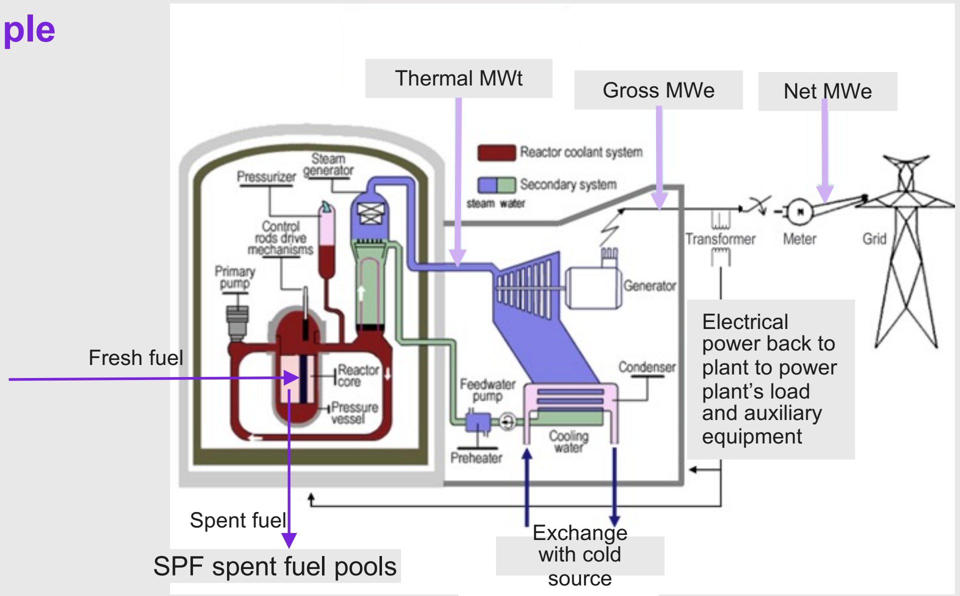
Basic working principles of fission nuclear reactors

- Nuclear reactors operate by exploiting the process of nuclear fission in a controlled manner. Fissile material (e.g., U-235) is used as fuel within the reactor core where the chain reaction occurs. The rate of the reaction is increased, moderated, or halted through neutron-absorbing control rods.
- Energy released from fission, mainly in the form of kinetic energy of the fission products, converts to heat due to the collisions between them and other atoms, which is transported by the reactor coolant system to the steam generators. The steam drives a turbine that activates a generator to produce electricity.
- Spent fuel continues to generate heat and radiation during long periods of time. After removal, it is stored in pools at the reactor site. This allows short-lived isotopes to decay, reducing the overall radiation and decay heat from the rods. The water cools the fuel and provides radiological protection. After that, a series of long-term storage solutions may be used, eventually culminating in the disposal in deep geological repositories.

Nuclear reactor schematic – PWR type example

- Pellets contain fissile ceramic uranium dioxide UO_2 material (U_{235}).
- Rods made from a Zirconium Zr alloy, transparent to neutrons, encapsulate pellets.
- Rods are arranged in fuel elements. A 1,000 MWe PWR may contain 250 fuel assemblies in its core.





Sources: World Nuclear Association; Kearney Energy Transition Institute analysis

2.2 Nuclear power reactors

There are 6 main nuclear reactor technologies, among which PWRs are the most common at the commercial level

Thermal reactors		Water Cooled Reactors	Light Water Reactors	Pressurized water reactors (PWRs)	They consist of a primary water circuit of pressurized, light water[1], which acts as both coolant and moderator, and a steam cycle (secondary circuit). They are fueled by enriched uranium (3-5%) that is necessary because light water is a good neutron absorber, so natural uranium would not be enough to ensure a sufficient neutron population.
				Boiling water reactors (BWRs)	They are similar to PWRs but integrate the two circuits in one so that the steam is produced directly using the heat from the core. They also require fuel enriched in U-235 (3-5%)
				Heavy water reactors (HWRs)	The design is virtually the same as a PWR, but they use heavy water as moderator and coolant. This improves overall neutron economy because heavy water[2] absorbs less neutrons, making possible the employment of natural uranium as fuel (no enrichment required although some might be used to increase efficiency).
				Advanced gas cooled reactors (AGRs)	They are fueled by enriched uranium dioxide pellets, and they use CO_2 as coolant and graphite as moderator. There is a high temperature version under development (HTGR) using helium as a coolant that achieves high fuel utilization.
	Fast reactors			Molten salt reactors (MSRs)	They are potentially safer than conventional reactors because they operate with fuel dissolved in the molten salt coolant at nearly atmospheric pressure. These designs have higher efficiencies (since they operate at much higher temperatures) and lower waste generation (they can use thorium fuel cycle or spent LWR fuel).
				Fast neutrons reactors (FNRs)	Also called fast breeder reactors (FBRs). Fast neutron spectrum increases the energy yield from natural uranium compared to thermal reactors, since the U-238 becomes fissionable. Higher fuel utilization (utilize uranium 60 times more efficiently than normal reactors) can extend lifetime and improve nuclear waste management.

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[1] Light water corresponds to ordinary water, which is deuterium depleted.

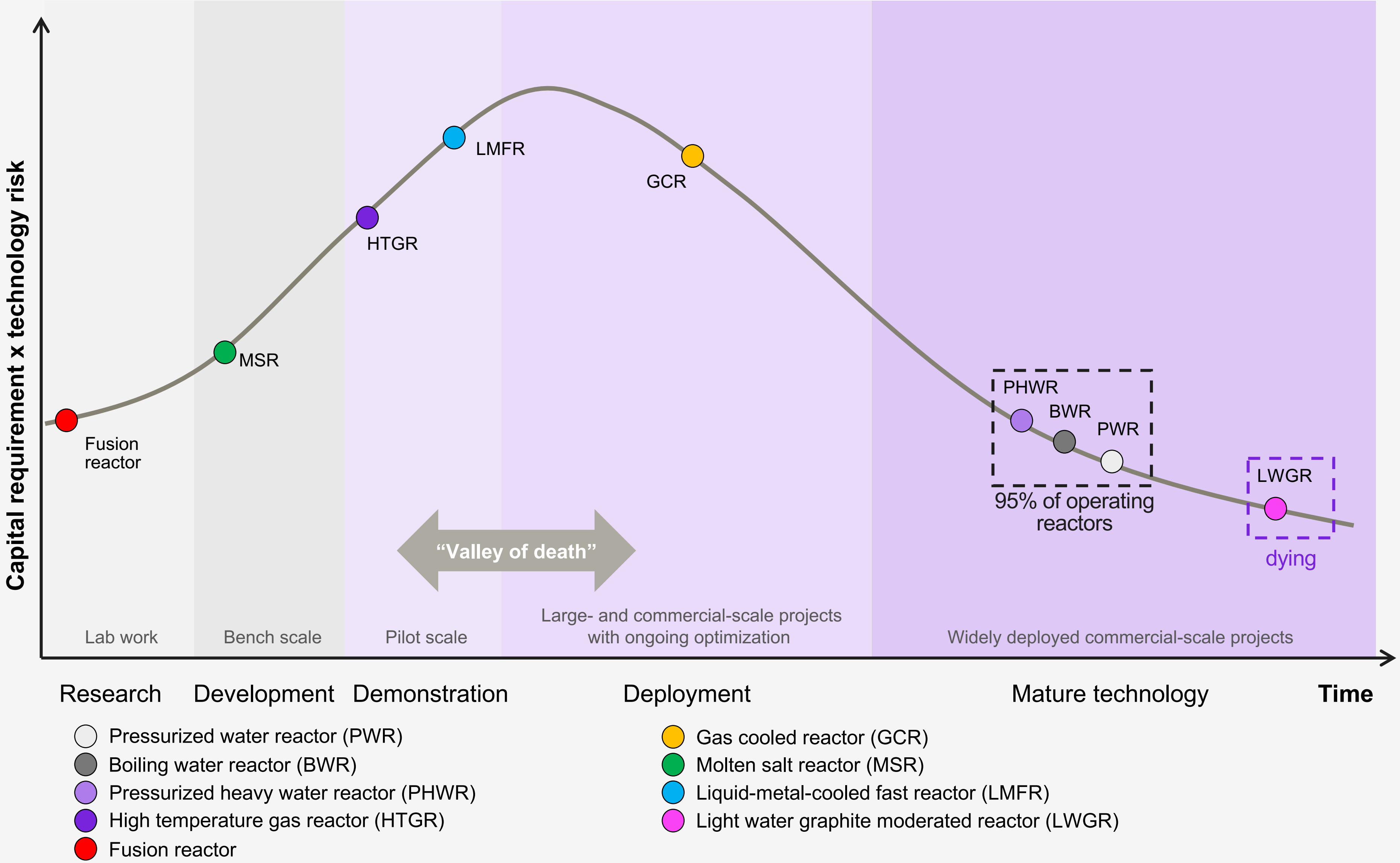
[2] Heavy water (D_2O) is water composed of deuterium, the hydrogen isotope with a mass double that of ordinary hydrogen, and oxygen. Heavy water is a more effective moderator because it slows fast neutrons more effectively.

Note: Technologies acronyms may differ depending on the sources.
Sources: IAEA; US DOE; Kearney Energy Transition Institute analysis

Water cooled reactors are at a mature stage, while the other designs are in earlier development phases

Illustrative
Non-exhaustive

Maturity curve of nuclear reactor types



Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

2.3 Technology curve

Nuclear technologies continue to improve with each reactor generation

Non-exhaustive

Advanced reactor designs seek to use combinations of new and existing technologies and materials to improve upon earlier generations in the following areas:
- Cost
- Safety
- Security
- Waste management
- Versatility

2.4 History and evolution of nuclear power

Nuclear power technological evolution

Generation I
Early prototypes
- Shipping port
- Dresden
- Magnox

Generation II
Commercial power
- PWRs
- BWRs
- CANDU

Generation III
Advanced LWRs
- CANDU 6
- System 80+
- AP600

Generation III+
Evolutionary designs
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV
Revolutionary designs
- Safe
- Sustainable
- Economical
- Proliferation resistant and physically secure

1950 1960 1970 1980 1990 2000 2010 2020 2030

Gen I
- First nuclear reactor prototypes
- Not cost-effective
- No longer in operation

Gen II
- First commercial reactors
- Mostly PWRs
- Traditional, mostly active, safety mechanisms
- Produce significant quantities of used fuels
- ~ 40 years design operational life

Gen III / **Gen III+**
- Evolutionary design improvements in the areas of fuel technology, thermal efficiency standardization, and safety
- Integrate lessons learned from Three Mile Island and Chernobyl accidents
- ~ 60 years design operational life
- Produce less used fuel
- Gen III+ include more passive safety features

Gen IV
- Novel designs have the potential to operate at higher temperatures, improving efficiency and supporting new applications
- Advanced actinide management resulting in lower radioactivity of spent fuel
- Fast neutron reactors

Notes: PWR is pressurized water reactor. BWR is boiling water reactor. ABWR is advanced boiling water reactor. APWR is advanced pressurized water reactor. EPR is European pressurized water reactor. ESBWR is economic simplified boiling water reactor. CANDU is Canada deuterium uranium.
Sources: American Academy of Arts and Sciences, 2011, Nuclear Reactors: Generation to Generation; Generation IV International Forum; Frederik Reitsma, Small Modular Reactors and Generation IV A Short Overview; Kearney Energy Transition Institute analysis

Military purposes preceded the use of nuclear for peaceful purposes. Nuclear for electricity generation was led by the Soviet Union and United States

Non-exhaustive

	1930–1950	1951–1970	1971–1990	1991–2010	2011–Present
	The science	**Commercial scale up**	**Stagnation and decline**		**Renaissance?**
Power	Enrico Fermi's first controlled nuclear chain reaction in a laboratory based on the works of Marie Curie, Henri Becquerel, Albert Einstein, Otto Hahn, Lise Meitner, and Niels Bohr, among others. First nuclear medicine department is established at the Oak Ridge National Laboratory, in the US.	First nuclear power plant opens in Russia (5 MW) in 1954. By the end of the period nuclear power plant capacities ranging from 500 MW to 1,300 MW become common.	The largest nuclear power plants built during these decades have capacities ranging from 1,300 MW to 1,500 MW. The share of nuclear in world electricity is constant at 16-17%. Three Mile Island accident and Chernobyl disaster.	Third-generation reactors being built. Two European PWR (EPR), two Westinghouse AP1000 in the US, and one advanced BWR in Japan. Few new reactors ordered. Output increased 60% due to one-third increase in capacity plus improved load factors. A budding renaissance was detectable starting 2005 by steadily increasing plant orders and construction starts until 2011.	The Fukushima accident brought the renaissance to a halt and led to operating suspension, premature plant closures in several countries, mainly in Japan and Germany, plus phase-out policies in Belgium, Switzerland, Taiwan… Accelerated growth in Asia revived plans for expansion in the West, awareness of the importance of energy security and need to limit carbon emissions. New designs for SMRs.
Military	United States drops atomic bombs on August 6 and 9 of 1945, leading to the end of World War II.	Atoms for Peace Speech by President Eisenhower. Treaty on the Non-Proliferation of Nuclear Weapons is signed, today with 191 member states. USS Nautilus is the first nuclear-powered submarine (13 MW).	The 1980s was dominated by the Cold War tensions and the nuclear weapons race. Popular anti-nuclear protests worldwide and the nuclear freeze movement in the United States.	North Korea announces its withdrawal from the Non-Proliferation of Nuclear Weapons. Nine countries have nuclear weapons.	The New Strategic Arms Reduction Treaty (New START) enters into force. The United States and Russia agree to reduce strategic and offensive weapons.

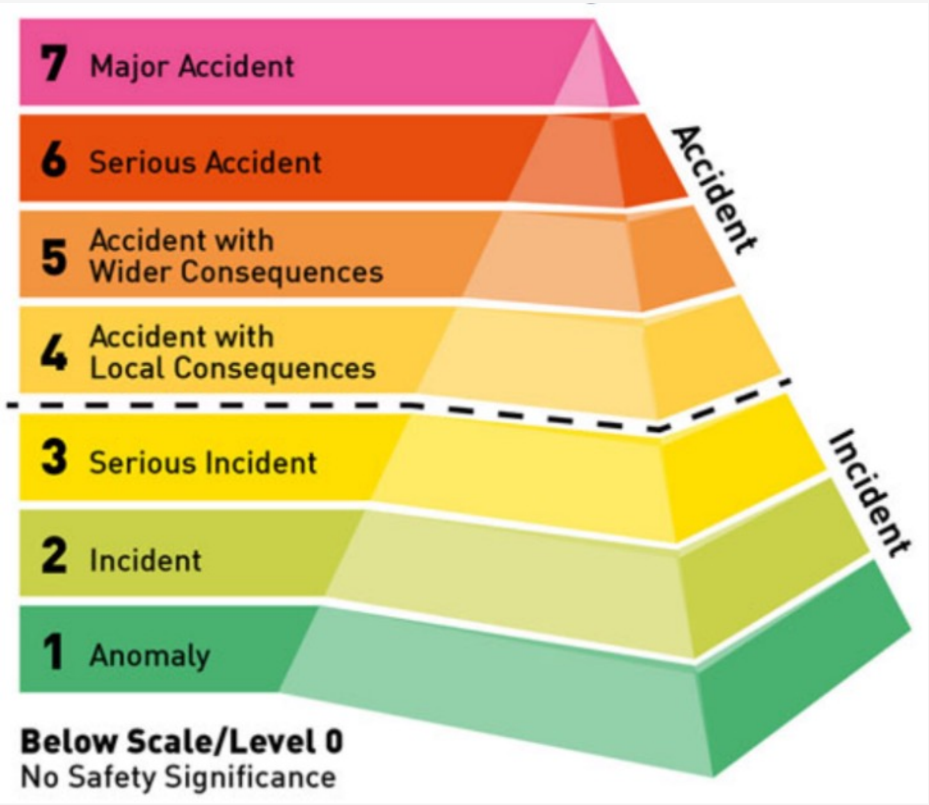
Sources: World Nuclear Association, 2023, Nuclear power in the world today; Kearney Energy Transition Institute analysis

The International Nuclear and Radiological Event Scale (INES) is a tool for communicating the safety significance of nuclear and radiological events to the public

The scale is based on a logarithmic approach; that is, the severity of an event is about 10 times greater for each increase in level of the scale.

Events are considered in terms of three areas of impact

- **People and the environment:** considers the radiation doses to people close to the location of the event and the release of radioactive material from an installation
- **Radiological barriers and control:** covers events without any direct impact on people or the environment and only applies inside major facilities. It covers unplanned high radiation levels and spread of significant quantities of radioactive materials confined within the installation
- **Defense-in-depth:** also covers events without any direct impact on people or the environment, but for which the range of measures put in place to prevent accidents did not function as intended[1]



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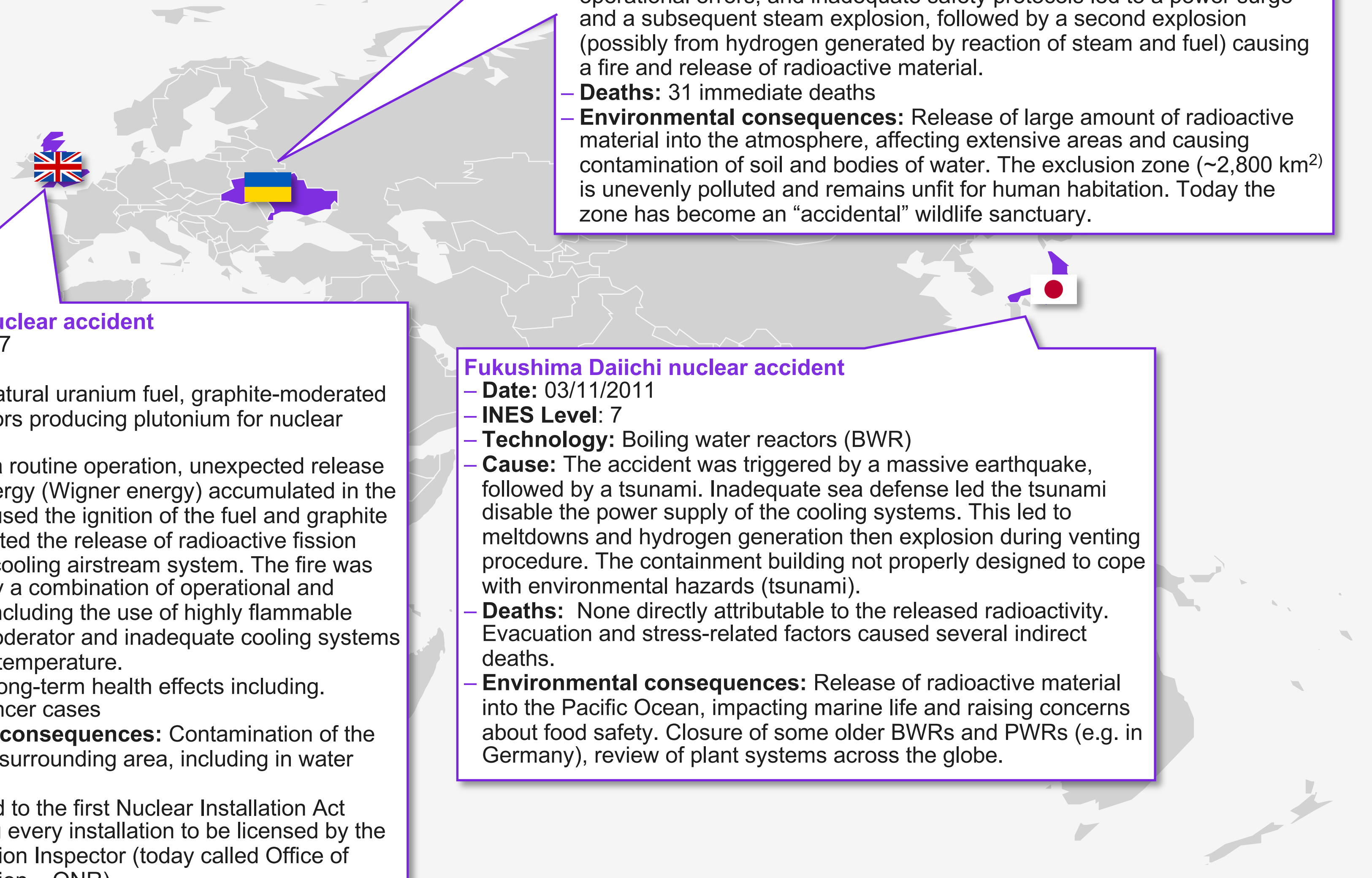
[1] Defense-in-depth is a fundamental approach to hazard control for nuclear facilities that is based on several layers control for nuclear facilities that is based on several layers of protection to prevent the release of radioactive material. These protective layers are generally redundant and independent of each other to compensate for human and mechanical failures.

Sources: IAEA; NRC; US Department of Energy, Office of Nuclear Safety; Kearney Energy Transition Institute analysis

Nuclear accidents involved the combination of multiple factors (1/2)

Nuclear accidents around the world

Europe and Asia



Chernobyl nuclear accident
- **Date:** 26/04/1986
- **INES Level:** 7
- **Technology:** RBMK, graphite-moderated nuclear power reactor.
- **Cause (combination of multiple factors):** A combination of design flaws, operational errors, and inadequate safety protocols led to a power surge and a subsequent steam explosion, followed by a second explosion (possibly from hydrogen generated by reaction of steam and fuel) causing a fire and release of radioactive material.
- **Deaths:** 31 immediate deaths
- **Environmental consequences:** Release of large amount of radioactive material into the atmosphere, affecting extensive areas and causing contamination of soil and bodies of water. The exclusion zone (~2,800 km$^{2)}$ is unevenly polluted and remains unfit for human habitation. Today the zone has become an "accidental" wildlife sanctuary.

Windscale fire nuclear accident
- **Date:** 10/10/1957
- **INES Level**: 5
- **Technology:** Natural uranium fuel, graphite-moderated air-cooled reactors producing plutonium for nuclear weapons.
- **Cause:** During a routine operation, unexpected release of excessive energy (Wigner energy) accumulated in the graphite first caused the ignition of the fuel and graphite and then generated the release of radioactive fission products in the cooling airstream system. The fire was thus triggered by a combination of operational and design issues, including the use of highly flammable graphite as a moderator and inadequate cooling systems and operation's temperature.
- **Deaths:** Some long-term health effects including. possible 200 cancer cases
- **Environmental consequences:** Contamination of the atmosphere the surrounding area, including in water (North Sea)
- This accident led to the first Nuclear Installation Act (1959), requiring every installation to be licensed by the Nuclear Installation Inspector (today called Office of Nuclear Regulation – ONR)

Fukushima Daiichi nuclear accident
- **Date:** 03/11/2011
- **INES Level**: 7
- **Technology:** Boiling water reactors (BWR)
- **Cause:** The accident was triggered by a massive earthquake, followed by a tsunami. Inadequate sea defense led the tsunami disable the power supply of the cooling systems. This led to meltdowns and hydrogen generation then explosion during venting procedure. The containment building not properly designed to cope with environmental hazards (tsunami).
- **Deaths:** None directly attributable to the released radioactivity. Evacuation and stress-related factors caused several indirect deaths.
- **Environmental consequences:** Release of radioactive material into the Pacific Ocean, impacting marine life and raising concerns about food safety. Closure of some older BWRs and PWRs (e.g. in Germany), review of plant systems across the globe.

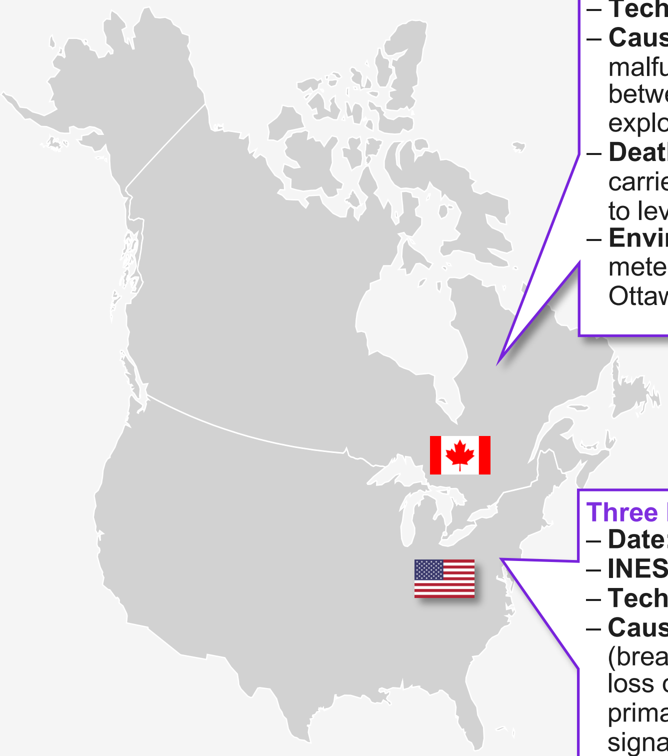
Sources: IAEA; Kearney Energy Transition Institute analysis

2.4 History and evolution of nuclear power

Nuclear accidents generally involved the combination of multiple factors (2/2)

Nuclear accidents around the world

North America



Chalk River nuclear accident

- **Date:** 12/12/1952
- **INES Level:** 5
- **Technology:** Pressurized heavy water reactor (PHWR)
- **Cause:** An operator manually removed three or four control rods by mistake, then a mechanical malfunction prevented them from being introduced back into the reactor. Miscommunication between the operators aggravated the situation, resulting in power escalation that led to an explosion inside the reactor vessel and to the leakage of radioactive water onto the reactor floor.
- **Deaths:** No one died or was seriously injured as an immediate result of the accident. A study carried out in 1982 concluded that workers involved in the clean up of the accident were exposed to levels of radiation 40 to 135 times higher than the accepted yearly limit.
- **Environmental consequences:** Higher-than-normal radiation levels were detected within a 400-meters radius. Contaminated water was safely disposed of, and it did not compromise the nearby Ottawa River.

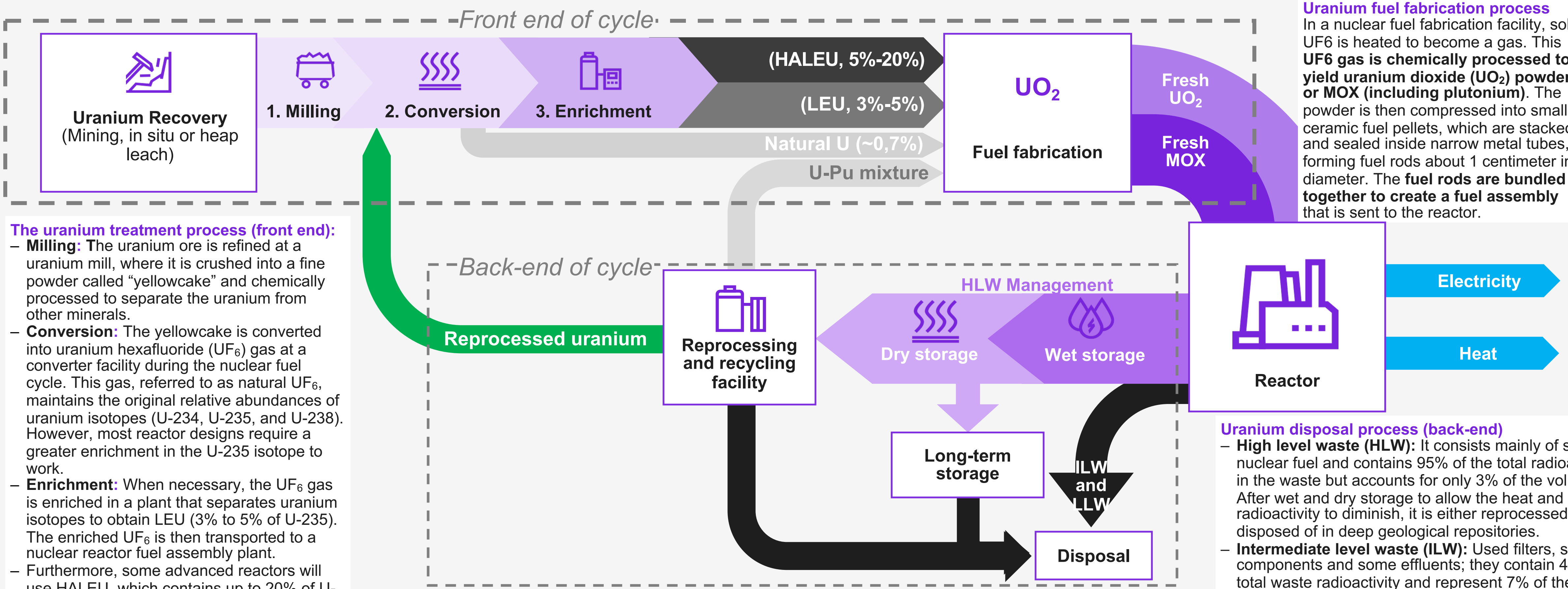
Three Mile Island accident

- **Date:** 28/03/1979
- **INES Level:** 5
- **Technology:** Pressurized water reactor (PWR)
- **Cause (multiple factors):** A series of malfunctions (access to feedwater) and operator errors (breach of operating rules) led to a partial meltdown of the reactor core in Unit 2. The complete loss of feedwater led the steam generator rapidly dry out, leading to failure of cooling of the primary water circuit, which overpressure led to the lift of safety relief valve that was not properly signaled to the operator. This led to a series of wrong interpretation and decisions. Despite ignition of hydrogen, there was only a minor leakage of radioactivity to the atmosphere.
- **Deaths:** No immediate deaths
- **Environmental consequences:** While most of the radiation was contained, there were concerns about the release of radioactive gases and effluents into the environment, and clean-up and monitoring measures were undertaken in the affected area.

Sources: IAEA; P. Jedicke (Fanshawe College, Ontario), 1989, The NRX Accident; Kearney Energy Transition Institute analysis

Uranium fuel cycle goes through the stages of mining, conversion, fabrication, use in reactors, long-term storage, disposal and partial recycling

The nuclear fuel cycle



The uranium treatment process (front end):

- **Milling:** The uranium ore is refined at a uranium mill, where it is crushed into a fine powder called "yellowcake" and chemically processed to separate the uranium from other minerals.
- **Conversion:** The yellowcake is converted into uranium hexafluoride (UF_6) gas at a converter facility during the nuclear fuel cycle. This gas, referred to as natural UF_6, maintains the original relative abundances of uranium isotopes (U-234, U-235, and U-238). However, most reactor designs require a greater enrichment in the U-235 isotope to work.
- **Enrichment:** When necessary, the UF_6 gas is enriched in a plant that separates uranium isotopes to obtain LEU (3% to 5% of U-235). The enriched UF_6 is then transported to a nuclear reactor fuel assembly plant.
- Furthermore, some advanced reactors will use HALEU, which contains up to 20% of U-235, to date, at least one project is in demonstration phase.

Uranium fuel fabrication process

In a nuclear fuel fabrication facility, solid UF6 is heated to become a gas. This **UF6 gas is chemically processed to yield uranium dioxide (UO_2) powder or MOX (including plutonium)**. The powder is then compressed into small ceramic fuel pellets, which are stacked and sealed inside narrow metal tubes, forming fuel rods about 1 centimeter in diameter. The **fuel rods are bundled together to create a fuel assembly** that is sent to the reactor.

Uranium disposal process (back-end)

- **High level waste (HLW):** It consists mainly of spent nuclear fuel and contains 95% of the total radioactivity in the waste but accounts for only 3% of the volume. After wet and dry storage to allow the heat and radioactivity to diminish, it is either reprocessed or disposed of in deep geological repositories.
- **Intermediate level waste (ILW):** Used filters, steel components and some effluents; they contain 4% of total waste radioactivity and represent 7% of the volume.
- **Low level waste (LLW):** Lightly contaminated items such as tools and clothing containing 1% of waste radioactivity; they constitute 90% of the total volume.

Notes: HALEU is high-assay low-enriched uranium; LEU is low-enriched-uranium and MOX is mixed oxide fuel, U-Pu is uranium plutonium mixture.
Sources: EIA, Nuclear explained: The fuel cycle; United States Nuclear Regulatory Commission; Nuclear Innovation Alliance; World Nuclear Association; Kearney Energy Transition Institute analysis

Different enrichment technologies exist, but only one is widely used today

Because the same technique that can produce LEU for reactor fuel can also be used to produce HEU for nuclear weapons, uranium enrichment presents a risk of nuclear proliferation. International treaties and legal restrictions are the only thing preventing nations possessing enrichment capability from using their resources to enrich uranium to the higher levels needed for nuclear weapons.

2.5 Uranium value chain

Obsolete

Gaseous diffusion

- Uranium hexafluoride (UF_6) gas is fed into the plant's pipelines where it is pumped through special filters called barriers or porous membranes.
- It takes many hundreds, or even thousands, of barriers, one after the other, before the UF_6 gas contains enough U-235 to be used in nuclear fuel.
- These facilities utilized massive amounts of electricity and as the centrifuge technology matured the existing gaseous diffusion plants were replaced.

Commercial use

Gas centrifuge

- UF_6 gas is placed in a gas centrifuge cylinder and rotated at a high speed. This rotation creates a strong centrifugal force so that the heavier gas molecules (containing U-238 atoms) move toward the outside of the cylinder. The lighter gas molecules (containing U-235) collect closer to the center. The enriched and depleted gases are removed by scoops.
- In the centrifuge process, the number of stages may only be 10 to 20, instead of a thousand or more for diffusion.

Centrifuges pose a unique proliferation challenge because detecting covert facilities in a timely manner is very difficult and existing centrifuges can be quickly reconfigured to produce HEU.

Under development

Laser separation

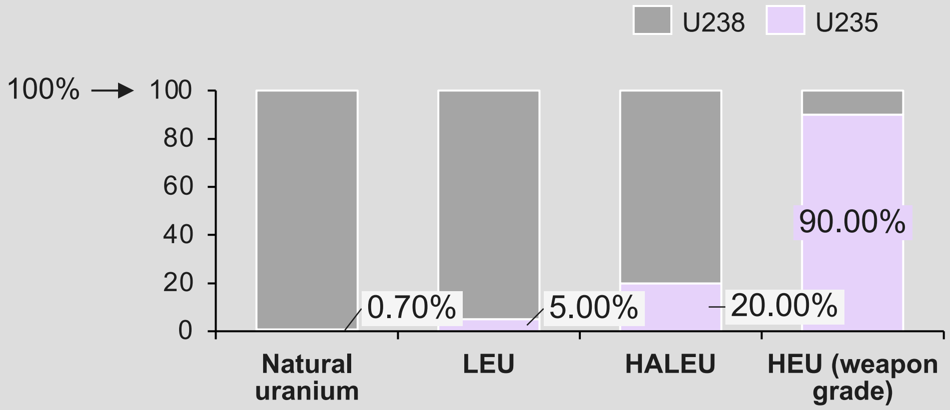
- This technology is still under development, with one process being almost ready for commercial use. It provides higher enrichment efficiency, potentially offering lower overall costs.
- Tunable lasers are used to deliver a highly monochromatic light (light of a single color), which can photo-ionize a specific isotopic species while not affecting the others. This enables the separation.

Sources: US NRC; 2020, Uranium Enrichment; WNA, 2022, Uranium Enrichment; A. Glaser, 2006, On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels; Kearney Energy Transition Institute analysis

Reactor fuel varies depending on the fissile material, enrichment level, and form

Most common fissile material is uranium, but mixed uranium and plutonium (oxide, metal, or salt) and thorium (to produce the fissile isotope uranium-233) can also be used.

Fuel enrichment levels (%)



- **Uranium enrichment** is the process through which the isotopic proportion of U-235 is increased from 0.7% to up to 94%.
- **Natural uranium** consists of ~0.7111% U-235 isotope. Most of the current commercial fleet of reactors use **LEU (low-enriched uranium)** which is <5% U-235. **High-assay LEU (HALEU)** fuel has enrichment levels of 5-20% and is often used as an advanced reactor. Within this enrichment of 5-10% reactor fuel is referred to as **LEU+.** Enrichment levels of > 20% are referred as **highly enriched uranium (HEU)** while enrichment levels of 90%+ are classified as a weapon grade.

Key fuel forms	Description	Key attributes
Oxide/ceramic	Sintered pellet UO_2 or MOX fuel similar in design to an existing-LWR oxide fuel pellet	– Extensive operating, manufacturing, and irradiation experience with UO_2 and MOX fuel – Extensive recycling experience of UO_2 and some experience with MOX
Metallic	U-Zr or U-Pu-Zr alloy rods for good irradiation stability	– Some recycling experience (pyro – processing / electrochemical and aqueous polishing process)
TRISO	Tri-structural isotropic particle fuel, made up of uranium, carbon, and oxygen fuel kernel, with each kernel encapsulated by three layers of carbon and ceramic-based materials. Arranged in blocks – hexagonal “prisms” of graphite or in billiard ball-sized pebbles of graphite	– No successful recycling efforts demonstrated yet and will have high waste-to-fuel ratio
Liquid fuels	Molten fluoride or chloride salt containing fissile material. No fuel structures like cladding, fuel ducts, grid spacers, etc.	– Expected to be possible to fuel online during operation and real-time conditioning/recycling/waste processing (removal of fission products)

Sources: Thirdway.org, Advanced Nuclear Reactors: Technology Overview and Current Issues (US congress report); Sven Bader, 2021, Back-End of the Nuclear Fuel Cycle; Kearney Energy Institute analysis

Out of the different companies involved in the nuclear fuel cycle, some operate in several sectors while others specialize in a single service

Non-exhaustive

Main players in the nuclear fuel cycle

		orano	中核集团 CNNC	ROSATOM	Cameco	NDA	urenco	CONVERDYN	KAZATOMPROM	HOLTEC INTERNATIONAL		GNS	SKB	ANDRA	Posiva Solutions	Others[1]
Mining	Natural uranium	✓	✓	✓	✓		✓		✓	✓						
Front end	Milling	✓	✓	✓	✓											
	Conversion	✓	✓	✓	✓			✓		✓						
	Enrichment	✓	✓	✓			✓									
Back-end	Reprocessing and recycling	✓		✓		✓										
	Storage	✓								✓	✓	✓				
	Disposal												✓	✓	✓	
	Logistics	✓														✓

2.5 Uranium value chain

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[1] Logistics is a highly fragmented market.

Sources: Institute Montaigne; companies' websites; Kearney Energy Transition Institute analysis

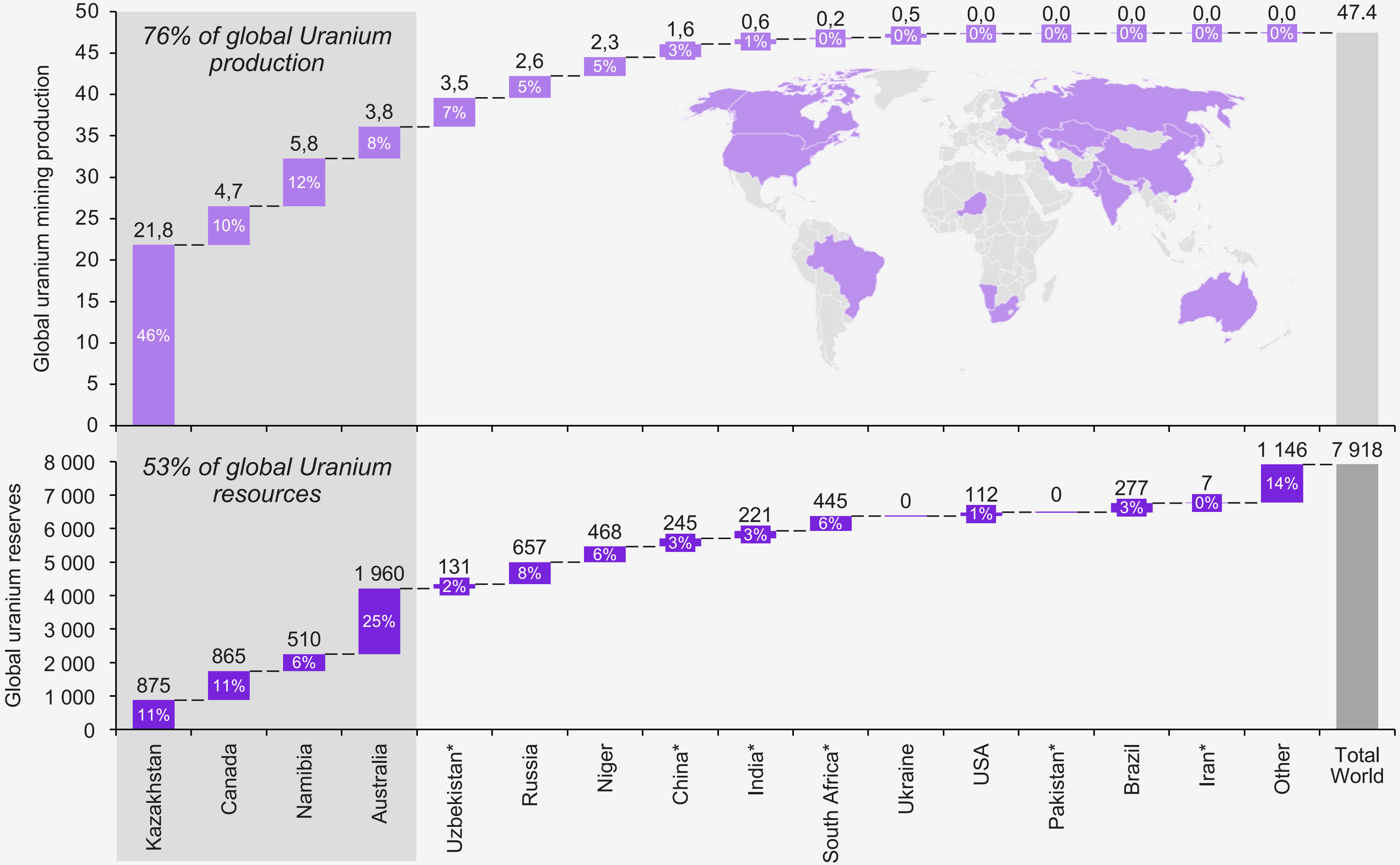
Four countries concentrate about 80% of the global uranium mining production and over 50% of global uranium reserves

The IAEA and the NEA estimated the total recoverable resources of uranium at 7,918 kt U[1] in 2021. Demand amounted to 60.1 kt, while mined production only reached 47.4 kt, the rest being supplied by secondary sources (excess inventories, reprocessing, re-enrichment of depleted uranium and down-blending of highly enriched uranium).

