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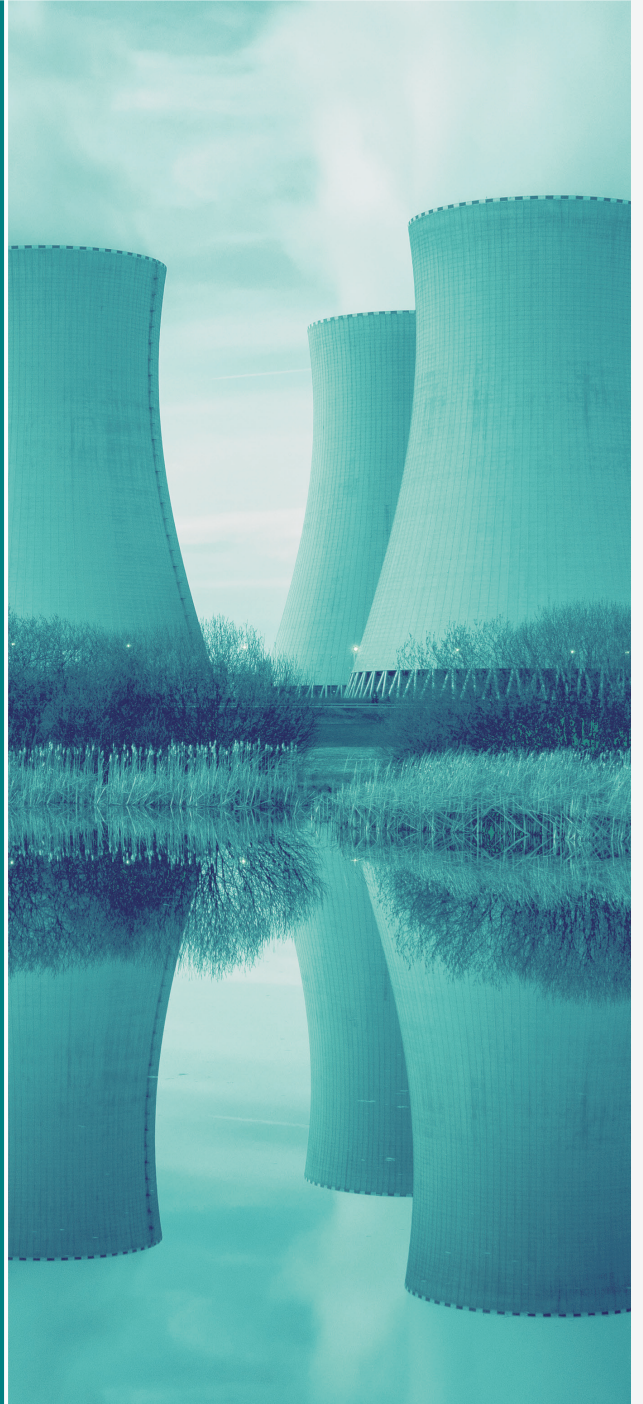
Energy Futures Lab

White Paper

Nuclear

Challenges and Opportunities

The Future of
Nuclear Power
in the UK



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Acronyms & Abbreviations

ABWR	Advanced Boiling Water Reactor	LFR	Lead-cooled Fast Reactors
AFCP	Advanced Fuel Cycle Programme	LLW	Low-level Waste
AGR	Advanced Gas-cooled Reactors	LWR	Light Water Reactor
BWR	Boiling Water Reactor	MOX	Mixed-Oxide
CANDU	CANada Deuterium Uranium	MSR	Molten Salt Reactor
CCS	Carbon Capture and Storage	mSv	Millisieverts
CfD	Contracts for Difference	NDA	Nuclear Decommissioning Authority
CNS	Convention on Nuclear Safety	NEA	Nuclear Energy Authority
CO₂	Carbon Dioxide	NFF	Nuclear Fuel Fund
COEX	CO-EXtraction	NLF	Nuclear Liabilities Fund
CPPNM	Convention on the Physical Protection of Nuclear Material	NPP	Nuclear Power Plant
D₂O	Deuterium Oxide	NRA	Nuclear Regulation Authority
DECC	Department for Energy and Climate Change	NZIP	Net Zero Innovation Portfolio
FBR	Fast Breeder Reactor	O&M	Operation and Maintenance
FDP	Funded Decommissioning Programme	OECD	Organisation for Economic Co-operation and Development
FEED	Front End Engineering Designs	ONR	Office for Nuclear Regulation
FiT	Feed-in Tariffs	PCI	Pellet-clad Interaction
GBN	Great British Nuclear	PPA	Power Purchase Agreement
GDF	Geological Disposal Facility	PUREX	Plutonium URanium EXtraction
GDP	Gross Domestic Product	PWR	Pressurised Water Reactor
GFR	Gas-cooled Fast Reactors	R&D	Research and Development
GJ	Gigajoule	RAB	Regulated Asset Base
GWe	Gigawatt electrical	RBMK	Reaktor Bolshoy Moshchnosti Kanalnyy reactor
HLW	High-level Waste	REMIX	REgenerated MIXture
HWR	Heavy Water Reactor	SCWR	Super-critical Water Reactor
IAEA	International Atomic Energy Agency	SFR	Sodium-cooled Fast Reactors
IEA	International Energy Agency	SMR	Small Modular Reactor
ILW	Intermediate-level Waste	UF₆	Uranium Hexafluoride
INES	International Nuclear and Radiological Event Scale	UO₂	Uranium Dioxide
ISDC	International Structure for Decommissioning Costing	VHTR	Very High Temperature Reactor
ISO	International Standard of Operation	VLLW	Very low-level Waste
LCOE	Levelised Cost of Electricity	VVER	Vodo-Vodyanoi Energetichesky Reactor
		WANO	World Association of Nuclear Operators

Executive Summary

Nuclear power can potentially play a critical role in achieving net-zero carbon emissions in the UK's energy landscape. With the nation committed to ambitious targets for decarbonisation, nuclear energy presents a low-carbon alternative, offering reliable electricity generation and contributing to energy security. Globally, nuclear power continues to be a cornerstone of many nations' energy strategies, with investments in research and development driving advancements in safety, efficiency, and cost-effectiveness. The UK's nuclear industry faces a pivotal moment as the nation steers toward a net-zero carbon future. Central to this transition is the cultivation of a skilled workforce, strategic international partnerships, and robust policy frameworks.

Demographic shifts within the workforce underscore the urgency for knowledge continuity and skills transfer. The impending retirement of experienced professionals threatens to lose invaluable tacit knowledge, necessitating immediate interventions to address skills deficiencies and foster talent pipelines. Collaborative initiatives with academia and research institutions are essential for cultivating a skilled workforce equipped to meet industry's evolving and increasing demands.

International collaborations emerge as a key player in advancing nuclear power ambitions. Partnerships with organizations such as the World Association of Nuclear Operators (WANO) and the International Atomic Energy Agency (IAEA) facilitate technology sharing, expertise access, and cost-sharing, driving innovation and safety standards. By aligning with global standards and promoting knowledge exchange, the UK can leverage international partnerships to bolster its nuclear capabilities.

As the UK charts its course towards a sustainable energy future, the economics of nuclear power loom large. Balancing the upfront capital costs against long-term electricity pricing

is paramount; and this balance influences the viability of nuclear projects and their contribution to the energy mix. Strategic workforce planning, international collaborations, and policy frameworks play pivotal roles in shaping the trajectory of the nuclear industry, ensuring it remains resilient and competitive in a rapidly evolving energy landscape.

In the context of the UK's nuclear energy aspirations, the identified gap between planned and proposed capacities and the targeted 24 GWe nuclear generation capacity by 2050 underscores the financial and strategic challenges ahead. Bridging this gap necessitates substantial investment, with potential implications for public finances and policy and private sector involvement. In addition to the upfront costs of nuclear projects, ongoing operation and maintenance (O&M) costs and decommissioning expenses also need to be considered. Policy frameworks must account for these comprehensive costs to ensure sustainable financing and long-term viability of nuclear power in the UK. Given the urgency of reaching targets before 2050, the UK needs to address these economic considerations promptly to effectively finance nuclear projects.

Diversified funding sources and public-private partnerships are essential for financing nuclear projects and fostering innovation. Public engagement initiatives play a critical role in building trust and support for nuclear power, highlighting its significance in achieving net-zero objectives. Assuming the proposed projects proceed as planned, the calculated cost to produce the remaining required gigawatts (GW) of nuclear power ranges from 5.2 to 10.4 billion pounds per year.

In conclusion, with collaborative efforts to develop the workforce and supportive policies, the UK can position itself as a leader in nuclear energy, driving the transition to a low-carbon economy.

1. Introduction

A global growth of both population and living standards is driving an increase in worldwide energy consumption. The energy consumption per capita has increased from 27.2 to 61 GJ/y since the 1950s (Syvitski et al., 2020). which results in increased carbon dioxide (CO₂) emissions. This exacerbates already significant CO₂ cumulative total emissions, leading towards a global rise in temperature. In order to limit global warming to 1.5 °C, a major transition to decarbonised energy

is being studied and implemented. Currently, the main sources of global electrical energy generation are coal-based thermal power and natural gas followed by hydroelectric plants and nuclear power.