2.5 Uranium value chain

Global uranium mining annual production and estimated resources

ktU, 2021



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[1] Identified resources recoverable at a cost of < 260 USD/kgU. There are an additional 2,754 kt in-situ reserves, whose recoverability is uncertain.

* Estimated values

Sources: IAEA, NEA, 2022, Uranium Resources, Production and Demand ("Red Book"); Kearney Energy Transition Institute analysis

Main fuel alternatives include uranium enrichment, thorium-based fuels and recycling of fuels (1/2)

Non-exhaustive

	Fuel	Description	Advantages	Challenges	Availability and maturity of fuel
Freshly produced fuel	**Enriched uranium**	– Uranium with higher concentrations of U-235, between 3 to 5%[1]	– Due to the slow or nonexistent growth in demand, the increased supply of uranium has driven the decrease of prices in the last years. – Uranium-based nuclear reactors have undergone extensive research and development, and progress has been made in enhancing safety features. – Currently, there is no nuclear fission power plants operating with other fuel than uranium.	– U-235 constitutes less than 1% of natural uranium. – Enrichment of natural uranium accounts for about half of the total fuel cost. – U-235 is less stable than other elements which means more risk.	– The largest provider of uranium is Kazakhstan with 15% of the world's resources. It is followed by Canada and Australia. – The development of nuclear reactors using uranium as fuel began in the mid-20th century.
	Thorium (Th-232)	– Thorium (Th-232) is not itself fissile and so is not directly usable in a thermal neutron reactor. However, it is "fertile" and upon absorbing a neutron will transmute to uranium-233 (U-233), which is an excellent fissile fuel material.	– Th-232 generates more U-233 than is consumed, meaning the fuel cycle is more efficient so less mined fuel is needed. – Thorium-based fuels have higher melting points, better thermal conductivity, and improved resistance to radiation damage.	– The radioactivity of the mined products is much higher for thorium than for uranium. – The amount of thorium that can be mined cost-effectively is not as great as that of uranium. This, however, could change if there was a higher demand for thorium.	– It is 3-4 times more abundant in nature than uranium. – China had been working on various Th-232 molten salt reactor (TMSR) prototypes, including the TMSR-SF (solid fuel) and TMSR-LF (liquid fuel). – Germany operated a 300 MWe for two years in 1981. Today, Australia, Brazil, and Egypt (in construction) have demonstrated Th-232 use in power reactors. – Thorium extraction, or Thorex process, has been demonstrated in pilot-plant facilities but has yet to reach the maturity of the commercial PUREX (plutonium uranium reduction extraction) process.

Sources: World Nuclear Association; International Atomic Energy Agency; OECD- Nuclear Energy Agency; Kearney Energy Transition Institute analysis

Main fuel alternatives include uranium enrichment, thorium-based fuels and recycling of fuels (2/2)

Non-exhaustive

	Fuel	Description	Advantages	Challenges	Availability and maturity
Recycled fuel	**Reprocessed uranium (RepU)**	– RepU is an alternative[1] to re-use spent nuclear fuel which results in the recovery of uranium and plutonium.	– Reprocessing significantly increases the energy potential of today's uranium resources by around 70 times, because it allows recycling of generated plutonium. – The arising RepU could theoretically meet up to 10–20% of the worldwide annual uranium needs for fuel reactors. – Improves fuel utilization by about 30-40% compared to the open cycle. – Reduces the quantity of troublesome long-lived radioactive elements in the remaining waste.	– RepU is mostly U-238, 1% U-235 and impurities of U-232 and U-236 formed during neutron capture in the reactor increasing with higher burn-up levels and strong gamma radiation. – U-236 acts as a neutron absorber, so higher U-235 enrichment is needed to compensate. – Reprocessed uranium is usually recyclable only once.	– Argentina, Canada, and the Republic of Korea are considering recycling concepts involving RepU in pressurized heavy water reactors. – Some countries with a small NPP fleet chose a policy of overseas reprocessing (e.g., Belgium, Italy, the Netherlands, Spain, etc.). – Countries with a significant number of nuclear energy plants were more inclined to establish domestic reprocessing capabilities (e.g., France, India, Japan, Russian Federation, UK).
	Mixed oxide (MOX) fuel	– MOX fuel is manufactured from plutonium recovered from spent reactor fuel, mixed with depleted uranium.	– Enables the closure of fuel cycle instead of just using the prepared nuclear fuel once and then disposing of it as waste. – MOX fuel also provides a means of burning weapons-grade plutonium (from military sources) to produce electricity.	– Very little recovered uranium is recycled at present. – New technology not yet commercialized to recycle all the uranium and plutonium without separating them and topping up with some fresh uranium enriched to a higher level than usual. This is regenerated mixture (REMIX) fuel.	– Only one plant in Europe currently produces commercial quantities of MOX fuel, in France (~195 ton/year). – Japan and Russia have production plants with 140 and 60 ton/year of production capacity respectively.

[1] DUPIC is another alternative to re-use spent fuel through direct recycling (without chemical processing) of spent PWR fuel in HWR reactors such as the CANDU.

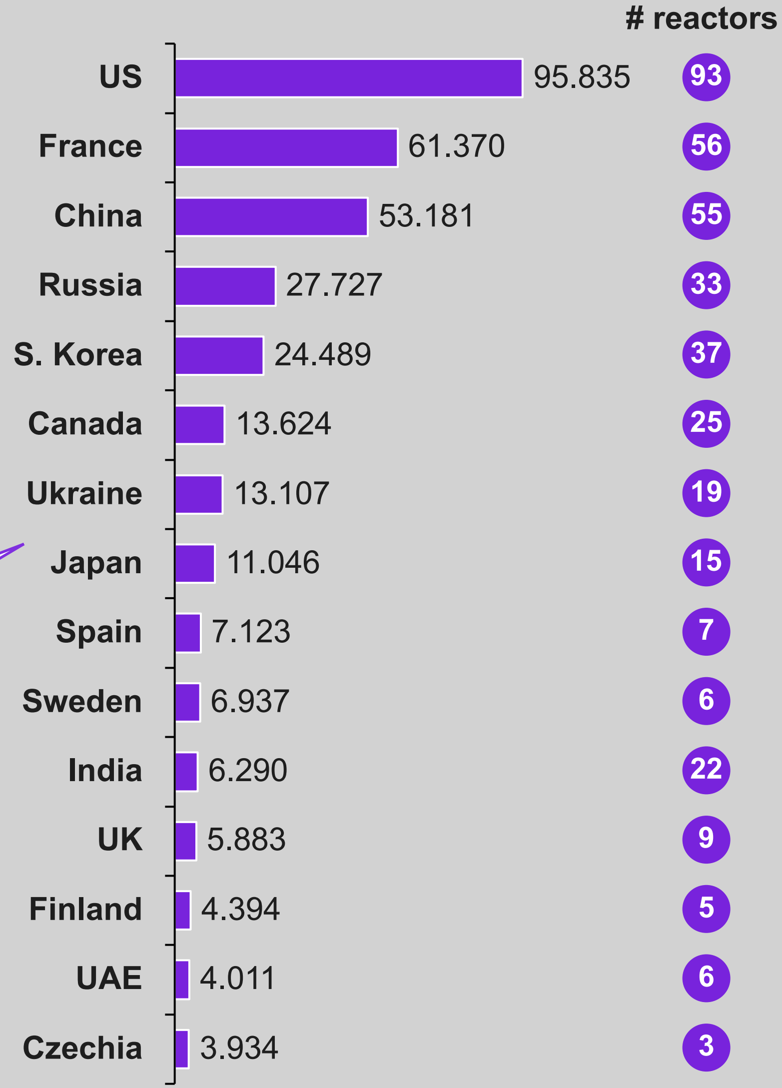
Sources: International Atomic Energy Agency; OECD- Nuclear Energy Agency; Kearney Energy Transition Institute analysis

The United States, France, and China represent more than 50% of the global installed capacity of nuclear energy, while Germany has historically been the country with the largest capacity shutdown

Ukraine has been a big player in the nuclear energy sector for a long time. The current war occurring in its territory caused the **shutdown of multiple plants** (for security matters) and the **takeover by Russian military forces of Zaporizhzhia, the largest nuclear power plant in Europe.**

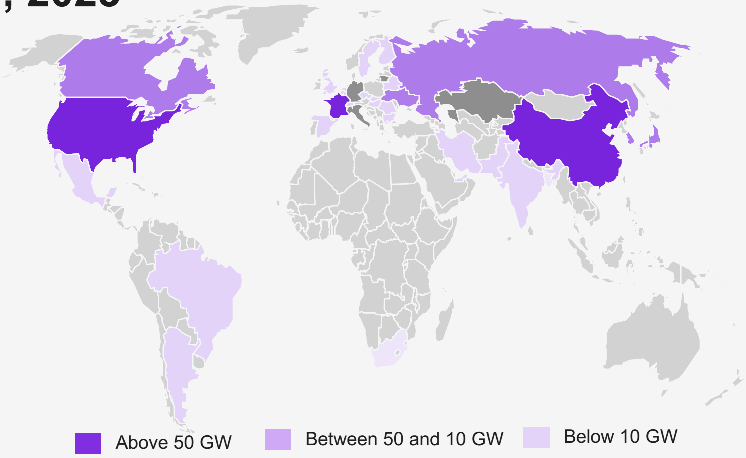
2.6 Nuclear power capacities

Global nuclear operating capacity
GW, Nov. 2023, top 15 countries

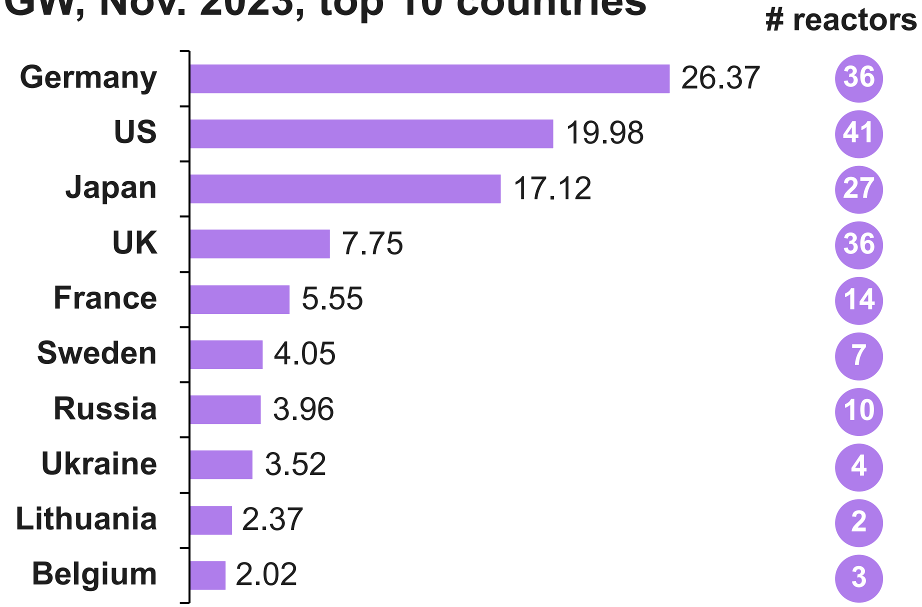


Sources: IAEA, PRIS database, November 2023; Kearney Energy Transition Institute analysis

Worldwide operating capacity distribution
GW, 2023



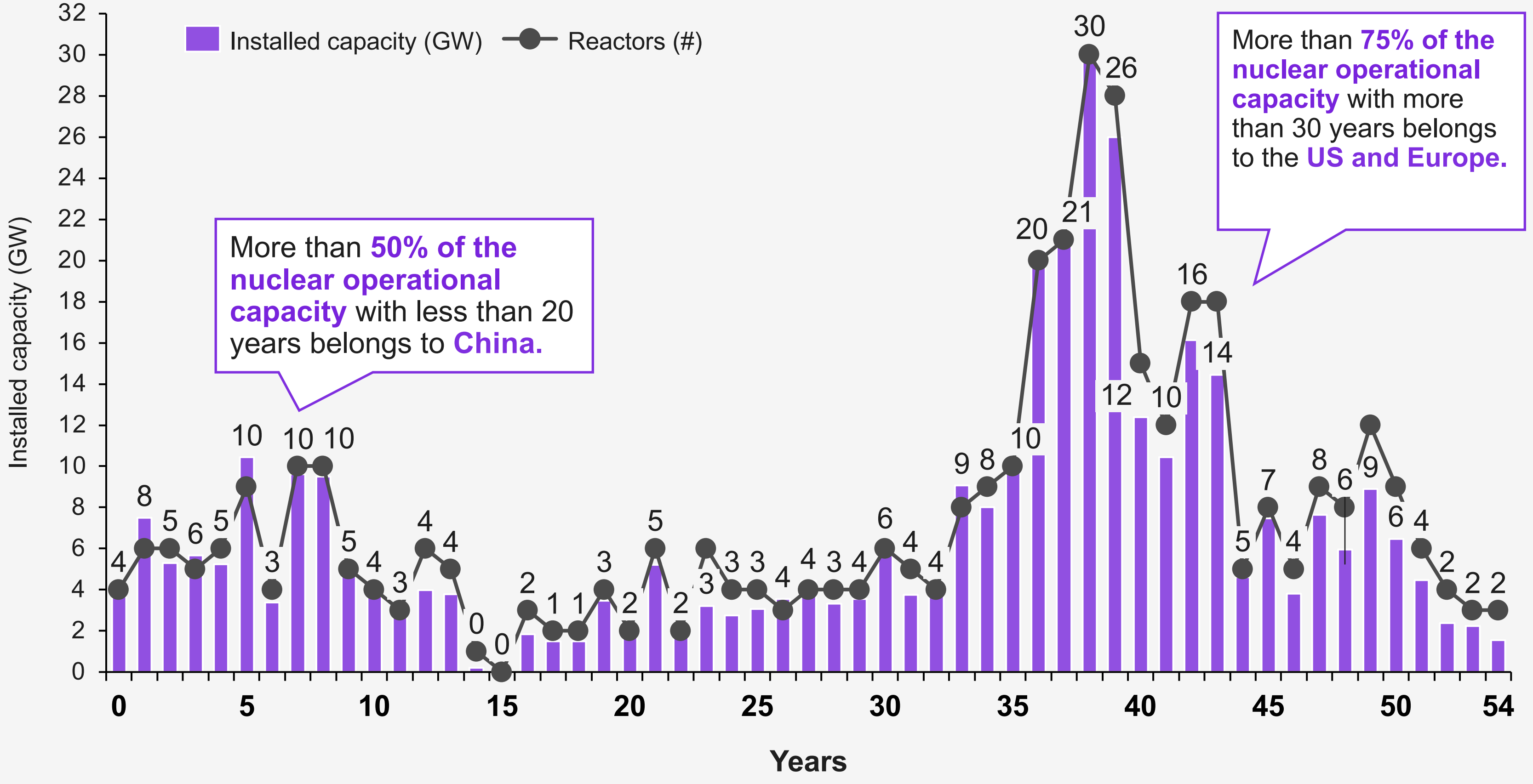
Global shutdown capacity and reactors
GW, Nov. 2023, top 10 countries



Nevertheless, the actual installed capacity is aging, with more than 70% of the current reactors being more than 30 years old

Age of the nuclear fleet

2023



More than **50% of the nuclear operational capacity** with less than 20 years belongs to **China.**

More than **75% of the nuclear operational capacity** with more than 30 years belongs to the **US and Europe.**

Key insights

- When nuclear power became a reliable energy source, the **average plant had a lifetime of 30 years.**
- As of today, there are more than **190 power reactors in 20 countries that have been shut down.**
- Up to 100 power reactors face decommissioning by 2030, but many plants have or plan to apply for license extension.
- The reactors with less than 20 years **are mostly advanced designs and located in Asia.**

Sources: IAEA, PRIS database; IEA, Nuclear Power and Secure Energy Transitions; Kearney Energy Transition Institute analysis

Électricité de France (EDF) is the operator with the most installed capacity and number of reactors in the world

Non-exhaustive

Global nuclear energy operators

Top 10 operators, 2022

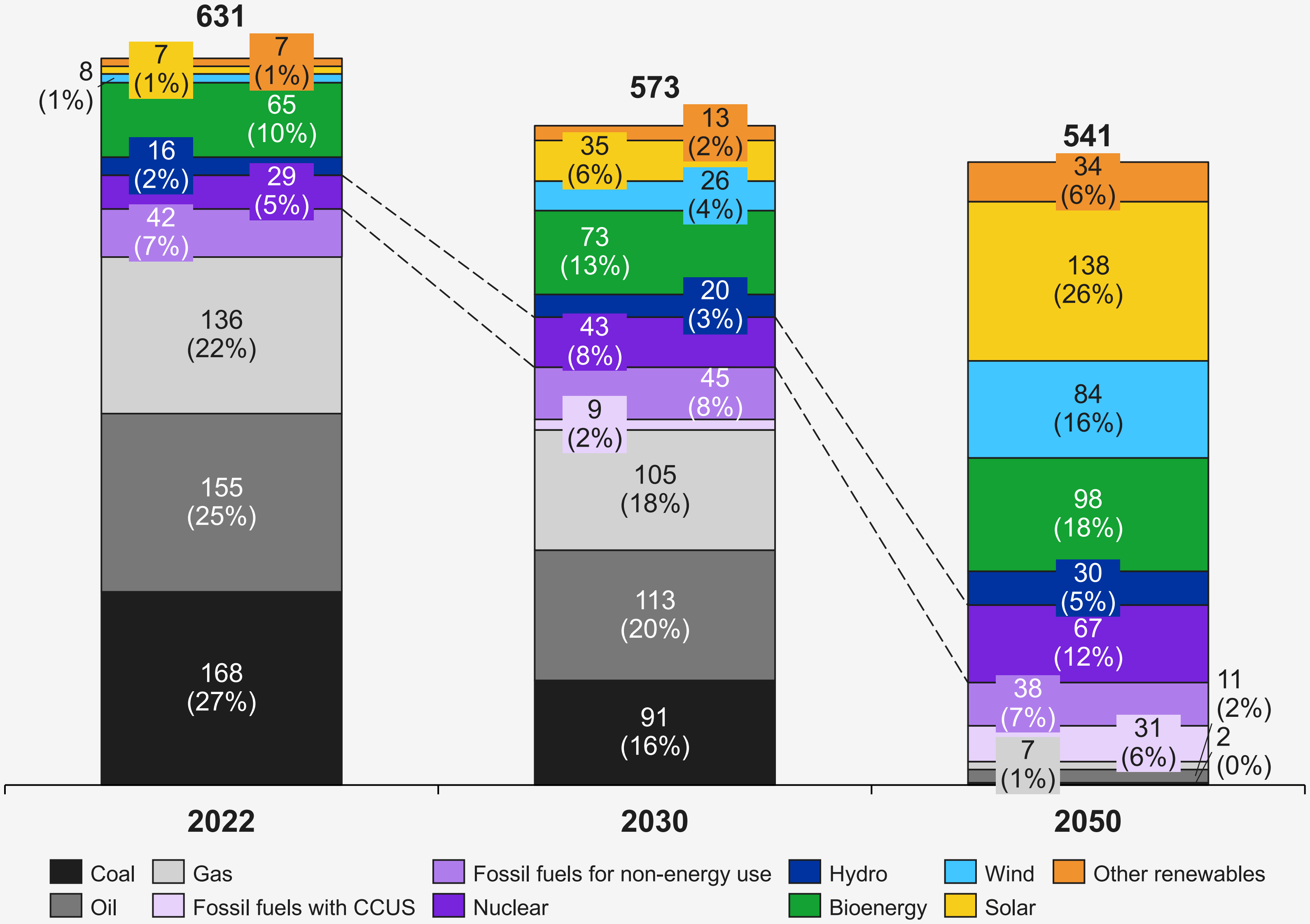
Ranking	Operator	Country	Net installed capacity (GW)	Gross installed capacity (GW)	Reactors (#)
1	EDF	🇫🇷	61.4	64.0	56
2	ROSATOM	🇷🇺	27.7	29.6	37
3	KHNP	🇰🇷	24.5	25.7	25
4	Exelon	🇺🇸	21.5	22.7	21
5	ЕНЕРГОАТОМ ENERGOATOM	🇺🇦	13.1	13.8	15
6	TVA	🇺🇸	8.2	8.6	7
7	DUKE ENERGY	🇺🇸	7.2	7.5	7
8	OPG	🇨🇦	6.6	7.0	10
9	LHNPC	🇨🇳	6.4	6.7	6
10	BrucePower	🇨🇦	6.4	6.9	8

Sources: IAEA, Nuclear Power Reactors in the World, 2023; Kearney Energy Transition Institute analysis

In 2050, under IEA's Net Zero scenario, nuclear energy will represent 12% of the global primary energy consumption

IEA estimates the installed nuclear power capacity to more than double from 417 GW in 2022 to 916 GW in 2050.

Primary energy supply according to "Net Zero" emissions IEA scenario
(EJ, 2022–2050)



Notes: Bioenergy in 2022 includes biomass, for the years 2030, 2040 and 2050, biomass contribution is zero.
Sources: IEA, Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, 2023 update; Kearney Energy Transition Institute analysis

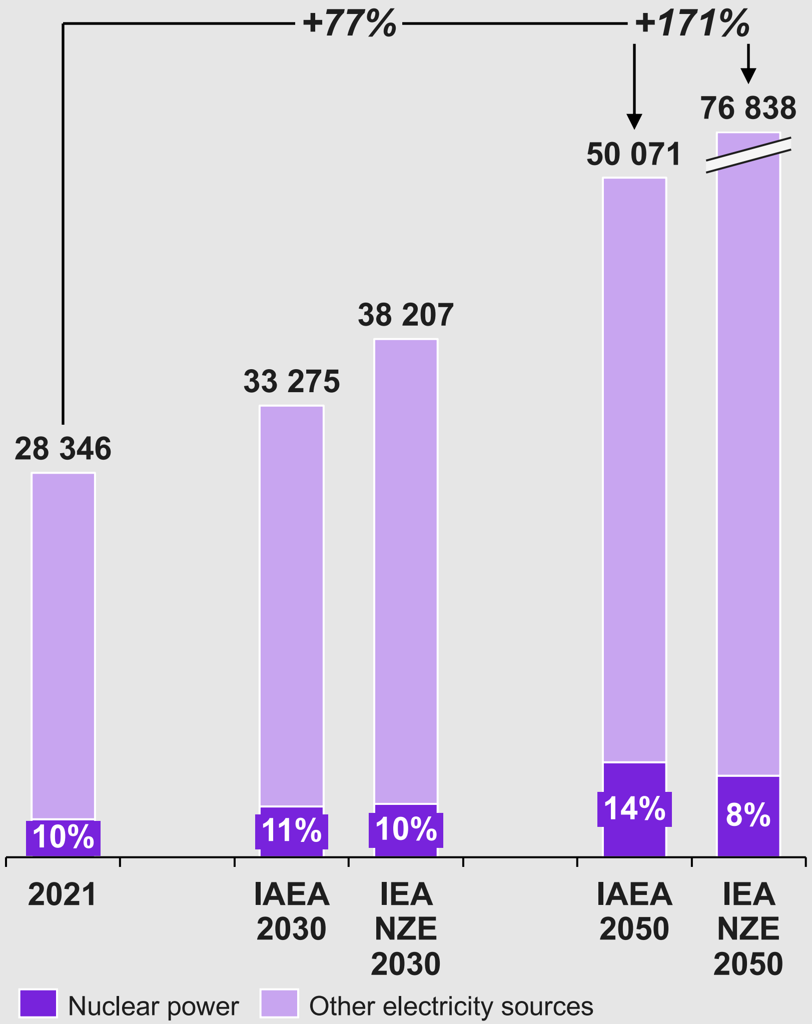
Even though subject to considerable uncertainty, prospective studies concur that nuclear energy will continue to play a significant role in electricity generation in the future

Nuclear electricity share does not show much growth expectations in relative terms (decline in the case of IEA NZE scenario), even though installed capacity will rise as electricity demand grows.

2.7 Future of nuclear power

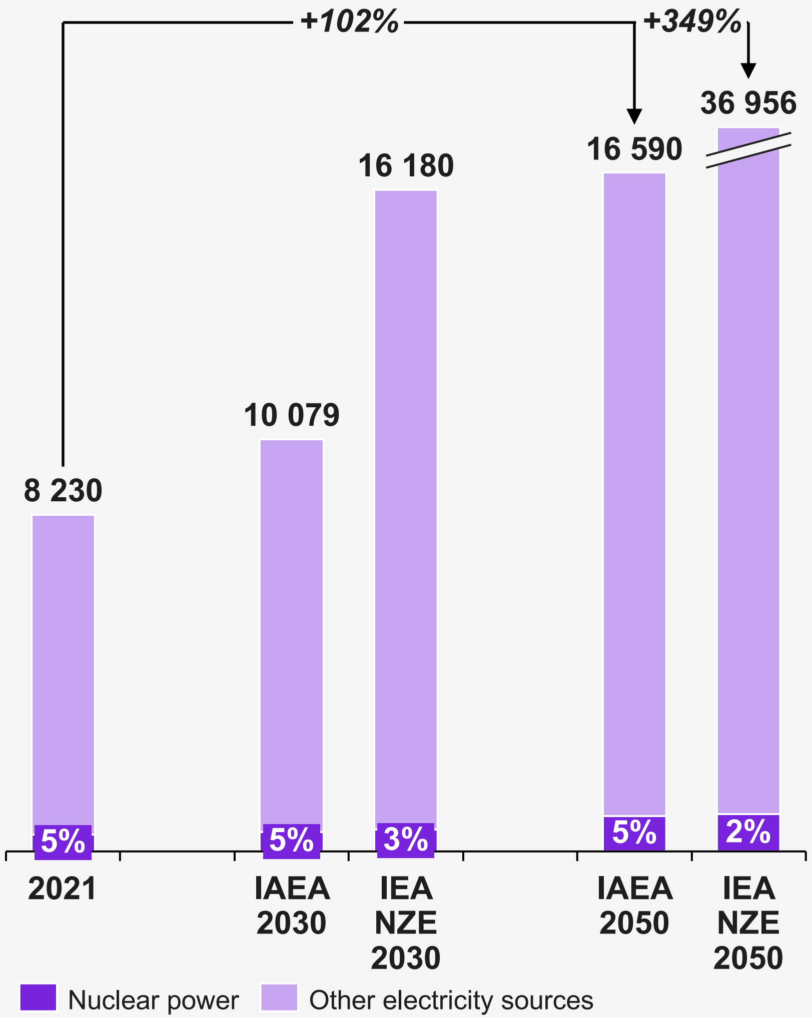
Total electricity generation and nuclear share

TWh, World, 2030, 2050



Total installed capacity and nuclear share

GWe, World, 2030, 2050

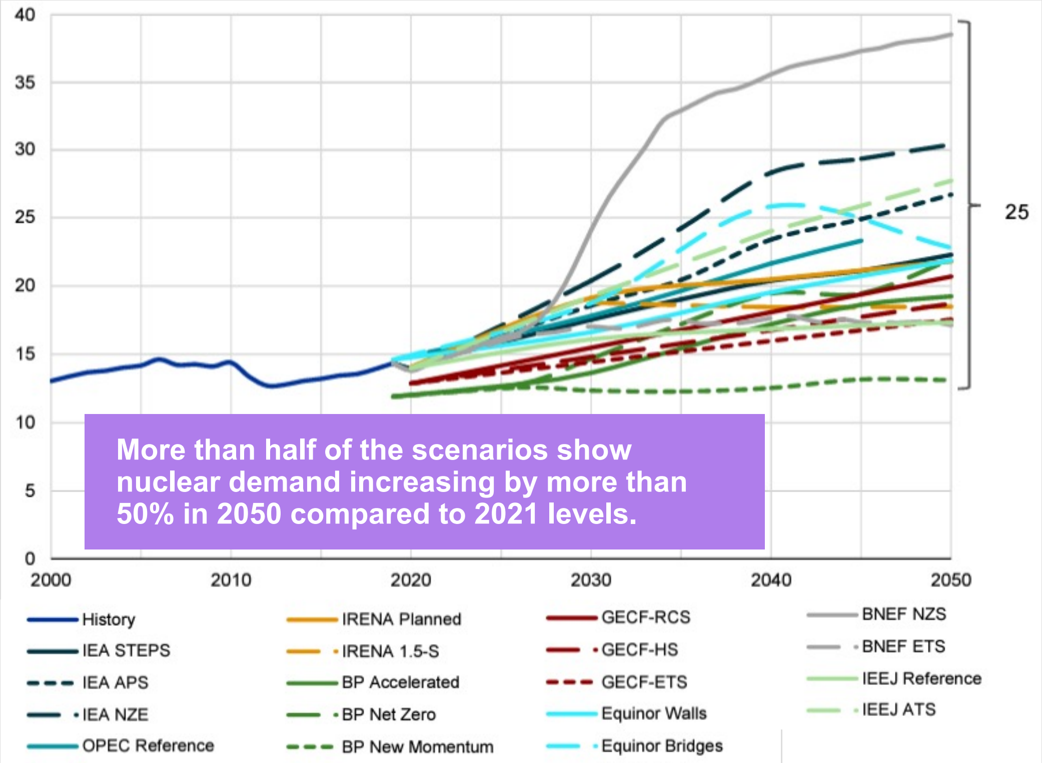


Note: IAEA estimates are based on the high scenario.
Sources: IAEA, 2022, Energy, electricity and nuclear power estimates for the period up to 2050; IEA, 2023, World Energy Outlook; Kearney Energy Transition Institute analysis

Outlook for Nuclear Power to 2050: Wide divergence between scenarios- but rising projections in recent years

Nuclear demand scenarios through 2050

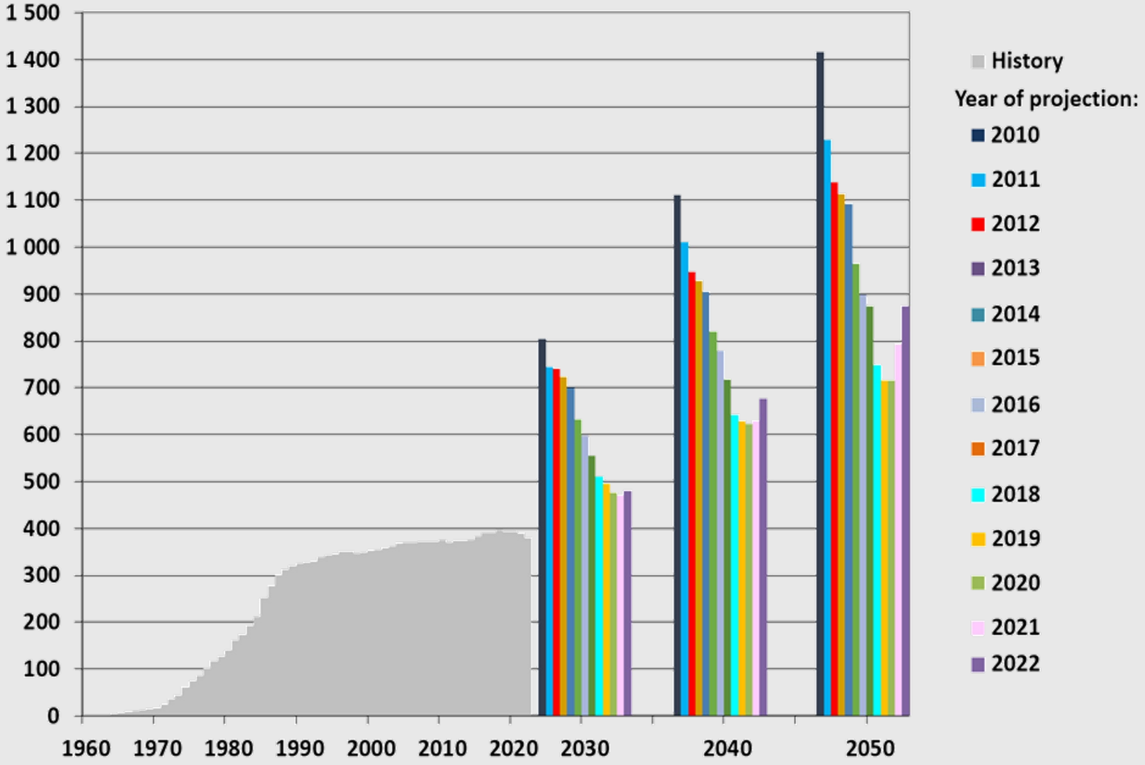
IEF, Mboe/day



More than half of the scenarios show nuclear demand increasing by more than 50% in 2050 compared to 2021 levels.

Global nuclear capacity, projections by year of assessment

IAEA, 2010 to 2022, GWe



Note: In the nuclear demand scenarios through 2050, differences in baselines may stem from different primary energy conversion efficiency assumptions. Primary energy was converted from EJ per year to Mboe/day by multiplying by 0.4825 Mboed/EJ.
Sources: International Energy Forum (IEF), 2023, Outlooks Comparison report; H. Holger Rogner, 2023, Nuclear capacity graph

Currently, nuclear projects under construction total 61,779 MWe; new projects are needed to replace old reactors and increase world capacity in line with energy scenarios

Reactors under construction by region

As of May 2023

Region	# of reactors	Estimated installed capacity (MW)
Asia	39	40,131
Central and Eastern Europe	10	9,666
Western Europe	3	4,890
Africa	3	3,300
Latin America	2	1,365
Middle East	1	1,310
North America	1	1,117
TOTAL	**59**	**61,779**

10 global biggest projects under construction

As of November 2023

Country	Project	# of reactors	Installed capacity (MWe)	CAPEX (billion USD)[1]	USD/ kWe	Commercial operation
🇹🇷	**Akkuyu**	4	4,800	20	4,167	2023
🇮🇳	**Kudankulam**	4	4,000	6.7	1,675	2027
🇪🇬	**El Dabaa**	3	3,600	22,5	6,250	2030
🇬🇧	**Hinkley Point C**	2	3,440	40	11,628	2025
🇰🇷	**Saeul**	2	2,800	9,2	3,286	2024
🇨🇳	**Xudabu**	2	2,548	8,1	3,179	2028
🇨🇳	**Tianwan**	2	2,530	8	3,162	2027
🇷🇺	**Kursk 2**	2	2,510	3,5	1,394	2025
🇨🇳	**Haiyang**	2	2,506	6,2	2,474	2027
🇨🇳	**Sanmen**	2	2,502	6,2	2,478	2027

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[1] Estimated values

Sources: IAEA, PRIS database; newspaper desk research for CAPEX and commercial operation; Kearney Energy Institute analysis

3. Characteristics of SMR technologies and possible applications

AGENGA

SMRs are like conventional nuclear reactors but they have the essential attributes of small size and modularity, which unlock new markets and applications

Introduction to the technology. Small Modular Reactors (SMRs) are nuclear reactors that generate low-carbon electricity and heat by means of harnessing and transforming the energy liberated in the nuclear fission process. Many of them are scaled-down models of large, traditional reactors and include advanced features; others are revolutionary, fourth-generation designs. Apart from their size, a defining characteristic of SMRs is their modularization; that is, they are designed for being manufactured in modules of up to 300 MWe and then transported to the installation site for assembly. This allows for gradual addition of modules.

SMR classification. SMRs are categorized according to the nature of the coolant and moderator they use, in the same way as large reactors. There are SMRs of many types in development, including Pressurized Water Reactor (PWRs), High Temperature Gas Cooled Reactors (HTGRs), Liquid Metal Fast Reactors (LMFRs), and Molten Salt Reactor (MSRs), among others. They each have their advantages and disadvantages, and hence their preferred areas of applicability.

SMR applications. Nuclear reactors are primarily constructed for electricity production, and SMRs are no exception. The dispatchability of nuclear power makes it perfect for load-following and for pairing with renewables and balancing off their variability. SMRs' versatility can be further exploited for other non-electrical applications, such as taking advantage of the temperature as the main output and not as a by-product. Potential uses depend on the operation temperature, which varies from one reactor technology to another, and include district heating, water desalination, hydrogen production, and other industrial processes.

Small modular reactors (SMR) are advanced nuclear reactors that can be modularly built, transported, and installed

Small

- Significantly smaller than typical large reactors
- Capacity of 10-300 MWe generated per reactor or up to 1,000 MWt thermal capacity.

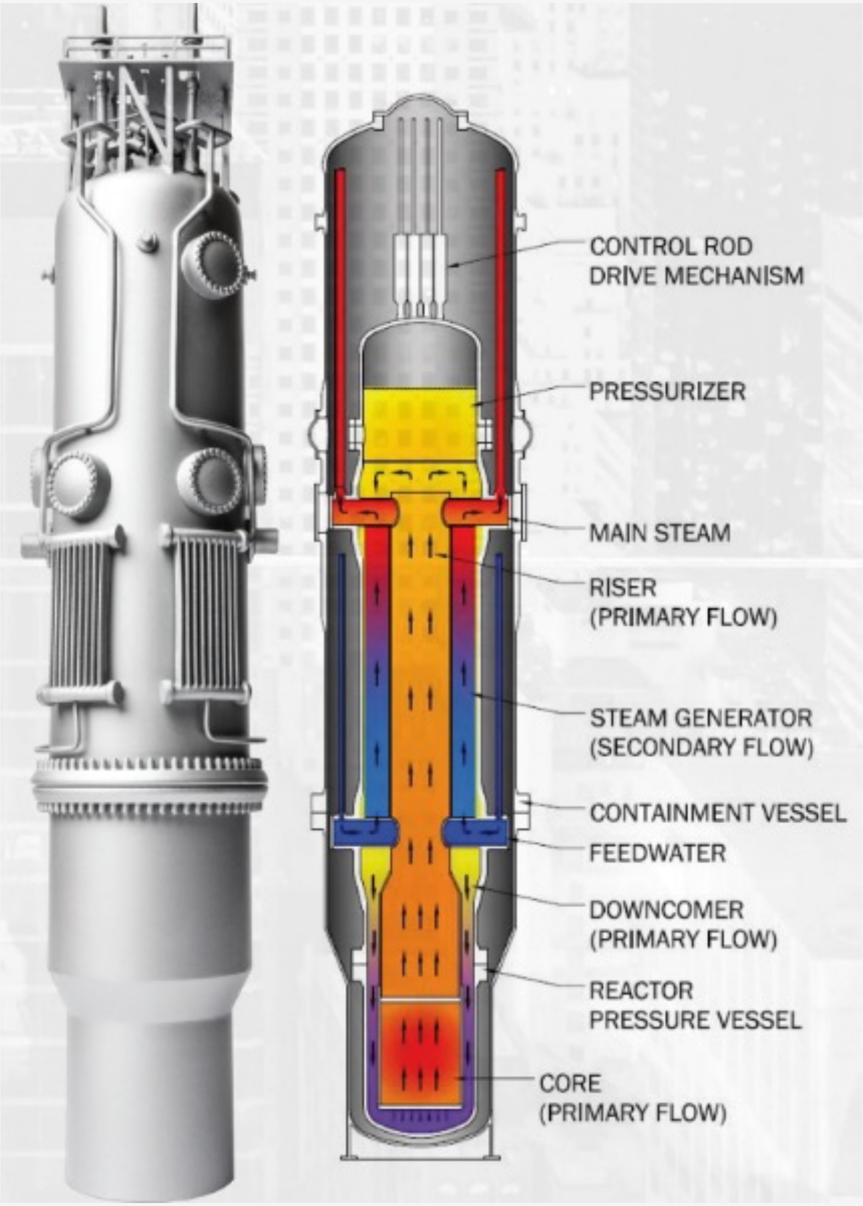
Modular

- All or large part assembled at factory and shipped to site.
- Host several individual SMR modules, or single module.

Reactors

- Supplying electricity and other energy services to energy-intensive industries, to locations with small grids or serving isolated and remote locations.

NuScale Power Module™



3.1 Introduction to SMR

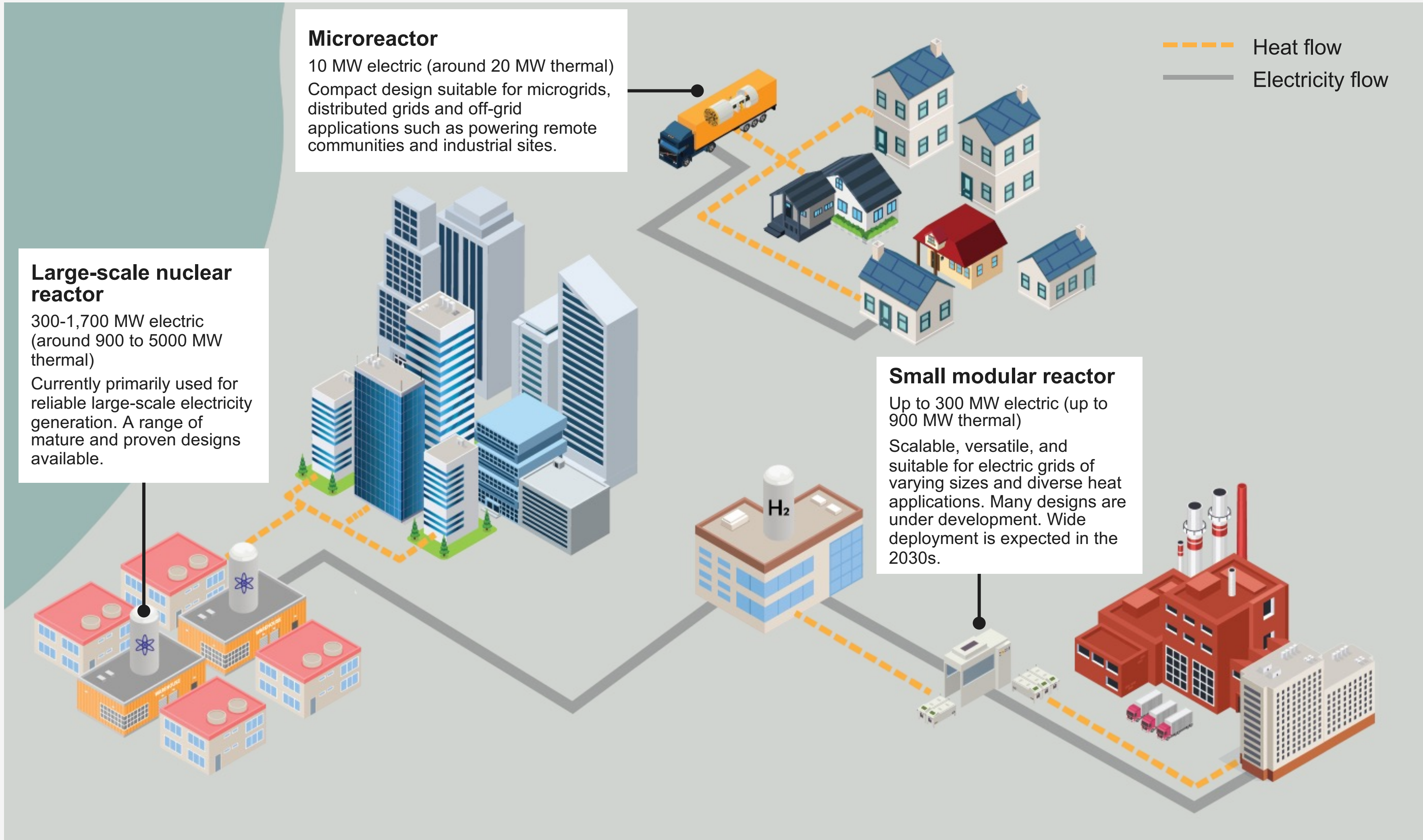
Sources: A. Shihab-Eldin, 2023, Progress on Small Modular (Nuclear) Reactors; NuScale; Kearney Energy Transition Institute analysis

Nuclear power can be scaled down from traditional large-scale nuclear reactors

Future SMR and advanced reactor designs are expected to provide the needed performance (such as high temperatures) and flexibility (such as co-siting with industrial facilities) to address markets not easily serviceable by the large reactors currently (as these are mainly geared to provide bulk electricity).

3.1 Introduction to SMR

Different types of nuclear power plants (based on size)



Microreactor

10 MW electric (around 20 MW thermal)

Compact design suitable for microgrids, distributed grids and off-grid applications such as powering remote communities and industrial sites.

Large-scale nuclear reactor

300-1,700 MW electric (around 900 to 5000 MW thermal)

Currently primarily used for reliable large-scale electricity generation. A range of mature and proven designs available.

Small modular reactor

Up to 300 MW electric (up to 900 MW thermal)

Scalable, versatile, and suitable for electric grids of varying sizes and diverse heat applications. Many designs are under development. Wide deployment is expected in the 2030s.

Sources: Adapted from UNECE, Technology brief on nuclear power, 2020; Kearney Energy Transition Institute analysis

Nuclear power can be scaled down from traditional large-scale nuclear reactors

Overview of the key types of nuclear reactors (based on size)

	Large reactors	Large reactors (advanced)	Small modular reactors	Microreactors
Timeline	Since 1950s (current fleet)	Deployed/recently	In development	In development
Footprint (km²)	6	Varies	0.2	< 0.004
Electrical capacity (MW)	1,000+	400-1,400	20-300	< 20
EPZ (km)	16	0.24-16	0.31[1]	< 0.31[1]
Coolant	Water	Water, gas, metal, salt	Water, gas, metal, salt	Water, gas, metal, salt
Control approach	Active	Mostly passive	Mostly passive	Mostly passive
End products	Electricity, heat	Electricity, heat, steam	Electricity, heat, steam	Electricity, heat, steam
Applications	Base load electrical power	Base load, demand response, industrial electricity, industrial processes such as hydrogen production	Base load, demand response, industrial electricity, industrial processes such as hydrogen production	Power for remote locations, mobile backup power, maritime shipping, mining, military, disaster relief, space missions
Customers	Large utilities	Mostly large utilities with some associated industries	Utilities, municipalities, industry	Military, municipalities, industry
Cost range	USD 5–9 billion	Mixed	USD 800 million – 3 billion	USD 49–86 million
Scalability	Adding new reactors is difficult	Mixed	Designed to add new reactors as demand increases	Designed to add new reactors as demand increases

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[1] Indicative value subject to revision. Will depend on the regulations and standards which are still not finalized

Note: EPZ (Emergency Planning Zone)

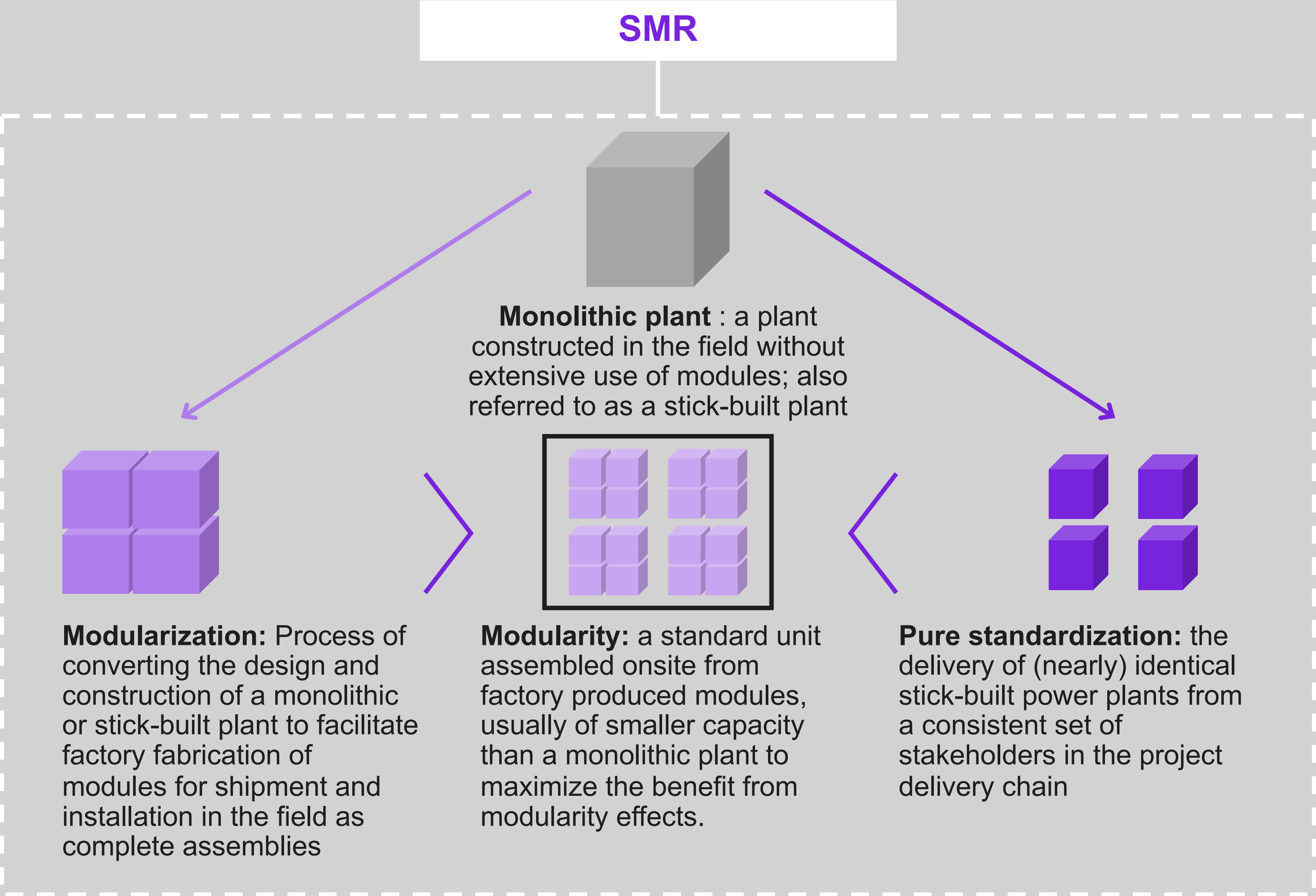
Sources: Idaho National Laboratory; Kearney Energy Transition Institute analysis

SMR designs take advantage of modularization, modularity and standardization

Not every small reactor is a SMR. Key characteristics are:

- Modular construction
- Standardized modules
- Factory built in large numbers
- Easily shipped to the site
- Assembled on the site
- Modules can be added per demand

3.1 Introduction to SMR



SMR

Monolithic plant : a plant constructed in the field without extensive use of modules; also referred to as a stick-built plant

Modularization: Process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies

Modularity: a standard unit assembled onsite from factory produced modules, usually of smaller capacity than a monolithic plant to maximize the benefit from modularity effects.

Pure standardization: the delivery of (nearly) identical stick-built power plants from a consistent set of stakeholders in the project delivery chain

Sources: UNECE, Technology brief on nuclear power, 2020; Kearney Energy Transition Institute analysis

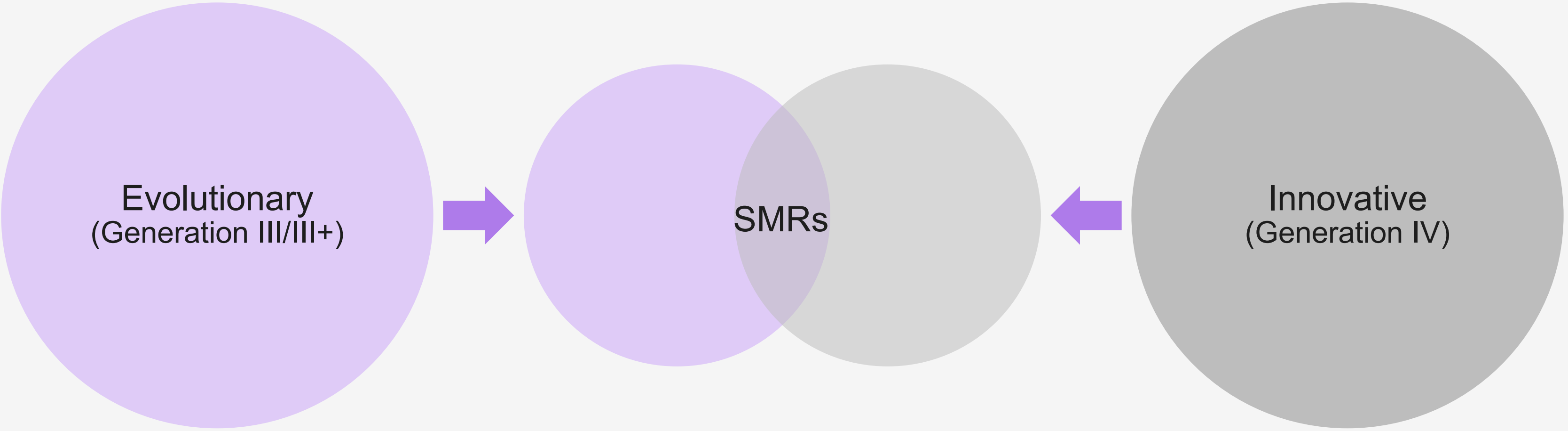
The vast majority of SMRs are based on advanced reactor designs

Advanced reactor designs include both evolutionary and innovative reactor designs/technologies.

3.1 Introduction to SMR

Advanced reactor design objectives

Reducing costs and improving safety



ABWR, ACR 1000, AP1000, APWR, Atmea-1, CANDU 6, EPR, ESBWR, VVER 1200, CAP1400, APR1400, HPR1000…

CAREM-25, HTR-PM, BWRX-300, KLT-405, RITM-200, AHWR, NuScale, SMART, 4S, PRISM …

LFR, GFR, SFR, SCWR, VHTR, MSR, ADS

Evolutionary designs improve on existing designs through small or moderate modifications with a strong emphasis on maintaining proven design features to minimize technological risk.

Advanced nuclear designs include both evolutionary and innovative reactor technologies.

Innovative[1] designs incorporate radical changes in the use of materials and/or fuels, operating environment and conditions, and system configurations.

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[1] Innovative designs include generation IV and advanced modular reactors (AMRs) which refer to reactors with novel and innovative fuels, coolant and technologies modularly-built as SMRs.

Sources: IAEA, Small Modular Reactors and Generation IV A Short Overview; F. Reitsma; UK Government, Advanced nuclear technologies, 2023; Kearney Energy Transition Institute analysis

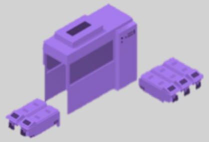
Advanced designs comprise several individual and combined variables

Non-exhaustive

A. Size

Capacity of the reactor

Large-scale reactor



Small modular reactor

Microreactor

B. Fuel

Feedstock considerations of the reactor

Fuel material

- LEU
- HALEU
- Plutonium
- Thorium

Fuel form

- Oxide (metal)
- TRISO (pebble)
- Other TRISO
- Molten salt
- Metal
- Ceramic matrix
- Carbide

Fuel cycle

- Open
- High burnup
- Closed

C. Reactor

Parameters defining reactor design

Neutron energy

- Thermal
- Fast

Moderator

- Light water
- Heavy water
- Graphite
- None

Coolant

- Light water
- Heavy water
- Gas
- Liquid metal
- Molten salt

Light water is ordinary water depleted of uranium; **heavy water** has an extra neutron in the hydrogen component. Examples of **liquid metal coolants** are sodium and lead. A reactor with no moderator is a fast reactor.

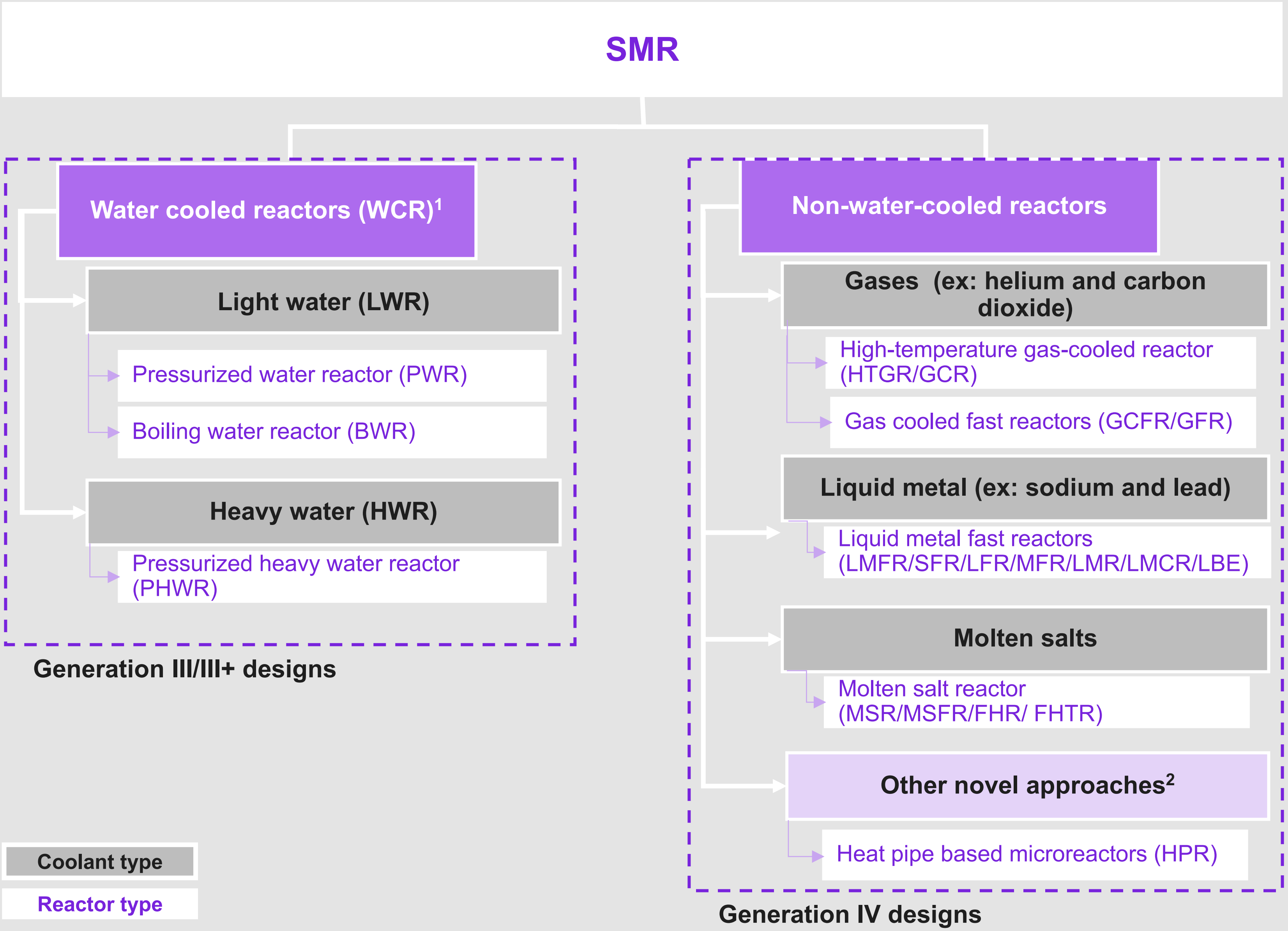
LEU=low enriched uranium; **HALEU**=high-assay low enriched uranium (5%-20% enriched in U-235). Thorium in fuel must first be transmuted to uranium-233 to be fissile.

In an **open fuel cycle**, spent nuclear fuel is intended for permanent disposal. In a **closed fuel cycle**, spent fuel is reprocessed to separate uranium, plutonium, and other materials that can be used in new fuel. In the **high-burnup cycle**, fuel produces power for a long period before permanent disposal but is not reprocessed.

Sources: US Congressional Research Service, 2022, Advanced Nuclear Reactors: Technology Overview and Current Issues; Kearney Energy Transition Institute analysis

SMR technology reactors are classified by the nature of coolant and reactor types

Most common classification is based on the type of the cooling system used in the reactor.



SMR

- **Water cooled reactors (WCR)[1]**
  - **Light water (LWR)**
    - Pressurized water reactor (PWR)
    - Boiling water reactor (BWR)
  - **Heavy water (HWR)**
    - Pressurized heavy water reactor (PHWR)

Generation III/III+ designs

- **Non-water-cooled reactors**
  - **Gases (ex: helium and carbon dioxide)**
    - High-temperature gas-cooled reactor (HTGR/GCR)
    - Gas cooled fast reactors (GCFR/GFR)
  - **Liquid metal (ex: sodium and lead)**
    - Liquid metal fast reactors (LMFR/SFR/LFR/MFR/LMR/LMCR/LBE)
  - **Molten salts**
    - Molten salt reactor (MSR/MSFR/FHR/ FHTR)
  - **Other novel approaches[2]**
    - Heat pipe based microreactors (HPR)

Generation IV designs

Coolant type

Reactor type

---

[1] Supercritical water-based small modular reactors (SCW SMR) have been proposed based on supercritical water reactor (SCWR) concept which uses supercritical water to improve efficiency vs. LWR. SCWR could be designed to operate in either the fast or thermal neutron spectrums, and to use either light or heavy water as the coolant and/or moderator. Proposed SCWR designs in Canada, EU, China, Japan, and Russia use light water as a coolant. Some SCW SMR designs are in process of being conceptualized but it has not been profiled here as the concept is still in very preliminary stages. Once developed it would be classified under Generation IV designs.

[2] Such as liquid hydrogen, sulfur, others (sulfate, plasma, dust, etc.)

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

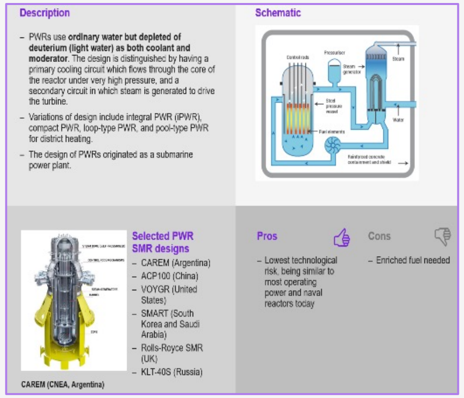
Overview and key technical parameters for the main SMR technologies

Listing of SMR factcards (accessible later in the factbook as “Appendix: factcards”)

Press “CTR + graphic” to directly link to the relevant factcard

3.3 Summary of key categories

Pressurized Water Reactor (PWR)



Description

- PWRs use **ordinary water but depleted of deuterium (light water) as both coolant and moderator.** The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine.
- Variations of design include integral PWR (iPWR), compact PWR, loop-type PWR, and pool-type PWR for district heating.
- The design of PWRs originated as a submarine power plant.

Schematic

CAREM (CNEA, Argentina)

Selected PWR SMR designs

- CAREM (Argentina)
- ACP100 (China)
- VOYGR (United States)
- SMART (South Korea and Saudi Arabia)
- Rolls-Royce SMR (UK)
- KLT-40S (Russia)

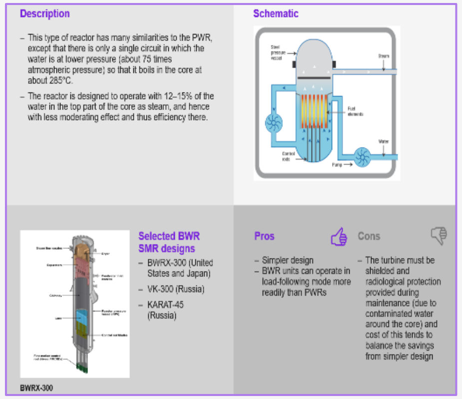
Pros

- Lowest technological risk, being similar to most operating power and naval reactors today

Cons

- Enriched fuel needed

Boiling Water Reactor (BWR)



Description

- This type of reactor has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C.
- The reactor is designed to operate with 12–15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there.

Schematic

BWRX-300

Selected BWR SMR designs

- BWRX-300 (United States and Japan)
- VK-300 (Russia)
- KARAT-45 (Russia)

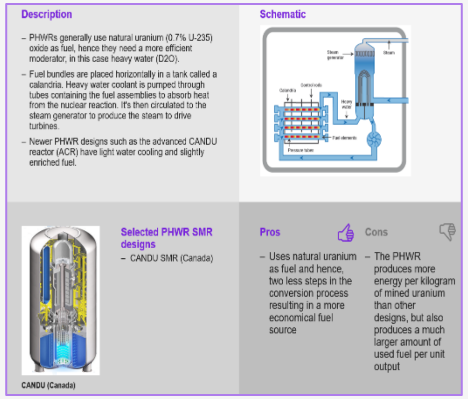
Pros

- Simpler design
- BWR units can operate in load-following mode more readily than PWRs

Cons

- The turbine must be shielded and radiological protection provided during maintenance (due to contaminated water around the core) and cost of this tends to balance the savings from simpler design

Pressurized Heavy Water Reactor (PHWR)



Description

- PHWRs generally use natural uranium (0.7% U-235) oxide as fuel, hence they need a more efficient moderator, in this case heavy water (D2O).
- Fuel bundles are placed horizontally in a tank called a calandria. Heavy water coolant is pumped through tubes containing the fuel assemblies to absorb heat from the nuclear reaction. It's then circulated to the steam generator to produce the steam to drive turbines.
- Newer PHWR designs such as the advanced CANDU reactor (ACR) have light water cooling and slightly enriched fuel.

Schematic

CANDU (Canada)

Selected PHWR SMR designs

- CANDU SMR (Canada)

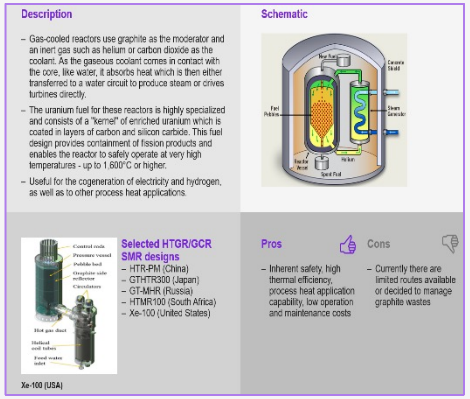
Pros

- Uses natural uranium as fuel and hence, two less steps in the conversion process resulting in a more economical fuel source

Cons

- The PHWR produces more energy per kilogram of mined uranium than other designs, but also produces a much larger amount of used fuel per unit output

High Temperature Gas Cooled Reactors (HTGR)



Description

- Gas-cooled reactors use graphite as the moderator and an inert gas such as helium or carbon dioxide as the coolant. As the gaseous coolant comes in contact with the core, like water, it absorbs heat which is then either transferred to a water circuit to produce steam or drives turbines directly.
- The uranium fuel for these reactors is highly specialized and consists of a "kernel" of enriched uranium which is coated in layers of carbon and silicon carbide. This fuel design provides containment of fission products and enables the reactor to safely operate at very high temperatures - up to 1,600°C or higher.
- Useful for the cogeneration of electricity and hydrogen, as well as to other process heat applications.

Schematic

Xe-100 (USA)

Selected HTGR/GCR SMR designs

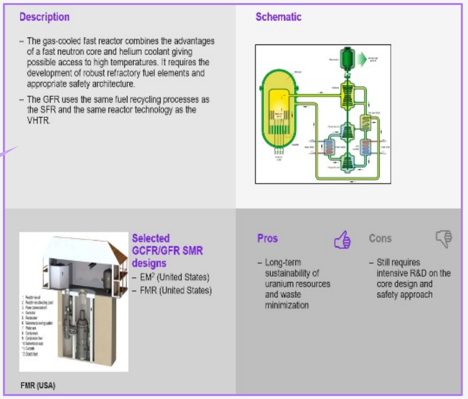
- HTR-PM (China)
- GTHTR300 (Japan)
- GT-MHR (Russia)
- HTMR100 (South Africa)
- Xe-100 (United States)

Pros

- Inherent safety, high thermal efficiency, process heat application capability, low operation and maintenance costs

Cons

- Currently there are limited routes available or decided to manage graphite wastes



Description

- The gas-cooled fast reactor combines the advantages of a fast neutron core and helium coolant giving possible access to high temperatures. It requires the development of robust refractory fuel elements and appropriate safety architecture.
- The GFR uses the same fuel recycling processes as the SFR and the same reactor technology as the VHTR.

Schematic

FMR (USA)

Selected GCFR/GFR SMR designs

- EM² (United States)
- FMR (United States)

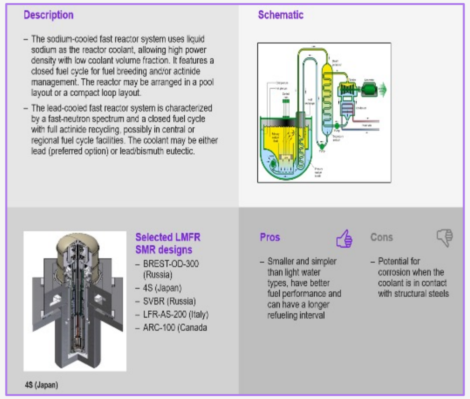
Pros

- Long-term sustainability of uranium resources and waste minimization

Cons

- Still requires intensive R&D on the core design and safety approach

Gas-Cooled Fast Reactors (GCFR)



Description

- The sodium-cooled fast reactor system uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. It features a closed fuel cycle for fuel breeding and/or actinide management. The reactor may be arranged in a pool layout or a compact loop layout.
- The lead-cooled fast reactor system is characterized by a fast-neutron spectrum and a closed fuel cycle with full actinide recycling, possibly in central or regional fuel cycle facilities. The coolant may be either lead (preferred option) or lead/bismuth eutectic.

Schematic

4S (Japan)

Selected LMFR SMR designs

- BREST-OD-300 (Russia)
- 4S (Japan)
- SVBR (Russia)
- LFR-AS-200 (Italy)
- ARC-100 (Canada

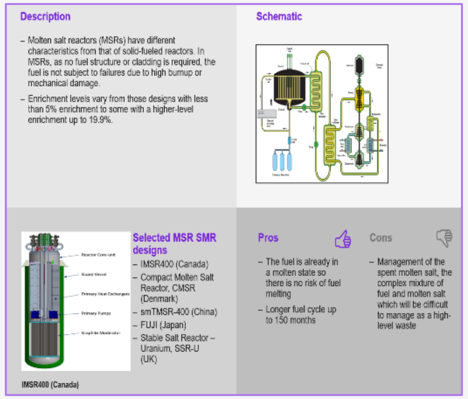
Pros

- Smaller and simpler than light water types, have better fuel performance and can have a longer refueling interval

Cons

- Potential for corrosion when the coolant is in contact with structural steels

Liquid Metal Fast Reactors (LMFR)



Description

- Molten salt reactors (MSRs) have different characteristics from that of solid-fueled reactors. In MSRs, as no fuel structure or cladding is required, the fuel is not subject to failures due to high burnup or mechanical damage.
- Enrichment levels vary from those designs with less than 5% enrichment to some with a higher-level enrichment up to 19.9%.

Schematic

IMSR400 (Canada)

Selected MSR SMR designs

- IMSR400 (Canada)
- Compact Molten Salt Reactor, CMSR (Denmark)
- smTMSR-400 (China)
- FUJI (Japan)
- Stable Salt Reactor – Uranium, SSR-U (UK)

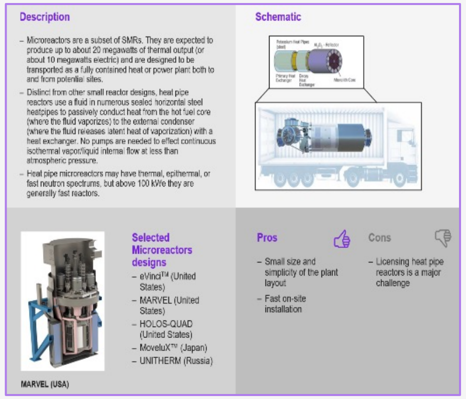
Pros

- The fuel is already in a molten state so there is no risk of fuel melting
- Longer fuel cycle up to 150 months

Cons

- Management of the spent molten salt, the complex mixture of fuel and molten salt which will be difficult to manage as a high-level waste

Molten Salt Reactor (MSR)



Description

- Microreactors are a subset of SMRs. They are expected to produce up to about 20 megawatts of thermal output (or about 10 megawatts electric) and are designed to be transported as a fully contained heat or power plant both to and from potential sites.
- Distinct from other small reactor designs, heat pipe reactors use a fluid in numerous sealed horizontal steel heatpipes to passively conduct heat from the hot fuel core (where the fluid vaporizes) to the external condenser (where the fluid releases latent heat of vaporization) with a heat exchanger. No pumps are needed to effect continuous isothermal vapor/liquid internal flow at less than atmospheric pressure.
- Heat pipe microreactors may have thermal, epithermal, or fast neutron spectrums, but above 100 kWe they are generally fast reactors.

Schematic

MARVEL (USA)

Selected Microreactors designs

- eVinci™ (United States)
- MARVEL (United States)
- HOLOS-QUAD (United States)
- MoveluX™ (Japan)
- UNITHERM (Russia)

Pros

- Small size and simplicity of the plant layout
- Fast on-site installation

Cons

- Licensing heat pipe reactors is a major challenge

Microreactor

Sources: Kearney Energy Transition Institute analysis

Summary – SMR design characteristics

Non-exhaustive

	Water cooled reactors (WCR)			Non-water-cooled reactors				
	PWR Pressurized water reactor	**BWR** Boiling water reactor	**PHWR** Pressurized heavy water reactor	**HTGR** High-temperature gas-cooled reactor	**GCFR** Gas cooled fast reactors	**LMFR** Liquid metal fast reactors	**MSR** Molten salt reactor	**Micro-reactors**
Status	**Operating**	**Design ready**	**Early design**	**Operating**	**Early design**	**Under construction**	**Design ready**	**Design ready**
Lifetime	40–80+ years	60+ years	20+ years	60 years	60 years	60 years	20+ years	<40 years
Plant footprint (m^2)	4,320 (floating) – 200,000	9,000–40,000	21,000	5,000–256,100	38,000–90,000	1,100–157,000	5,000–45,000	10–10,000
Expected capacity range (MWe)	30–470	250–300	300	35–300	50–265	10–300	16–200	0.015–10
Coolant	Water	Water	Heavy water	Gas	Gas	Liquid metal	Molten salt	Varied
Moderator	Water	Water	Heavy water	Graphite	None	None	Graphite	Varied
Fuel	5%> uranium	5%> uranium	Natural uranium	Coated fuel particles (>5% and <15%)	15–20% uranium carbide / oxide	15–20% uranium nitride	Molten salts and enriched uranium	5–20% uranium
Refueling frequency	Up to 6 years	Up to 7 years	Up to 7 years	Up to 10 years	Up to 30 years	Up to 20 years	Up to 10 years	Up to 20 years

Sources: IAEA ARIS database and Advances in Small Modular Reactor Technology Developments, 2022; Kearney Energy Transition Institute analysis

3.3 Summary of key categories

Summary – SMRs pros and cons

In general, advanced designs offer better fuel safety and security features but face challenges on economics, licensing, and environment authorization when compared to water cooled reactors designs.

3.3 Summary of key categories

+ – Well-established technology and supply chain – Simplest regulatory process – Integral version offers more compact reactor containment	+ – Simpler design leading to lower costs – Well established technology and supply chain	+ – Requires no/very little uranium enrichment – Flexible, and can use any type of fuel	+ – Greater thermal efficiency achieved by operating at very high temperatures – TRISO particles can withstand high heat resulting in better safety
PWR	**BWR**	**PHWR**	**HTGR**
− – Pressurized, need for a large pressure vessel – Enriched fuel needed – Increased waste volume and difficult maintenance in integral version	− – Complicated maintenance as primary coolant is in direct contact with turbines, so if a fuel rod had a leak, radioactive material could be placed on the turbine	− – Some variants have positive coolant void coefficients, leading to safety concerns – Proliferation risks	− – The low power density and larger size also increases the capital cost and size of facility – Graphite dust creates a potential contamination challenge – Less operating experience

+ – Capable of achieving a high breeding ratio, which allows a self-sustained fuel cycle not dependent on uranium supply	+ – Designed to breed its own fuel and burn its own waste – Metallic fuel and excellent thermal properties of sodium allow for passively safe operation	+ – Designed to constantly breed new fuel – Able to fuel with thorium – Liquid fuel also means that structural dose does not limit the life of the fuel, allowing the reactor to extract very much energy out of the loaded fuel	+ – High reliability due to the reduced number of components and systems, with minimal moving parts – Smaller footprints, lower costs, better portability
GCFR	**LMFR**	**MSR**	**Microreactors**
− – Compatibility of fuel and in-core structural materials and components with extreme conditions – Development costs likely to be very high given material and safety challenges	− – Sodium coolant is reactive with air and water. Thus, leaks in the pipes results in sodium fires – Proliferation risks	− – Molten salts are corrosive, introducing structural material challenges or need for stringent chemistry control – Removal of fission products creates and additional waste stream	− – Typical working fluids used in heat pipes, sodium and potassium, react with air and water – Limited operating experience

Source: Kearney Energy Transition Institute analysis

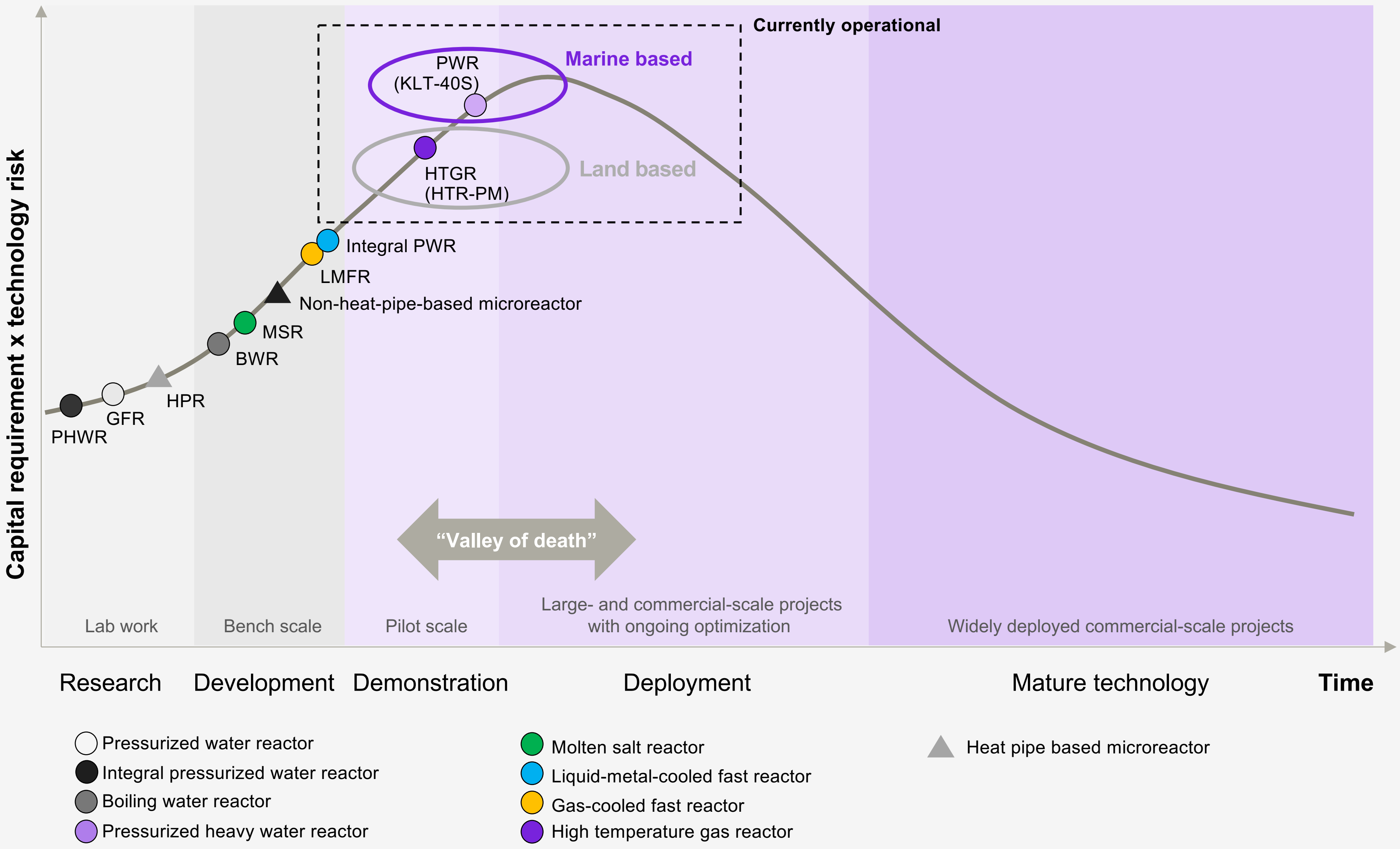
Most SMR designs are in the research and development phase

Non-exhaustive

Illustrative

Maturity curve of SMR reactor types

Non-exhaustive



Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

3.4 Technology maturity curve

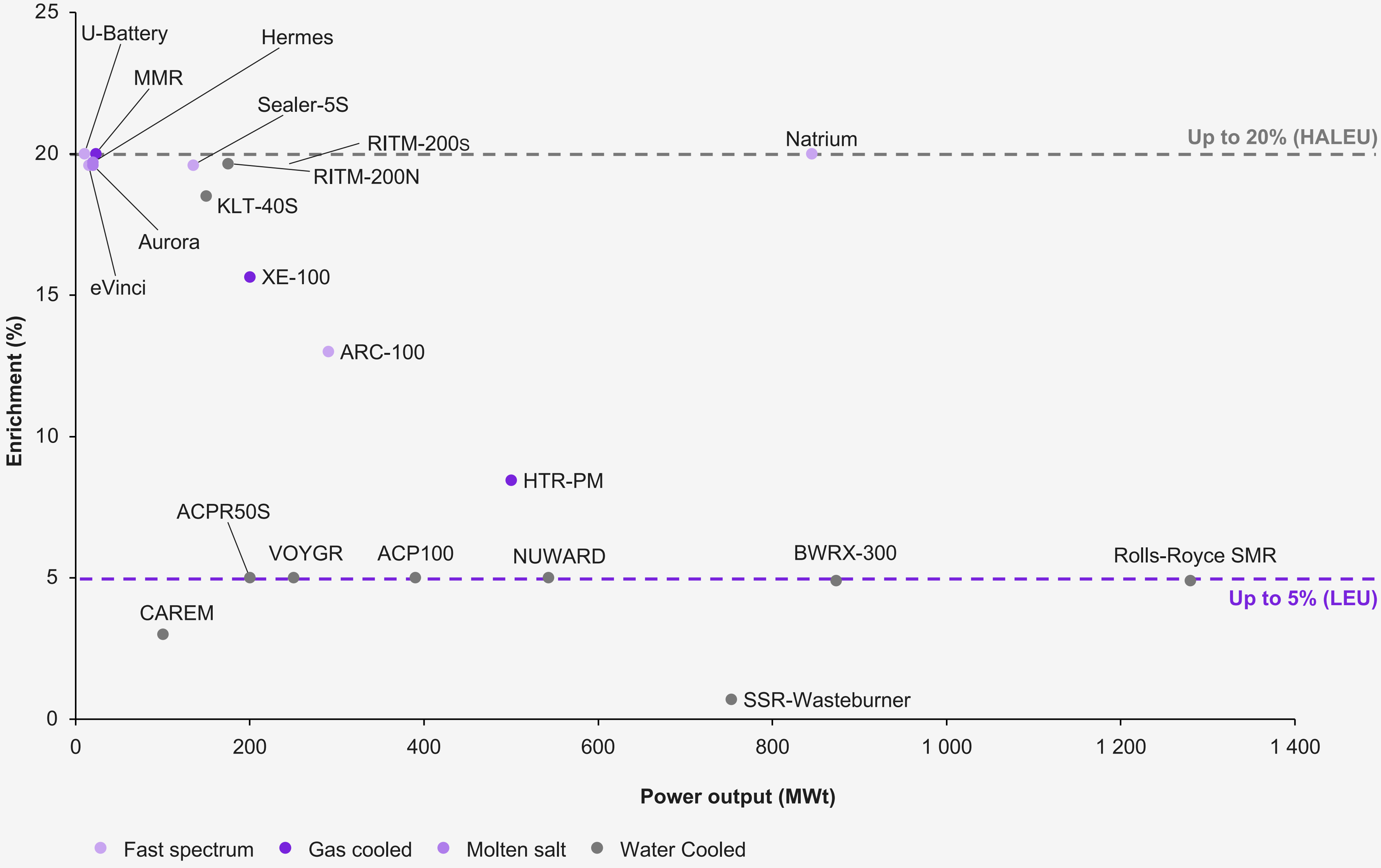
SMR designs use fuels with a wide range of enrichment

Non-exhaustive

A considerable variety of SMRs exists, these have a broad range of thermal power output, and their fuels have different enrichment levels.