A range of technologies will be needed to achieve net-zero. These include not only renewable generation-based technologies, but also nuclear power, as well as fossil fuel

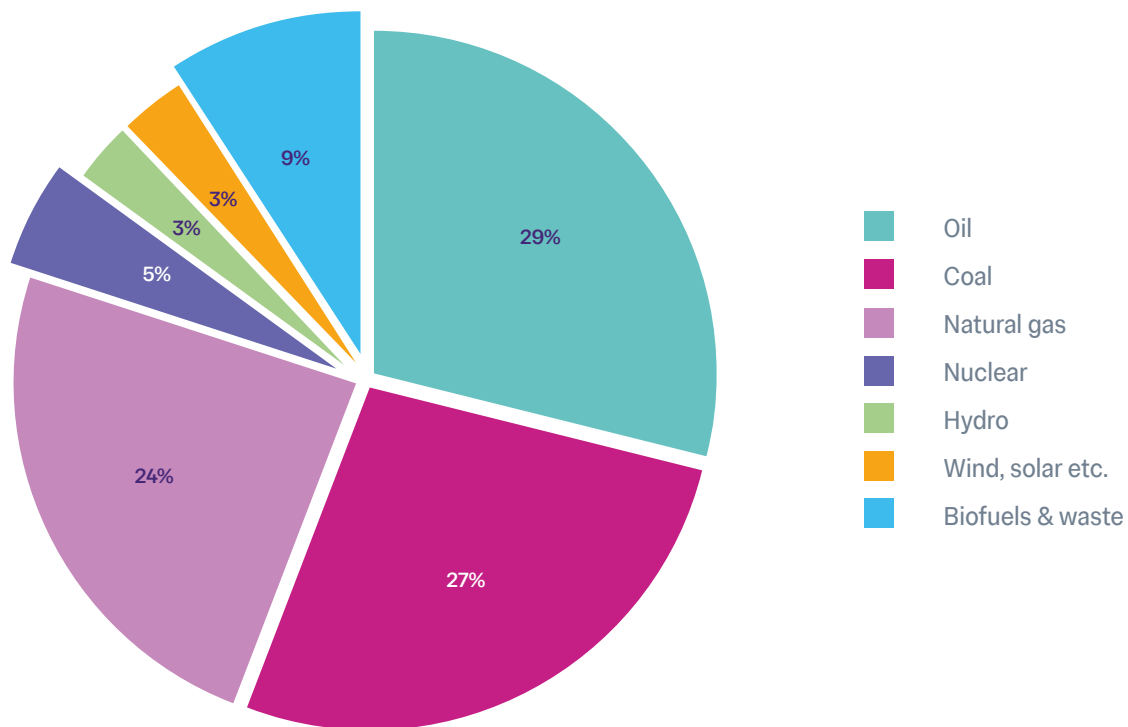


Figure 1-1: Global energy supply by source. Adapted from (IEA 2023)

generation with carbon capture and storage (CCS). Nuclear power has historically been a significant contributor to low-carbon electricity. However, it faces unique challenges including high capital costs, sufficient long-term storage of nuclear waste, disposal of used fuel and low public acceptance. Nuclear power is crucial to secure a global pathway to net zero under the IEA Net Zero Emission (NZE)

2050 scenario, where the global share of nuclear power is projected to amount to ~8% by 2050 (NZE) scenario, where the global share of nuclear power amounts to ~8% by 2050 (IEA, 2022)

Nuclear power accounts for 10% of the world's overall electricity generation and 18% of electricity in OECD

countries, however, nuclear power production varies substantially by country. Countries such as the UK, France, China, Poland and India have announced energy strategies that include significant roles for nuclear power (Bloomberg, 2023; DESNZ, 2024a; Press Information Bureau, 2023). At the United Nations Climate Change Conference (COP28), 22 countries pledged to triple nuclear power capacity from their 2020 levels, by 2050. Countries participating in the pledge include the UK, USA, Canada, and France (U.S. Department of Energy, 2023). Moreover, the United States is investing in advanced technologies for nuclear power generation (Office of Nuclear Energy, 2023). The OECD's International Energy Agency (IEA) concluded in a 2019 report that failure to invest in existing and new nuclear power plants in advanced economies would hinder the transition to cleaner energy (IEA, 2022). In addition, an IEA report published in 2022 concluded that achieving net-zero targets globally will be significantly harder and more expensive without nuclear energy (IEA, 2022).

The UK currently generates ~15% of its electricity from about 6.5 GW of nuclear capacity. New government plans have ambitions for nuclear power to reach 25% of electricity production (DESNZ, 2022). However, most existing nuclear generation capacity will be decommissioned in the next 10 years. Hence, there is a need to explore current and future nuclear power technologies, as well as their technology readiness level, costs, and the required policy and funding mechanisms to sustain and expand nuclear power generation in the UK and maintain British energy security in line with government policies.

This white paper will evaluate the prospects for new nuclear technology to contribute to a significant proportion of UK power generation, whilst providing a rigorous, evidence-based evaluation of realistic timescales, costs, funding mechanisms, and required skillsets for its development. It aims to address key questions surrounding the future of nuclear power in the UK, including providing insight to the following questions:

1. What are the critical skill sets required for the successful implementation, operation, and maintenance of nuclear power projects in the UK, and how can the workforce be developed and sustained?
2. What role does international collaboration play in the UK's nuclear power ambitions, particularly in terms of technology sharing, expertise access, and cost-sharing?
3. What are the economic implications of new nuclear power projects in the UK, including upfront costs, operation and maintenance expenses, and decommissioning obligations, and how should these be factored into policy frameworks for financing and sustainable prioritization?
4. Are timelines realistic for the deployment of new nuclear power plants in the UK, considering regulatory approval processes, construction lead times, and technology readiness levels?
5. How can the high upfront capital costs of nuclear projects be managed, and what funding mechanisms are available to support new nuclear developments?

By addressing these questions, this briefing paper aims to provide policymakers, industry stakeholders, and the public with a comprehensive understanding of the opportunities and challenges associated with the expansion of nuclear power generation in the UK. Through evidence-based analysis and strategic recommendations, it seeks to inform decision-makers and contribute to the development of a sustainable and resilient energy future.

2. Technology

A nuclear reactor is designed to convert the binding energy of atoms (the energy released when combining individual protons and neutrons into a single nucleus) into thermal energy and eventually electrical energy. The binding energy in the nucleus of an atom is about 6 orders of magnitude higher than what any chemical reaction can release, meaning that a very large amount of energy can be released from a very small amount of material (Haydock, 2005). The atomic binding energy can be released using two different nuclear

reaction mechanisms: nuclear fission and nuclear fusion. Nuclear fission revolves around splitting a larger nucleus, whereas nuclear fusion includes the merging or ‘fusing’ of nuclei together. Currently, all energy released from nuclear reactors globally is produced through nuclear fission. Nuclear fusion is at a much lower technology readiness level and is currently in the R&D and early demonstration phases, with no commercially operating plants. See box 1 for more information on nuclear fusion.

Box 1: Nuclear Fusion

Nuclear fusion powers the sun and stars. In a fusion reaction, two light nuclei merge to form a single heavier nucleus, chiefly hydrogen atoms fusing together to form helium. Fusion is very difficult to achieve due to the strong repulsive electrostatic forces between the positively charged nuclei. However, at extremely high temperatures repulsion can be outweighed by the attractive nuclear force that bonds protons and neutrons together allowing the nuclei to undergo fusion.

Nuclear fusion is a promising technology and is being intensively researched. It can generate four times more energy per kilogram of fuel than fission and nearly four million times more energy than burning oil or coal (IEF, 2022). Generally, fusion reactor technology uses a mixture of deuterium or tritium, both of which are heavy isotopes of hydrogen. Deuterium can be extracted from seawater. However, tritium is not as common, and the process of breeding is required for its production (World Nuclear Association, 2022g). Breeding in fusion reactors refers to the

production of tritium from lithium using neutrons generated in the fusion reactions. Furthermore, unlike nuclear fission, fusion reactors are not expected to produce long-lived radioactive products, and only intermediate level waste (World Nuclear Association, 2022g).

A challenge with nuclear fusion is to achieve a net energy gain - more energy emitted from the reaction than the energy inputted into the process. Essentially, for fusion to occur, temperatures over 100 million degrees Celsius are needed, whilst managing pressure, materials’ integrity, and magnetic forces simultaneously. Many countries are involved in fusion research including countries in the EU, UK, USA, Russia, and Japan as well as China, Brazil, Canada, and South Korea (Max Planck Institute, 2023). Relatively close conditions that are required for fusion have been achieved in experiments, but it is still a heavily developing research area. There is considerable uncertainty about when fusion power will be commercialised, however estimates range from as close as 2030 to ‘decades away’ (IEF, 2022).