3.5 SMR key applications

Selected reactor designs as a function of thermal power and enrichment



Sources: OECD, 2023, The NEA small modular reactor dashboard; Kearney Energy Transition Institute analysis

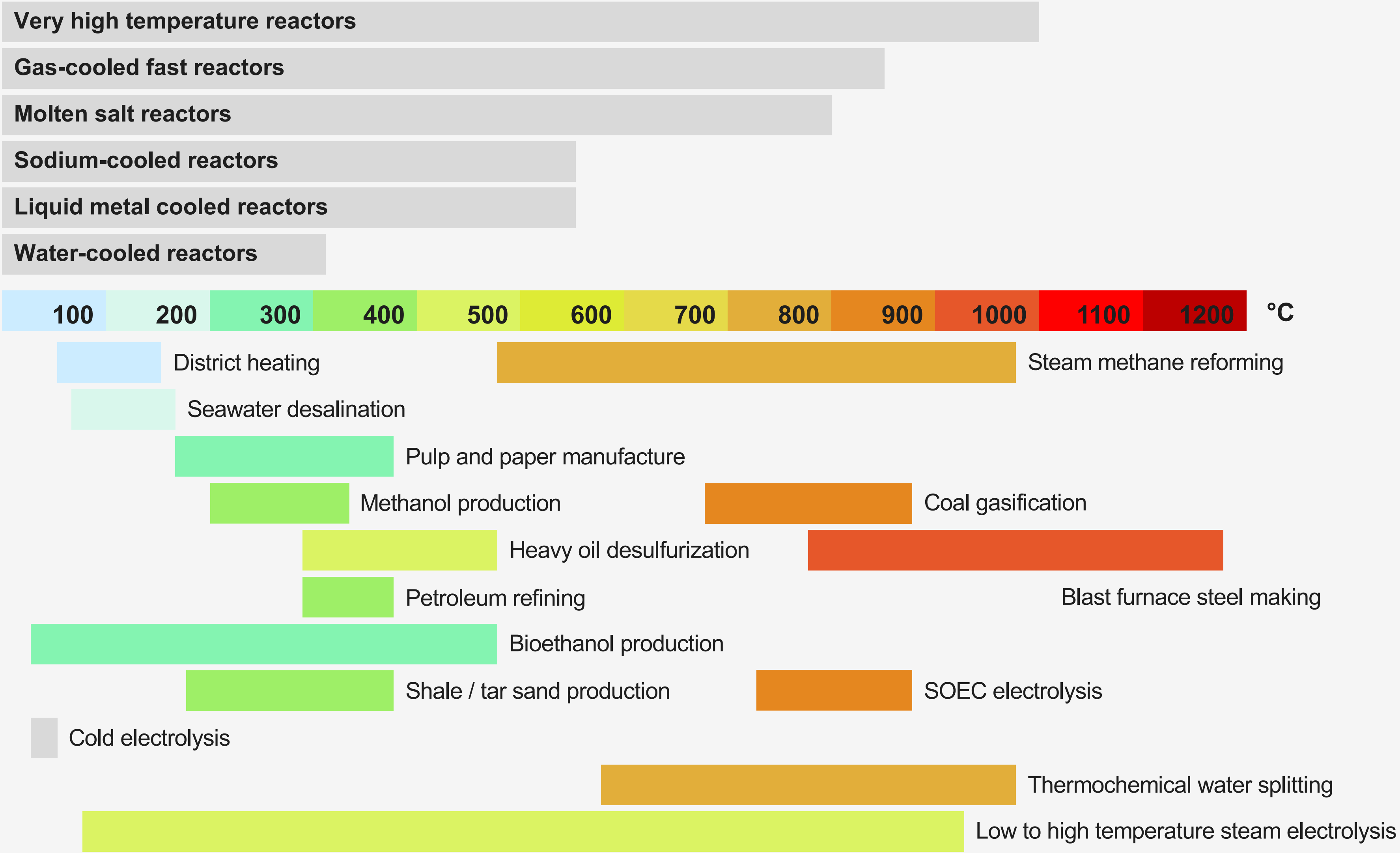
SMRs primarily generate electricity, but to make a substantial contribution to net zero, they will need to support non-electrical applications

Non-exhaustive

There is a massive need for low carbon heat and fuel to support the decarbonization of the “hard-to-abate” sectors (that is, those that cannot be electrified), and SMRs have the potential to contribute to this.

3.5 SMR key applications

SMR non-electrical potential applications depending on the operation temperature



Note: LWRs are best suited for district heating and desalination, while other technologies with higher operation temperatures are better for industrial processes.
Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; K. Katovsky, SMRs for Nuclear Process Heat Delivery; Kearney Energy Transition Institute analysis

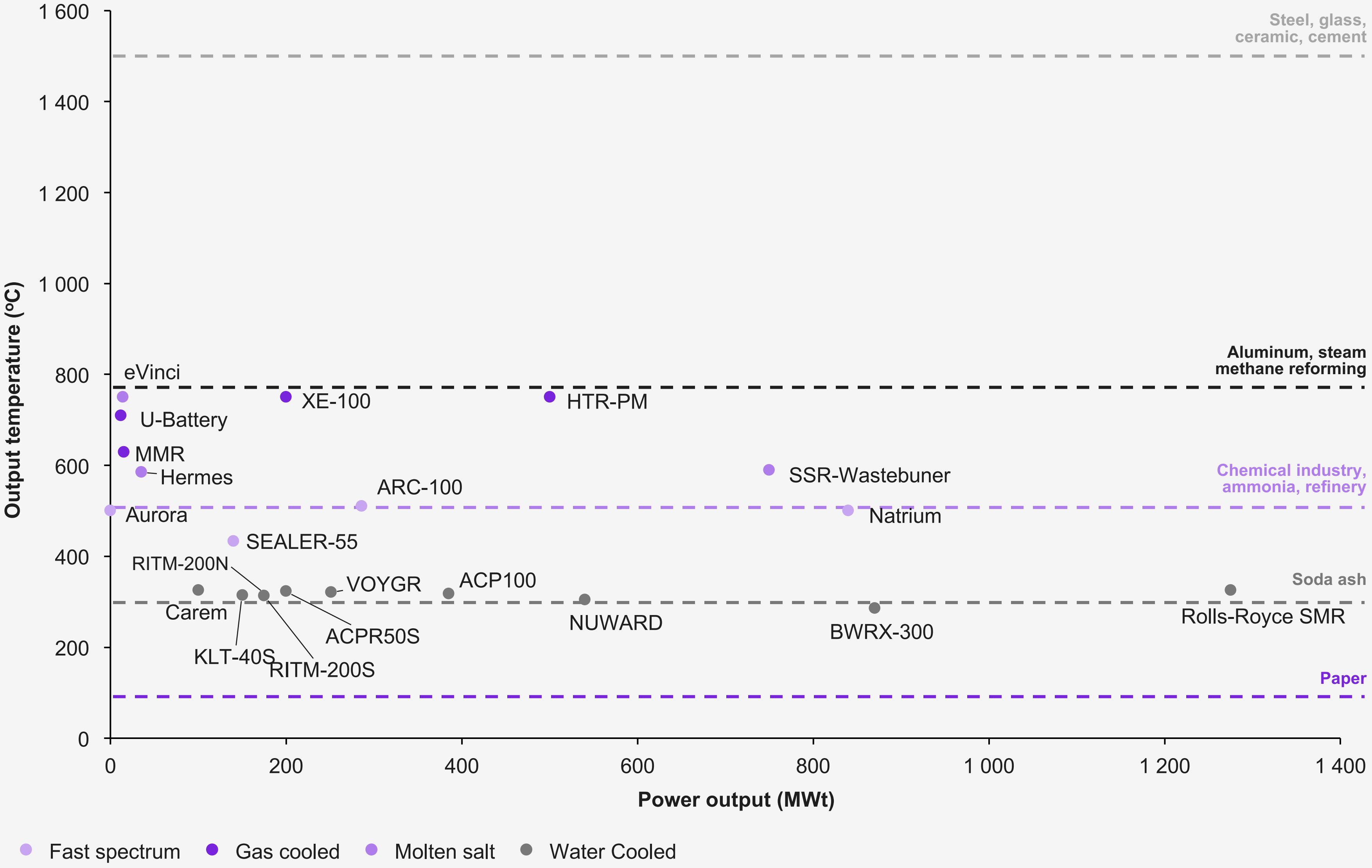
SMR designs with various fuel cycles have the potential to meet different market needs with reactors of different sizes and temperatures

Non-exhaustive

A considerable variety of SMRs exists, these have a broad range of thermal power output, and different output temperature levels.

3.5 SMR key applications

Selected reactor designs as a function of power output and core outlet temperature



Sources: OECD, 2023, The NEA Small Modular Reactor Dashboard; Kearney Energy Transition Institute analysis

Although not an efficient process and economics are still unknown, hydrogen production is technically possible with SMRs

SMR can be co-located with the hydrogen facility and reducing the cost of hydrogen production. One NuScale VOYGR module (250 MWt) is estimated to produce 2,053 kilograms of hydrogen per hour.

Hydrogen production technologies requiring electricity and heat

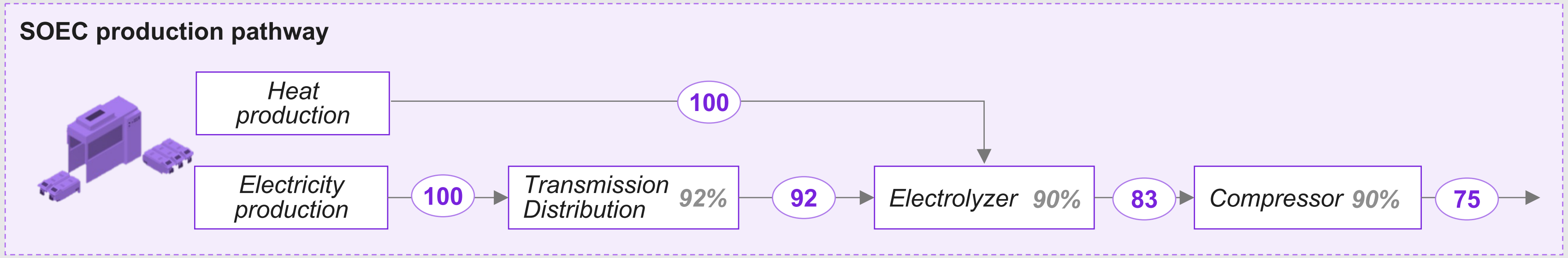
SOEC electrolysis temperatures

		Temperature (°C)	% Lower heating value	Feedstock
Electrolysis	**Alkaline electrolysis (AE)**	60-80	50–69%	Water/Electricity
	Proton-exchange membrane (PEM) electrolysis	50–80	60–77% up to 86%	Water/Electricity
	Solid oxide electrolyzer cell (SOEC) electrolysis	650-1,000	74–81%[1]	Steam/Electricity
Microbial	**Microbial electrolysis**	n.a.	n.a.	Water/Electricity

SOEC has a higher potential of economical benefits if coupled with the heat source from SMR.

Nuclear electricity and heat uses in hydrogen production

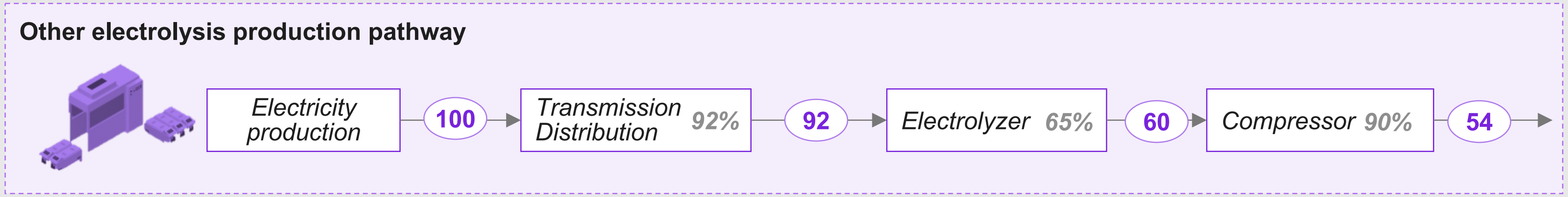
Energy efficiency along the chain



SOEC production pathway

Heat production → 100 → *Electrolyzer*

Electricity production → 100 → *Transmission Distribution 92%* → 92 → *Electrolyzer 90%* → 83 → *Compressor 90%* → 75



Other electrolysis production pathway

Electricity production → 100 → *Transmission Distribution 92%* → 92 → *Electrolyzer 65%* → 60 → *Compressor 90%* → 54

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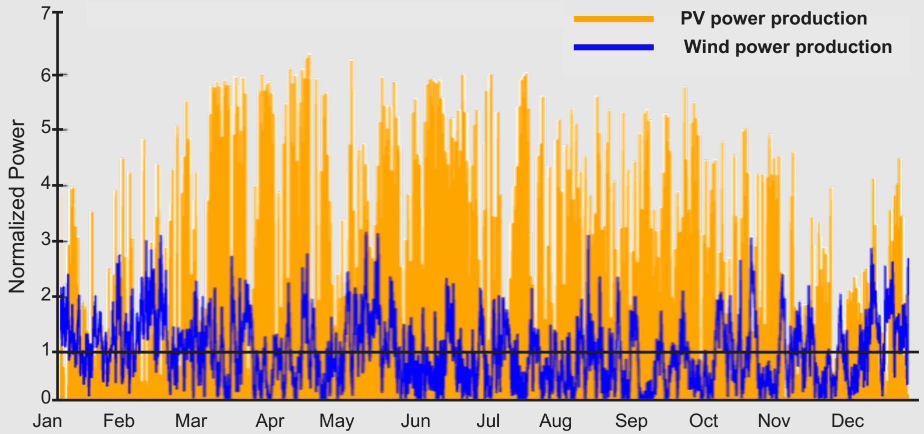
[1] Excluding the energy required for heat to vaporize water; [2] Preliminary results show that the power-to-hydrogen production efficiency of ~90% (LHV) can be achieved when coupling high temperature heat from the nuclear reactor.

Source: Zao et al., 2021, System level heat integration and efficiency analysis of hydrogen production process based on solid oxide electrolysis cells; Kearney Energy Transition Institute, 2020, “Hydrogen applications and business models” Factbook

Nuclear power is a dispatchable energy source that can compensate for renewables' variability and respond rapidly to changing loads in demand

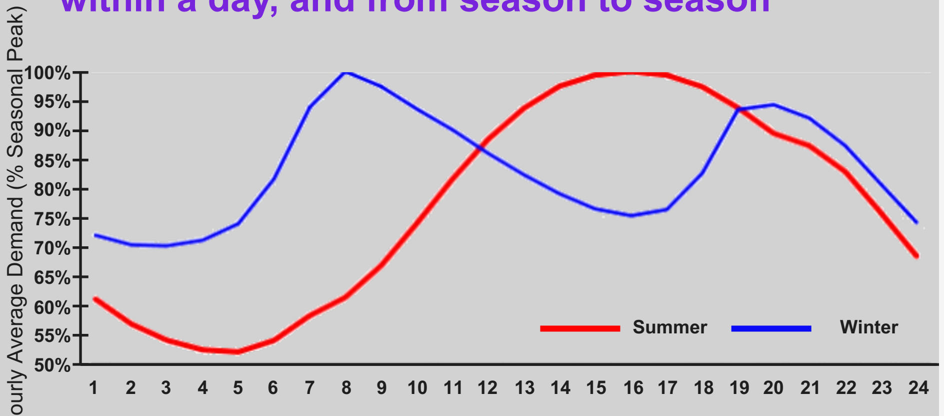
Pairing nuclear power (in particular with SMRs) with renewable generation drives renewable penetration while ensuring a robust, low-carbon energy mix.

Wind and solar power outputs are by nature variable and hard to accurately predict



Variability of wind and solar power production throughout the year in Switzerland, normalized by their respective annual mean values

Electricity demand fluctuates considerably within a day, and from season to season



Variability of the daily demand for Florida, US, in winter and summer

Nuclear power can cover the base load, compensate for renewables' output fluctuation, and respond swiftly (i.e., within minutes) to variations in the electricity demand

Several mechanisms make this possible:

- For immediate power regulation, steam can bypass the turbine with little effect on the reactor core, reducing the electrical output.
- To compensate for slower variations (for example, daily changes in solar generation), reactor power can be adjusted via the control rods.
- To accommodate seasonal variations, SMRs have the possibility to reduce production or redirect generation to desalinate or produce hydrogen. Additionally, maintenance and refueling can be planned and conducted during these periods.

Downsides of using nuclear reactors for supply regulation

- As all electricity generation forms, LCOE depends inversely on the capacity factor.
- The turbines are operated at less-than-optimal efficiency, although in an SMR with several smaller turbines the overall efficiency loss is reduced.

Sources: KAPSARC, 2022, Keeping the Nuclear Energy Option Open; IAEA, 2021, Technology Roadmap for SMR Deployment; NEA, 2011, Technical and economic aspects of load following with nuclear power plants; Kearney Energy Transition Institute analysis

4. SMR competitivity outlook

AGENGA

▶|

SMRs exhibit strong theoretical competitive edges over large reactors but it is yet to be proven if this will suffice to compensate for their scale disadvantages

Advantages and challenges. SMRs are expected to have several advantages compared to other electricity sources, such as low capex, modularity and reduced land footprint, among others. Despite these benefits, some challenges still need to be resolved including reducing the competing number of SMRs designs, adapting the nuclear fuel cycle or ensuring security and non-proliferation.

Economic competitiveness. SMRs lose the economies of scale that have led to the construction of larger nuclear power plants in the last decades. However, serial in shop manufacturing (instead of on-site construction) offers the possibility to compensate for this and render SMRs competitive, at least in comparison to alternative technological options for the specific applications they target, with higher reliability as to on time and on budget delivery.

Environmental benefits. SMR land use has large footprint variations, ranging from 1,100 m² up to 260,000 m². Water consumption is similar to other technologies such as coal power plants and could drastically be reduced depending on the reactor type. Carbon footprint of nuclear power is comparable to renewables in terms of range, and SMRs perform on average as traditional large nuclear reactors in terms of CO_2 equivalent emissions per MWh.

Comparison with large reactors. From a technological and non-technological point of view, SMRs’ have specific advantages such as lower upfront costs, enhanced safety with passive safety systems, flexibility or factory-based fabrication; and disadvantages or challenges, including reduced heat transformation efficiency, higher specific decommissioning costs and uncertainties around plant and back-end fuel expenses, waste production and management.

SMRs: the promise, key questions, and challenges

Expected advantages

Economics	– Lower upfront capital costs – Economy of serial production	→ *Better affordability*
Modularization	– Multi-module – Modular construction	→ *Shorter construction time*
Flexible applications	– Remote regions or small grids – Less dependent on existing grid – Non-electrical uses	→ *Wide range of users*
Smaller land footprint	– Reduced emergency planning zone (EPZ)	→ *Site flexibility*
Replacement of aging fossil-fired plants	– Limited carbon footprint – Responsive power	→ *Reduced CO_2 emissions*
Potential for hybrid energy systems	– Supplying flexible baseload – Ensuring system stability and reliability	→ *Integration with renewables*

Questions

Some unknowns remain :

- Will SMRs be subject to economics of multiples (technology learning) and compensate for the economics of scale of LRs?
- Will there be long-term government and policy support?
- How will public acceptance of nuclear energy evolve?
- Will there be ease of entry to emerging markets where demand pressures are highest and rapid capacity delivery is a bonus?

Challenges

Difficulties still need to be overcome:

- Too many designs competing for limited market entry
- Adaptation of HLW disposal and spent fuel management and disposal
- Multi-unit safety approach, ensuring individual modules continue operating safely in case of incident in the plant
- Security and safeguard due to the transportability and locations of SMRs

Sources: A. Shihab-Eldin, 2023, Progress on Small Modular (Nuclear) Reactors; C. McCombie, 2023, Will SMRs simplify or complicate solutions to waste disposal; Asia-Pacific Leadership Network, 2022, Small Modular Reactors: Addressing Security and Safeguards Challenges; Kearney Energy Transition Institute analysis

Assuming effective manufacturing development, SMR costs could reach that of large conventional reactors

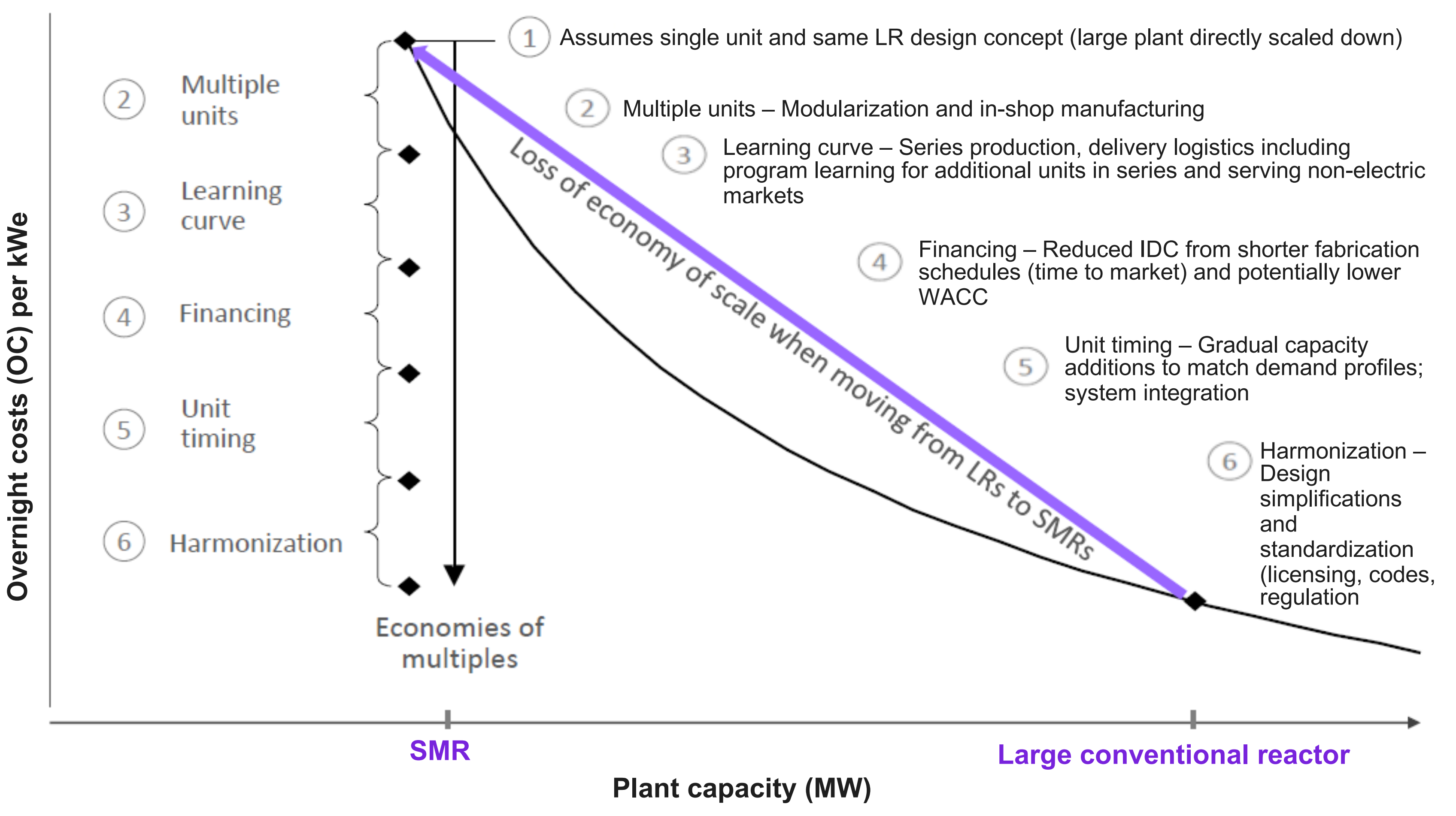
As an example, a 2,000 MWe capacity demand can be met:

- by two large reactors of 1,000 MWe each (implying 1 iteration)

OR

- by 10 SMRs of 200 Mwe each (implying 9 iterations, helping realize meaningful cost reductions faster)

Measures leading to SMR economic competitiveness to large conventional reactors



① Assumes single unit and same LR design concept (large plant directly scaled down)

② Multiple units – Modularization and in-shop manufacturing

③ Learning curve – Series production, delivery logistics including program learning for additional units in series and serving non-electric markets

④ Financing – Reduced IDC from shorter fabrication schedules (time to market) and potentially lower WACC

⑤ Unit timing – Gradual capacity additions to match demand profiles; system integration

⑥ Harmonization – Design simplifications and standardization (licensing, codes, regulation

Notes: IDC is interest during construction, OC is overnight costs, LRs is large reactors (1,000–1,700 MWe), WACC is weighted average cost of capital.
Sources: Adapted from IAEA, 2014 (H.H. Rogner) and NEA, 2022; Kearney Energy Transition Institute analysis

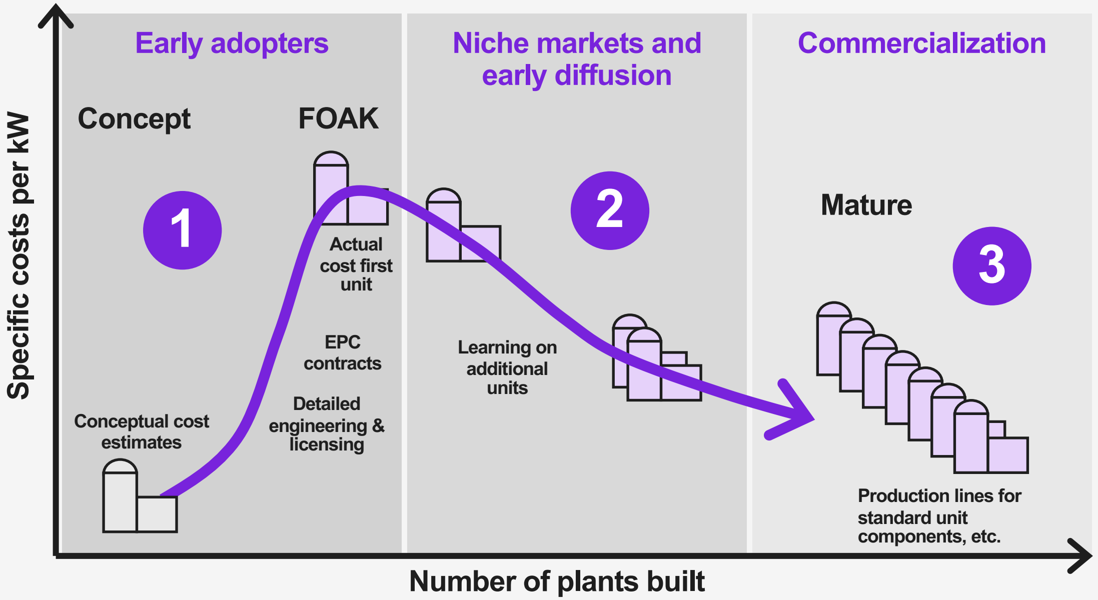
SMRs from first-of-a-kind economics to competitiveness; will SMRs be subject to economics of multiple and compensate for the loss of scale?

Learning dynamics are measured by indicators other than investment costs—product functionality, material intensity, reliability, among others. Not all investment costs are subject to learning effects and parts of it may even increase.

4.2 Economics

Economics to reach competitiveness

FOAK risks and dynamics



① FOAK are expected to be 20–30% more capital intensive than large reactors on a per kWe installed basis.

② There is market pull and technology push to overcome initial economic disadvantage.

③ Declining unit production costs directly link to the cumulative installed capacity.

SMRs have lower upfront cost per unit than large reactors

Potential benefits of lower capex

Lower capital per reactor
- Easier to mobilize investment
- Affordable to entities with lower levels of capitalization

Lower interest during construction
- Shorter manufacturing and delivery time

Reduce risk of unforeseen events
- Manufactured in-shop and then shipped for installation
- Higher product quality assurance

Mitigate demand uncertainty for investing entities
- Shorter time to market

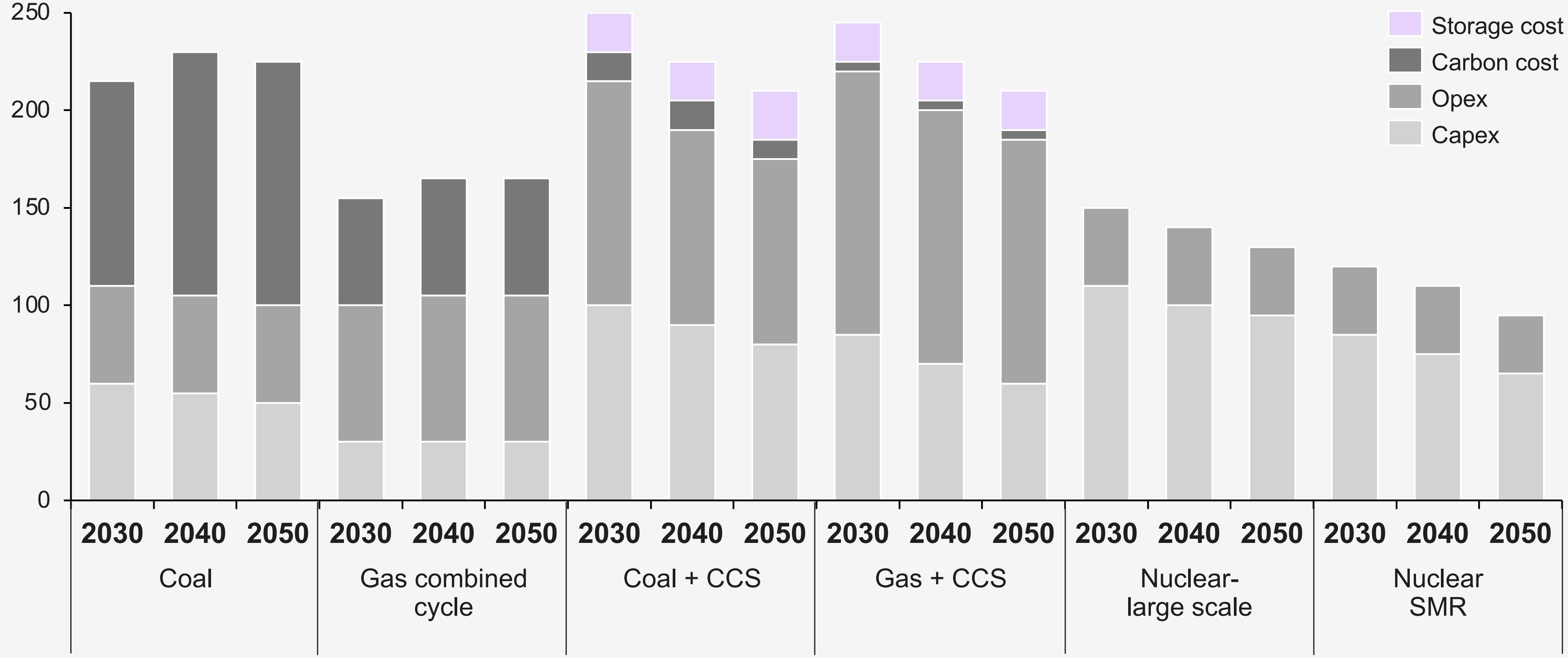
Sources: International Institute for Applied Systems Analysis (IIASA), H. Rogner, 2023, Is there an economic rationale for Small Modular Reactors (SMRs)?; Kearney Energy Transition Institute analysis

The economics of SMR are still unknown, one estimate predicts SMRs could be competitive with PWR nuclear, gas, and coal by 2030-2040 in some regions

4.2 Economics

Expected levelized cost of electricity (LCOE) for selected technologies

USD/MWh, average values for Europe



- Required capacity levels to allow gains from learning rates to kick in: at least 10 to 15 projects—between 3,000 and 4,500 MW of capacity for a standard 300 MW SMR—need to be under development between 2030 and 2040.
- Historically, emerging power generation technologies, such as solar and wind, have required 10 to 15 years, thousands of MW, and continued public policy support to achieve competitiveness.
- This analysis assumes carbon price for Europe of USD 140/tonne in 2030 and USD 177/tonne in 2050.

Sources: Woodmac, 2023, "The nuclear option: Making new nuclear power viable in the energy transition"; Kearney Energy Transition Institute analysis

SMR projects commissioned and some currently under construction are not commercial projects

Costs projections based on engineering approaches often ignore non-technical factors such as policy intervention.

4.2 Economics

SMR projects delays and costs increase

Impacted by covid-19 and other uncertainties

Russia and China

- The construction cost for the operating floating SMR in Russia increased six-fold from 6 billion rubles to 37 billion rubles.
- China's HTGR SMR's estimated construction cost is ~USD 5 billion / GW – about twice the initial cost estimates due to higher material, labor and component costs and project delays.

CAREM (Argentina)

- The project was initiated in 2014 but has witnessed multiple delays due to the breach of the construction contract by the national government, during the administration of Mauricio Macri.
- In November 2019, work was halted by contractor Techint Engineering & Construction due to late payments from the government, design changes, and late delivery of technical documentation.

NuScale (United States)

- The target price for power was pegged at 58 USD/MWh in mid-2021; is now estimated at 89 USD/MWh (53% higher).
- Estimated construction cost for the project has risen from USD 5.3 billion to USD 9.3 billion dollars (75% rise) which was attributed by the company to inflationary pressures for the costs of commodities, including steel, copper wiring, and electrical equipment, and uptick in the interest rate.
- Carbon Free Power Project (CFPP) in Utah was cancelled in November 2023 due to cost pressures.

Sources: Press search; Kearney Energy Transition Institute analysis

Nuclear energy, in general, performs similarly to renewables with respect to climate change and human well-being, and small modular reactors perform slightly better than their larger counterparts

Environmental impact per categories (average values)

per MWh of electricity produced, based on NuScale power LWR based design

Water depletion	**7.64 m^3**
Fossil depletion	**0.89 kg oil_{eq}**
Metal depletion	**2.03 kg Fe_{eq}**
Human toxicity	**18.02 kg 1,4-DB_{eq}**
Ionizing radiation	**441.07 kBq $235U_{eq}$**
Climate change	**4.55 kg CO_{2eq}**

Water depletion refers to the amount of water used for the different processes considered throughout the life cycle, whether or not the water is consumed (reported in m^3).

Fossil and metal depletion consider the metals and fossil resources extracted and consumed for the purpose of processes in the life cycle (reported in kg oil equivalent and kg iron equivalent).

The **human toxicity** impact category considers the adverse impacts to human health, which is caused by harmful chemicals or pollutants making their way into the human food chain (reported in kg 1,4-dichlorobenzene (DB) equivalents).

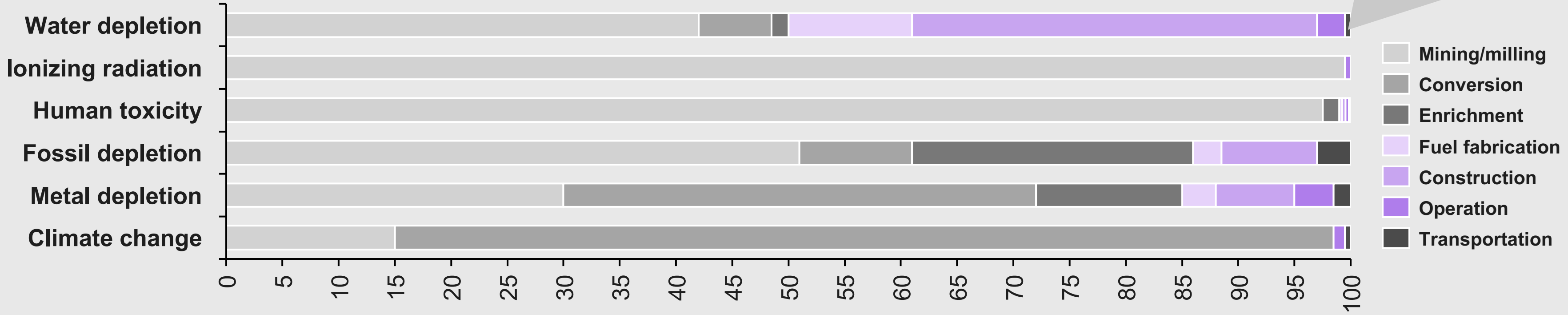
The **ionizing radiation** impact category considers the potential for human exposure to and health impacts from ionizing radiation from routine releases of radionuclides throughout the fuel cycle (reported in equivalents of exposure from an atmospheric release of 235U expressed in Becquerel (Bq) which is the number of atom nuclei that decay per second, 1kBq = a decay of 1000 nuclei per second).