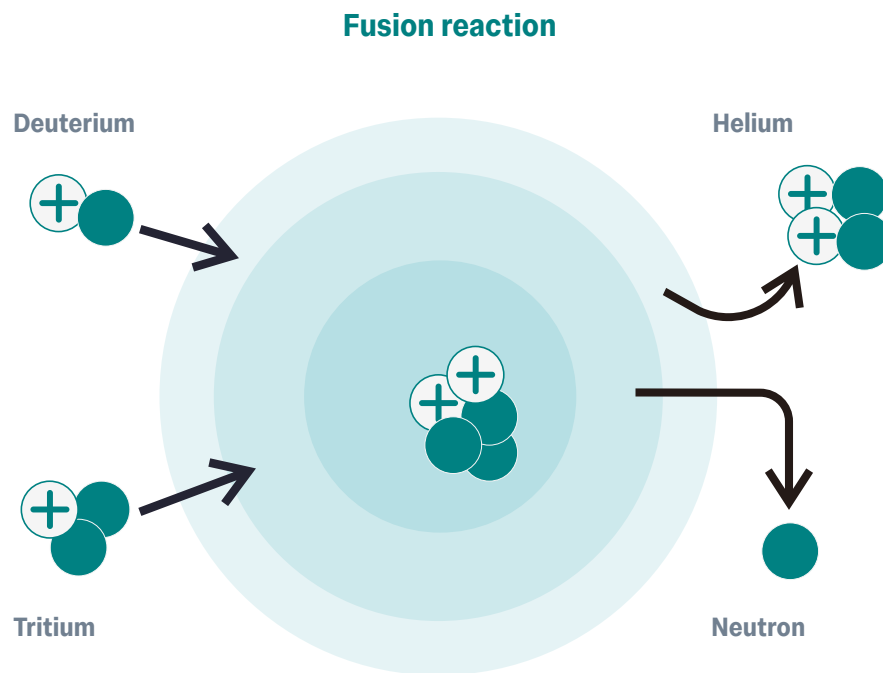


Figure 2-1: Fusion reaction between deuterium and tritium to form a helium nucleus

2.1 Nuclear Fission Fuel Cycle

The events associated with electricity generation from nuclear fission reactions are collectively referred to as the “nuclear fuel cycle”. The nuclear fuel cycle starts with the mining of uranium ore and ends with the disposal of spent fuel.

Uranium is a metal that emits radiation slowly in the form of alpha particles. There are several areas around the world where the concentration of uranium in the ground is high enough to make its extraction economically feasible. At such concentrations, it is commonly referred to as “uranium ore”. Global uranium deposits are identified based on their geological setting and divided into different categories identified by the IAEA (IAEA, 2013). Generally, uranium is more abundant than gold and roughly as common as tin (IAEA, 2013). For most nuclear reactor types used today, U-235 is required due to its fission capability after absorbing low energy

neutrons. In nature, only 0.7% of natural uranium contains U-235, with the remainder made up of U-238 (World Nuclear Association, 2022f). Enrichment, described in section 2.2, may be required for some fuels for nuclear reactors. However, the need for enrichment arises due to parasitic absorption of neutrons often by the water coolant.

To prepare uranium for use in a nuclear reactor, the metal undergoes mining, milling, conversion into uranium hexafluoride, enrichment, and fuel fabrication. After using uranium in the reactor for electricity production, the used fuel undergoes further processing steps including temporary storage, reprocessing, and recycling before waste disposal. The nuclear fuel cycle is described in Figure 2-2.

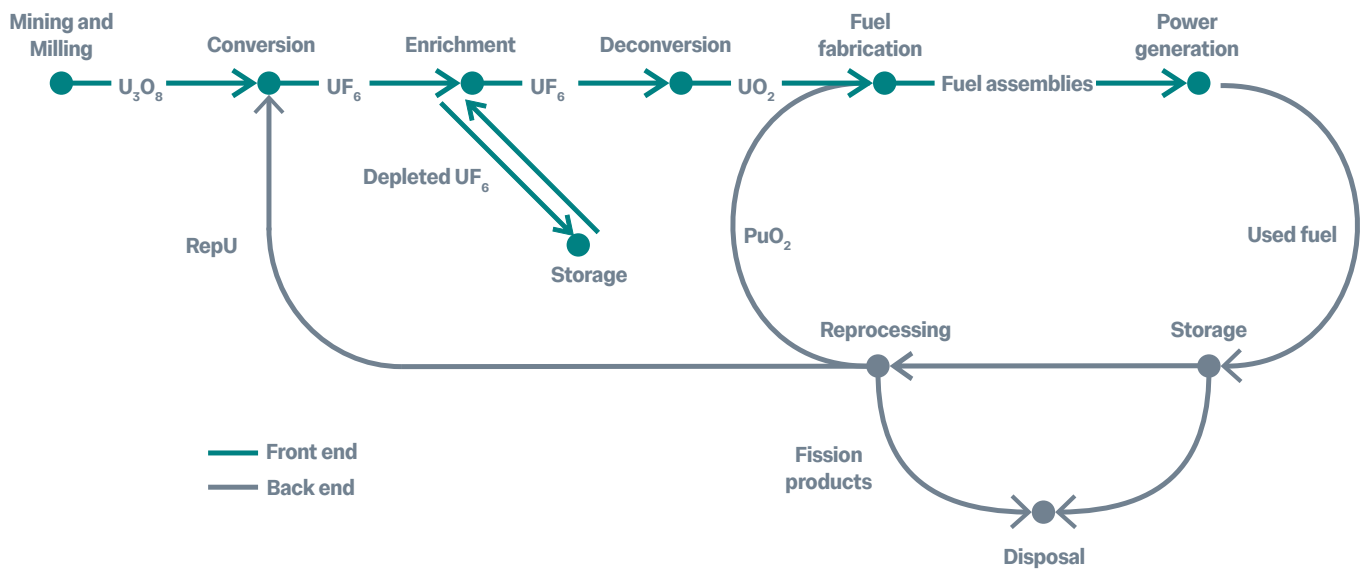


Figure 2-2: Nuclear fuel cycle

Uranium mining

The method used for mining is chosen based on the nature of the ore, its safety, and economic considerations. A large proportion of the world's uranium is mined using in situ leaching, which circulates oxygenated groundwater to dissolve the uranium oxide in the porous ore and bring it to the surface. Other types of mines, including underground and open pits, as well as heap leaching are also used to extract uranium. Heap leaching revolves around irrigating the ore with acid or alkaline solvents. The recovered liquid phase is further treated to recover uranium using separation techniques such as ionic exchange. Although the extracted ore is radioactive, the likelihood of receiving a harmful dose from the ore is minuscule. For a person to receive a dose of 1 millisieverts (mSv), they would have to stand one meter away from a 200-litre drum for 1000 hours (USEC, 1995).

Uranium milling

Milling is usually carried out close to the uranium mine and revolves around extracting uranium from the ore. In a mill, the ore is crushed until it forms a fine slurry which is dissolved in sulfuric acid. Uranium is then recovered from the solution in the form of a uranium oxide precipitate. It is then dried

and packed as a concentrate that is commonly referred to as "yellowcake", which typically contains more than 80% uranium. The remaining ore is considered tailings and must be isolated since it contains most of the radioactivity.

Conversion and enrichment

This process focuses on converting uranium oxide to fissile uranium so that it can be used as fuel in a nuclear reactor. Most thermal reactors need the U-235 isotope's concentration to be between 3.5 – 5% to sustain the chain reaction (see below). The enrichment process requires uranium to be in a gaseous form. Initially, uranium oxide is converted to uranium dioxide, which can be used in some reactors as fuel. Uranium dioxide is then converted to uranium hexafluoride (UF_6). UF_6 can be gasified at low temperature and pressure (from approximately -4°C and 0.4 psi, UF_6 is a gas). Differences in solid, liquid, and gas states are observed based on temperature and pressure, respectively. UF_6 is then enriched using a common centrifuging process, that separates the uranium isotopes based on their mass. The enriched UF_6 is then converted back to enriched uranium oxide.

Fuel fabrication

The nuclear reactor fuel is generally used in the form of ceramic pellets, which are approximately 1 cm wide in diameter (EIA, 2023) and 1.5 cm in length (World Nuclear Association, 2024d). Uranium oxide is baked (or sintered) at temperatures as high as 1600 – 1750 °C to form the pellets. The pellets are then milled to precision, before being inserted into fuel rods that are used in most reactor designs. Precise dimensions of the fuel pellets must be ensured, to provide quantity consistency. The fuel rods hold the pellets in place, and contain radioactive gases released by the pellets. A combination of fuel rods, held in grid spacers, form the fuel assembly for the reactor (IAEA, 2013).

Used fuel

After using the nuclear fuel, the concentration of fission products will increase to an extent that makes the fuel impractical for use. The disposal of the used fuel will differ based on the existing policies in different countries. Generally, it is unloaded into a storage pond where the water acts as a radiation shield and absorbs the generated heat. The heat is removed through external heat exchangers. The used fuel can either be reprocessed for recovery and recycling or it may eventually undergo final disposal.

2.2 Nuclear Reactors

During nuclear fission, the nucleus of a heavy atom splits into two or more smaller nuclei and releases energy. For instance, when U-235 is bombarded by a neutron, it forms an excited state U-236, before splitting into Ba-144 (barium) and Kr-89 (krypton) atoms. (World Nuclear Association, 2022) A few neutrons (two or three) and energy are also released. The extra

neutrons produced will cause nuclear fission in surrounding U-235 atoms, hence giving rise to the original name of the reaction as “nuclear chain reaction”.

Nuclear fission

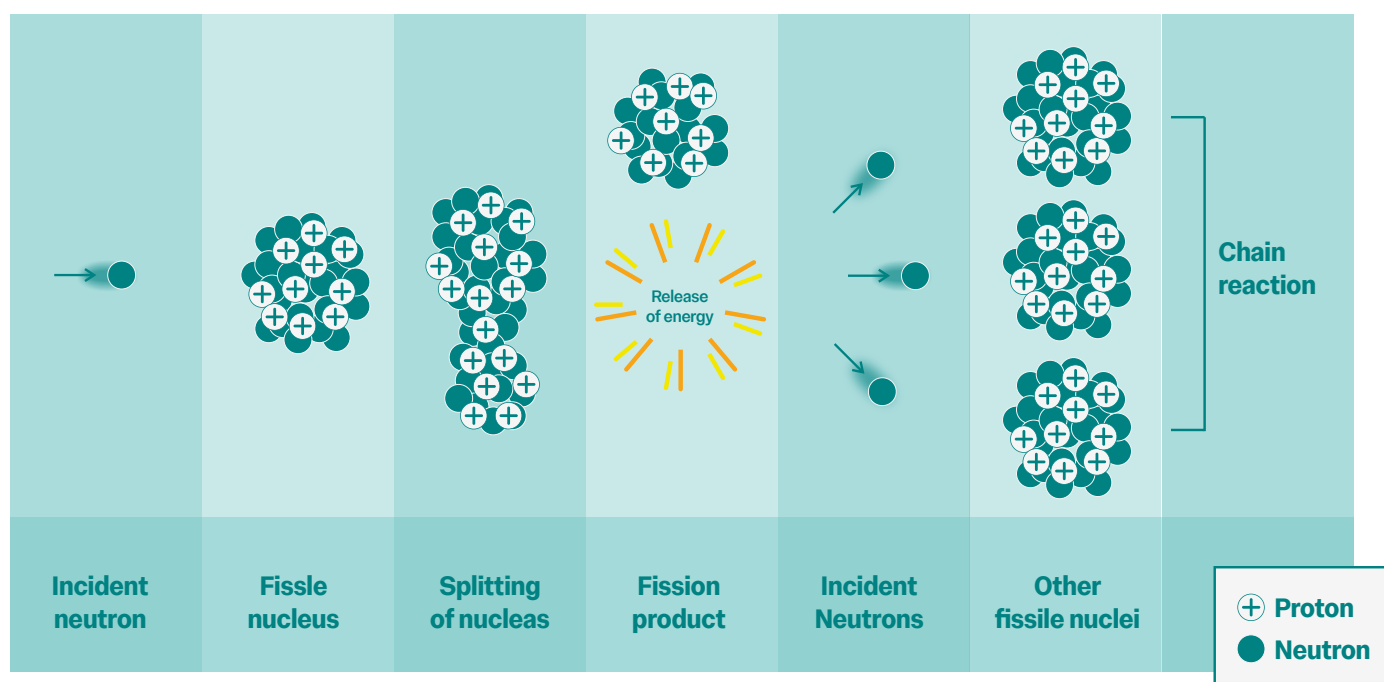


Figure 2-3: Fusion reaction

The nuclear fission process revolves around nuclei splitting, and the splitting of nuclei decreases as the speed and energy of emitted neutrons increases. To maintain a chain reaction, neutrons therefore need to be slowed down by a moderator. Energy from the neutrons released during the fission process must be extracted from the reactor core, which is done by the coolant. A coolant ideally needs certain properties to be suitable for use in the nuclear reaction process, including a large thermal capacity, stability when exposed to radiation, low absorption rate of neutrons and being non-corrosive.

Nuclear reactor types can be distinguished according to several constituents, including their fuel, moderator, and coolant. A reactor which uses slow or “moderated” neutrons is called a thermal reactor, whereas reactors that do not use a moderator are called fast breeder reactors. There are usually three types of thermal reactors, as explained below (Wealer et al., 201 C.E.)

Graphite-moderated

Neutron energies are moderated by graphite and the reactor is composed of many channels in which coolants capture and transport heat. Depending on the reactor type, the coolant can be a gas (CO_2 , helium), water, or molten salts. This type of reactor does not operate under as high a pressure as many water-cooled reactors and hence the fuel rods containing uranium can, to an extent, be loaded and unloaded in a continuous mode. Generally, graphite and gas-cooled reactors have a lower fuel cycle cost but higher capital costs.

Heavy water reactors (HWR)

Heavy water is a form of water where the hydrogen atoms are replaced with deuterium. Heavy water (D_2O) is usually used as both the moderator and coolant. HWRs are also able to use natural uranium oxide (UO_2) as fuel due to the low neutron absorption rate of the moderator. However, a HWR is associated with relatively high capital costs due to its need of significant space and material.

Light water reactors (LWR)

LWRs are the most widely deployed reactor type globally, and they use water both as moderator and coolant. The boiling water reactor (BWR) and pressurised water reactor (PWR) are the two main types of LWRs. The BWR has one circuit that transports the steam from the reactor core into the turbine and back to the core, whereas the PWR utilises two water circuits. The first circuit in a PWR heats water by pumping it through the reactor core. At the same time, the heat is passed through a heat exchanger in the secondary circuit, where steam is generated to be expanded in the turbine. Reactor coolant pumps are used to circulate the water back to the first circuit. LWRs are associated with relatively low capital cost due to their compactness but a higher fuel cycle cost.

Fast breeder reactors (FBRs) are reactors that do not use a moderator, in contrast to typical thermal fission reactors. The lack of a moderator enables fast neutrons to be used in the transmutation process. FBRs can be designed based on two different fuel cycles: the Th-232 - U-233 cycle or the U-238 – Pu-239 cycle. FBRs can regenerate their own fuel, for example, if U-238 in the uranium-plutonium is partially converted to Pu-239 after being exposed to neutron bombardment, it can be later used as a fuel again. Often, FBRs produce more fuel than they consume, which explains the name “breeder reactors” (Karam, 2006). The three fast breeder reactor types are gas-cooled fast reactors (GFR), sodium-cooled fast reactors (SFR), and lead-cooled fast reactors (LFR).

In contrast to conventional thermal fission reactors, FBRs are mostly experimental (the conditions required for operation are tested) despite having been developed many decades ago. However, some countries have been operating certain types of fast reactor. Examples include Russia, who has operational sodium-cooled fast reactors at present. Additionally, five experimental reactors and three demonstration reactors are operational worldwide, and are located in Russia, India, China, and Japan. Demonstration reactors typically use proof-

of-concept designs for reactors which have not been built (World Nuclear Association, 2021b). The future of FBRs lies in the Generation IV reactor fleet, with three fast reactors with different cooling mechanisms listed as a part of this generation, as described below.

Gas-cooled fast reactors

A very-high-temperature reactor (VHTR) with an outlet temperature of 750-1000 °C. The coolant used is helium, with multiple fuel forms under consideration.

Sodium-cooled fast reactors

These reactors are operational at outlet temperatures of 500-550 °C. Liquid sodium is used as a coolant, which can be implemented as a pool or loop-type cooling. Fuel types of potential use for these reactors are mixed oxide (MOX) fuels.

Lead-cooled fast reactors

These reactors are operational at outlet temperatures between 500 °C to 600 °C. Molten lead or lead-bismuth eutectic is used as a coolant. Fuel designs use? uranium metal, metal oxides or metal nitrides.

2.2.1 Generations of Nuclear Reactors

Overall, nuclear power technologies have been developed in four generations, depending on design capabilities (Figure 2-4). Generation I includes the prototype and nuclear power reactors that were developed for civil power generation. They include the Shippingport in Pennsylvania, Dresden-1 in Illinois and Calder Hall-1 in the UK. A commercial fleet of Generation I nuclear reactors included Magnox reactors which are CO₂ gas-cooled reactors that use natural uranium as fuel and graphite as moderator. A total of 11 Magnox reactors were

built in the UK, and other countries such as Japan and Italy have implemented the reactor design. The fuel cladding is made of magnesium-aluminium alloys, which explains the use of the acronym Magnox (Magnesium non-oxidising). Fuel cladding serves as a protective layer around the nuclear fuel, preventing the release of fission products into the reactor coolant. All Magnox reactors in the UK have now been shut down, the last one of which, based at Wylfa on Anglesey, ceased operations in 2015 (Xenofontos, 2018).

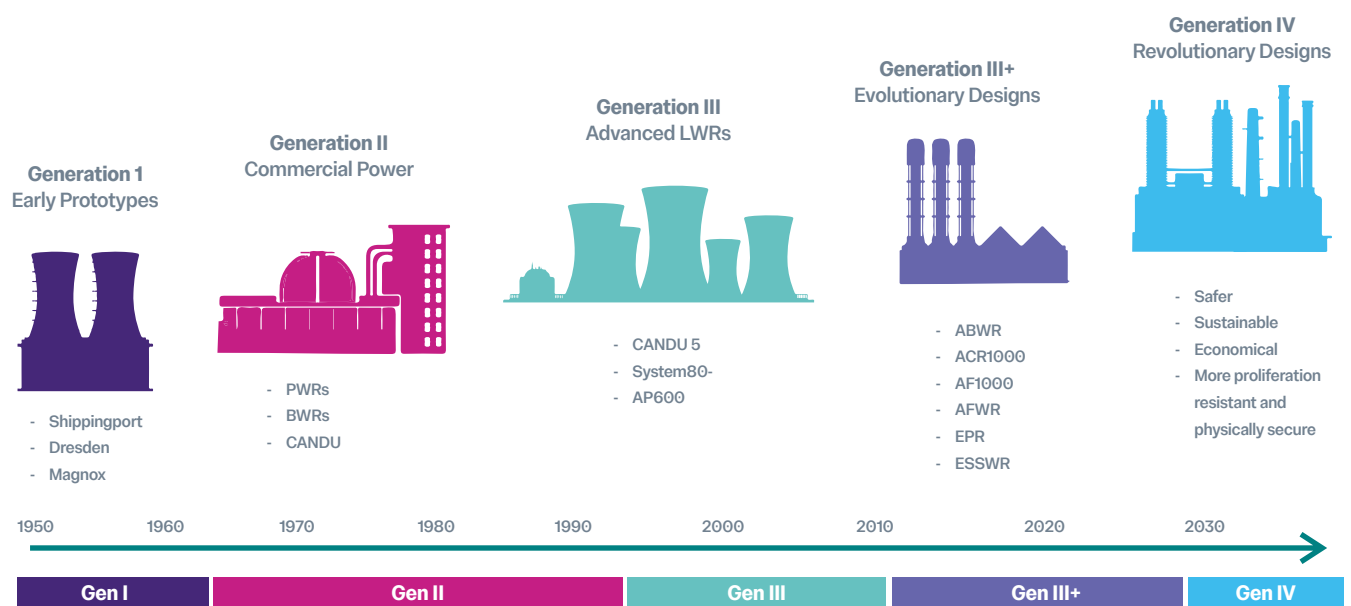


Figure 2-4: Generation I to Generation IV of the nuclear reactor fleet (Xenofontos, 2018)