The **climate change** impact category considers the adverse effects to the climate (reported in kg CO_2 equivalent).

Share distribution of impacts over the life cycle stages

for SMR

The majority (>95%) of climate change impact is due to processes in the front end of the fuel cycle.

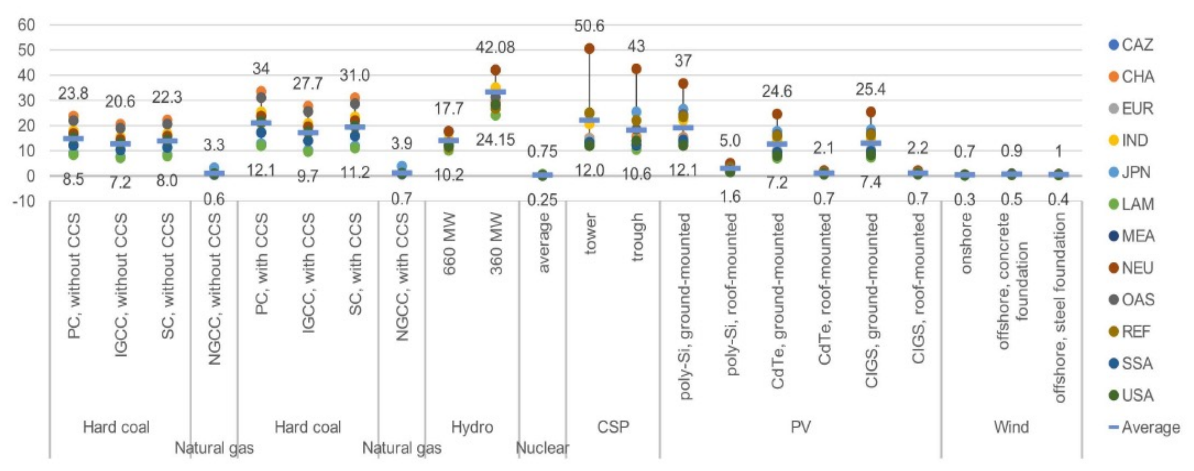


Sources: Godsey, 2019, Life Cycle Assessment of Small Modular Reactors Using US Nuclear Fuel Cycle; Kearney Energy Transition Institute analysis

SMR designs display a clear advantage over large reactors in terms of land and water use

Total land occupation (agricultural and urban)

in m²/MWh/y, 2020



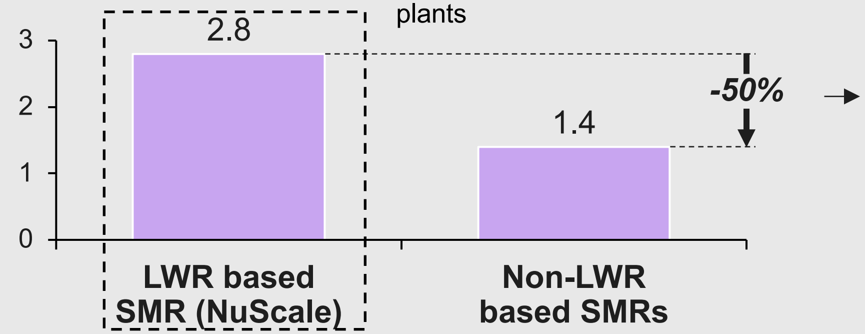
CAZ : Canada, Australia and New Zealand
CHA: China
EUR: Europe
IND: India
JPN: Japan
LAM: Latin America
MEA: Middle-East and Africa
NEU: Non-EU Europe
OAS: Other Asia
REF: Reforming Countries
SSA: Sub-Saharan Africa
USA: United States

- Land occupation (or use) includes both agricultural and urban land occupation, direct and indirect.
- Large footprint variations exist among SMR technologies, ranging from 1,100 m² up to 260,000 m².

Water consumption comparison

m^3/MWh

In the normal range of nuclear plants, coal fired plants, oil-fired plants, gas-fired plants, solar-thermal plants, and biofuel fired plants



Non LWR SMRs have outlet temperatures higher than conventional LWRs. As a result, the overall thermal efficiency is higher (generally between 40% and 50%). This also reduces associated water use for waste heat rejection by up to 50% on a per-unit-electricity-generated basis

- Dry cooling adoption has the potential to reduce by 95% water use (at the cost of a reduction in overall thermal efficiency).
- This feature is important for more arid locales.
- Water use for waste heat rejection is related to thermal efficiency of the SMR.

4.3 Environmental benefits

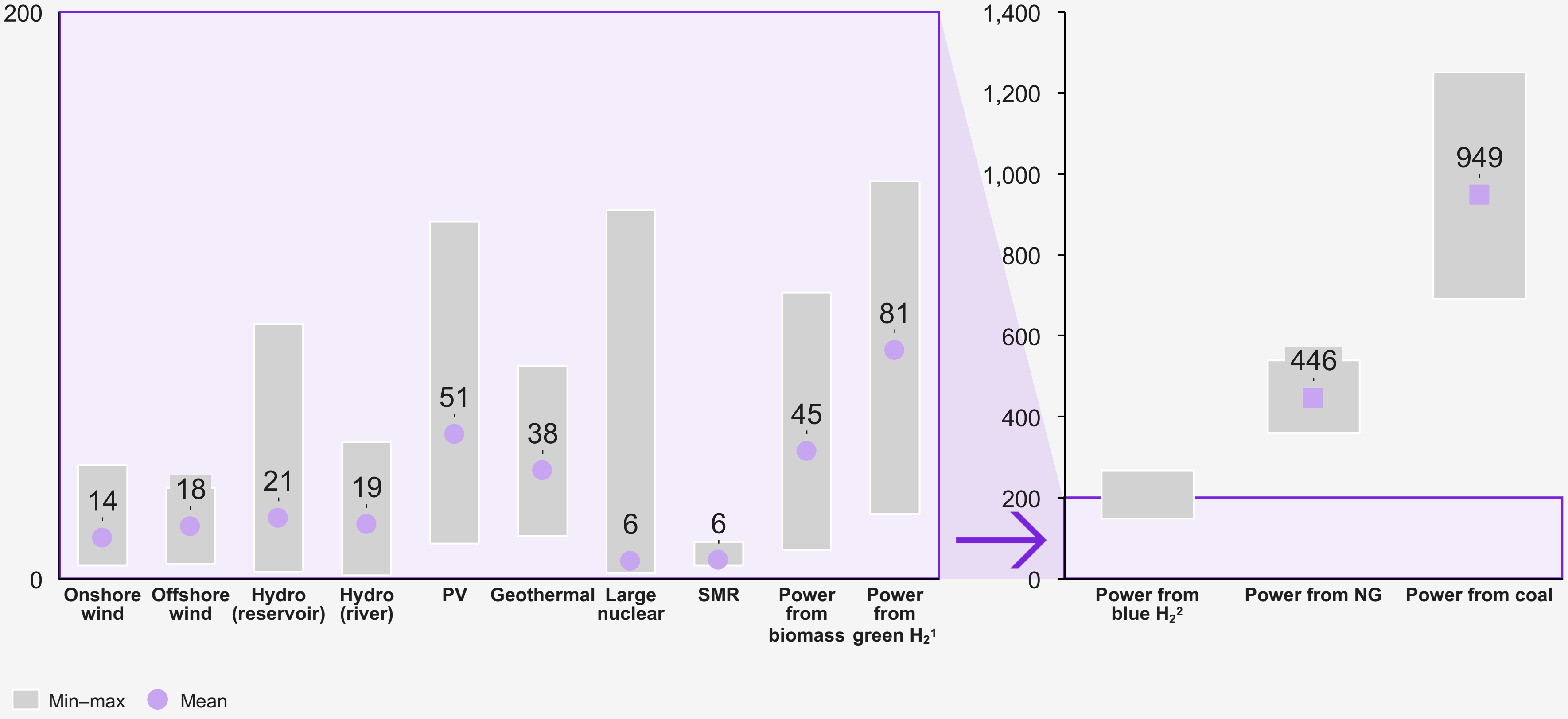
Sources: UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources; MIT, 2019, The Future of Nuclear Energy in a Carbon-Constrained World; NuScale, Kearney Energy Transition Institute analysis

Considering LCA results, nuclear, renewables and green H_2 have very low carbon footprints compared with fossil sources

SMR's average environmental impact falls in the lower range of traditional nuclear reactors

Electricity sources' carbon footprint review

Carbon footprint gCO_{2eq}/kWh



LCA results for various electricity sources show high variability in terms of related carbon footprint which could be considered when assessing other value chains embodying energy inputs.

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[1] Green hydrogen values based on electrolysis from wind electricity with an overall yield of the power to hydrogen to power value chain of 22.8%.

[2] Blue hydrogen values based on methane steam reforming with 93% carbon capture (with 0.2% fugitive methane emissions) with an overall yield of hydrogen to power value chain of 40.2%.

Sources: Ostfold, 2019, "Life cycle GHG emissions of renewable and nonrenewable electricity generation technologies"; WNA, 2011, Comparison of Life Cycle Greenhouse Gas Emissions of Various Electricity Generation Sources; ADEME, 2020, Rendement de la chaine hydrogène Cas du « power-to-h2-to-power », CertifHy Definition of Green Hydrogen, Blue Hydrogen GCCSI, Avril 2021; Godsey, 2019, Life Cycle Assessment of Small Modular Reactors Using U.S. Nuclear Fuel Cycle; Kearney Energy Transition Institute analysis

Compared to traditional large-scale nuclear reactors, SMRs bring a number of attributes that underpin their future commercial viability

Reduced investment risks are expected via smaller project size, modularization, off-site factory production, standardization of components/systems, and shorter construction and installation times.

4.4 Comparison with large nuclear reactors

1 Location flexibility and wider use

Suitable for installation:

- At the place of consumption, e.g., directly in small grids found in many developing countries
- In brownfields replacing coal generation
- At the industrial plants/parks for cogeneration with heat

No need for large amount of cooling water, therefore not limiting location to large water sources

2 Commercial efficiency

Potential low technology costs due to mass factory assembly in future

Expected low construction costs as SMR is only transported and installed

Low operation costs, e.g., innovative designs which require refueling once in 3-7 years (vs. conventional nuclear, every 1-2 years) and in some cases even 30 years

Low decommissioning costs due to ability to remove reactor module at the end of lifetime

3 Increased safety

Potential for underground or underwater locations for maximal protection from natural disasters

Reduced need for on-site radioactive inventory

Lower reliance on active safety systems (enhanced, often passive) due to small power as well as lower radioactive inventories

Reduced EPZ requirements due to enhanced safety features

Note: EPZ is emergency planning zone.
Sources: IAEA; World Nuclear Association; Kearney analysis

Studies remain inconclusive on SMR waste production and management issues with respect to large reactors; the few studies available have contrasting results

Non-exhaustive

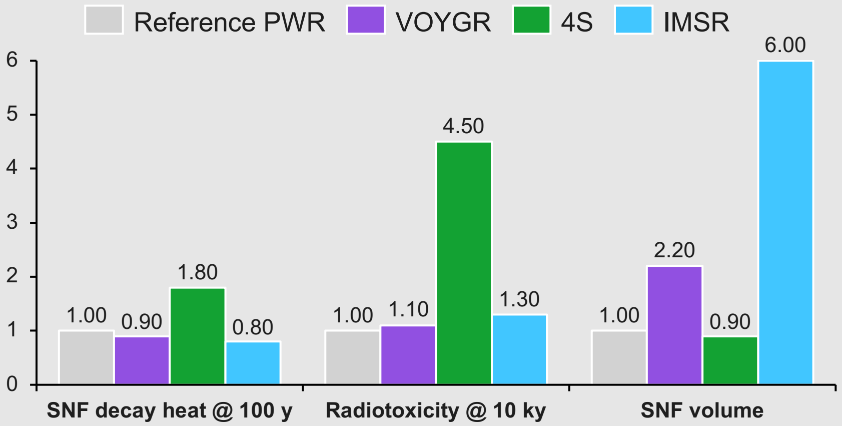
Comparison of waste characteristics from various SMRs and a large reactor

Decay heat intensity, radiochemistry of spent nuclear fuel, and SNF volume

Krall et al., 2022

Compared **SMR reactors**: NuScale's VOYGR (**iPWR**), Toshiba's 4S (**LMFR**), and Terrestrial Energy's IMSR (**MSR**).

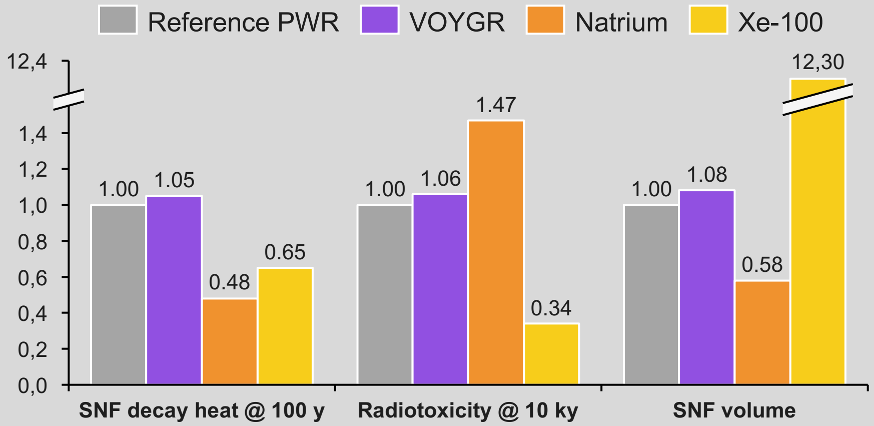
Reference PWR: Westinghouse's AP1000 (3,400 MWt)



Kim et al., 2022

Compared **SMR reactors**: NuScale's VOYGR (**iPWR**), TerraPower's Natrium (**LMFR**), and X-Energy's Xe-100 (**HTGR**).

Reference PWR: Unspecified (3,500 MWt)



Metrics are **normalized against a reference PWR large reactor;** they impact the management and disposal processes (affecting the size and performance of the disposal repositories).

Remarkably few studies have analyzed this issue; **further investigation is needed** with the input of manufacturers. The development of SMRs will require the **adaptation of existing** waste management and disposal **strategies** (in the case of LWR designs) **or novel approaches** (for more revolutionary reactors), especially if fuel reprocessing is foreseen.

Sources: L. Krall, A. Macfarlane and R. Ewing, 2022, Nuclear waste from small modular reactors; T.K. Kim, L. Boing, W. Halsey and B. Dixon, 2022, Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment; C. McCombie, 2023, Will SMRs simplify or complicate solutions to waste disposal; Kearney Energy Transition Institute analysis

SMR development can be bolstered by its inherent advantages over the large reactors

SMR advantages and disadvantages

	+ Advantages	Disadvantages −
Technology aspects	Design and operation simplicity	Licensability of FOAK designs
	Factory-based fabrication of full or good portion of SMR	Construction of FOAK designs
	Enhanced, often passive , safety aspects and reliability, including increasing feasibility of SNF take back	Advanced RD&D needs, especially for non-LWR technologies
	Long refueling cycles	Operability and maintainability (due to lack of experience)
	Integrability with intermittency and suitability for providing non-electric energy services (including hard to abate sectors)	Value chain adaptation needed to SMR (transport, treatment, storage, packaging and disposal)
	Suitable for smaller electricity grids	Supply chain for multi-module plant
	Higher prospects for technology learning	Smaller LWR designs are less efficient at burning fuel
Non-technology aspects	Lower upfront capital cost exposure	Economic competitiveness of FOAK designs
	Easier financing	Loss of economy of scale
	Lower exposure to future demand uncertainty	Large number of designs
	Site flexibility	Regulatory frameworks based on large reactors
	Reduced EPZ	Security issues due to the variety of users worldwide
	Better environmental footprints	Uncertainty around plant and back-end costs estimates
	Address markets/customers not serviceable by large reactors	Higher estimated decommissioning costs per kWe
	Shorter construction times	Social acceptance

Note: FOAK means first of a kind
Sources: A. Shihab Eldin, 2023, "What Role for Nuclear Power in Energy Transition: Framing Remarks"; Kearney Energy Transition Institute analysis

5. Status of SMR development

AGENGA

SMRs have recently seen much interest as their development is expected to play an important role in energy transitions as well as prove profitable for involved parties

State-of-the-art of SMR deployment. Around eighty SMR projects are currently under development in eighteen countries. Just two of them are in operation as of 2023 - one in Russia and one in China. Four are under construction (in China, Russia, the United States, and Argentina). Seventeen projects are in advanced instances (in final design phases, design ready, or undergoing the licensing process), and it is expected that the first commercial reactor will be operational by the end of this decade. The rest of the projects are still in early, conceptual stages. The United States is the country with the highest ambitions in terms of SMR development, followed by Russia, China, Japan, and Canada. There is a wide variety of reactor types (more than 10 different technologies), but just four of them—PWR, HTGR, LMFR, and MSR—make up over 80% of all projects. PWRs are the most developed technology, and they also have the greatest projections for future deployment.

Involved stakeholders. The SMR value chain includes several important players. Firstly, materials and technology providers, comprising nuclear fuel cycle companies, equipment and consumables suppliers. Secondly, SMR designers and engineering, procurement and construction (EPC) contractors that develop and execute projects. Finally, the operating organizations, technical support, and off-takers of the generated electricity and/or heat. Interacting with one or many of these parties are the investors (private funds or governments), regulating authorities, and the public, whose acceptance remains crucial for a project's smooth development.

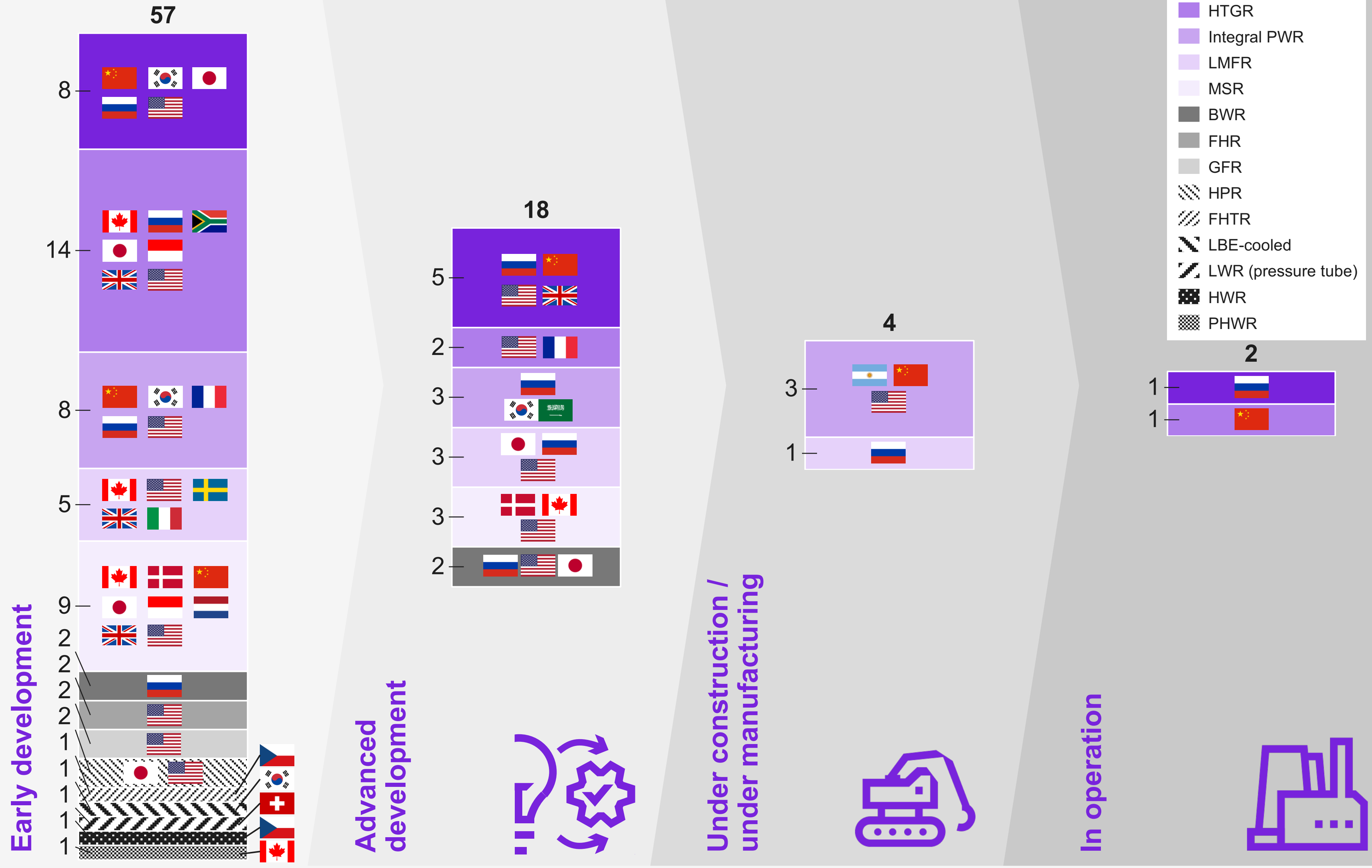
Business models. There are two types of SMR projects, those driven by private companies and those driven by a state-owned organization. Most reactors currently in development fall in the former category, although the only prototypes already in operation belong to the latter group. Government support remains key for either type.

SMR enablers. Several obstacles need to be tackled to enable SMR competitivity and widespread deployment, including the lack of government support in many countries, the lag in the regulatory system adaptation, the large variety of competing designs and the uncertainties around rentability, construction times and enhanced safety that stem from the newness of the technology.

Among existing SMR reactors and those in the pipeline, PWRs are the most developed ones at present, and they also have the greatest projections for the future

Early development covers all stages from preconceptual design to the completion of the preliminary design. Advanced development spans from detailed design to licensing and construction planning.

Number of SMR designs by stage of development



Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; Kearney Energy Transition Institute analysis

As of 2023, only China and Russia have operating SMRs, which supply electricity to the grid

	Shidao Bay 1
Model	HTR-PM
Reactor type	HTGR
Technology developer	INET, Tsinghua University
Output	210 MWe
Sitting	Land-based
First grid connection	14 December 2021
Electricity supplied since commissioning	86.4 GWh
Coolant	Helium
Moderator	Graphite
Fuel type	Spherical elements with coated particle fuel
Fuel enrichment	8.5%
Refueling cycle	Refueling in operation

	Akademik Lomonosov[1]
Model	KLT-40S
Reactor type	PWR
Technology developer	JSC Afrikantov OKBM
Output	2 x 35 MWe
Sitting	Marine-based
First grid connection	19 December 2019
Electricity supplied since commissioning	454.4 GWh
Coolant	Light water
Moderator	Light water
Fuel type	UO$_2$ pellet in *silumin*[2] matrix
Fuel enrichment	18.6%
Refueling cycle	30 – 36 months

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[1] The Akademik Lomomosov also supplies district heat to Pevek.

[2] Silumin is an alloy based on silicon and aluminum.

Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; IAEA, 2023, PRIS Database; Kearney Energy Transition Institute analysis

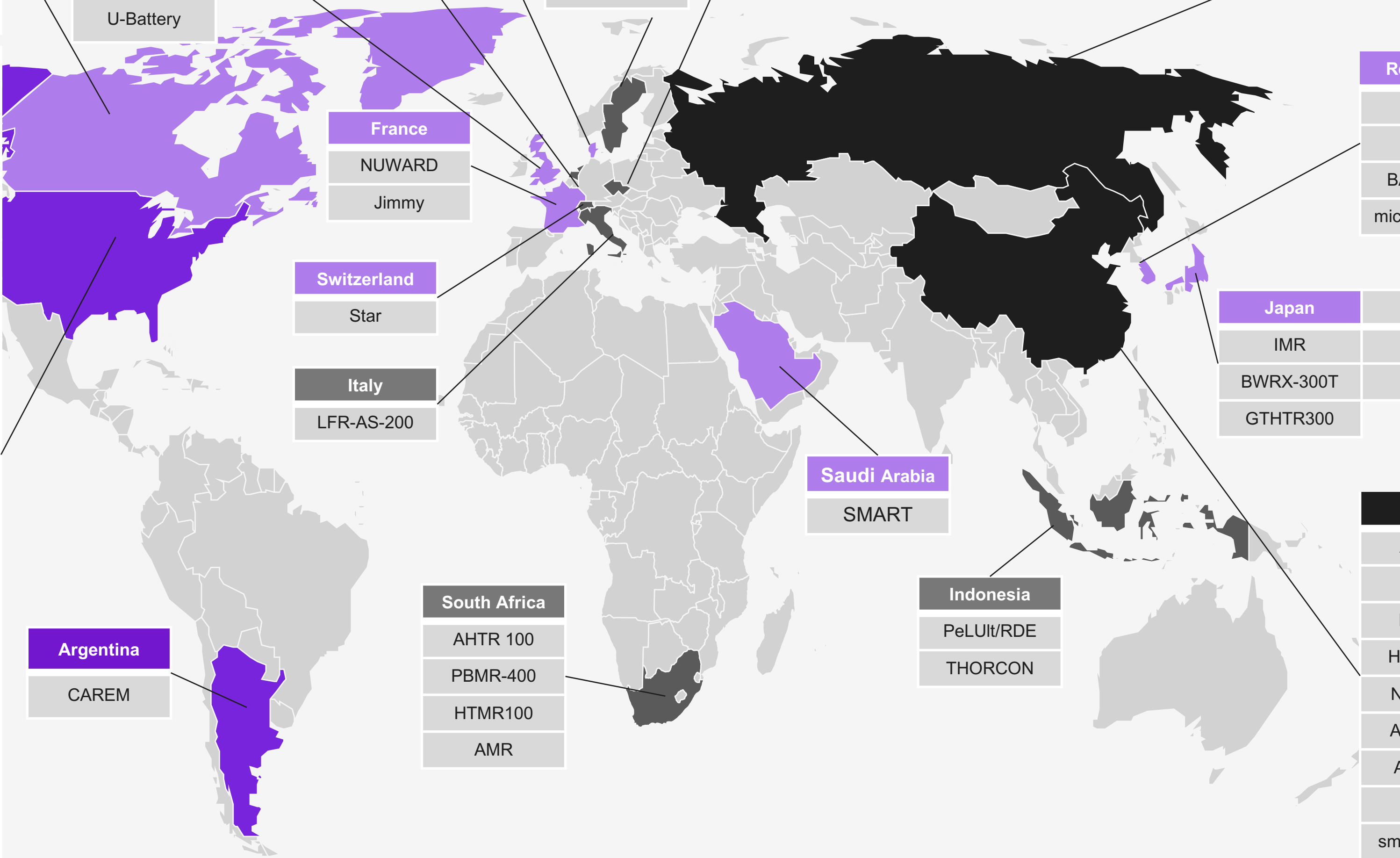
Eighteen countries are actively developing SMR prototypes today

Non-exhaustive

Other countries also have small reactors (<300 MWe) in operation, but they are not considered SMRs because they do not have all the defining features, namely modularity, enhanced safety systems, and being designed for factory assembly and transportation.

5.1 Overview of SMR projects

Status of the most advanced SMR projects in each country



Canada
- CANDU SMR
- ARC-100
- STARCORE
- IMSR400
- SSR-W

United Kingdom
- Rolls Royce SMR
- SSR-U
- LFR-TL-X
- U-Battery

Netherlands
- HORIZON

Denmark
- CA WB
- CMSR

Czechia
- TEPLATOR
- Energy Well

Sweden
- Sealer-55

Russia
- KARAT-100
- RITM-200M
- UNITHERM
- RITM-200
- RUTA-70
- VBER-300
- BREST-OD-300
- VK-300
- ABV-6E
- SHELF
- ELENA
- KARAT-45
- KLT-40S
- GT-MHR
- MHR-T
- MHR-100
- SVBR

United States
- VOYGR
- BWRX-300
- SMR-160
- mPower
- OPEN20
- FMR
- EM²
- Xe-100
- SC-HTGR
- KP-FHR (Hermes)
- MCFSR
- Natrium
- LFTR
- THORCON
- AURORA
- MMR
- eVinci
- MK1 PB-FHR
- Westinghouse SMR
- Westinghouse LFR

France
- NUWARD
- Jimmy

Switzerland
- Star

Italy
- LFR-AS-200

Rep. Korea
- i-SMR
- SMART
- BANDI-60X
- microURANUS

Japan
- 4S
- IMR
- FUJI
- BWRX-300T
- MoveluX
- GTHTR300

Saudi Arabia
- SMART

Argentina
- CAREM

South Africa
- AHTR 100
- PBMR-400
- HTMR100
- AMR

Indonesia
- PeLUIt/RDE
- THORCON

China
- ACP100
- CAP200
- DHR400
- HAPPY200
- NHR200-II
- ACPR 50S
- ACP100S
- HTR-PN
- smTMSR-400

■ In operation ■ Under construction / under manufacturing ■ Advanced development ■ Early development ■ No SMR projects

Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; Kearney Energy Transition Institute analysis

More than 90% of SMRs in development will be used mainly for electricity generation... (1/2)

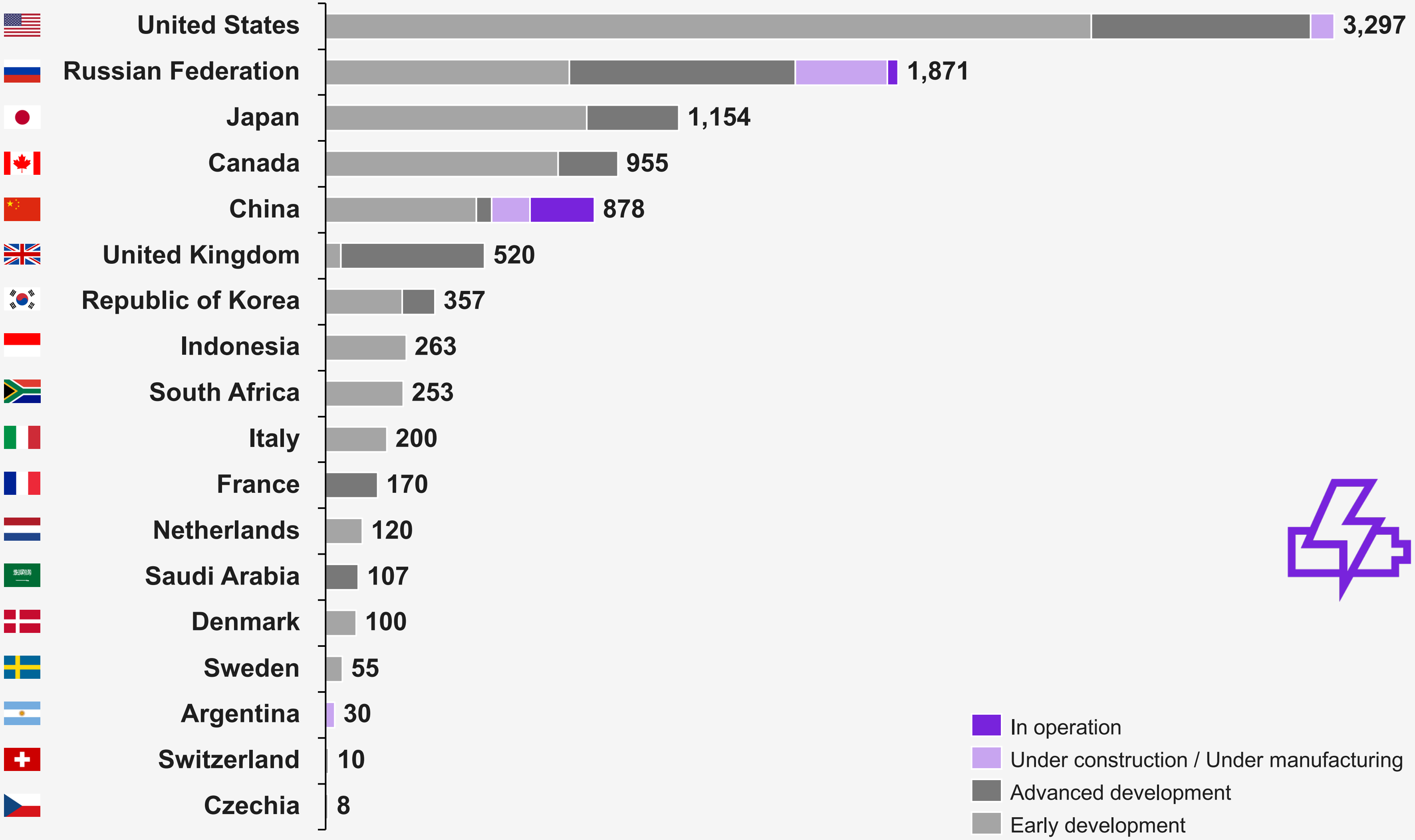
In the majority of countries, most SMR projects are still in early development stages, regardless of the reactor technology.

The United States is the country with the highest ambitions in terms of SMR development.

5.1 Overview of SMR projects

SMR projects by country and status

MWe, 2022



Note: Only first-of-a-kind prototypes and individual modules are considered.
Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; Kearney Energy Transition Institute analysis

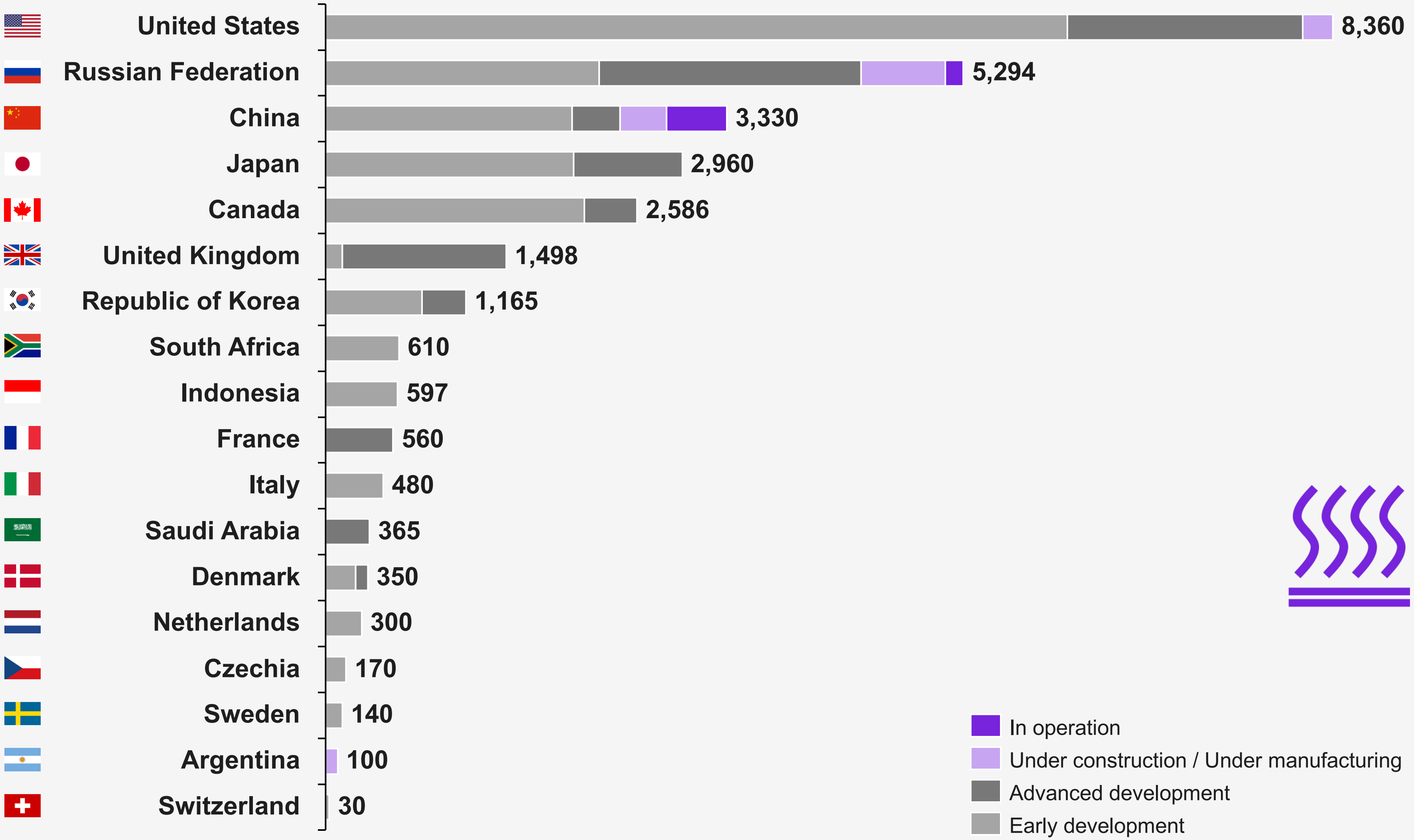
…however, some SMRs only have thermal (non-electrical) applications, and thus do not produce electricity (2/2)

Non-electrical SMR designs:
- DRH400 (China)
- HAPPY200 (China)
- NHR200-II (China)
- TEPLATOR (Czechia)
- RUTA-70 (Russian Federation)
- JIMMY (France)
- CAWB (Denmark)

5.1 Overview of SMR projects

SMR projects by country and status

MWt, 2022

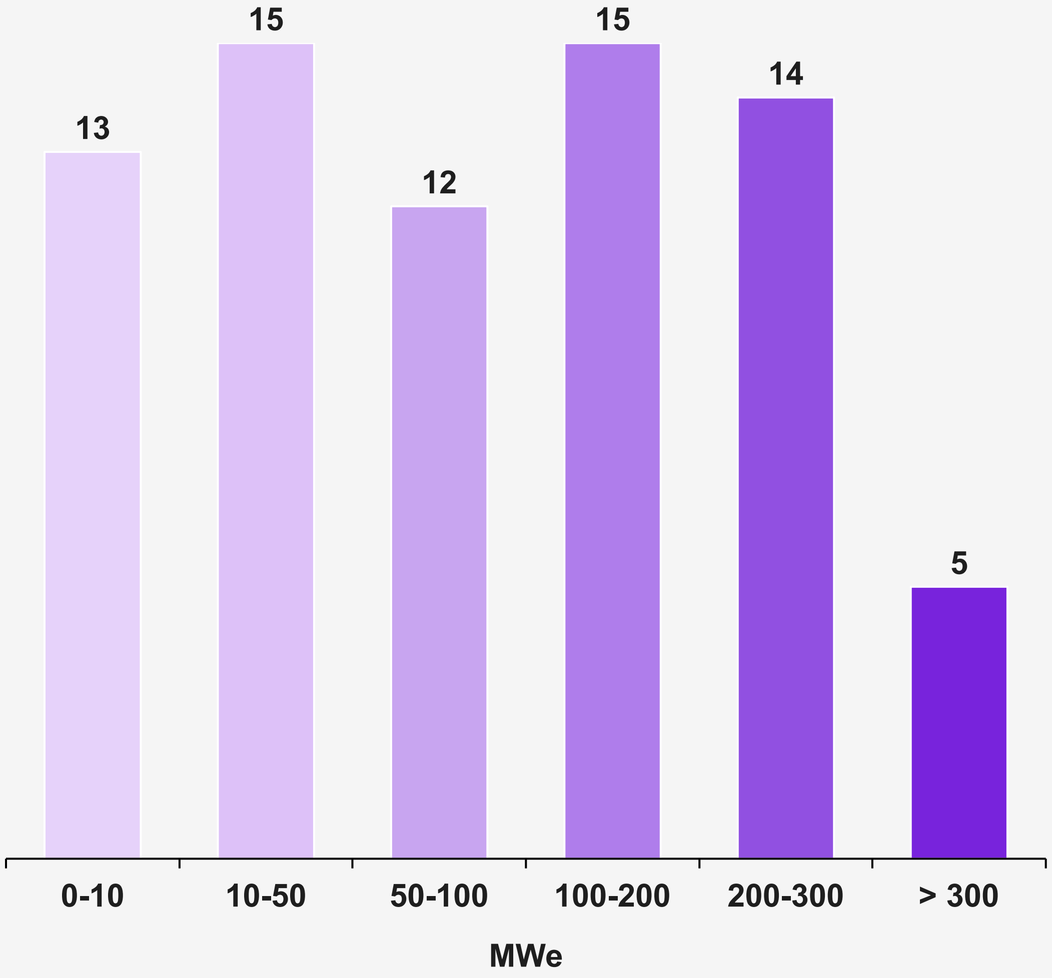


Note: Only first-of-a-kind prototypes and individual modules are considered.
Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; Kearney Energy Transition Institute analysis

SMRs in development have sizes ranging from a few kWe to 300 MWe, and some modules are even bigger

Histogram of electricity-generating SMR projects in development based on output

MWe



Source: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; Kearney Energy Transition Institute Analysis

There is a wide variety among reactor sizes, ranging from:

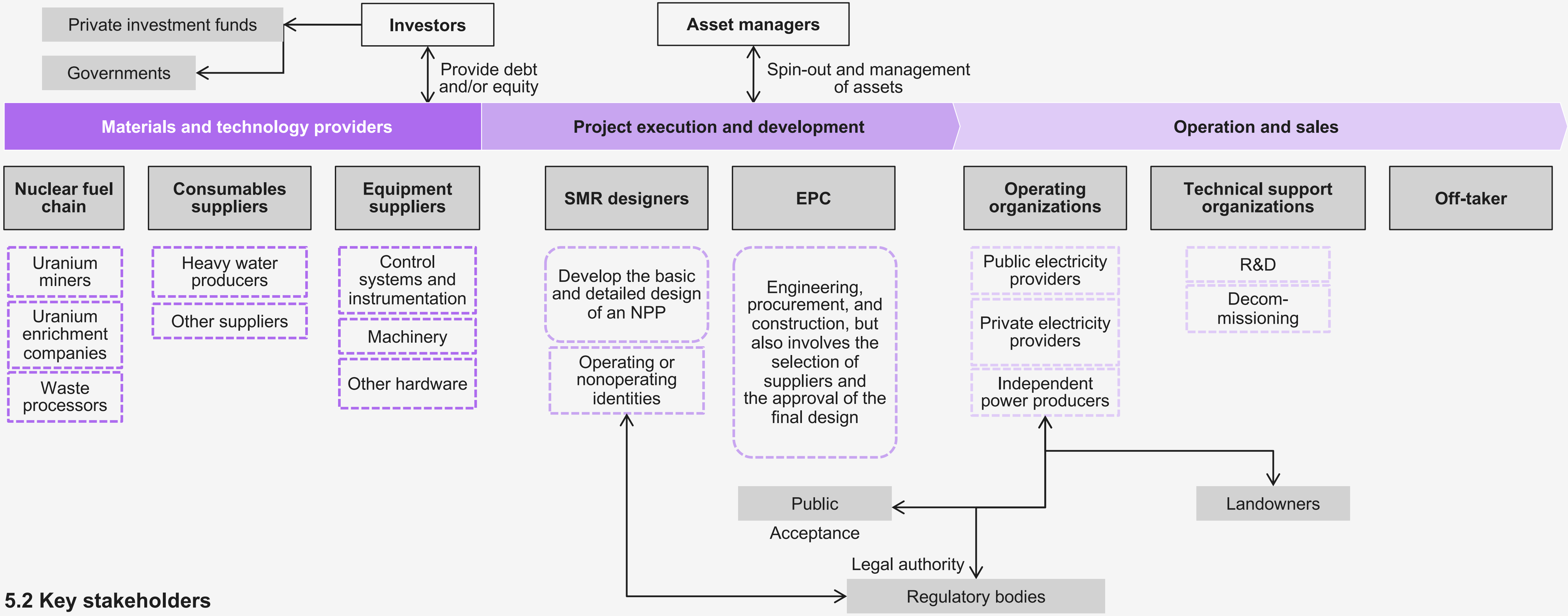
- Microreactors (<10 MWe)
- To medium-sized modules (>300 MWe) such as the Rolls Royce SMR (470 MWe)

Currently, no specific size segment is favored over the others, since they can all target different applications.