Generation II reactors account for most of the world’s current commercial nuclear energy production. Those reactors mainly include pressurised water reactors (PWRs) and boiling water reactors (BWRs). In the UK, several Advanced gas-cooled reactors (AGRs) at Hartlepool, Torness and Heysham and a single PWR at Sizewell B are still in operation. Other reactor designs include the CANada Deuterium Uranium reactors (CANDU) (Canadian Nuclear Association, 2024), Vodo-Vodyanoi Energetichesky

Reactors (VVER) (Rosatom, 2024), and the Reaktor Bolshoy Moshchnosti Kanalnyy reactors (RBMK) (World Nuclear Association, 2022b). These reactor designs are described in more detail below.

Advanced gas-cooled reactors (AGRs)

AGRs use the Generation I gas-cooled reactor design, with three main changes made to the reactor design. These changes include using a higher operating temperature

for the cooling gas, using stainless steel fuel cladding and enriched uranium (UO_2) fuel. Graphite moderation and CO_2 coolants are retained from the original gas-cooled Magnox reactor design.

CANada Deuterium Uranium reactors (CANDU)

CANDU is a pressurised heavy water reactor, which uses deuterium oxide as a moderator. Heavy water is employed due to the extra neutron that deuterium contains, which decreases its neutron absorption. Unenriched uranium can be used as fuel, alongside other mixed oxide (MOX) fuel systems such as U-Pu and U-Th. Different to other reactors, the CANDU reactor has a central unpressurised calandria. This calandria replaces the pressure vessel used in other Generation II reactors. Fuel tubes (a fuel bundle) are contained in pressure tubes in the calandria, and deuterium is used as moderator.

Vodo-Vodyanoi Energetichesky Reactors (VVER)

VVER is a pressurised water reactor, which uses water both for moderating and cooling purposes. The fuel used is low-enriched UO_2 , and the fuel is inserted into fuel rods in hexagonal fuel assemblies. The reactor pressure vessel is composed of steel, and the reactor building is a concrete containment building.

Reaktor Bolshoy Moshchnosti Kanalnyy reactors (RBMK)

This is the only reactor worldwide that uses both a water coolant and graphite moderation (which is considered one of its major design flaws). The fuel uses enriched uranium oxide and zirconium alloy fuel cladding (Onimus et al., 2020). The reactor core is different to other reactors because the core is set in a reinforced concrete cavity. Steel plates are placed

on the top and bottom parts of the reactor core. Changes were made to the RBMK design after the Chernobyl accident, those include the reduction of the positive void coefficient of reactivity by the addition of extra fixed neutron absorber control rods and the increase in the fuel enrichment. The void coefficient of reactivity dictates the fission reaction rate which occurs following a loss of coolant (World Nuclear Association, 2022c). The other major RBMK design flaw, which led to the large radioactive release of fission products to the environment, was the lack of a concrete containment vessel. It is worth noting that currently, no reactor is licenced without such a containment building which would have prevented the widespread contamination seen at Chernobyl.

Generation III reactors have improved Generation II reactor designs in terms of safety systems, fuel technology, thermal efficiency, modularised construction and standardised designs. Table 2-5 shows the comparisons between electric power output of Generation II and Generation III designs. As observed, most Generation III designs have a higher power output, alongside other improved factors compared to Generation II reactors, as mentioned above.

Table 2-5: Comparison between Generation II and advanced Generation III reactor plant electric power output.

Generation	Reactor	Company and Model	Plant Output, MWe	Ref.
II	BWR	Hitachi, BWR-5	1100	(Hitachi, 2016)
	PWR	Westinghouse, 212 – 2 loops	600	(Westinghouse Electric Corporation, 1984)
	CANDU	CANDU, CANDU 6	700	(SNC Lavalin, 2015)
III	ABWR	Hitachi, ABWR	1350	(Hitachi, 2016)
	APWR	Westinghouse, AP1000	1100	(Westinghouse, 2024)
	A-CANDU	CANDU, EC6	700	(SNC-Lavalin, 2015)

The goal of standardised designs is to reduce maintenance and capital costs. The capital costs are highly dependent upon the location and accessibility of the component materials. The Westinghouse 600 MW advanced PWR (AP-600) was one of the first-Generation III reactor designs. In parallel, the Advanced Boiling Water Reactor (ABWR) was designed by GE Nuclear Energy. Other designs include the Enhanced CANDU 6 and System 80+. Generation III are considered advanced LWRs, and Generation III+ are significantly more developed and were considered transitional technologies until Generation IV reactors were available. Generation III+ offer improvements in safety when compared to Generation III reactors. For instance, Westinghouse’s original AP600 PWR design for Generation III reactors was further developed into the AP1000 PWR design for Generation III+ reactors. Both reactor designs use passive safety, where little or no human intervention is required. However, the height of the AP1000 containment was increased in comparison to the AP600, providing extra volume. This provided the vessel design with an increased pressure margin to minimize the risk of accidents (World Nuclear Association, 2024a).

When compared to previous generations, Generation III reactors are simpler and have a more standardised design, and longer operating lifetimes, which span to 40 to 60 years. One of the most significant improvements in Generation III designs was the incorporation of passive safety features in the reactor design which avoids the need for operator interventions in emergencies. The only Generation III reactor technology currently under operation is the ABWR in Japan built by Hitachi and Toshiba. Generation III+ reactors are currently being built, and AP-1000 PWRs are under construction in China and the US. EPRs are being built in Finland, France and China; Taishan 1 and 2 in China are already operational. EPRs are also currently being built in the UK by EDF Energy, at both Hinkley Point C and Sizewell C sites.

Generation IV designs have all the features of Generation III+ reactors, and some can also produce hydrogen. Generation IV reactors exploit fundamentally different technological concepts such as the use of fast neutron or breeder reactors. Alternative fuels such as MOX, are also utilised in Generation IV reactors, such as sodium-cooled fast reactors. Generation

IV reactors include the sodium-cooled fast reactor (SFR), the lead-cooled fast reactor (LFR), the gas-cooled fast reactor (GFR), the molten salt reactor (MSR), the super-critical water reactor (SCWR) and the very high temperature gas reactor (VHTR). MSR, SCWR and VHTR will be further described below (World Nuclear Association, 2024a).

Molten salt reactor (MSR)

MSRs are either fast or thermal reactors that are cooled by molten salts with graphite, which is used as a moderator for thermal designs. In MSRs the fuel is liquid and dispersed in the coolant. MSRs generally use a mixture of fluorides of thorium and uranium dispersed in lithium fluoride molten salt. One of the main advantages of MSRs is that they do not need fuel fabrication, which increases safety because less mass of fissile materials is necessary and because they provide more flexibility to remove the nuclear fuel from the core in accidental situations (World Nuclear Association, 2021a).

Super-critical water reactor (SCWR)

The SCWRs operate at a high temperature and pressure above the thermodynamic critical point of water. Light or heavy water

can be used as a moderator. Fuel types investigated for these reactors include UO_2 , MOX, and thorium-based fuels. There are two main design categories: pressure vessel and pressure tube. Pressure vessel designs are similar to the majority of reactor designs already in operation, whereas the pressure tube design is similar to that observed in CANDU reactors (Edwards & Leung, 2022).

Very high temperature reactor (VHTR)

VHTRs are based on HTRs, which were developed in the 1970/80s. VHTRs are the thermal reactors moderated by graphite and cooled by helium. The reactor core can either have a prismatic block construction, or a pebble bed construction. The core structure is formed of graphite. Process heat and hydrogen can also be produced as by-products to nuclear power generation. Fuel types considered are TRISO (Tri-structural ISotropic) coated particle fuels, alongside alternative fuel cycles such as U-Pu, Pu, MOX and U-Th (GEN IV International Forum, 2024).

2.2.2 Small Modular Reactors (SMRs)

While large NPPs face increasing costs and time of construction, SMRs are presented as an alternative solution. They are flexible in terms of construction because they can be built relatively quickly (around 3-5 years) and installed at numerous existing nuclear licenced sites. They are estimated to have an operational lifetime of approximately 60 years (World Nuclear Association, 2024b). The definition of SMRs can be ambiguous since both small and medium sized reactors are used (Wealer et al., 2018). SMRs have been arbitrarily defined by the IAEA as reactors that can generate less than 300 MWe. However, in reality, SMRs are reactors that can be built in factories in modularised units, within a much shorter timeframe.

The general idea is to shorten build times by moving to a factory mass-production line instead of a plant site to increase build quality whilst decreasing costs. Shortening build times has a significant impact on financing since 80% of the NPP life-cycle costs are incurred during the initial build phase (Ho et al., 2019). However, global manufacturing capacity must scale up to meet the demand of SMRs to make them a viable option. Furthermore, by having smaller power outputs, SMR units can respond better to the intermittent supply demand on the grid by potentially varying the reactor power output (Gillen, 2019). SMRs are often advertised as versatile because they are able to be switched on and off, responding to grid demand. However, care must be taken upon operating SMRs in terms of varying reactor power output. As observed in conventional, large-scale reactors, pellet-clad interaction (PCI) can be an issue when power fluctuations are observed. Upon operating the reactor at high temperature, the pellet can swell causing the pellet and cladding to come into contact. As the power is reduced, the pellet-clad gap reopens, leading to numerous failure modes, including clad cracking (Gillen, 2019).

SMRs are suited to countries with new nuclear programs, many of which are facing the retirement of aging coal fired power plants. They are also suitable for countries with NPPs due for decommissioning (Ho et al., 2019). It should be noted that economies of scale can only be reached if a substantial number of reactors in the particular country are of similar design. SMR designs include large water reservoirs to safely remove fission-product decay heat after the reactor is shutdown. This lowers the risk of accidents caused by a station blackout as seen in Fukushima (Ho et al., 2019). They can also provide additional features such as heat reuse for district heating or desalination systems, and hydrogen production (IAEA, 2021).

There are several SMR projects in different stages of development. Typically, nuclear reactor technology development progresses in a series of steps: (i) preliminary, basic, and detailed design (ii) licensing (iii) under construction (iv) commissioning (v) in operation. Examples of SMRs include:

Light water-cooled reactors

Given the extensive operational expertise with LWRs, it was a technology chosen for SMRs development to reduce investment risk and time-to-market. The overall configuration includes the traditional loop design. There are several different designs from the USA, UK, Russia, South Korea, France, China and Argentina (IAEA, 2022a).

Heavy water-cooled reactors (HWRs)

Heavy water i.e., water in which two hydrogen atoms are replaced by deuterium atoms, is an attractive coolant and moderator. This is because it allows the reactor to bypass the complex and expensive enrichment process of uranium and instead use natural uranium as fuel. Hence, this reactor

technology has become attractive to countries with low abundance in uranium such as India.

Gas-cooled reactors

Gas-cooled reactors are the second most common reactor type used for commercial power application, due to the CO₂-cooled reactors deployed in the UK. All gas-cooled SMRs under development use helium as the primary coolant. The main advantage of helium-cooled reactors is their ability to operate at substantially higher temperatures and hence their ease to manage and increases efficiency. However, this requires the gas to be pumped at a relatively high velocity which presents further challenges.

Liquid-metal-cooled reactors

Liquid metals used as coolants in SMRs under development include sodium, lead, and lead-bismuth. Liquid-metal coolants

result in more neutrons produced per fission when compared to reactors that use water coolants. The excess neutrons can be used for other purposes such as resource recovery and waste management. This concept is called a fast-spectrum reactor.

Molten salt-cooled reactors (MSRs)

MSRs generally use fluoride salts as a coolant, which is not a novel concept. However, the novelty is that the fuel can be dissolved in the coolant as a fuel salt which means that reprocessing can occur in the nuclear reactor. Thorium, uranium, and plutonium can all form fluoride salts.

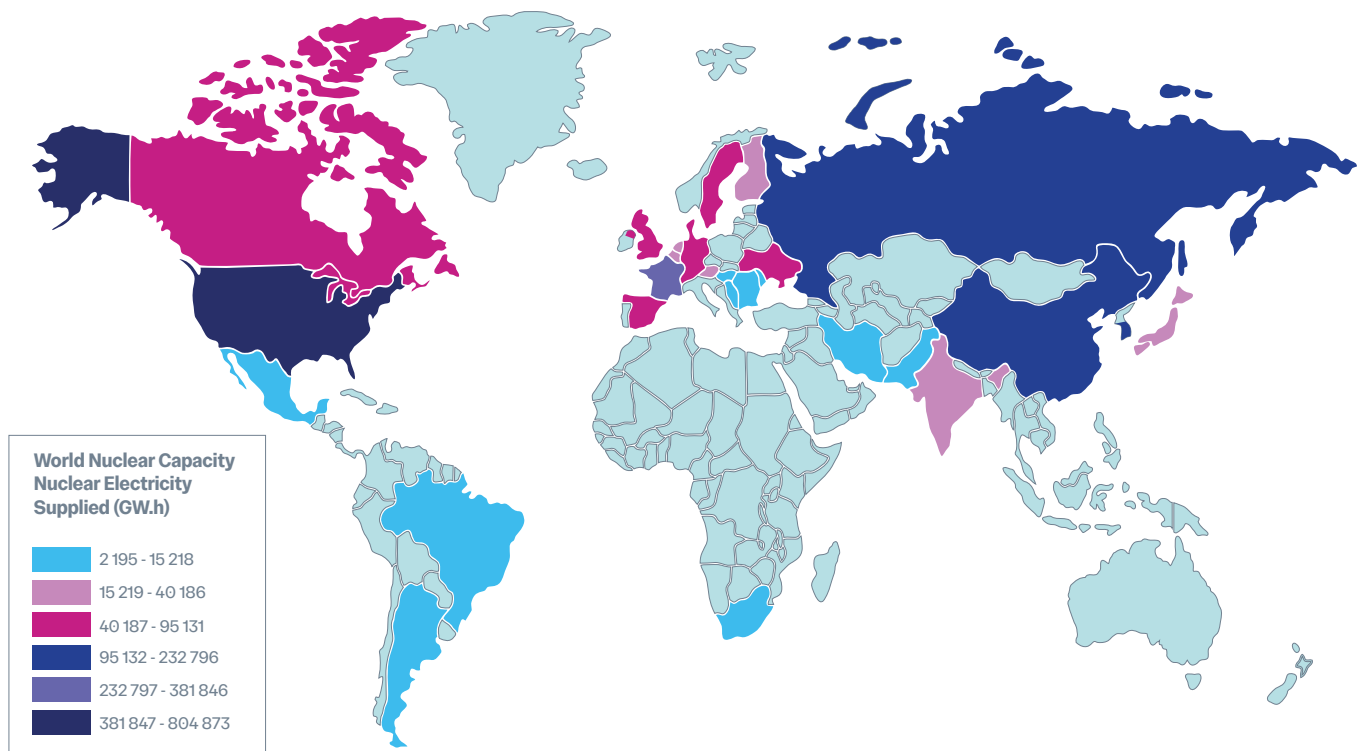
2.3 Conclusions

A standard method is adopted when producing UO₂ fuel for conventional nuclear reactors. This allows the nuclear fission process of generating energy to be well understood in commercial nuclear reactors used today, including the Generation I to Generation III reactors, seen nationally in the UK, and worldwide. Experimental reactors such as FBRs, are attracting the industry's interest, because they do not contain a moderator to slow the neutrons. Such reactor designs are beneficial when considering the use of alternative fuels such as U-Th or U-Pu, and thus, several different FBRs are under investigation. Generation IV reactors provide the next fleet of commercial nuclear reactors for power generation, and they are also under discussion. Generation IV reactor designs are improved compared to previous generations in terms of safety,

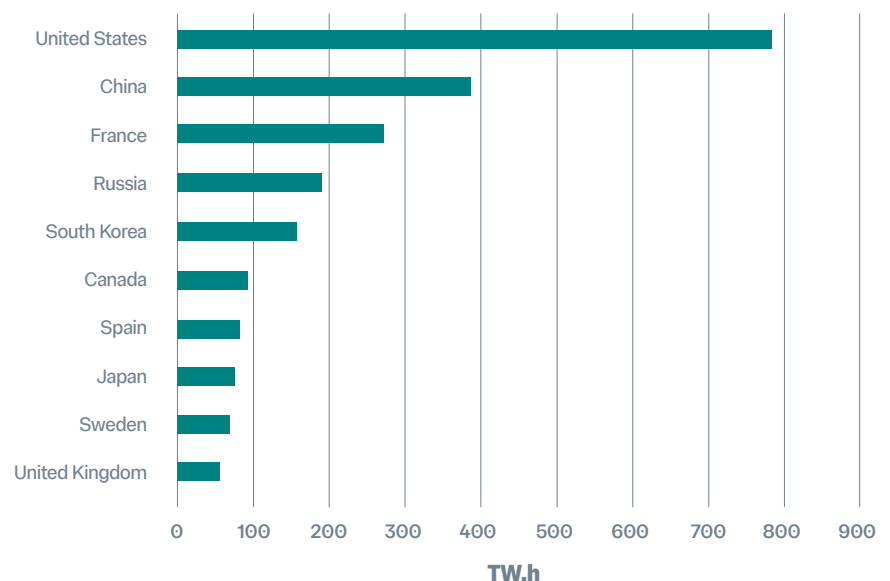
reliability, economics, and sustainability, ensuring that nuclear power generation is feasible in all aspects. Moreover, SMRs are gaining significant interest when it comes to generating nuclear power on smaller scales, and in areas which may not be as accessible for a large scale commercial nuclear power stations. SMRs can provide benefits in terms of construction times and costs and can be scalable to meet the energy demand and grid connections. Reactor designs for SMRs are being pushed forward by multiple vendors, with worldwide aims of pursuing SMRs soon. However, efficient use of SMRs must be considered. Using the outputs from SMRs for process or district heating, or hydrogen production, alongside electricity generation should be considered.