5.1 Overview of SMR projects

There are several important stakeholders who need to be considered when developing a nuclear power project, in particular an SMR (1/2)

SMR value chain



Private investment funds

Governments

Investors

Provide debt and/or equity

Asset managers

Spin-out and management of assets

Materials and technology providers

Project execution and development

Operation and sales

Nuclear fuel chain
- Uranium miners
- Uranium enrichment companies
- Waste processors

Consumables suppliers
- Heavy water producers
- Other suppliers

Equipment suppliers
- Control systems and instrumentation
- Machinery
- Other hardware

SMR designers
- Develop the basic and detailed design of an NPP
- Operating or nonoperating identities

EPC
- Engineering, procurement, and construction, but also involves the selection of suppliers and the approval of the final design

Operating organizations
- Public electricity providers
- Private electricity providers
- Independent power producers

Technical support organizations
- R&D
- Decommissioning

Off-taker

Public Acceptance

Landowners

Legal authority

Regulatory bodies

5.2 Key stakeholders

Sources: IAEA, 2021, Technology Roadmap for SMR Deployment; Kearney Energy Transition Institute analysis

There are several important stakeholders who need to be considered when developing a nuclear power project, in particular an SMR (2/2)

Overview of involved actors.

Stakeholders	Description
Designers	Are responsible for developing the **basic and detailed design** associated with an NPP, as well as maintaining design codes and methods and having specialized knowledge of all the systems and components important to **safety**
Operating organizations	(Including their contractors) undertake the **siting, construction, commissioning, operation, and maintenance** of a nuclear facility
Investors	**Finance a project** with the expectation of achieving a profit after a given period of time; can be private or public organizations.
Technical support organizations	Provide **in-depth assistance** to support nuclear power plant licensing, siting, design, construction, operations, and/or decommissioning activities
External suppliers and providers	**Involved** in the construction and/or operation of an NPP, be that as suppliers or as service providers
Regulatory bodies*	Authority, or system of authorities, designated by the government of a state as having the **legal authority** for developing the safety principles and criteria, **establishing the regulations,** and conducting the regulatory process (e.g. plant licensing and enforcing regulation)
Governments*	Have a role in facilitating the deployment of SMR technology by clearly specifying in **national policies** what it is hoping to achieve from this deployment, whether this is the decarbonization of electricity or heat production, grid stability in the presence of high shares of intermittent renewables, guaranteeing the power supply in remote areas, or promoting macroeconomic growth by developing a local industry
Public*	Their **acceptance** of nuclear power continues to be one of the most important elements in establishing a credible nuclear power program

*discussed in section 6

Sources: IAEA, 2021, Technology Roadmap for SMR Deployment; Kearney Energy Transition Institute analysis

5.2 Key stakeholders

Designers, operating organizations, and investors are at the core of an SMR enterprise’s buildout

Non-exhaustive

SMR designers

Nonoperating entity	They must demonstrate the **ability to build the reactor** plant that it has designed **on time and within budget**. They can emphasize the design features that differentiate SMRs from a large NPP, and in which situations these might be an attractive option for operating organizations and governments.	НИКИЭТ OKBM AFRIKANTOV ROLLS ROYCE SMR NUSCALE Westinghouse Candu
Operating entity (BOO scheme)	They receive a contract to **finance, design, construct, and operate** an NPP.	中核集团 CNNC EDF JAEA

Operating organizations

Public electricity company	**State-owned** electricity providers that are already operating or will soon operate SMRs.	ROSENERGOATOM ROSATOM EDF ONTARIO POWER GENERATION CHINA HUANENG
Private electricity company	**Privately-owned** electricity providers that will potentially operate SMRs in the near future.	Xcel Energy Constellation GS Energy
Independent power producer	**Industries** that would use an SMR to meet their electricity demand, or for non-electrical applications.	KGHM POLSKA MIEDŹ NOVA POWER AND GAS

Investors

Private investment funds	Nuclear projects are **capital intensive** and historically have exposed investors to significant schedule risks, which in turn amount to long-term cost escalations and investor disappointment. Perhaps one of the most significant aspects of **SMR** technology is the **promise of shorter construction periods and lower upfront capital investment.**	FLUOR JGC DOOSAN Enerbility GS Energy ROLLS ROYCE QIA QATAR INVESTMENT AUTHORITY
Governments	Their financial support is key to **boost the SMR development in its early stages**. Additionally, they could invest on SMRs for the electricity supply of off-grid regions.	GOUVERNEMENT Liberté Égalité Fraternité Government of Canada Gouvernement du Canada UK RI Innovate UK U.S. DEPARTMENT OF ENERGY

Note: BOO is build – own – operate.
Sources: IAEA, 2021, Technology Roadmap for SMR Deployment; Companies’ websites; IAEA, 2018, Technical Support to NPPs and Programs; Kearney Energy Transition Institute analysis

5.2 Key stakeholders

External suppliers, providers, and consultants contribute know-how and resources all along the value chain

Non-exhaustive

External suppliers and providers

Uranium miners	**Mining companies** operating in the countries with the greatest uranium reserves. They also carry out the industrial process for **producing uranium oxide** from the mined uranium ore.	orano KAZATOMPROM Cameco RioTinto BHP ROSATOM 中核集团 CNNC urenco
Uranium enrichment companies	For most reactors, uranium must be **enriched in the fissile isotope U-235**, whose natural abundance is 0.7%, in a **complex** process that requires uranium to be in a gaseous form.	TENEX ROSATOM urenco 中核集团 CNNC Centrus orano
Heavy water producers	Heavy water (D_2O) is an **important supply** for some nuclear reactor types (PHWR) that need it because they use **natural uranium.**	HWB ISOWATER
Waste disposers	Nuclear waste must be processed to make it **safe for disposal**. This includes its collection and sorting; reducing its volume and changing its chemical and physical composition; and finally, its conditioning so it is immobilized and packaged for storage. Waste disposal can become a key challenge if there is no “take-back” or multinational disposal, especially for newcomer countries.	EnergySolutions NUKEM Technologies GNS
Equipment suppliers	They provide a wide range of **equipment and components**, including turbines, generators, control systems, instrumentation, pumps, and other hardware.	TOSHIBA MITSUBISHI HEAVY INDUSTRIES framatome BWXT
EPC contractors	They plan and execute all engineering, procurement, and construction activities needed to complete a capital project, including the selection of suppliers and the approval of the final design.	ansaldo energia OMEXOM NUVIA NUSCALE TSM ENERJİ

Technical support organizations

R&D	They intervene mainly in the **design phase**, reviewing engineering documents and proposing changes to improve **efficiency, safety, and rentability.**	НИКИЭТ IRSN Westinghouse GE HITACHI
Decommissioning	They assist the decisions on establishing and following national **decommissioning policies and strategies.**	NDA orano Magnox Sellafield Ltd

Note: no commercial SMR project is advanced enough for all these contractors to have been solicited yet; in such cases leading companies in the nuclear sector are listed.
Sources: IAEA, 2021, Technology Roadmap for SMR Deployment; Companies' websites; IAEA, 2018, Technical Support to NPPs and Programs; Kearney Energy Transition Institute analysis

Current SMR business development models are classified into two groups according to the nature of the undertaking company

Private sector driven projects

- In countries such as the United States, the United Kingdom, Canada, and Japan, SMR development is spearheaded by private companies that aim to commercialize their designs.
- The governments contribute with incentives like grants to support the early stages of projects when gathering private funds can be challenging because of the risks and uncertainties.

Leading examples

VOYGR™

Rolls Royce SMR

Candu

+ 40 projects

+ $3 billion in government funding

First reactors to be operational by the end of this decade

Public sector driven projects

- In countries such as China, Russia, France, and Argentina, SMRs are currently developed by state-owned organizations; some projects are considered for commercializing, while others will serve a particular purpose in the country's nuclear fleet.

Leading examples

CAREM25

nuward EDF GROUP

+ 25 projects

+ $1 billion invested by governments

Two reactors already in operation

Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; companies' websites; Kearney Energy Transition Institute analysis

5.3 Business development

NuScale is working on commercial SMR development, and has advanced projects in the United States, Eastern Europe, and Asia

Example of a private sector driven project : NuScale's VOYGR

- The first NuScale SMRs, the VOYGR design are expected to be commissioned in **2029.**
- Their business plan consists of **delivering turnkey projects** and **providing plant services** (fulfilling the roles of **designer, EPC,** and **technical support** companies).
- Each module, including the containment vessel, can be **entirely fabricated in a factory** and **shipped** by **rail, truck, or barge** to the power plant site for assembly and installation.
- The modules can be **fabricated in parallel with the site preparation and civil engineering works.**
- NuScale **does not have manufacturing assets** and relies on third-party manufacturers to build its modules and associated equipment.

VOYGR SMR	
Thermal capacity (MWt)	250
Electrical capacity (MWe)	77
Design life (years)	60
Fuel enrichment (%)	< 4.95

Advanced projects

Carbon Free Power Project

- VOYGR-6 plant (462 MWe)

Cancelled in November 2023 because of insufficient economic attractiveness and/or customer adoption

S.N. Nuclearelectrica

- VOYGR-6 plant (462 MWe)
- Operational by 2030
- Application: replacement and repurposing of coal plant sites

KGHM Polska Miedź

- VOYGR-6 plant (462 MWe)
- Operational by 2029
- Application: repurposing of coal plant sites and electricity supply to industrial users

GS Energy

- VOYGR-6 plant (462 MWe)
- Operational by 2030
- Application: electricity supply to a hydrogen production complex

Potential projects (only MOU signed)

- Dairyland Power Cooperative (Wisconsin, US)
- Associated Electric Cooperative (Missouri, US)
- Nucor (North Carolina, US)
- Prodigy Marine Power Station (Quebec, Canada)
- Indonesia Power (Indonesia)
- Kazakhstan Nuclear Power Plant (Kazakhstan)
- Kozloduy Power Plant (Bulgaria)
- ČEZ Group (Czechia)
- Energoatom (Ukraine)
- Getka and UNIMOT (Poland)
- Jordan Atomic Energy Commission (Jordan)

VOYGR SMR design has already been approved by the US NRC, and licensing applications have also been submitted to the Romanian, Polish, and South Korean nuclear authorities.

NUSCALE™
Power for all humankind

5.3 Business development

Sources: NuScale Power's website; companies' websites; WNN, 2023, KGHM seeks approval for SMR project; NEI Magazine, 2022, Two Polish companies apply for regulator's opinion on SMR technology assessment; Kearney Energy Transition Institute analysis

NUWARD aims to position itself as a pan-European SMR solution on the back of a pioneering European early joint regulatory review

Non-Exhaustive

NUWARD SMR is being developed with a fast and efficient build process with an estimated plant construction period of 40 months.

5.3 Business development

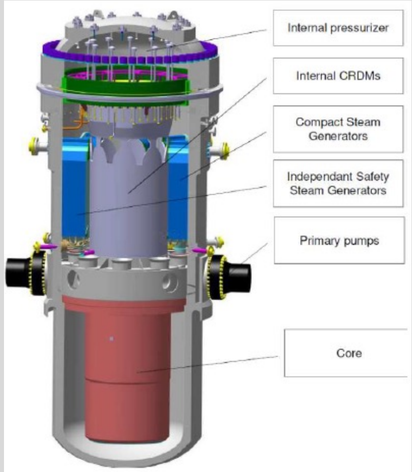
Example of a public sector driven project : EDF's NUWARD

- In 2023, EDF created a wholly owned subsidiary NUWARD to focus on developing NUWARD SMR technology.
- NUWARD SMR has been developed through the contributions of strategic partners:
  - **EDF and Edvance:** Design activities, safety studies, dedicated expertise and research, business development activities
  - **CEA:** providing core nuclear design expertise, research and testing facilities
  - **TechnicAtome and Framatome:** Nuclear Steam Supply System (NSSS) and fuel design, safety studies, and safety case
  - **Naval Group:** Design of the steel containment, industrialization of the compact steam generator, studies on modularity.
  - **Tractebel:** Studies on conventional island (CI) and balance of plant (BOP), including systems, safety and site-specific studies.

NUWARD	
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity (MWt/MWe)	2 x 540 / 2 x 170
Fuel type/assembly array	UO2 pellets / 17x17 square pitch arrangement
Fuel enrichment (%)	<5
Refueling cycle (months)	24 (half core)
Design life (years)	60
Plant footprint (m²)	3,500

Proposed design and timelines

- **2023:** Start of basic design and safety option file (DOS) submission
- **2025:** Start of commercialization
- **2026:** Start of detailed design and formal application for a new nuclear facility
- **2030:** First concrete in France



Key developments

- The **Autorité de Sûreté Nucléaire (ASN), Radiation and Nuclear Safety Authority (STUK), and State Office for Nuclear Safety (SUJB)**—the nuclear safety authorities in France, Finland, and the Czechia
- , respectively—are collaborating on the pre-licensing review of the NUWARD reactor design.
- The French government has provided more **than EUR 500 million (USD 592 million)** in funding for NUWARD development.
- EDF owns 18 licensed nuclear sites in France that could be suitable for the NUWARD FOAK. In addition, EDF has signed a cooperation agreement with Respect Energy to conduct siting studies for NUWARD in Poland.

Sources: Nuward; IAEA's Advanced Reactors Information System (ARIS); OECD, 2023, The NEA Small Modular Reactor Dashboard; Kearney Energy Transition Institute analysis

To enable SMR deployment and competitivity, several improvement areas need to be addressed

Key improvement areas of SMR deployment and competitivity

Boosting political, financial, regulatory, and organizational **support from governments** for first-of-a-kind SMRs.

Improving the international **regulatory system** and enhancing licensing and oversight while building public and political support.

Narrowing down the number of **potential designs** enough to ensure sufficient market demand to allow factory production methods to be employed and justify large scale investments.

Proving via **technology learning** and **economies of multiples** that SMRs can have competitive capital costs per MW and production costs per kWh. This implies the availability of SMR fabrication centers.

Ensuring **short construction times** (taking about 60% less time than today's FOAK reactors), to lower financial risk and lead to affordable schemes.

Demonstrating that the designs being developed effectively offer **enhanced safety.**

5.4 SMR enablers

Sources: Nuclear Engineering International Magazine, 2022, SMRs: what are the barriers to deployment?; Kearney Energy Transition Institute analysis

6. Regulatory landscape

AGENGA

The future success of SMR development is highly dependent on the adaptation of the regulatory framework

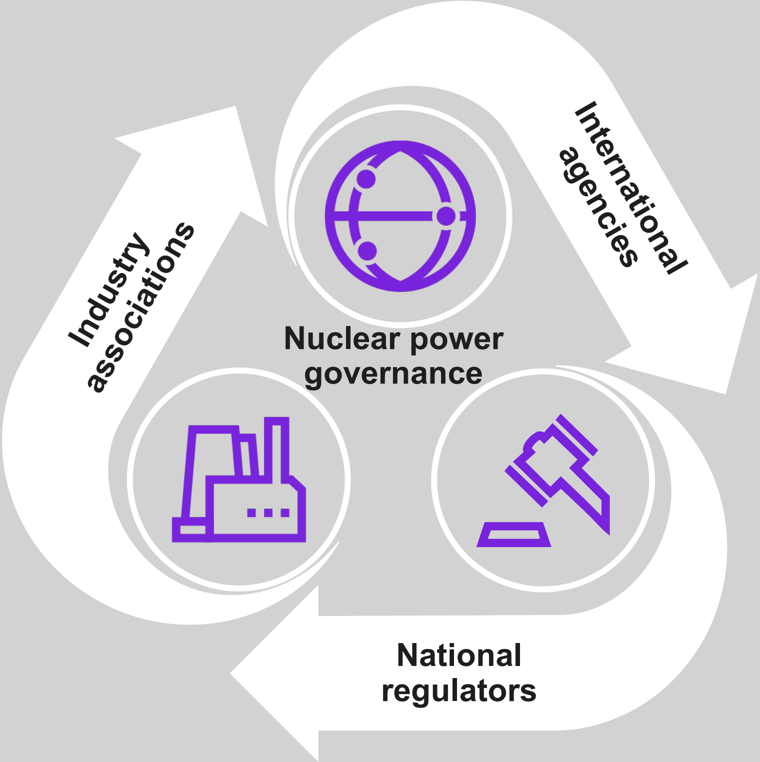
Regulatory framework and agencies. There are international and multilateral bodies that provide guidelines and recommendations to national organizations, which are ultimately responsible for licensing processes in their respective countries. The most prominent of these organizations is the International Atomic Energy Agency (IAEA), whose mission is to identify, understand, and address regulatory challenges that may arise in future SMR regulatory discussions. Other multilateral organizations bring together national regulatory agencies with the objective of sharing good practices and experiences, and of attempting to harmonize regulations.

Bilateral and multilateral developments. A joint early review has been done between the safety agencies from Finland, Czechia and France, with the view of providing timely feedback at early-stages of the NUWARD SMR basic design. These review provided useful insights on each other's regulatory approaches and the opportunity to consider evolutions of national regulations. In Europe, resurgence of nuclear interest has motivated the creation of a European nuclear energy alliance. This alliance aims to push the nuclear agenda as part of the decarbonization strategy by 2050 and foster collaboration among members.

Country level developments. Important SMR-related developments have recently taken place in the United States, UK, France, and Canada, including the approval of the first commercial SMR design by the US NRC in 2020 and the signing of the Inflation Reduction Act, which includes several incentives for nuclear power.

International organizations and industrial associations play a key role in the regulation of nuclear energy, despite it being the responsibility of each country

Main stakeholders in nuclear energy and technology regulation



Nuclear regulatory frameworks and policies are the domain of national governments.

Source: Kearney Energy Transition Institute analysis

International and multilateral agencies

Description: Organizations established through international agreements or treaties that focus on nuclear energy-related issues

Functions: Setting global standards, providing technical expertise, and facilitating cooperation among nations

IAEA International Atomic Energy Agency · NEA Nuclear Energy Agency · EURATOM · ENSREG European Nuclear Safety Regulators Group

Regional/national regulators

Description: Governmental body responsible for overseeing and regulating the nuclear industry within a specific region or country

Functions: Entities responsible for overseeing the safe, secure, and compliant operation of nuclear power plants within their jurisdictions

United States Nuclear Regulatory Commission · asn · ONR Office for Nuclear Regulation · Western European WENRA Nuclear Regulators' Association · 中核集团 CNNC

Industry associations

Description: Collective organization that represents the interests of companies, organizations, and professionals operating within the nuclear power sector

Functions: Advocate for industry interests, facilitate information exchange, provide technical expertise, foster collaboration, and engage in public outreach

World Nuclear Association · NEI Nuclear Energy Institute · ENS European Nuclear Society

6.1 Regulatory institutions

International organizations provide guidelines and programs that promote the development of regulatory frameworks in countries that are involved with nuclear technologies[1]

	Safety standards	Security guidelines	Nuclear safeguards	Technical cooperation programs	Emergency preparedness and response	Policy analysis and advice	Data collection and analysis	Technology developments
Description	– Guidelines on the **safe design, construction, operation, and decommissioning** of nuclear facilities	– Guidelines and recommendations to enhance the **security of nuclear materials, facilities, and information**	– Safeguards to **verify the peaceful use of nuclear energy** and prevent the proliferation of nuclear weapons	– Sharing **nuclear technology to address key development priorities** in nuclear knowledge management	– Guidance and support in **emergency preparedness and response** to nuclear and radiological incidents	– Collection, analysis, and dissemination of nuclear energy data and information to support evidence-based decision-making	– Comprehensive understanding of various aspects of nuclear energy, including its safety, performance, economics, waste management, and emerging technologies	– Technology development in advanced reactor systems, nuclear fuel cycle, materials, and innovative concepts to advance nuclear energy and improve safety and performance
Key modules	– General safety recommendations – Site evaluation – Design – Construction – Commissioning – Operation – Preparation for decommissioning	– Basis for nuclear security systems and measures for nuclear materials – Detection systems and measures – Response systems and measures	– Legal and regulatory framework – State System of Accounting for and Control of Nuclear Material (SSAC) – Nuclear material measurements – Safeguards implementation and inspection	– Water and environment – Industrial applications – Nuclear knowledge development and management – Nuclear techniques for health and nutrition, and food and agriculture	– Incident and emergency communication – Response and assistance – Fundamentals and planning – Emergency preparedness and medical response (EPR) – Communication in emergencies	– Nuclear energy policy – Safety and regulation – Waste management	– Energy data collection – Waste and spent fuel data – Economics and cost data – Capacity building in energy system analysis – Capacity planning regarding the role of nuclear energy[2]	– Advanced reactor systems – Nuclear fuel cycle – Materials and technologies

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[1] International organizations also provide guidelines to countries with naturally occurring radioactive materials (NORMs).

[2] Except for *waste and spent fuel data*, these items have little 'regulatory' relevance

Sources: IAEA; World Nuclear Association; NEA; Euratom; Kearney Energy Transition Institute analysis

The IAEA is widely recognized as the leading intergovernmental organization in the field of nuclear energy and technology due to its expertise, global reach, and significant impact on development

⬚ Leading international agency ⬚ Leading industry association

	IAEA International Atomic Energy Agency	NEA Nuclear Energy Agency	EURATOM	WORLD NUCLEAR ASSOCIATION
Mission	Promote the peaceful use of nuclear energy, prevent the proliferation of nuclear weapons, enhance nuclear safety and security, and facilitate the transfer of nuclear technology for peaceful purposes. IAEA also provides assistance to countries that are considering or planning their first nuclear power plant through the Milestone approach.	Promote safe, efficient, and sustainable use of nuclear energy through policy analysis, data collection, and technology development.	Ensure the secure and safe use of nuclear energy, promote nuclear safety and research, and support the development of secure nuclear technologies within the EU.	Advocate for the peaceful and sustainable use of nuclear energy, provide industry leadership, facilitate market development, promote accurate information, and support sustainable development.
Foundation	1957	1958	1957	1975
Members	176 nations	34 nations	27 nations	181 companies

Main guidelines and programs of nuclear power

	IAEA	NEA	EURATOM	WORLD NUCLEAR ASSOCIATION
Safety standards	4	1	3	3
Security guidelines	4	1	3	3
Safeguards	4	0	2	0
Fuel Cycle	4	3	3	2
Nuclear programs assistance	4	2	3	1
Technical cooperation	3	2	4	3
Emergency response	3	2	3	4
Policy analysis and advice	2	4	3	3
Data collection and analysis	2	4	1	4
Technology development	1	4	0	2

Note: 1. IAEA
Sources: IAEA; World Nuclear Association; NEA; Euratom; Kearney Energy Transition Institute analysis

4 Fully developed & constantly updated; **3** Fully developed; **2** Partially developed; **1** Generic characterization; **0** Not covered

According to the IAEA, the area of internationally harmonized regulation and licensing is among the most significant challenges for SMRs' success[1] (1/2)

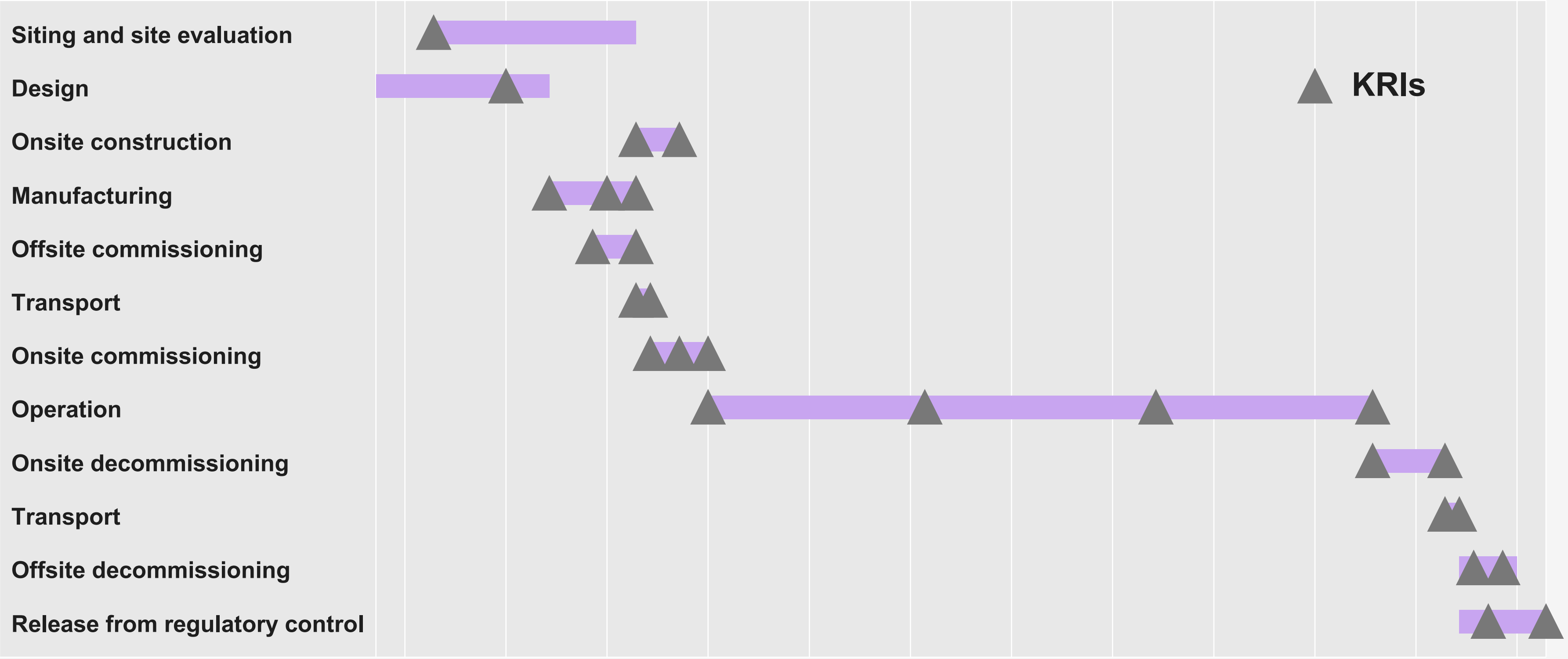
Illustrative

Recommendations of the SMR Regulators' Forum Report

1. Key regulatory interventions (KRI)

- A KRI is defined as **a strategic regulatory point of interest** during the life cycle of an SMR; that is, a moment of **higher safety risk** when inspections would be appropriate.
- Validation of safety requires an established licensing process to facilitate **effective and efficient** validation.
- The novel design of SMRs requires comprehensive **regulation of modularity** and **transportation.**

Sample SMR licensing process and proposed KRIs



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[1] otherwise, economies of multiples are difficult, if not impossible, to achieve.

Sources: SMR Regulators' Forum, 2021, Licensing Issues Report; IAEA, 2020, Technology Neutral: Safety and Licensing of SMRs; Kearney Energy Transition Institute analysis

According to the IAEA, the area of internationally harmonized regulation and licensing is among the most significant challenges for SMRs' success (2/2)

Illustrative

Recommendations of the SMR Regulators' Forum Report

6.1 Regulatory institutions

2. First-of-a-kind (FOAK) vs Nth-of-a-kind (NOAK)

- To compensate uncertainties, a more conservative approach on safety cases must be applied to FOAK.
- **Gradually account for lessons learned**, allowing the licensing process to **evolve over time**.
- **Graded approach** is defined by the IAEA Safety Glossary as a process or method in which the stringency of the control measures and conditions to be applied is **commensurate**, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control. Without compromising safety, a graded approach on licensing needs to be applied by regulators.

3. Licensing of multiple module/unit facilities

- **Cooperation** with adjacent facilities requires to be ensured for emergency management.
- **Contractual arrangements** for **shared personnel** need to be established to guarantee they do not compromise safety.
- Safety functions must be **available for all modules** when needed.
- Heat sink capacity must cover the combined heat loads from all modules.
- **Multi-unit events** are to be considered in emergency plans.
- It must be proven that **shared control rooms** do not negatively impact **overall safety.**

Sources: SMR Regulators' Forum, 2021, Licensing Issues Report; IAEA, 2020, Technology Neutral: Safety and Licensing of SMRs; Kearney Energy Transition Institute analysis

In comparison to existing reactors, proposed SMR designs are generally simpler, and their safety concept relies on passive systems and inherent safety characteristics of the reactor.

In SMRs, the requirement of robust containment and emergency response measures is reduced.

These enhanced safety features require highly qualified regulators to assess them, which is a complex issue.

Multilateral organizations bring together national regulatory agencies with the objective of sharing good practices and experiences, and of attempting to harmonize regulations

International Nuclear Regulators' Association

Established in 1997, its mission is "to influence and enhance nuclear safety, from the regulatory perspective, among its members and worldwide."

Members: 10 national nuclear regulatory authorities

European Nuclear Safety Regulators Group

Independent, expert advisory group set up in 2007, following a decision of the European Commission, "to help to establish the conditions for continuous improvement and to reach a common understanding in matters of nuclear safety, and of spent fuel and nuclear waste management."

Members: 56 senior officials from European agencies and ministries representing 28 countries

Western European Nuclear Regulators' Association

Created in 1999, it aims "to work together as national nuclear regulators to harmonize and continuously improve nuclear safety to a level that is as high as reasonably practicable, thus protecting people and the environment."

Members: 18 European countries

Source: Associations' websites; Kearney Energy Transition Institute analysis

6.1 Regulatory institutions

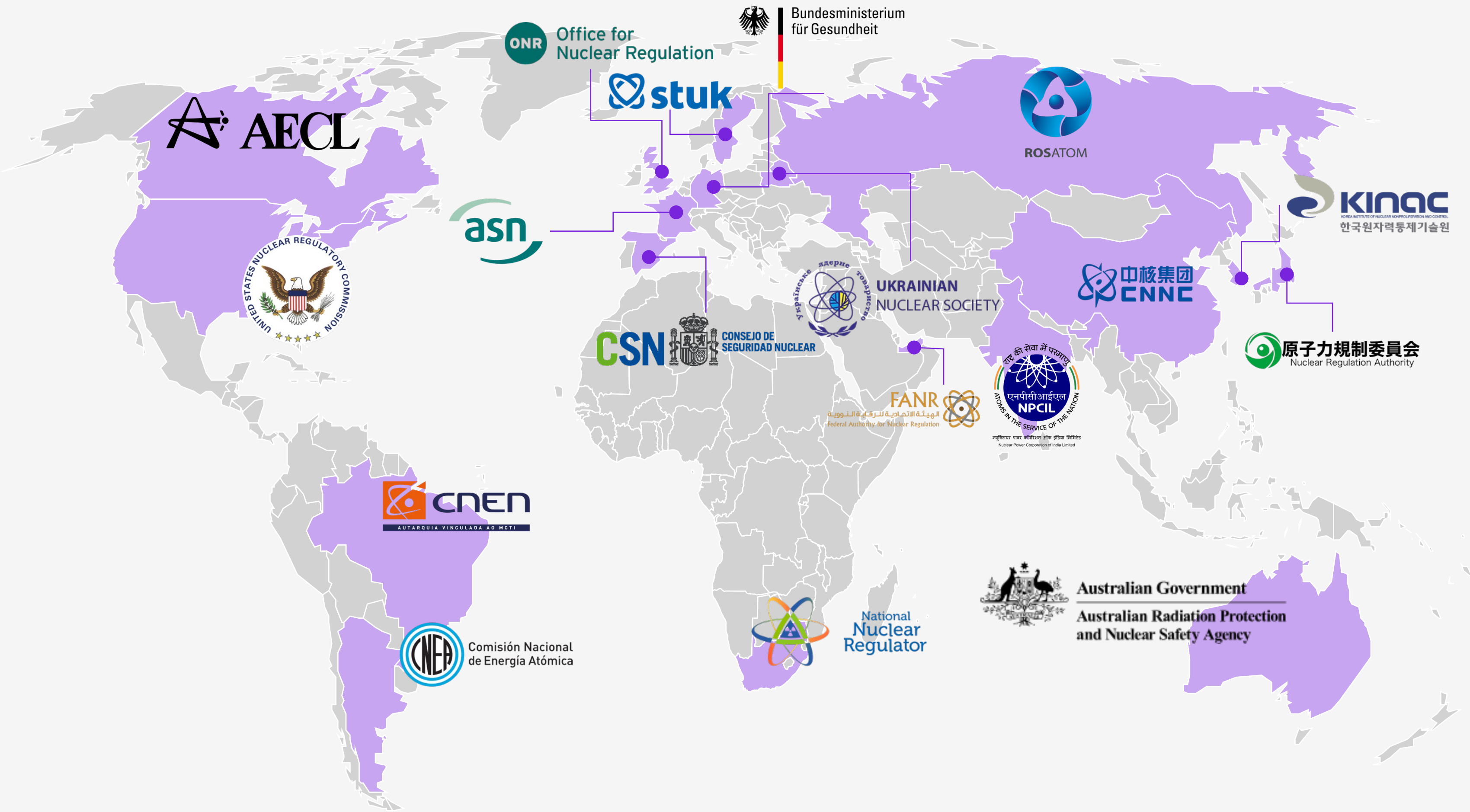
Countries with peaceful nuclear energy facilities have government bodies that oversee and regulate the nuclear industry in collaboration with international organizations and associations

Non-exhaustive

Collaboration among agencies is especially essential for newcomer countries.

6.1 Regulatory institutions

Main national regulatory bodies worldwide



Source: Kearney Energy Transition Institute analysis

There have been several SMR-licensing-related advancements in recent years

Non-exhaustive

The collaboration between the NRC and the CNSC regarding the BWRX-300 reactor design was formally established by the charter agreement on advanced reactor and small modular reactor (SMR) technologies signed in 2019.

6.1 Regulatory institutions

US – NRC

- In August of 2020, the NRC **approved a design** for an SMR, **VOYGR**, from NuScale Power.
- On December 4, 2015, the Fixing American's Surface Transportation Act was enacted. Title 41 (FAST-41) of this law is intended to **increase efficiency, transparency, and consultation in infrastructure projects** being reviewed by the federal government. **Energy production facilities** (like NPPs and SMRs in particular) are FAST-41 covered.

Canada – CNSC

- The CNSC provides an optional **Pre-Licensing Vendor Design Review** (VDR) process for vendors of reactor designs. The VDR process, which takes **place prior to the licensing process**, provides an early opportunity for vendors of a reactor technology to engage with the CNSC and to **seek clarity** on the regulatory requirements and **the expectations of their design**.
- In 2018, Canada developed an **SMR road map** to map out the **role** SMRs could play in the country's **energy mix.**

France – ASN

- In July of 2023, the **pre-licensing process** for the NUWARD, France's first electricity-producing SMR, started[1].
- In parallel, the ASN has conducted a **joint preliminary examination** of this reactor in **collaboration** with the regulators of **Finland** and the **Czechia.** The conclusions of this scrutiny have led to **tangible progress in the harmonization** of the **licensing processes** applicable to SMRs.

UK – ONR

- The ONR and the Environment Agency have developed an assessment process called **Generic Design Assessment** (GDA). The regulators use GDA to **scrutinize new nuclear power plant designs** and assess their **acceptability** for use in the UK. GDA is not a legal requirement, and the regulators will only carry out GDA for the nuclear power plant designs that the UK government has asked them to consider.

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[1] The other SMR project in the pipeline in France is the JIMMY project, a non-electrical advanced design.

Note: no available information for China, Japan, or the Russian Federation

Sources: Agencies' websites; UK Government, 2019, New nuclear power plants: Generic Design Assessment guidance for Requesting Parties; Federal Permitting Improvement Steering Council, 2015, FAST 41 Fact Sheet; ASN, 2023, NUWARD SMR Joint Early Review; Kearney Energy Transition Institute analysis

Development of internationally accepted standardized reactor designs and a harmonized approach to licensing can speed up SMR adoption

Non-exhaustive

The current national approach to the licensing of reactors results in designs approved by a lead regulator being subjected to regulatory reviews in another country against different regulations.

Harmonization in reactor design and licensing

Key drivers for pursuing harmonization

- Enabling nuclear power to fulfill its potential as the world transitions to low-carbon energy systems
- Energy security
- Realizing the benefits of innovative technologies such as small modular reactors (SMRs)

Current challenge

It is often cited that nuclear reactor safety regulation is already harmonized through near universal adherence to International Atomic Energy Agency (IAEA) safety standards. However, these qualitative standards are interpreted differently in national regulations resulting in non-uniform requirements and a lack of standardization.

Multilateral Design Evaluation Programme (MDEP)

Starting with harmonizing approaches to reactor licensing, this experience can be used for a deeper and more concerted collaboration among regulators (in consultation with other industry stakeholders), which could extend, for example, to common design review and certification among interested countries and their national regulators for both SMRs and large-scale nuclear plants.

In December 2019, the CNSC (Canadian Nuclear Safety Commission) and NRC (US Nuclear Regulatory Commission), under an updated version of the previously agreed MoC, established a mechanism that allows an SMR design to be jointly reviewed by the two regulators.

Lessons from the past

International nuclear transport regulations

The harmonized regulatory framework for transport has contributed to a safe and practical system for the movement of radioactive material over the last many decades. The process entailed three steps:

- Development of an international model for the regulations
- Adoption of these regulations into the legally binding and nonbinding instruments of international organizations
- Incorporation into national regulations

Case studies

- CNSC, NRC, and the US Department of Transportation (DOT) cooperated in 2009 to produce a joint guide—NUREG-1886 in the US, RD-364 in Canada—to be used for Canadian and US regulatory approvals of Type B (U) and fissile package designs.
- DN30 package license issued by French Nuclear Safety Authority (ASN), which has considerable experience with uranium hexafluoride (UF_6) transport, was validated on fast track by countries to which UF_6 is transported, namely Belgium, Brazil, Canada, Germany, Netherlands, Russia, South Korea, Sweden, the UK, and the US. For example, in Netherlands and Sweden the French certificate was validated within six weeks, under an ADR multilateral process which mainly involved administrative checks.

Sources: WNA, 2020, Harmonization of Reactor Design Evaluation and Licensing: Lessons Learned from Transport; Kearney Energy Institute analysis

The Joint Early Review of the NUWARD design has marked a milestone in the harmonization of nuclear legislation

A working group formed by members of the three regulatory agencies - ASN (France), STUK (Finland), and SUJB (Czechia) - has conducted this preliminary study from June 2022 to June 2023 since energy companies from these countries have expressed interest in the NUWARD reactor.

6.2 Focus on country/regions

Lessons learned on the initiative and the working methodology

Reviewing an initial basic design **together with other regulators** helps **identify possible challenges** related to this design at a very early stage, so that **timely feedback** can be provided **to the vendor** on topics considered as among the riskiest and the most impactful for the project.

There are **differences in the participating countries' regulatory frameworks**, how safety requirements are distributed across the different levels of regulations, and how they are understood.

The initiative gave the working group useful **insights on each other's regulatory approaches** and thus the **opportunity to consider evolutions** of their national regulatory framework, including the regulatory safety guides.

Conclusions of the review

The technical details are not yet publicly available for intellectual property reasons

During the discussions on the safety objectives, it has been observed that **several criteria and event categorization definitions were different** between the agencies. This risks hindering the licensing process and hence the **modification of some requirements is being considered** in the ongoing renewal of regulations.

It was noted that the considered **frequencies and dose boundaries** associated with the different categories of incidents and accidents are **not the same** as those applied in the **Czech** and **Finnish** approach. This gives the possibility to pave the way for **further verification and consideration** in the NUWARD SMR **basic design** studies.

On the **integration of two modules** inside one NUWARD SMR installation, the working group reviewed NUWARD's preliminary strategy for the **staffing of the control room** and considered that it will potentially **meet regulatory expectations** with adequate justifications.

Sources: ASN, 2023, NUWARD SMR Joint Early Review; Kearney Energy Transition Institute analysis

Europe's public-funding efforts are more focused toward renewables, but a nuclear energy alliance is pushing to include nuclear in the decarbonization agenda

The Green Deal did not sideline nuclear energy per se but introduced additional conditions as part of the taxonomy (e.g., waste solutions must be operational in the country by 2050).

Level playing field for all low-carbon technologies

European nuclear energy alliance

A joint declaration was signed by **15 European countries** aiming to develop **150 GW** of installed nuclear capacity by 2050 (100 GW approximately today) as part of the decarbonization agenda of the EU.

The declaration aims to encourage European cooperation in the field of nuclear energy based on the following pillars:

- Positioning nuclear power in the European energy strategy
- Enhancing safety and waste management
- Strengthening industrialization and sovereignty
- Ensuring the skills availability
- Promoting research and innovation

6.2 Focus on country/regions

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[1] Countries participating in the nuclear energy alliance: Belgium, Bulgaria, Croatia, Czechia, Estonia, Finland, France, Hungary, Italy, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden

Notes: Green Deal is a set of policies and investments approved in 2020 with the aim of making the European Union climate neutral by 2050.

Sources: SFEN, 2023, La relance du nucléaire dans le monde; Euractiv, 2023, Nuclear alliance aims for 150 GW of nuclear capacity in EU by 2050; Euractiv, 2023, EU to try again for renewable energy deal after nuclear row; Kearney Energy Transition Institute analysis

In the United States, the IRA signed in 2022 includes several incentives for nuclear power

The Inflation Reduction Act (IRA) enacted in August 2022

Tax credits, loan programs, and other investments for the energy transition

1. **Zero-emission Nuclear Power Credit**
   - Tax credit of up to USD 15/MWh for electricity produced in NPPs (that are compliant with certain labor and wage requirements).
2. **Code 45J – Incentives for clean energy technologies including advanced reactors and SMRs**
   - Technology-neutral production tax credit of USD 25/MWh for the first 10 years of operation or a 30% investment tax credit on new power plants.[1]
3. **Availability of High-Assay Low-Enriched Uranium (HALEU)**
   - Investment of USD 700 million to support the development of a domestic, diverse, and market-based supply chain for HALEU. This is expected to eliminate the current dependance on Russia for enrichment services.
4. **Idaho National Laboratory (INL) Infrastructure Investments**
   - Investment of USD 150 million to support infrastructure improvements at the INL, where nearly a dozen advanced-reactor projects are being undertaken, including the construction of the first SMR in the United States by NuScale.
5. **Funding for the DOE's Loan Programs Office**
   USD 3.6 billion in credit subsidy for loan guarantees. This loan authority is open to innovative clean energy technologies including nuclear energy.

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[1] Placed into operation in 2025 or after, plus an additional 10% bonus if the plant is built on a brownfield site (abandoned due to pollution from industrial use) or a fossil energy community

Sources: The White House, 2023, A Guidebook To The Inflation Reduction Act's Investments In Clean Energy And Climate Action; US Office of Nuclear Energy; 2022, Inflation Reduction Act Keeps Momentum Building for Nuclear Power; Kearney Energy Transition Institute analysis

7. Remaining challenges of traditional nuclear energy projects

AGENGA

SMRs seek to alleviate some of the main challenges that stand out for the commercial development of traditional nuclear energy projects

Challenges of traditional nuclear energy

Economic competitiveness

- High operational and increasingly high financing costs in a capital-intensive industry.
- Growing adoption of renewable energy sources has increased competitiveness within the energy sector.
- Policymakers fostering the adoption of renewable energy by establishing favorable market conditions.
- Lengthy construction timelines and substantial cost overruns are often encountered in nuclear projects.
- Value chain-associated challenges may increase manufacturing costs.

Public acceptance

- Public perception of nuclear power's safety risks and potential incidents.
- Perception of nuclear energy as environmentally damaging.
- Focus on renewable energy as the preferred alternative to fossil fuels.
- Major incidents like Chernobyl and Fukushima have heightened safety concerns and significantly influenced public perception.

Waste management

- Importance of nuclear waste management, since it contains radioactive materials that can remain hazardous for thousands of years.
- Regulations requirements related to the disposal of nuclear waste have become more stringent due to safety concerns.
- Technical and mainly socio-political challenges related to nuclear waste disposal strategies (i.e., site selection, transportation), even though some projects are already under way in Finland and Sweden.

Safety, security, safeguards

- Governments have strengthened safety policies to prevent radioactive incidents and maintain the integrity of nuclear reactors.
- Nuclear security strives to protect nuclear materials, facilities, and information against unauthorized access or malicious activities.
- Nuclear non-proliferation agreements require safeguards to verify and ensure that nuclear materials are exclusively utilized for peaceful purposes.
- Some countries do not have an existing safety agency, so they would have to subcontract their safety regulation.

Workforce attractiveness

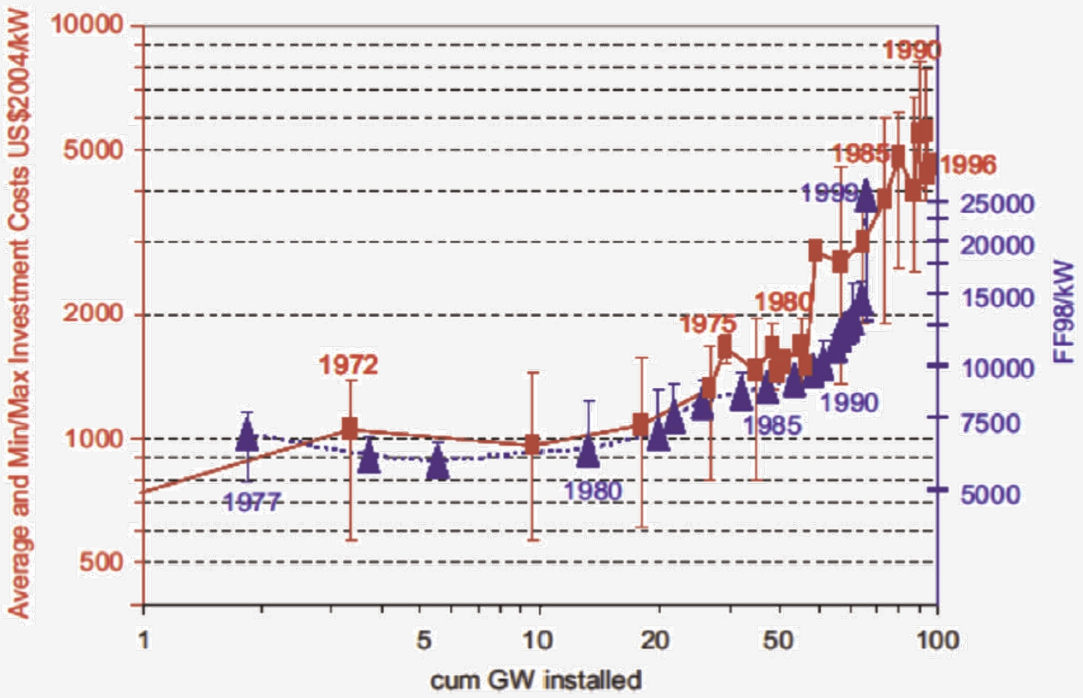
- Nuclear resurgence is challenged by the lack of skilled labor and expertise.
- Many workers in these fields are approaching retirement age and the replacement rate is lower, which is a possible consequence of political choices, media and opinion leaders affecting the public perception of nuclear technology.
- The needed workforce has triggered programs for reskilling and education.

Sources: IAEA; UMASS; ERIA; NEA; European Commission; Kearney Energy Institute analysis

However, the past experience in nuclear energy gives rise to concerns around the future development

In contrast to other power generation technologies, historical costs for nuclear power plants frequently show increasing rather than decreasing trends with cumulative installed capacity.

Negative learning rates[1]



Many factors associated with nuclear plant construction costs, ranging from new safety regulations to generational differences in nuclear reactor designs, add complexity from the viewpoint of technological learning.

Positive (and higher than conventional nuclear reactors) learning rates are expected for SMR and advanced reactor technologies.

Mixed results globally

- Negative learning rates from 1972 to 2015 in seven countries (United States, Canada, Germany, France, Japan, Korea, and India) comprising 58% of all power reactors ever built globally.
- Various other studies found positive learning rates in OECD but negative in Eastern Europe.
- **French and American nuclear experience (see graph):** Initially, cost escalations are positive, but modest until a threshold value of ~20 GW installed capacity is reached, followed by a phase of accelerated cost escalation to another threshold level at some 40–50 GW beyond which cost escalation is even more rapid.
  - Regulatory interventions, due to nuclear incidents, for additional safety upgrades/requirements (often after the construction had begun), higher interest payments and subsequent public resistance explain some of the cost increases and schedule delays in this historical data.

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[1] Reactor construction costs per kW as a function of cumulative installed capacity for both the French (triangle markers, using scale on right) and United States (rectangle markers, using scale on left) and currency.

Sources: Rubin et al., 2015, A review of learning rates for electricity supply technologies; Lang, 2017, Nuclear Power Learning and Deployment Rates; Disruption and Global Benefits Forgone; Kearney Energy Transition Institute analysis

NPP licensing is usually a time-consuming and costly process

These steps may take even longer for SMRs if regulatory agencies do not work together. This is why their role and the cooperation between them is key for a streamlined licensing process, the success and adoption of these reactors

1

Site evaluation

- Shortlisting suitable sites
- Safety and environmental assessment
- **Site approval by regulator**

2

Design certification

- **Feasibility study** elaboration
- Ensuring compatibility of site and design
- Structure, system, and material **compliance with standards and laws**

3

Construction license

- Granting **authorization for construction**
- Control of security at construction site
- Continuous **compliance** check with regulation

4

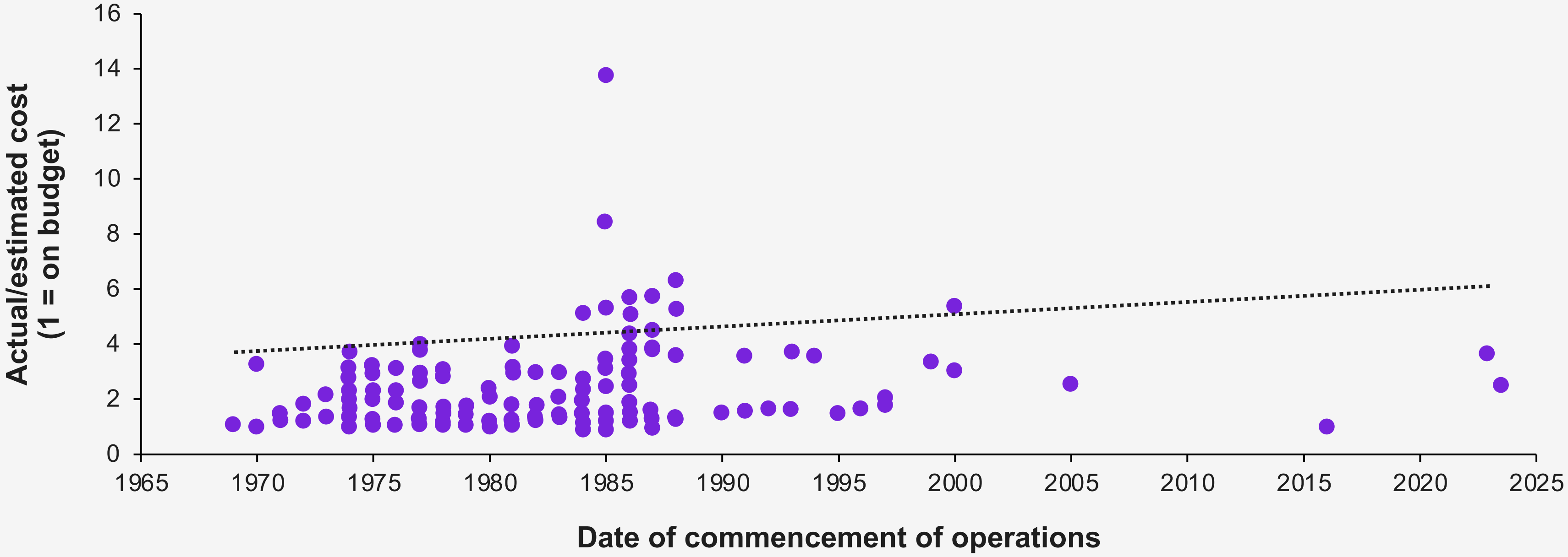
Operation license

- Training and licensing of staff
- Non-nuclear and nuclear testing
- Completing **operational tests, limits, and procedures**

Sources: IAEA, 2022, Advances in Small Modular Reactor Technology Developments; B. Mignacca, G. Locatelli, 2020, Economics and finance of Small Modular Reactors: A systematic review and research agenda; Kearney Energy Transition Institute analysis

Nuclear projects have been characterized by schedule delays and cost overruns

Cost overruns over time for nuclear new-built projects
(ratio actual / initial budget)



Nuclear ranks at the bottom[1]

– Nuclear waste storage has a mean cost overrun of 238%, while with nuclear power it's 120%.
– In contrast, solar power has a mean cost overrun of 1%, wind power 13%, and fossil thermal power 16%.

Many recent advanced **nuclear projects** continue to **face delays**, **cost overruns**, and **cancellations** in Western countries:

– Hinkley Point C (UK, delayed by 10 years and estimated cost increased to GBP 33 billion from the initial forecast of GBP 20.5 billion).
– Flamanville (France, costs have increased to EUR 12.7 billion, around four times more than the initial forecast of EUR 3.3 billion).
– Vogtle 3 (United States, construction costs climbed from its original estimate of USD 14 billion to close to USD 35 billion).
– V.C. Summer (United States, was cancelled in 2017).
– Olkiluoto 3 (Finland, EPR is the first new reactor built in Europe in more than 15 years. The initial cost estimate was EUR 3 billion, while final cost estimates reached EUR 11 billion; commissioned in 2023 after a 14-year delay).

[1] Per academic database of Oxford Global Projects from 1970s

Sources: A. Budzier et all, Oxford, 2018; Press search; Kearney Energy Transition Institute analysis

Public acceptance of nuclear power continues to be one of the most important elements in establishing a credible nuclear power program

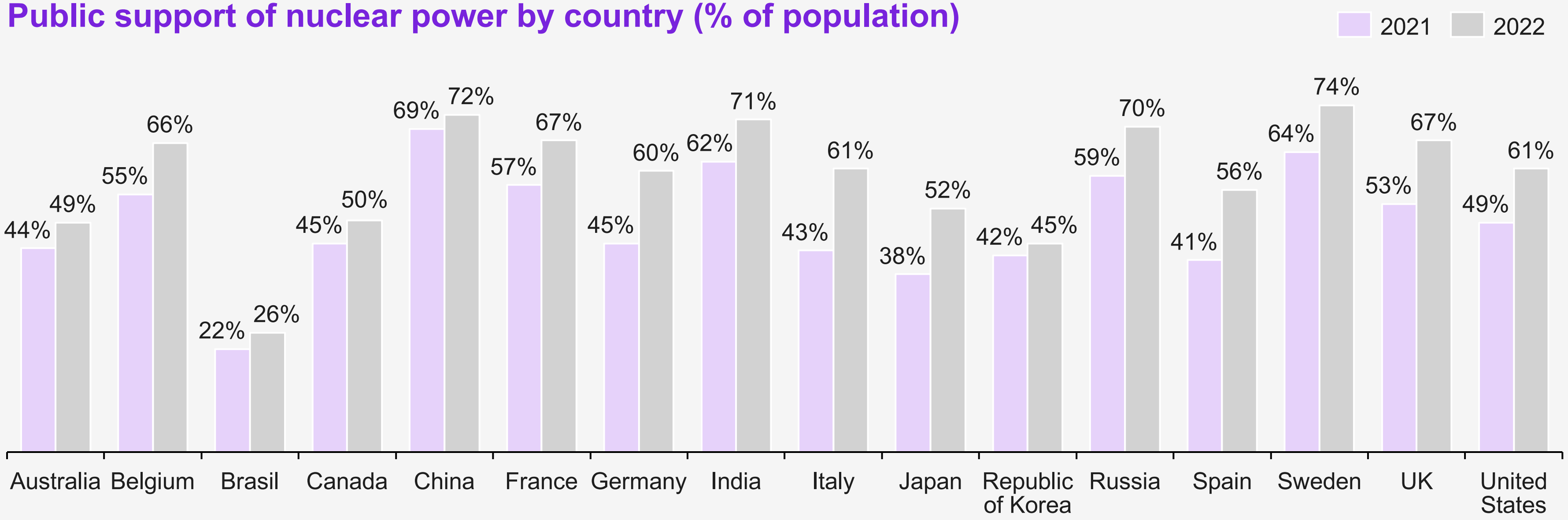
Following the war in Ukraine, many countries, in particular Europe, have seen an increase in public opinion and government policies concerning nuclear energy, which is increasingly being regarded as an option to reduce reliance on oil and natural gas and avoid a return of coal not to endanger climate mitigation objectives

7.2 Public acceptance

There is a disproportionate fear of nuclear power, in great part due to the few, but major nuclear accidents and a large part of the media and opinion leaders feeding these fears

- Key public concerns include **safety, health effects of radiation, and environmental impact of nuclear waste.**
- **Public opposition** has led to **abandoned nuclear projects** in the past. The strongest example of this is the anti-nuclear movement in Germany in the 1970s.

Public support of nuclear power by country (% of population)



Addressing the challenge of gaining social trust necessitates

- Spreading **awareness** about NP and related issues and addressing concerns in a **simple, understandable, and credible** manner. Clear example: organizing visits of different target groups to NPPs
- **Stakeholder engagement** by including of neighborhoods / surrounding population
- **Transparency**
- Monitoring **public perception** about nuclear projects
- **Partnerships** with professional organizations

Source: Nuclear Engineering International Magazine, 2022, SMRs: what are the barriers to deployment?; T20 Saudi Arabia 2020 Think, 2020, Policy brief – Does a climate-constrained world need nuclear energy?; N. Nagaich, 2017, Challenges in developing Nuclear Power Infrastructure; Sfen, 2023, La relance nucléaire dans le monde; Kearney Energy Transition Institute analysis

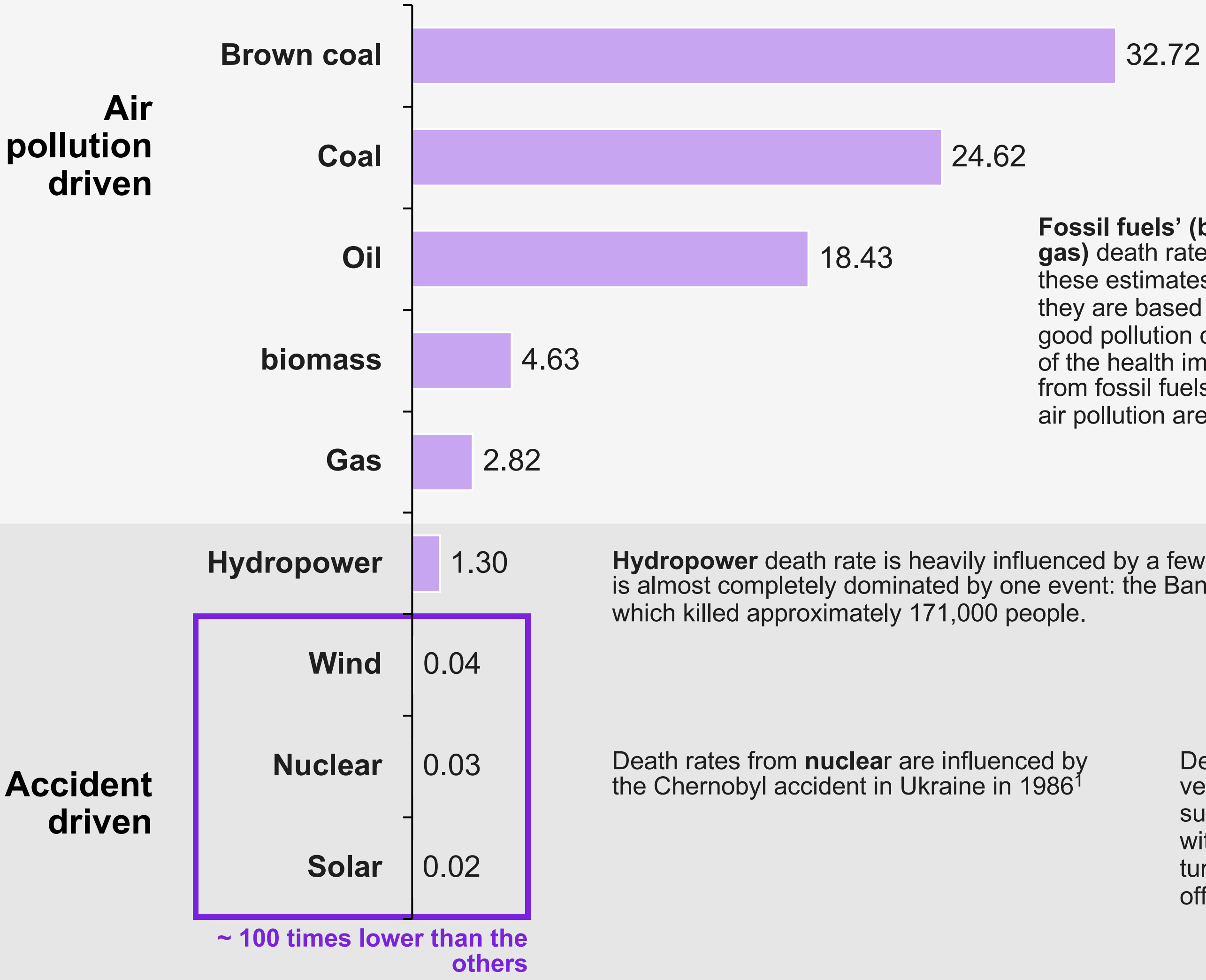
Nuclear energy is one of the safest sources of energy when measured by mortality rates

Nuclear power is the only electricity technology that uses radioactive material as a main fuel, and for which radioactive emissions are systematically measured.

As a consequence, it is the only technology that shows ionizing radiation emissions and presents radiation exposure risks although coal-fired electricity can cause high radiation exposure but is not monitored as strictly as nuclear, or not at all.

Death rates per unit of electricity production

From air pollution and accidents per terawatt-hour (TWh) of electricity



Fossil fuels' (brown coal, coal, oil, biomass, and gas) death rates are driven by air pollution. However, these estimates are likely to be very conservative as they are based on power plants in Europe, which have good pollution controls, and are based on older models of the health impacts of air pollution. Global death rates from fossil fuels based on the most recent research on air pollution are likely to be even higher.

Hydropower death rate is heavily influenced by a few large-scale accidents. In fact, this rate is almost completely dominated by one event: the Banqiao Dam Failure in China in 1975 which killed approximately 171,000 people.

Death rates from **nuclear** are influenced by the Chernobyl accident in Ukraine in 1986[1]

Death rates from **solar and wind**, even if very low, are driven by accidents in the supply chain such as helicopter collisions with turbines; fires during the installation of turbines or panels; and drownings on offshore wind sites.

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[1] No recorded death directly attributable to Fukushima accident; death estimates of long-term effects are based on calculations using the no threshold assumption and that the numbers then vary widely.

Sources: ourworldindata.org/ (based on Markandya & Wilkinson (2007); Sovacool et al. (2016); UNSCEAR (2008; & 2018)); M. Hvistendahl, 2007, Scientific American; Kearney Energy Transition Institute analysis

Safe and reliable management and disposal methods for radioactive waste are crucial, as improper handling can pose a significant danger to human safety

Nuclear fuel cycle costs represent about 13% of the levelized cost of electricity[1] for LWR nuclear power plants.

Back-end costs range around 3%.

Types of radioactive waste from NPPs

Type of waste	Description	Radioactive content	Examples
Low level waste (LLW)	Waste with limited amounts of long-lived radionuclides	– >4 KBq/g – 90% of waste volume – 1% of overall radioactivity	– Paper – Clothing – Tools – Filters
Intermediate level waste (ILW)	Waste with large presence of long-lived radionuclides	– 4 kBq/g – 4 MBq/g – 7% of waste volume – 4% of overall radioactivity	– Resins – Chemical sludges – Metal fuel cladding
High level waste (HLW)	Waste with large presence of long-lived radionuclides and significant heat generation by radioactive decay	– >4 MBq/g – 3% of waste volume – 95% of overall radioactivity	– Fission products – Transuranic elements

Treatment and conditioning of nuclear waste

Incineration (LLW)	**Compaction** (LLW)	**Cementation** (ILW and LLW)	**Vitrification** (HLW)	**Synroc and composite** (HLW)	**Engineered encapsulation** (HLW)
					

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[1] Considering a 7% discount rate.

Source: World Nuclear Association, 2022, Radioactive waste management and Treatment and conditioning of nuclear waste; R. Taylor, W. Bodel and G. Buttler, A review of environmental and economic implications of closing the nuclear fuel cycle – part two: economic impacts; Kearney Energy Transition Institute analysis

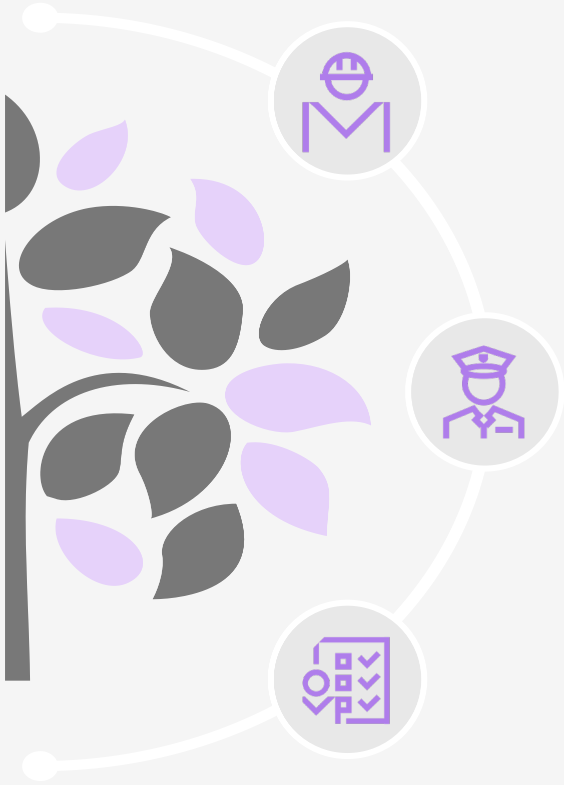
Storage methods are readily available and have been safely used for decades, while disposal facilities for HLW are under construction or in advanced stages of development in Finland, France, and Sweden

Method	Description	Challenges	Type of waste	Storage time
Deep geological repository disposal 	Burying the waste deep underground in stable geological formations at depths ranging from 250 m to 1,000 m in mined repositories or deeper in boreholes	– Site selection and construction standards – Periodic monitoring of DGR – Public acceptance – Safety standards	– High-level radioactive waste – Intermediate-level radioactive waste	**Permanent**
Near-surface disposal 	Involves placing the waste in specially designed facilities located relatively close to the surface of the ground	– Ensuring long-term safety – Site selection – Strict regulatory requirements	– Low-level radioactive waste – Intermediate-level radioactive waste	**Permanent**
Dry storage 	Surface or sub-surface temporary storage facilities before final disposal	– Transportation and logistics of waste – Duration and capacity – Safety standards of facilities	– High-level radioactive waste – Intermediate-level radioactive waste	**10 to 40 years**
Wet storage 	Intermediate step that consists of storing waste materials underwater, so they are cooled, and their radioactive properties dispersed, before dry storage and/or disposal	– Uses substantial amounts of energy – Limited capacity in NPPs	– High-level radioactive waste – Intermediate-level radioactive waste	**1 to 10 years**

Sources: World Nuclear Association, CDC; Power Technology, 2020, “Wet” vs “dry”: the pros and cons of two storage methods for nuclear waste; Kearney Energy Institute analysis

7.3 Waste management

Strict measures are taken to ensure safety and security



	Description	Objectives	Measures
Nuclear safety	Ensuring the safe operation of nuclear facilities through the adherence to established international safety standards	– Ensure the safe operation of nuclear facilities – Prevent incidents that could lead to the release of radioactive materials – Mitigate the potential consequences to protect people and the environment	– Periodic inspections by regulatory agencies – High-quality materials and strict construction procedures – Qualified personnel who are trained in safety procedures – International cooperation to share best practices
Nuclear security	Protection and control of nuclear materials, facilities, and information from unauthorized access	– Prevent theft, sabotage, and other malicious acts that could lead to the misuse of nuclear materials	– Development of frameworks to monitor nuclear materials – Deployment of radiation portal monitors – Preventive radiological and nuclear detection operations
Nuclear safeguards	Verification of state's compliance to obligations and commitments under international non-proliferation agreements	– Strengthen the non-proliferation regime – Detect and deter the diversion of nuclear materials from peaceful nuclear activities	– Inspections of nuclear facilities by the IAEA – Inventories check – Sampling and analysis of materials – Remote monitoring techniques to detect illicit activities

Sources: IAEA; UMASS; NEA; European Commission; Kearney Energy Transition Institute analysis

Nuclear resurgence is challenged by the lack of skilled labor and expertise

Non-exhaustive

Many workers in these fields are approaching retirement age, and fewer people are replacing them.

A prolonged gap can lead to a loss of expertise in the industry as the knowledge and capabilities are lost along with the past generation of workers.

7.5 Workforce attractiveness

Workforce challenges in selected countries

United States

- According to the 2022 United States Energy Employment Report, **82% of utilities** report difficulties in hiring skilled workers, while **94% of nuclear construction firms** report difficulties in hiring skilled workers.
- The American Welding Society indicates that almost **half of US welders are over 45 years old**, and it predicts that **more than 300,000 new welders will be needed by 2024.**

UK

- In the UK, **high integrity pipe welding** is a major skills gap in engineering construction and has been cited as a specific skills risk to nuclear new build delivery.

France

- The **lack of qualified workers**, welders in particular, is already **causing delays** in maintenance operations. In 2022, **70% of** the needs for **welders, pipefitters, and boilermakers** were **not satisfied.**
- In the context of the investment plan France 2030 to reactivate the nuclear sector, it is expected that **100,000 new hires will be needed in the next 10 years.**

Canada

- In the near future, Canada will face a **shortage of at least 10,000 workers in nationally recognized Red Seal trades** - a deficit that swells **tenfold** when 250 provincially regulated trades are included
- Shortages are expected to be particularly severe among **industrial mechanics, boilermakers and welders (i.e. total # of welders in Canada declined by ~12% in 2011-2021 period)**
- Over **700,000** skilled tradespeople are projected to retire by 2028

Sources: Press search; Kearney Energy Transition Institute analysis

Various initiatives, by public and private sector institutions, have been launched to address gaps and shortages across the skill levels in the nuclear industry

Non-exhaustive

IAEA[1], through training tools and groups, also supports member states that are operating, expanding, or developing new nuclear power programs in acquiring and maintaining competent staff for all nuclear organizations and for all phases of the life cycle of a nuclear facility.

7.5 Workforce attractiveness

United States

- The Department of Energy's National Nuclear Security Administration (NNSA) awarded Hardinge Inc. and the Association of Journeyman and Apprentices of the Plumbing and Pipefitting Local 412 **5-year grants totaling USD 2.17 million to strengthen apprenticeship** training programs for technician positions.
- Westinghouse Electric Company, engineering firm Tecnatom, and Accelerant Solutions have agreed to form the **Nuclear Excellence Academy (NEXA)**, a nuclear training program for utilities in the United States and Canada.

UK

- Nuclear AMRC (Advanced Manufacturing Research Centre) has launched the Nuclear Skills Academy, which is now **training 200 apprentices a year**. It also created a new Nuclear Scientist and Nuclear Engineer Degree apprenticeship.
- The Engineering Construction Industry Training Board (ECITB) pledged more than **GBP 87 million to support workforce training** and tackle labor shortages and skills gaps over 2023–2025. This includes **GBP 4 million of funding into welding training** and development to support Nuclear New Build program.

France

- Hefaïs **welding school was launched in 2022** as a strong public/private partnership. It is supported by the state and the Normandy region as part of the IFPAI Action, a regional component of the Future Investments Program, operated by Caisse des Dépôts, and has also been selected under the *France Relance* plan.
- INSTN School, which is part of the French Alternative Energies and Atomic Energy Commission (CEA), will **extend the support to the IAEA** and its member states in **education and training** in various nuclear fields.

Canada

- Canadian Nuclear Roadmap to 2050 aims to **renew the nuclear workforce in Canada with a specific focus on SMR**—university engineering courses addressing SMR science and technology; expanded SMR-specific university secondments to R&D, etc.
- The Canadian federal government announced **CAD 6.6 million in funding for training** to meet the need for highly skilled pressure welders.

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[1] IAEA NKM (Nuclear knowledge management) addresses the issue of knowledge preservation and succession planning

Sources: Press search; Kearney Energy Transition Institute analysis

8. Bibliography and appendix

AGENGA

Picture credit - Peschke, Kevin

Acronyms and glossary (1/3)

AGR: Advanced gas reactors

ASN: *Autorité de Sureté Nucléaire* (French Nuclear Safety Authority)

BOO: Build-own-operate

BWR: Boiling water reactors

CANDU: Canada Deuterium Uranium

DOE: Department of Energy (US)

EPC: Engineering, procurement, and construction

EPR: European pressurized water reactor

EPZ: Emergency planning zone

EU: European Union

EUR: Euro

FHTR: Fluoride high-temperature reactor

FHR: Fluoride-salt-cooled high-temperature reactor

FOAK: First-of-a-kind

GBP: Great Britain pound

GCFR: Gas cooled fast reactors

GFR: Gas-cooled fast reactor

HALEU: High-assay low enriched uranium

HEU: Highly enriched uranium

HLW: High level waste

HPR: Heat pipe reactor

HTGR: High temperature gas-cooled reactor

HWR: Heavy water reactors

IAEA: International Atomic Energy Agency

I&C: Instrument and control maintenance

ILW: Intermediate level waste

INES: International Nuclear and Radiological Event Scale

KRI: Key regulatory intervention

LBE: Lead-bismuth cooled

LCOE: Levelized cost of electricity

LEU: Low enriched uranium

LLW: Low level waste

Acronyms and glossary (2/3)

LMFR: Liquid metal cooled fast reactor

LWR: Light water reactor

MeV: Megaelectron volt

MOU: Memorandum of understanding

MOX: Mixed oxide

MSR: Molten salt reactors

MWe: Megawatt (electrical)

MWt: Megawatt (thermal)

NEA: Nuclear Energy Association

NOAK: Nth-of-a-kind

NP: Nuclear power

NPP: Nuclear power plant

NRC: Nuclear Regulatory Commission

NTP: Nuclear thermal propulsion

NZE: Net Zero emissions

OECD: Organization for Economic Cooperation and Development

PHWR: Pressurized heavy water reactor

PWR: Pressurized water reactors

REMIX: Regenerated mixture

RepU: Reprocessed uranium

RW: Radioactive waste

R&D: Research and development

RD&D: Research, development and demonstration

SMR: Small modular reactor

SNF: Spent nuclear fuel

SOEC: Solid oxide electrolyzer cell

TRISO: Tri-structural isotropic

UK: United Kingdom

US: United States of America

USD: United States dollar

Acronyms and glossary (3/3)

HLW (High level waste): It contains long-lived radionuclides with high activity, which may also produce heat. It consists mainly of spent nuclear fuel or residues from the reprocessing of SNF and contains 95% of the total radioactivity in the waste, while it accounts for 1% of total nuclear waste

ILW (Intermediate level waste): The definitions differ from country to country. However, in general, ILW needs specific shielding during handling and, depending on the specific content of long-lived radionuclides, it may need geological disposal, or it may be suitable for surface or near-surface disposal. Used filters, steel components and some effluents; they contain 4% of total waste radioactivity and represent 7% of the volume.

LLW (Low level waste): This type of waste does not need significant shielding for handling and, because of the absence of long-lived radionuclides, is suitable for surface or near-surface disposal. Lightly contaminated items such as tools and clothing containing 1% of waste radioactivity; they constitute 90% of the total volume.

LEU (Low-enriched-uranium): 3% to 5% of U-235.

HALEU (High-assay low-enriched uranium): contains up to 20% of U-235.

HEU (Highly enriched uranium): above 20% of U-235, enrichment levels of 90%+ are classified as a weapon grade.

MOX: Mixed oxide fuel. A fuel for nuclear power plants that consists of a mixture of depleted uranium oxide and plutonium oxide.

Radionuclides: are elements in which the nucleus of the atom is unstable and undergoes decay naturally (even though the process may take thousands of years). Radionuclides include plutonium, radon, thorium, tritium and uranium, among others.

Sources: US DOE; Kearney Energy Transition Institute analysis

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Picture credits (1/2)

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Slide 43: Schematic view of nuclear power plants size **(link)**

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8.3 Picture credits

Picture credits (2/2)

Slide 109: Deep geological storage **(link) ;** dry storage **(link);** wet storage **(link)**, near surface disposal and interim storage **(link)**

Slides 122 to 136: all selected SMR designs **(link),** schematics **(link)**

Slide 139: Nuclear fission and fusion **(link)**

Slide 140: Tokomak **(link)**

Slide 143: Is the sun hot enough for fusion? **(link)**

Appendix: factcards

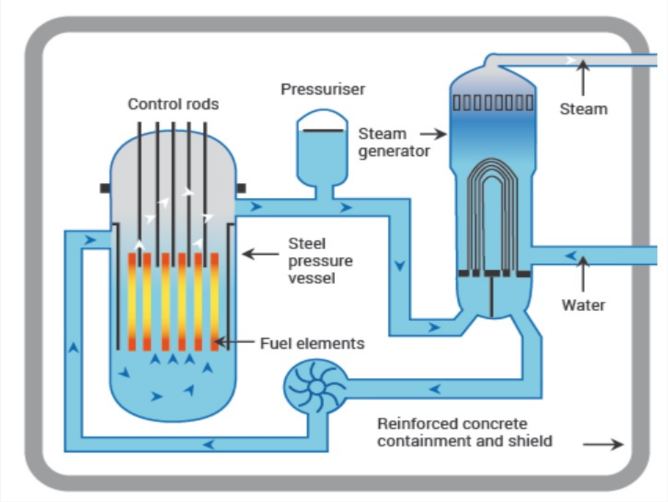
Pressurized water reactor (PWR) – overview

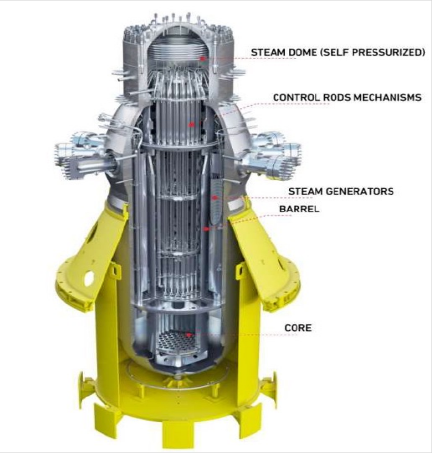
Fact card: Pressurized water reactor (PWR - SMR)

Description

- PWRs use **ordinary water but depleted of deuterium (light water) as both coolant and moderator**. The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine.
- Variations of design include integral PWR (iPWR), compact PWR, loop-type PWR, and pool-type PWR for district heating.
- The design of PWRs originated as a submarine power plant.