3. The Current Global Landscape

World map and select statistics of nuclear generating countries



The map is a graphical representation intended for general informational purposes only



3.1 Europe

3.1.1 France

France has one of the largest nuclear power programmes in the world with 56 operating nuclear reactors. Nuclear power plants account for 68% of France's annual electricity generation due to a long-standing policy focusing on energy security. Because France has a limited supply of fossil-fuel energy resources, it turned to nuclear power to decrease dependence on imports. 52 new nuclear reactors were built from 1975 to 1990. In 2005, a law established guidelines for energy policy and security where the importance of nuclear power was emphasized. Specifically, it was decided to build an initial unit of an EPR and to build a series of ~40 EPRs more by 2015. France has a strong position as the world's largest net exporter of electricity with its 56 existing nuclear power stations (IAEA PRIS, 2024a). The UK is a major customer of French electricity. Significant exports also include reactors and fuel products. The well-established PWR French design was sold to several countries including Iran, South Africa, South Korea, and China. Furthermore, the European PWR (EPR) developed jointly by France and Germany to meet the European Utility Requirements regulations which was approved in 2004. This reactor technology has been sold to France, China, and the UK.

This has led France to be the largest net exporter of power in Europe until 2022, when Sweden overtook the leadership. Although France exports more electricity than it imports,

structural problems with its nuclear fleet have led to an increase in its electricity imports since 2022 (EnAppSys, 2022). Climate change has contributed to hinder the country's water availability in the summer thus reducing the ability of energy companies to use water to cool the nuclear reactors. Additionally, more than 56 reactors were taken offline for repairs and those were delayed because of the Covid-19 pandemic (Plackett, 2022). Furthermore, in 2014, French authorities announced that their nuclear generating capacity would be capped to a total of 50% of the total energy output by 2025. At that time, nuclear power accounted for 75% of France's electricity production (WNN, 2014). This decision was considered unrealistic in 2017 by the French environment minister (WNN, 2020) and hence the policy target date was delayed for 2035. However, in 2020 the importance of nuclear power to France in terms of socio-economic impact as well as energy independence were again emphasized, and the government committed to invest 500 million euros in the nuclear sector (WNN, 2020). In February 2022, France announced a plan to build six new reactors with a possibility of an additional eight by 2050 (Ataman, 2022). All the current reactors in operation are PWRs.

3.1.2 Germany

In the 1960s and 70s, Germany was a world leader in nuclear power and more than 30 new nuclear reactors were running in the following decades. However, after the Chernobyl accident, the last nuclear power plant was commissioned in 1989. Following talks and negotiations, it was decided in 2001 that the lifetimes of the operating reactors would be limited to ~32 years. This was later extended in 2009, but after the events at Fukushima in 2011 all pre-1990 nuclear power plants were shut immediately due to public pressure. Despite safety assurances for the remaining 17 reactors, the government decided to re-implement the phase-out policy and decommission all reactors by 2022. After the Russia-Ukraine conflict the phasing out of nuclear power was delayed, but in April 2023 the last nuclear power plants in Germany were decommissioned. In total, Germany decommissioned 33 nuclear power reactors.

Nuclear power accounted for 27.6% and 5.8% of Germany's power generation in 2003 and 2022, respectively. Since Fukushima, Germany's nuclear energy has been primarily offset by increases in coal plants. Currently, Germany plans to replace the share of electricity production from nuclear with renewables. Germany already has a large wind power capacity, with a cumulated capacity of 61 GW in operation. However, this does not stop them being reliant on gas and coal, especially during the winter months. This is a crucial consideration given that Germany has consistently been the highest CO₂ emitting country in the EU since 2000 (CLEW, 2024; CNN World, 2023; IAEA PRIS, 2024b; IEA, 2024; Jarvis et al., 2022).

3.2 Asia

3.2.1 China

Chinese nuclear policies are not public; however, it is inferred that China aims to have a closed nuclear fuel cycle. China has become noticeably self-sufficient in reactor design and construction as well as other aspects of the fuel cycle. In 2014, the Chinese State Council published the 'Energy Development Strategy Action Plan 2014 – 2020', which aimed to promote the use of clean energy. It specifically set a 2020 target of 58 GWe of electricity production from

nuclear power, with an additional 30 GWe to be generated by nuclear plants under construction at that time (State Council of China, 2014). Ever since, the National Energy Administration (NEA) was set to manufacture 6-8 reactors annually and announced that China was aiming for world leadership in nuclear technology. This has also led to policies that extend to nuclear technology exports.

3.2.2 Russia

The world's first nuclear power plant was commissioned in 1954 in Russia (Rosatom, 2024). Since then, Russia has focused on exporting nuclear goods and services as a major Russian policy and economic goal (World Nuclear Association, 2024c). It has indeed become a world leader in the sector, and more than 50 countries are Russian nuclear clients with various degrees of dependence (Szulecki & Overland, 2023). Despite the Russia-Ukraine conflict, Russia remained a major player in the global nuclear power sector and has thus far not been covered by western economic sanctions (CNN, 2023; The New York Times, 2023). Russia's nuclear program is run

by Rosatom, which is a state corporation responsible for the countries' nuclear power industry, nuclear-powered icebreaker fleet, nuclear research institutions and nuclear and radiation safety (Schepers, 2019). Nuclear power accounts for around 19% of Russia's electricity mix generated by 37 nuclear reactors; 3 more reactors are under construction (IAEA PRIS, 2024c).

3.2.3 Japan

Commercial nuclear operations began in Japan in the 1960s, with almost 30% of its electricity usage powered by its own reactors (World Nuclear Association, 2024c). Following the Fukushima Daiichi accident in 2011, the plans for new nuclear reactors were paused. These plans had the target of generating 40% of Japan's electricity by nuclear power by 2017. After the accident, public protests called for Japan to abandon nuclear power, and all nuclear operations were paused. In 2013, the Nuclear Regulation Authority (NRA) established new regulations. This meant that all current reactors had to undergo checks before they were able to

restart. From the total of 25 reactors operable in Japan, currently only 12 have been granted permission to restart safely (IAEA, 2024a). Due to the reduced outputs from nuclear, Japan is now heavily reliant on fossil fuels such as coal and liquefied natural gas (The Oxford Institute for Energy Studies, 2021). Current plans for nuclear development in Japan include the goal of reaching 20 – 22 % of the country's energy share by 2030 (NEA, 2023).

3.3 North America

3.3.1 USA

The USA has more private sector participation in nuclear power production than any other country. Nonetheless, the government is notably involved in the country's nuclear agenda through safety and environmental regulations and R&D funding (World Nuclear Association, 2023b).

The USA is also the world's largest producer of nuclear power, accounting for more than 30% of the global nuclear power generation, and more than 90 nuclear reactors are

in operation in its territory (IAEA PRIS, 2024d). The USA is currently constructing two new nuclear reactors after more than 30 years of no developments on this front (Forbes, 2023). In January 2023, a commercial contract for a grid-scale SMR project was announced.

3.3.2 Canada

It has been recognized by the IEA that Canada's electricity system is amongst the cleanest in the world due to its hydro and nuclear power. Around 15% of Canada's electricity production comes from nuclear power from 19 reactors. Canada has developed a unique nuclear reactor technology (CANDU) which is utilised in 18 of the current reactors in Canada and further 10 reactors in operation outside of Canada. Additionally, Canada exports 75% of its uranium production for nuclear power development globally (Government of Canada, 2022a). However, the country does not have reactors under construction and its current fleet is ageing; its latest reactor was commissioned in 1993. Instead, refurbishments will be carried out to extend the life of current nuclear reactors beyond 2060 (National Energy Board, 2018). In 2022, Canada committed more than £500

million to finance and develop SMRs (Reuters, 2022) with the aim of being the leader in nuclear technology, goods, and service exports (Government of Canada, 2022b). The country already has an SMR action plan and roadmap (Canadian Small Modular Reactor Roadmap Steering Committee, 2018). Additionally, Canada released a report in 2021 showing that nuclear power would be a consistent source of electricity generation with its Evolving Policies Scenario for 2050. It was projected that although nuclear power would remain consistent with their policies, it would contribute less to the total power generation. This is because of the estimated lower costs of other technologies and current plans in place (Canada Energy Regulator, 2021).

3.4 Conclusions

Most countries are using nuclear power to their benefit, in an aim to achieve net zero carbon emissions and enhance energy security. However, some countries, such as Germany, have scaled back their nuclear power capacity for various reasons including public opinion which is connected to previous accident scenarios. The development of nuclear power in a global manner is beneficial for all countries because it permits them to share common reactor designs, improve understanding, and develop international standards of operation (ISOs). ISOs, licensing, and regulation would benefit the sector, especially when considering new technologies

coming online. Private sector funding has been a key role in the development of reactors in some countries, such as the USA, which has a large share of the world's nuclear energy generation. Further development and implementation of planned nuclear reactors worldwide can only improve the sector further and reduce the impact of fossil fuel energy generation on the global climate.

4. Safety, Security, and Safeguards

The safety of any technology is imperative to ensure that it can be used correctly and to avoid harm. Nuclear energy generation is subject to strict regulation and rigorous safety measures (UK Government, 2022), so much so that the United Nations International Atomic Energy Agency (IAEA) has stated that nuclear power plants ‘are among the safest and most secure facilities in the world’ (UK Government, 2022).

Nuclear power has been the subject of controversy over the years. Accidents, coupled with the use of nuclear weapons, have divided public perception on the technology, and whether it is safe to use. However, for over 60 years of nuclear power operation worldwide and with 18,500 years of combined reactor operations, only three major accidents have occurred, which include Chernobyl, Fukushima, and Three Mile Island.