Schematic





CAREM (CNEA, Argentina)

Selected PWR SMR designs

- CAREM (Argentina)
- ACP100 (China)
- VOYGR (United States)
- SMART (South Korea and Saudi Arabia)
- Rolls-Royce SMR (UK)
- KLT-40S (Russia)

Source: Kearney Energy Transition Institute analysis

Pros

- Lowest technological risk, being similar to most operating power and naval reactors today

Cons

- Enriched fuel needed

Pressurized water reactor (PWR) – key technical parameters

Non-exhaustive

Fact card: Pressurized water reactor (PWR - SMR)

Category	Sub-category	CAREM	ACP100	VOYGR	SMART	KLT-40S (Marine based)
General	Country	Argentina	China	United States	South Korea and Saudi Arabia	Russia
	Design organization(s)	CNEA	CNNC (NPIC)	NuScale	KAERI, K.A.CARE	JSC “Afrikantov OKBM”
	Design status	Under construction	Under construction	Equipment manufacturing	Detailed design	Connected to the grid in Pevek in December 2019. Entered full commercial operation in May 2020.
	Plant footprint (m^2)	36,000	200,000	140,000	90,000	4,320 (floating NPP)
	Life (years)	40	60	60	60	40
Reactor	Type/circulation	iPWR / natural circulation	iPWR / forced circulation	iPWR / natural circulation	iPWR / forced circulation	PWR
	Coolant/moderator	Light water/light water	Light water/light water	Light water/light water	Light water/light water	Light water/light water
	Thermal output, MW(t)	100	385	250	365	150
	Electrical output, MW(e)	30	125	77	107	35
Fuel	Fuel type/assembly array	UO_2 pellet/hexagonal	UO_2 pellet / 17x17 square	UO_2 pellet / 17x17 square	UO_2 pellet / 17x17 square	UO_2 pellet in silumin matrix
	# of fuel assembly	61	57	37	57	121
	Enrichment (%)	3.1	<4.95	<4.95	<5	18.6
	Refueling cycle (months)	14	24	18	30	28
	Reactivity control	Control rods	Control rods + Gd2O3 solid burnable + soluble boron acid	Control rods + soluble boron	Control rods + soluble boron	Control rods

Sources: IAEA’s Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

8.4 Appendix: factcards

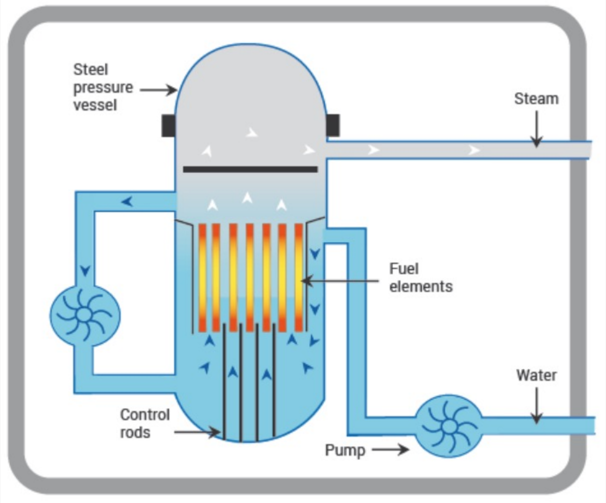
Boiling water reactor (BWR) – overview

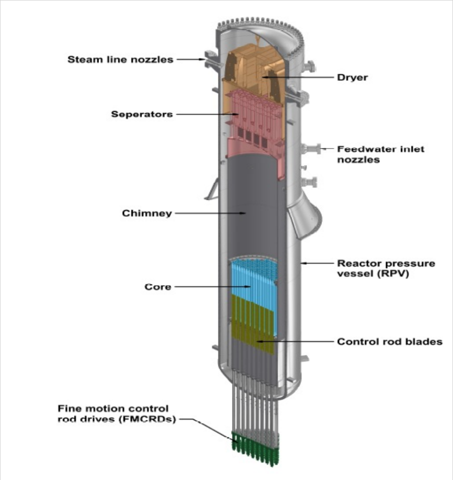
Fact card: Boiling water reactor (BWR - SMR)

Description

- This type of reactor has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C.
- The reactor is designed to operate with 12–15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there.

Schematic





BWRX-300

Source: Kearney Energy Transition Institute analysis

Selected BWR SMR designs

- BWRX-300 (United States and Japan)
- VK-300 (Russia)
- KARAT-45 (Russia)

Pros

- Simpler design
- BWR units can operate in load-following mode more readily than PWRs

Cons

- The turbine must be shielded and radiological protection provided during maintenance (due to contaminated water around the core) and cost of this tends to balance the savings from simpler design

Boiling water reactor (BWR) – key technical parameters

Non-exhaustive

Fact card: Boiling water reactor (BWR - SMR)

Category	Sub-category	BWRX-300	VK-300	KARAT-45	-	-
General	Country	United States and Japan	Russia	Russia	-	-
	Design organization(s)	GE Hitachi & Hitachi GE Nuclear Energy	NIKIET	NIKIET	-	-
	Design status	Detailed design	Detailed design	Conceptual design	-	-
	Plant footprint (m^2)	9,800	40,000	9,000	-	-
	Life (years)	60	60	80	-	-
Reactor	Type/circulation	BWR/natural circulation	Simplified passive BWR/natural circulation	BWR/natural circulation	-	-
	Coolant/moderator	Light water/light water	Light water/light water	Light water/light water	-	-
	Thermal output, MW(t)	870	750	-	-	-
	Electrical output, MW(e)	270–290	250	-	-	-
Fuel	Fuel type/assembly array	UO_2 pellet / 17x17 array	UO_2 pellet/hexagonal	UO_2 pellet/hexagonal	-	-
	# of fuel assembly	240	313	109	-	-
	Enrichment (%)	3.81 (avg) / 4.95 (max)	4	4.5	-	-
	Refueling cycle (months)	12 - 24	72	84	-	-
	Reactivity control	Rods + solid burnable absorber (B4C, Hf, Gd2O3)	Rods	Control rods drive	-	-

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

8.4 Appendix: factcards

Pressurized heavy water reactor (PHWR) – overview

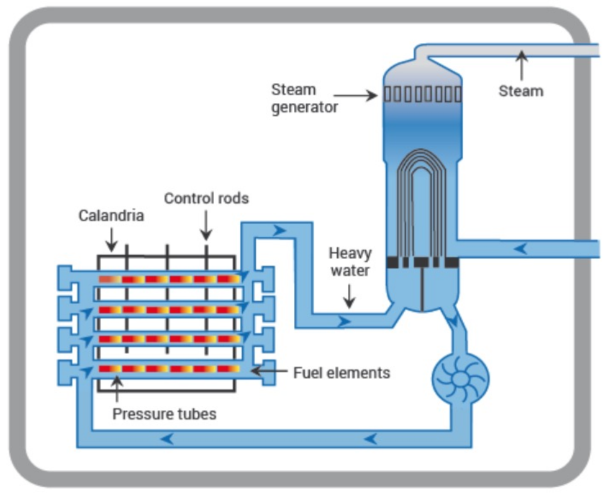
Fact card: Pressurized heavy water reactor (PHWR - SMR)

8.4 Appendix: factcards

Description

- PHWRs generally use natural uranium (0.7% U-235) oxide as fuel, hence they need a more efficient moderator, in this case heavy water (D2O).
- Fuel bundles are placed horizontally in a tank called a calandria. Heavy water coolant is pumped through tubes containing the fuel assemblies to absorb heat from the nuclear reaction. It's then circulated to the steam generator to produce the steam to drive turbines.
- Newer PHWR designs such as the advanced CANDU reactor (ACR) have light water cooling and slightly enriched fuel.

Schematic



CANDU (Canada)

Source: Kearney Energy Transition Institute analysis

Selected PHWR SMR designs

- CANDU SMR (Canada)

Pros

- Uses natural uranium as fuel and hence, two less steps in the conversion process resulting in a more economical fuel source

Cons

- The PHWR produces more energy per kilogram of mined uranium than other designs, but also produces a much larger amount of used fuel per unit output

Pressurized heavy water reactor (PHWR) – key technical parameters

Non-exhaustive

Fact card: Pressurized heavy water reactor (PHWR - SMR)

8.4 Appendix: factcards

Category	Sub-category	CANDU SMR	-	-	-	-
General	Country	Canada	-	-	-	-
	Design organization(s)	Candu Energy Inc. Member of the SNC-Lavalin Group, Canada	-	-	-	-
	Design status	Conceptual design	-	-	-	-
	Plant footprint (m^2)	21,000	-	-	-	-
	Life (years)	70	-	-	-	-
Reactor	Type/circulation	PHWR/forced circulation	-	-	-	-
	Coolant/Moderator	Heavy water/heavy water	-	-	-	-
	Thermal output, MW(t)	960	-	-	-	-
	Electrical output, MW(e)	300	-	-	-	-
Fuel	Fuel type/assembly array	37 elements	-	-	-	-
	# of fuel assembly	2,064	-	-	-	-
	Enrichment (%)	Natural uranium; not enriched	-	-	-	-
	Refueling cycle (months)	14	-	-	-	-
	Reactivity control	Zone controllers, mechanical adjusters	-	-	-	-

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

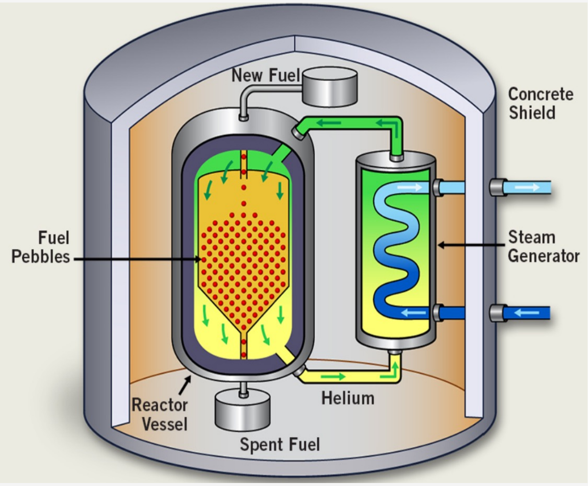
High temperature gas cooled reactors (HTGR/GCR) – overview

Fact card: High temperature gas cooled reactors (HTGR - SMR)

Description

- Gas-cooled reactors use graphite as the moderator and an inert gas such as helium or carbon dioxide as the coolant. As the gaseous coolant comes in contact with the core, like water, it absorbs heat which is then either transferred to a water circuit to produce steam or drives turbines directly.
- The uranium fuel for these reactors is highly specialized and consists of a "kernel" of enriched uranium which is coated in layers of carbon and silicon carbide. This fuel design provides containment of fission products and enables the reactor to safely operate at very high temperatures - up to 1,600°C or higher.
- Useful for the cogeneration of electricity and hydrogen, as well as to other process heat applications.

Schematic



Xe-100 (USA)

Selected HTGR/GCR SMR designs

- HTR-PM (China)
- GTHTR300 (Japan)
- GT-MHR (Russia)
- HTMR100 (South Africa)
- Xe-100 (United States)

Pros

- Inherent safety, high thermal efficiency, process heat application capability, low operation and maintenance costs

Cons

- Currently there are limited routes available or decided to manage graphite wastes

Source: Kearney Energy Transition Institute analysis

High temperature gas cooled reactors (HTGR) – key technical parameters

Non-exhaustive

Fact card: High temperature gas cooled reactors (HTGR - SMR)

8.4 Appendix: factcards

Category	Sub-category	HTR-PM	GTHTR300	GT-MHR	HTMR100	Xe-100
General	Country	China	Japan	Russia	South Africa	United States
	Design organization(s)	INET, Tsinghua University	JAEA, MHI, Toshiba/IHI, Fuji Electric, KHI, NFI	JSC “Afrikantov OKBM”	STL Nuclear (Pty) Ltd	X-energy LLC
	Design status	In operation	Basic design	Preliminary design	Basic design	Basic design
	Plant footprint (m^2)	256,100	~250m x 250m	9,110	5,000	340m x 385m
	Life (years)	40	60	60	40	60
Reactor	Type/circulation	Modular pebble bed HTGR/forced	Prismatic HTGR	Modular helium reactor/forced	HTGR pebble bed/forced	Modular HTGR/forced
	Coolant/moderator	Helium/graphite	Helium/graphite	Helium/graphite	Helium/graphite	Helium/graphite
	Thermal output, MW(t)	2 × 250	<600	600	100	200
	Electrical output, MW(e)	210	100–300	288	35	82.5
Fuel	Fuel type/assembly array	Spherical elements with coated particle fuel	UO_2 TRISO ceramic coated particle	Coated particle fuel in compacts, hexagonal prism graphite blocks of 0.36 m, LEU or WPu	TRISO particles in pebbles; LEU/Th	UCO TRISO/pebbles
	# of fuel assembly	420,000 (in each reactor module)	90	1,020	~150,000; ~ 125–150 pebbles/day throughput	220,000 pebbles per reactor
	Enrichment (%)	8.5	14	14–18%	10	15.5
	Refueling cycle (months)	On-line refueling	48	25	Online fuel loading	
	Reactivity control	Control rod insertion	Control rod insertion	Control rod insertion	Control rods in the reflector	Thermal feedback and control rods

Sources: IAEA’s Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

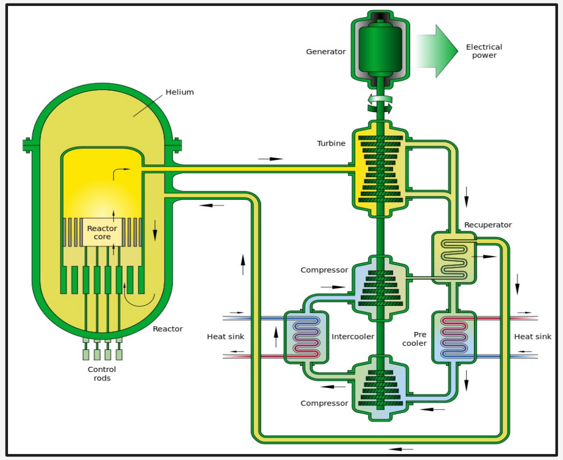
Gas-cooled fast reactors (GCFR/GFR) – overview

Fact card: Gas cooled fast reactors (GCFR/GFR - SMR)

Description

- The gas-cooled fast reactor combines the advantages of a fast neutron core and helium coolant giving possible access to high temperatures. It requires the development of robust refractory fuel elements and appropriate safety architecture.
- The GFR uses the same fuel recycling processes as the SFR and the same reactor technology as the VHTR.

Schematic



FMR (USA)

Selected GCFR/GFR SMR designs

- EM^2 (United States)
- FMR (United States)

Pros

- Long-term sustainability of uranium resources and waste minimization

Cons

- Still requires intensive R&D on the core design and safety approach

Source: Kearney Energy Transition Institute analysis

8.4 Appendix: factcards

Gas-cooled fast reactors (GCFR/GFR) – key technical parameters

Non-exhaustive

Fact card: Gas cooled fast reactors (GCFR/GFR - SMR)

Category	Sub-category	EM²	FMR
General	Country	United States	United States
	Design organization(s)	General Atomics	General Atomics
	Design status	Conceptual design	Conceptual design
	Plant footprint (m^2)	90,000	38,000
	Life (years)	60	60
Reactor	Type/circulation	Modular high-temperature gas-cooled fast reactor/forced	Gas-cooled fast reactor (GFR)/forced
	Coolant/moderator	Helium/none	Helium/none
	Thermal output, MW(t)	500	100
	Electrical output, MW(e)	265	50
Fuel	Fuel type/assembly array	Uranium carbide pellet/hexagonal	Uranium dioxide pellet/hexagonal
	# of fuel assembly	85	198
	Enrichment (%)	14.5	19.75
	Refueling cycle (months)	360	96
	Reactivity control	Control rod drive mechanism	Control rod drive mechanism

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

8.4 Appendix: factcards

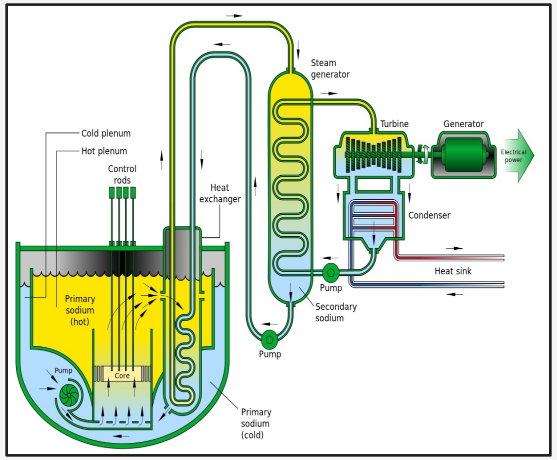
Liquid metal fast reactors (LMFR/SFR/LFR/MFR/LMR/LMCR) – overview

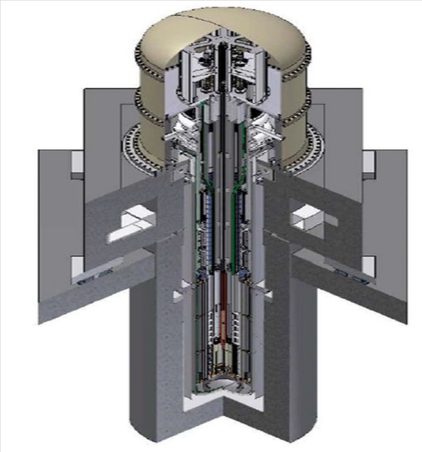
Fact card: **Fact card:** Liquid metal fast reactors (LMFR/SFR/LFR - SMR)

Description

- The sodium-cooled fast reactor system uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. It features a closed fuel cycle for fuel breeding and/or actinide management. The reactor may be arranged in a pool layout or a compact loop layout.
- The lead-cooled fast reactor system is characterized by a fast-neutron spectrum and a closed fuel cycle with full actinide recycling, possibly in central or regional fuel cycle facilities. The coolant may be either lead (preferred option) or lead/bismuth eutectic.

Schematic





4S (Japan)

Selected LMFR SMR designs

- BREST-OD-300 (Russia)
- 4S (Japan)
- SVBR (Russia)
- LFR-AS-200 (Italy)
- ARC-100 (Canada

Pros

- Smaller and simpler than light water types, have better fuel performance and can have a longer refueling interval

Cons

- Potential for corrosion when the coolant is in contact with structural steels

8.4 Appendix: factcards

Source: Kearney Energy Transition Institute analysis

Liquid metal fast reactors (LMFR/SFR/LFR) – key technical parameters

Non-exhaustive

Fact card: Liquid metal fast reactors (LMFR/SFR/LFR - SMR)

Category	Sub-category	BREST-OD-300	4S	SVBR	LFR-AS-200	ARC-100
General	Country	Russia	Japan	Russia	Italy	Canada
	Design organization(s)	NIKIET	Toshiba Energy Systems & Solutions Corporation	JSC Institute for Physics and Power Engineering and JSC EDB Gidropress	Newcleo srl	ARC Clean Energy
	Design status	Construction in progress	Detailed design	Detailed design for potential construction in 2025	Conceptual design	Preliminary design
	Plant footprint (m^2)	80m X 80m	157,000	150,000	1,100	56,000
	Life (years)	30	30	60	60	60
Reactor	Type/circulation	Liquid metal cooled fast reactor/forced	Liquid metal cooled fast reactor (pool type)/forced	Liquid metal cooled fast reactor/forced	Liquid metal cooled fast reactor (pool type)/forced	Liquid metal cooled fast reactor (pool type)/forced
	Coolant/moderator	Lead	Sodium	Lead-bismuth eutectic alloy	Lead	Sodium
	Thermal output, MW(t)	700	30	280	480	286
	Electrical output, MW(e)	300	10	100	200	100
Fuel	Fuel type/assembly array	Mixed uranium plutonium nitride	Metal fuel (U-Zr alloy) based on enriched uranium	UO$_2$/hexagonal	MOX/hexagonal	Metal fuel (U-Zr alloy) based on enriched uranium
	# of fuel assembly	169	18	61	61	99
	Enrichment (%)	<14.5	<20	<19.3	19% avg / 23.2% max in Pu	13.1
	Refueling cycle (months)	36–78	360	84–96	16	240
	Reactivity control	Reactivity compensation (RC), emergency protection (EP), and automatic control (AC) members	Axially movable reflectors/fixed absorber	Control rod drive mechanism	Ex-core, reversed-flag type B$_4$C rods, rotating B$_4$C rods	Control rods

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

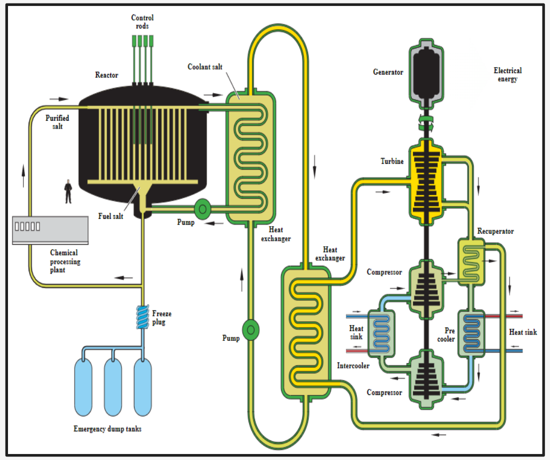
Molten salt reactor (MSR) – overview

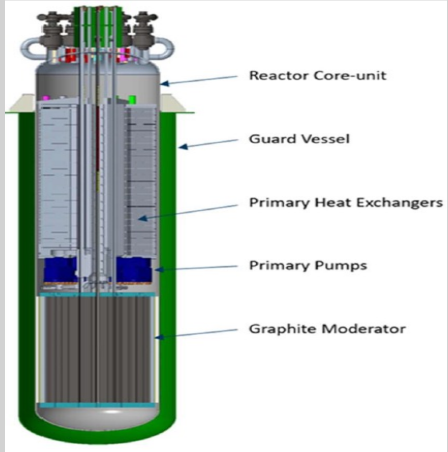
Fact card: Molten salt reactor (MSR - SMR)

Description

- Molten salt reactors (MSRs) have different characteristics from that of solid-fueled reactors. In MSRs, as no fuel structure or cladding is required, the fuel is not subject to failures due to high burnup or mechanical damage.
- Enrichment levels vary from those designs with less than 5% enrichment to some with a higher-level enrichment up to 19.9%.

Schematic





IMSR400 (Canada)

Selected MSR SMR designs

- IMSR400 (Canada)
- Compact Molten Salt Reactor, CMSR (Denmark)
- smTMSR-400 (China)
- FUJI (Japan)
- Stable Salt Reactor – Uranium, SSR-U (UK)

Pros

- The fuel is already in a molten state so there is no risk of fuel melting
- Longer fuel cycle up to 150 months

Cons

- Management of the spent molten salt, the complex mixture of fuel and molten salt which will be difficult to manage as a high-level waste

Source: Kearney Energy Transition Institute analysis

Molten salt reactor (MSR) – key technical parameters

Non-exhaustive

Fact card: Molten salt reactor (MSR - SMR)

Category	Sub-category	IMSR400	CMSR	smTMSR-400	FUJI	SSR-U
General	Country	Canada	Denmark	China	Japan	UK
	Design organization(s)	Terrestrial Energy Inc	Seaborg Technologies ApS	CAS/SINAP	ITMSF	Moltex Energy
	Design status	Detailed design	Conceptual design	Pre-conceptual design	Three experimental MSRs were built; detailed design not started	Basic design
	Plant footprint (m^2)	45,000	5,000–14,000	40,000	<5,000	100 (1 unit), ~10,000 (32 units)
	Life (years)	56	12	60	30	60
Reactor	Type/circulation	Molten salt reactor/forced	Molten salt reactor/forced	Molten salt reactor/forced	Molten salt reactor/forced	
	Coolant/moderator	Fluoride fuel salt/graphite	Fluoride fuel salt/NaOH salt (patented moderator)	LiF-BeF2-ZrF4-ThF4-UF4 fuel salt/graphite	Molten fluoride/graphite	Molten fluoride/graphite
	Thermal output, MW(t)	440 (per unit)	250	400	450	40 (per unit)
	Electrical output, MW(e)	195 (per unit)	100	168	200	16 (per unit)
Fuel	Fuel type/assembly array	Molten salt fuel	HALEU/molten salt fuel	Molten salt fuel	Molten salt with Th and U	Molten salt fuel within vented fuel tubes
	# of fuel assembly	NA	NA	NA	NA	NA
	Enrichment (%)	<5%	HALEU	19.75	2.0 (0.24% 233U + 12.0% Th), Pu or LEU can be used	6
	Refueling cycle (months)	84	144	120	Continuous operation possible	240
	Reactivity control	Short-term: negative temperature coefficient Long-term: online fuel addition	Negative temperature coefficients, regulating and safety rods, fuel salt draining	Control rods, online fuel addition, drain off fuel salt	Control rod, or pump speed, or fuel concentration	Strong fuel temperature coefficient, liquid neutron absorber thermometer

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

8.4 Appendix: factcards

Microreactors – overview

Fact card: Microreactors

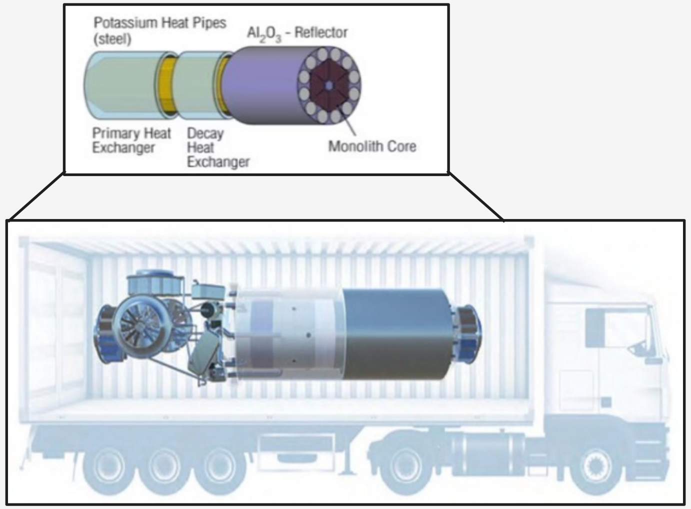
Microreactor types include generation III/III+ designs, i.e., light-water reactors (LWRs) as well generation IV designs such as molten salt reactors (MSRs), gas-cooled reactors (GCRs), metal-cooled fast reactors (MFRs), and novel heat pipe reactors (HPRs).

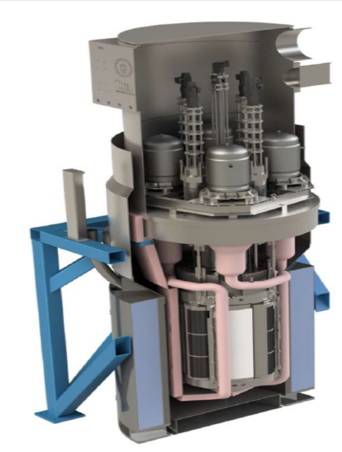
8.4 Appendix: factcards

Description

- Microreactors are a subset of SMRs. They are expected to produce up to about 20 megawatts of thermal output (or about 10 megawatts electric) and are designed to be transported as a fully contained heat or power plant both to and from potential sites.
- Distinct from other small reactor designs, heat pipe reactors use a fluid in numerous sealed horizontal steel heatpipes to passively conduct heat from the hot fuel core (where the fluid vaporizes) to the external condenser (where the fluid releases latent heat of vaporization) with a heat exchanger. No pumps are needed to effect continuous isothermal vapor/liquid internal flow at less than atmospheric pressure.
- Heat pipe microreactors may have thermal, epithermal, or fast neutron spectrums, but above 100 kWe they are generally fast reactors.

Schematic





MARVEL (USA)

Selected Microreactors designs

- eVinci^{TM} (United States)
- MARVEL (United States)
- HOLOS-QUAD (United States)
- MoveluX™ (Japan)
- UNITHERM (Russia)

Pros

- Small size and simplicity of the plant layout
- Fast on-site installation

Cons

- Licensing heat pipe reactors is a major challenge

Source: Kearney Energy Transition Institute analysis

Microreactors – key technical parameters

Non-exhaustive

Fact card: Microreactors

Category	Sub-category	eVinci™	MARVEL	HOLOS-QUAD	MoveluX™	UNITHERM
General	Country	United States	United States	United States	Japan	Russia
	Design organization(s)	Westinghouse Electric Company LLC	Idaho National Laboratory	HolosGen	Toshiba Energy Systems & Solutions Corporation	NIKIET
	Design status	Conceptual design	Equipment manufacturing in progress	Detailed design	Conceptual design	Conceptual design
	Plant footprint (m^2)	<4,000	9	30	100	10,000
	Life (years)	40	2–40 (depending on transients)	40	10–15	30
Reactor	Type/circulation	Heat pipe cooled	Liquid metal cooled thermal reactor	High-temperature gas reactor	Heat-pipe cooled/natural	PWR/natural
	Coolant/moderator	None (heat pipe cooled)/metal hydride	Sodium-potassium eutectic, hydrogen in fuel	Helium/graphite	None (heat-pipe cooled)/calcium hydride	High purity water/high purity water
	Thermal output, MW(t)	7–12	0.075–0.1	22	10	30
	Electrical output, MW(e)	2–3.5	0.015–0.027	10	3–4	6.6
Fuel	Fuel type/assembly array	TRISO or another encapsulation	Uranium zirconium hydride	TRISO-UCO hexagonal graphite elements	Silicide (U3Si2)/hexagonal	UO2 particles in a metallic silumin or zirconium matrix, metal-ceramic
	# of fuel assembly	Monolith core	6	NA	66	265
	Enrichment (%)	5–19.75	19.75	19.95	4.8–5.0	19.75
	Refueling cycle (months)	>36	>60 (up to 240)	96	Continuous	200
	Reactivity control	Ex-core control drums	Four ex-core, safety-related control drums, one defense-in-depth central shutdown rod	Redundant independent banks of control drums and shutdown rods	In-Ga expansion module (IGEM)	Soluble boron and control rod insertion

Sources: IAEA's Advanced Reactors Information System (ARIS); Kearney Energy Transition Institute analysis

Appendix: other information

Energy in fusion is released when nuclei collide at extremely high temperatures to form a new nucleus

Non-Exhaustive

8.5 Appendix: other information

Fusion - Theoretical definition

Nuclear fusion occurs when **nuclei collide** at extremely high temperatures forming a new nucleus.

– The high temperature provides the nuclei with enough energy to overcome the Coulomb barrier.

When the total mass of the resulting nucleus is **less than the mass of the two original nuclei,** energy is released.

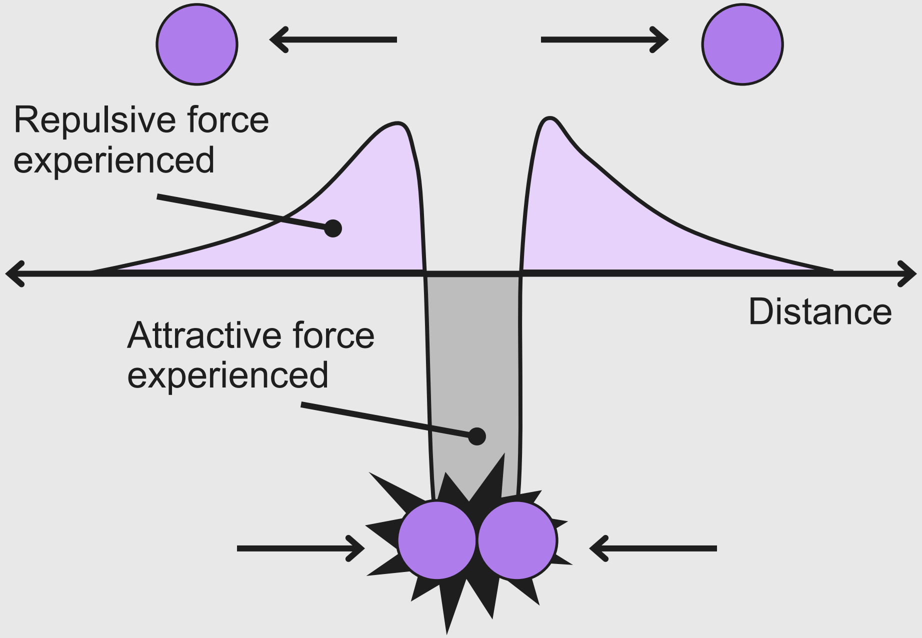
– The energy released maintains the high temperature plasma of the light nuclei, allowing the fusion to be self-sustained (no long-lived high-level waste is produced).

Concept limitations

It is unlikely that two positively charged nuclei get close enough to fuse due to the electrostatic repulsive force unless they have sufficient energy to overcome the Coulomb barrier

– In order to achieve this and obtain a sustained reaction, **systems must be heated to at least 90 million °F (about 50 million °C), which results in a significant challenge for today's material science.**

Proton experiencing Coulomb barrier



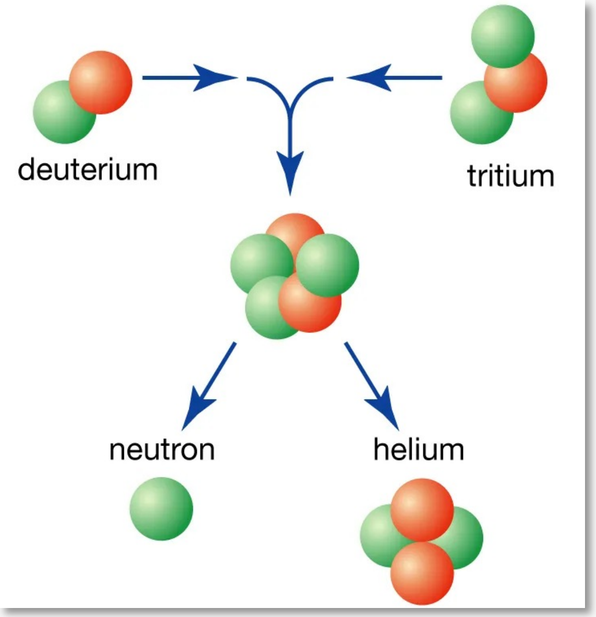
Sources: Britannica; IAEA; Kearney Energy Transition Institute analysis

Deuterium (D) and tritium (T) are set to be the fuel alternative for fusion with the greatest potential and efficiency

Fuel potential alternatives in fusion

- The most efficient fusion reaction for potential power generation is between **deuterium (D) and tritium (T)**, which form a helium nucleus and a neutron (D + T → He + n).
  - The energy released based on Einstein´s equation $E=mc^2$ is $E = (mHe + mn – mD – mT)c^2$ and has a positive value of 2.8×10^{-12} J.
- In perspective: 1,000 kg of deuterium contain ~3×10^{29} atoms
  - One ton of deuterium consumed through the fusion reaction with tritium releases 840 PJ.
  - One ton of deuterium burnt in a fusion reaction has the energy equivalent of ~29 billion tons of coal.

Schematic view of deuterium and tritium fusion



Energy density of materials

Material	Energy density (MJ/kg)
Firewood	16
Brown coal	< 17.4
Crude oil	42-47
Natural uranium	5×10^5 - in standard reactor
Enriched uranium[1]	3.9×10^6 - in standard reactor
Deuterium	840×10^9 – in fusion reaction

8.5 Appendix: other information

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[1] Enriched uranium to 3,5%

Note: EJ is exajoules, which corresponds to 10^{18}J, PJ is petajoules which corresponds to 10^{15}J; GJ is gigajoules which corresponds to 10^9J
Sources: Britannica; IAEA; World Nuclear Association, Heat values of various fuels; Kearney Energy Transition Institute analysis

Currently, the leading fusion experiments use magnetic confinement machines

Non-Exhaustive

There are other approaches to fusion such as inertial confinement, magnetized target fusion and hybrid fusion which combines fusion and fission reactions.

8.5 Appendix: other information

Fuel management in fusion experiments

– To make fusion possible, the gaseous reactants are heated and form a plasma, a state of matter in which electrons detach from atoms at extreme temperatures, forming an ionized gas.

– Most fusion experiments today use **magnetic confinement machines** to contain the plasma, such as tokamaks, stellarators and spheromaks, among others.

  – About 60 experimental tokamaks exist today

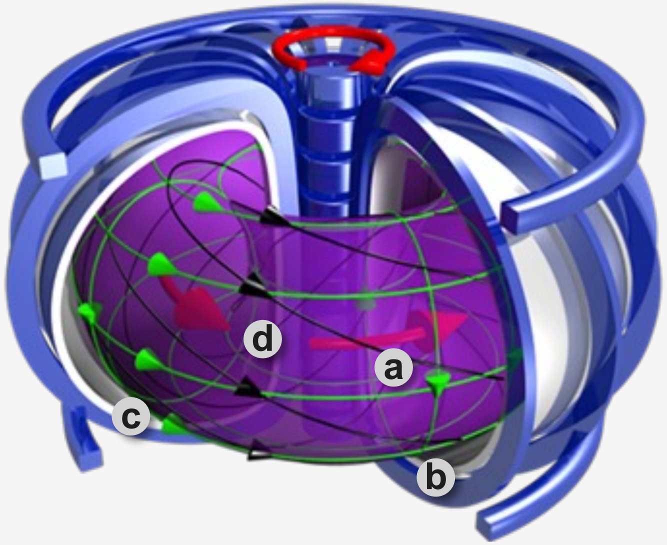
How a tokamak works

a An electric field induced by a transformer drives a current (big red arrows) through the plasma.

b This generates a magnetic field that bends the plasma current into a circle (green vertical circle). This prevents leakage and the doughnut-shaped vessel ensures the creation of ~~a~~ vacuum.

c The other magnetic field is going around the length of the doughnut (green horizontal circle).

d The combination of these two fields creates a helix (shown in black), so that the plasma is highly confined within the vessel, avoiding collisions of the plasma-constituting ionized atoms with the walls.



Sources: IAEA, Magnetic Fusion Confinement with Tokamaks and Stellarators; US Fusion Energy, Approaches to fusion; Kearney Energy Transition Institute analysis

The IAEA works with its Member States on setting and reviewing safety standards, and it is already addressing the challenges that exist around SMR licensing

International Atomic Energy Agency (IAEA)

176 member states

As part of the UN system, it is the international center for **nuclear cooperation**. It issues documents that contain **recommendations** and **good practices**, the most important of which are:

- Convention on Nuclear Safety (1994), which defines safety standards
- Vienna Convention, Paris convention, and the Joint Protocol relating them (1996), which establish compensation for injury to, or loss of life of any person; and for damage to, or loss of any property, caused by a nuclear accident

The mission of the IAEA is "*to work for the safe, secure, and peaceful uses of nuclear science and technology, contributing to international peace and security and the United Nations' Sustainable Development Goals.*"

Concerning SMRs, several member states supported the creation of the **SMR Regulator's Forum** in 2015, which is directed by the IAEA, *"to identify, understand, and address regulatory challenges that may arise in future SMR regulatory discussions."* It published **reports** in 2020 on **Licensing Issues**, on **Design and Safety Analysis**, and on **Manufacturing, Construction, Commissioning, and Operations.**

Additionally, the agency is working on the establishment of a **technology-neutral framework** for safety to help **harmonize international approaches** based on existing standards.

Sources: IAEA, 2021, Technology Roadmap for SMR Deployment; IAEA Website; Kearney Energy Transition Institute analysis

Former coal plant workers could be rehired and (re)trained on nuclear specifics as NPP workers depending on the plant-specific design and operational details.

Many of the positions require similar technical expertise and rehiring could be extensive when the necessary skills overlap closely, and the community is relatively remote.

8.5 Appendix: other information

Comparison of coal plant positions and nuclear positions

For NuScale 924 MWe SMR

Coal plant position	# Dedicated coal positions	SMR position	# Dedicated SMR positions	Position type	Degree of retraining required
Operations supervisor	5	Senior reactor operator	5	Supervisor	High
Control room operators	10	Reactor operator	15	Operator	High
Field operator	15	Non-licensed operator	25	Operator	Low
Lab operator/chemistry/scrubber	4	Chem tech	14	Craft	Medium
Maintenance supervisor	2	Maintenance supervisor	3	Supervisor	Medium
Mechanical craft	12	Mechanical craft	21	Craft	Low
I&C craft	9	I&C craft	10	Craft	Medium
Electrician craft	5	Electrician craft	11	Craft	Low
Technician	11	Technician	13	Laborer	Low
Security officer	20	Security officer	48	Laborer	Low
Sub total	**93**		**165**		
All other positions	14		72	42 are O&M support (planners, outage, etc.)	Medium
Total on-site positions	**107**		**237**		
Possible centralized positions			33		
Total positions			**270**		

Sources: NuScale; ScottMadden analysis, 2021, Gone with the steam; Kearney Energy Transition Institute analysis