Safety, security, and safeguards are all defined differently and yet interdependent and they are all required to ensure that the overall nuclear facility remains safe. Briefly, safety, security, and safeguards can be defined, by the IAEA, as follows (World Nuclear Association, 2022d).

Safety

“The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in the protection of workers, the public and the environment from undue radiation hazards”.

Security

“The prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities”.

Safeguards

“A set of technical measures applied by the IAEA on nuclear material and activities, through which the Agency seeks to independently verify that nuclear facilities are not misused, and nuclear material not diverted from peaceful uses”.

4.1 Safety

Safety has been a key factor in reactor design since their implementation in the 1950s. Generic factors must be considered when designing nuclear power stations, these include planning, designing with in-built safety margins, setting up back-up systems, using high quality components and materials, and ensuring a strong safety culture (World Nuclear Association, 2022d). The initiation of the IAEA by the UN in 1957 was an important step forward towards nuclear power station safety worldwide. The IAEA provides safety procedures and requires power stations to report accidents or incidents. Each country that operates nuclear power stations has a nuclear safety inspectorate which works closely with the IAEA to ensure that plants are safely operated. Safety protocols are continually revised and improved in the nuclear sector, by learning from past incidents and accidents. This also enables improvements to existing designs that will be implemented, increasing the operational lifetime of the nuclear power station.

When considering reactor operation, three key components are required to ensure safety. Firstly that reactivity is controlled, secondly that fuel can be cooled, and finally that radioactive substances are contained. Reactivity is controlled using the control rods in the reactor core. Control rods are made from neutron absorbing materials, and therefore their absorption cross section is an important property to consider when designing control rods. Typical materials include hafnium, boron, indium, and silver (Lamarsh & Baratta, 2001). Depending on the reactor type, the fuel is cooled either with a gas or with water. The efficient use of coolants ensures that the fuel is kept at an optimal temperature and pressure in the core, and at the same time, it permits heat transfer to the turbines for electricity generation (Murray, 2009). The efficient containment of radioactive substances depends on the choice of materials, which act as physical barriers. Multiple

barriers are in place, starting with the fuel pellet, cladding, pressure vessel in the reactor core, and containment structure. The materials used for the reactor pressure vessel, which contains the reactor fuel, include steels which are lined with radial neutron reflectors. Neutron reflectors are used to reduce radiation damage from neutrons and ensure that the reactor vessel withstands an operational lifetime of at least 40 years.

Safety features are also used during the operation of the reactor. In reactors, the fuel and coolant materials need to have a negative temperature coefficient and a negative void coefficient to ensure that the reactor becomes less reactive as temperature or voids increase. The fuel's negative temperature coefficient and negative void coefficients of reactivity are properties which determine the operational response of the reactor. The negative temperature coefficient means that as temperature increases, the power-related reactivity of the reactor decreases. Therefore, if the temperature were to increase in the reactor, fission rate would decrease, and ultimately suppress the reactions in the core. A negative void coefficient is observed when the energy and heat produced by the reactor decrease when voids in the coolant increase. For instance, in water-cooled reactors, voids may form if the water boils within the reactor forming gaseous steam bubbles. This would in turn cause the power to decrease, resulting in a slow shut down of the reactor. Positive void coefficients are also possible for some reactors such as those that are gas cooled. A positive void coefficient causes the reactivity in the reactor to increase with increased voids. Unfortunately, this was one of the main drawbacks of the RBMK design of the Chernobyl reactor, in which a positive feedback loop was initiated because of the positive void coefficient of the reactor. As large amounts of steam were generated during the Chernobyl disaster, the reactivity in the core also increased, which was one of the factors contributing to the accident. Ensuring

inherent safety in nuclear reactor designs is extremely important and beneficial for reactor operators. (World Nuclear Association, 2022d).

Reactors can undergo a SCRAM, which is the name given to a sudden reactor shutdown. SCRAMs can occur due to malfunction, because of a manual instruction, or due to other events such as earthquakes. The SCRAM procedure causes the fission reaction to cease. However, there is still residual heat from the decay of the fission products in the fuel of approximately 6 to 7% of the power at shutdown. This heat dissipates exponentially to about 0.2% of its original heat after about a week of shutdown.

It is imperative that staff working at nuclear power stations encourage an operational safety culture. Moreover, nuclear facilities have a duty to ensure that staff are exposed to limited radiation during their working time. Operations hazardous to human health, such as those in the reactor core can be conducted remotely. Physical shielding of radioactive areas is also carried out, alongside limiting workers' exposure times in highly radioactive areas. This is often conducted by asking workers to monitor the radioactivity in their surroundings. It is worth noting that nuclear industry workers typically are subjected to doses below those received by the general public because of the protection measures put in place (UK Health Security Agency, 2023).

Operators are largely accountable for incidents at nuclear power stations following their decisions. At Chernobyl, an operator decision was the contributing factor to the accident. Reduction in the impact of human error while operating reactors can be achieved by increasing organizational safety culture, which includes continuous education and training (including simulator training). Some scenarios may be too difficult to train for, and unpredictable. Simulator training offers workers the experience to observe such situations and train on how they would handle the scenario (EDF, 2024b). Effective training and understanding of the technology are beneficial, especially when advanced knowledge is required for reactor operation. For example, EDF in the UK detail that their 'emergency arrangements are meticulously planned and rehearsed', showing how safety culture is implemented in the workplace (EDF, 2024b).

4.1.1 Developments in Safety

As mentioned, developments in safety have been made from learning from past accidents and incidents. Additionally, each generation of nuclear reactors was improved in terms of safety from the previous fleet. An OECD-NEA report in 2010, calculated a theoretical value for the frequency of large radioactivity releases from a severe nuclear power station accident. When comparing Generation I and Generation III/III+ reactors, this frequency had decreased by a factor of 1600, showing the effect of improving safety in later reactor designs (World Nuclear Association, 2022d).

The “defence in depth” approach can also be adopted when improving nuclear power station safety. This uses a multi-component safety approach, including inherent features of the reactor core. The defence in depth approach is made of three key factors: Prevention, Monitoring and Action. Aspects to consider when analyzing the key factors include, opting for high quality design and construction, mitigating human failure and error by using sophisticated equipment, monitoring and testing to find defects or failures, using redundant and diverse systems to control damage and prevent radioactive release, and designing facilities to confine effects of severe fuel damage.

International collaborations have also contributed to improving safety. The World Association of Nuclear Operators (WANO) was set up in 1989, with the goal of maximising “... the safety and reliability of nuclear power plants worldwide by working together to assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practices”. WANO also set a clear objective for its members, envisioning they “will be worldwide leaders in pursuing excellence in operational nuclear safety for commercial nuclear power”. To meet the goal and vision that WANO set, and to ensure that operational safety and reliability

is achieved, the activities described below are conducted (WANO, 2024b).

Peer Reviews

Comparisons can be made against standards by an independent team. Strengths and areas for improvement are highlighted by the review.

Member Support

WANO members assist each other over improvements to reliability and safety.

Performance Analysis.

A global library of operational experience and performance data can be used for the benefit of other nuclear power stations.

Industry Learning and Development

Leadership skills and professional knowledge can be enhanced by members of WANO through specific training

The IAEA organized meetings between 1992 and 1994 as part of the Convention on Nuclear Safety (CNS). This resulted in international benchmarks set to ensure the safety of civil nuclear power stations. The three main objectives of the CNS were as follows (IAEA, 1994):

- 1.** Attain and maintain a high level of nuclear safety worldwide. This is achieved by national and international measures and cooperation.
- 2.** Establish and maintain effective defenses for nuclear constructions against radiological hazards, which protects individuals, society, and the environment.
- 3.** Prevent accidents which may cause radiological effects. Ensure that mitigations are in place if accidents do occur.

After the creation of the convention, the objectives were first implemented in 1996. In March 2021, the number of signatories to the CNS was 91, with 65 being contracting parties from all countries with operational nuclear power stations. (World Nuclear Association, 2022d)

Safety reviews of reactor design documentation can also be conducted by member states of the IAEA. This exercise is conducted to ensure that design documentation generated for reactors is complete and comprehensive. The review is conducted by international experts and benchmarks against the IAEA's published safety requirements. Design safety reviews (DSRs) and generic reactor safety reviews (GRSRs) have been conducted in many countries.

To increase public awareness of safety at nuclear and radiological sites, the International Nuclear and Radiological Event Scale (INES) was developed. It was developed in 1990 by the IAEA and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA). The scale's purpose is to rate the severity of events in which radioactive materials are released to the environment, which may harm workers or the public. Events

that do not have any consequences can also be rated against this scale if protective measures fail. Many of the IAEA Member States actively use this scale and have designated INES National Officers. If events that are rated level 2 or higher occur, the IAEA encourages the Member State in question to share information openly on the event (IAEA, 2024b).

The scale is shown in Figure 4-1, where the level of incident or accident is rated on a scale from 1 to 7. Rating 0 also exists, which accounts for events without safety significance. The scale is logarithmic, that is, the severity of an event increases ten-fold between each increment. The ratings have been set to be dependent on three factors which consider people and the environment, radiological barriers and control, and defense in depth.

The first 3 ratings cover incident scenarios and consider events classified as anomalies, incidents, and serious incidents. Ratings 4 to 7 are events considered as accidents, and include accidents with local consequences, accidents with wider consequences, serious accidents, and major accidents (U.S. NRC, 2017).

The International Nuclear and Radiological Event Scale

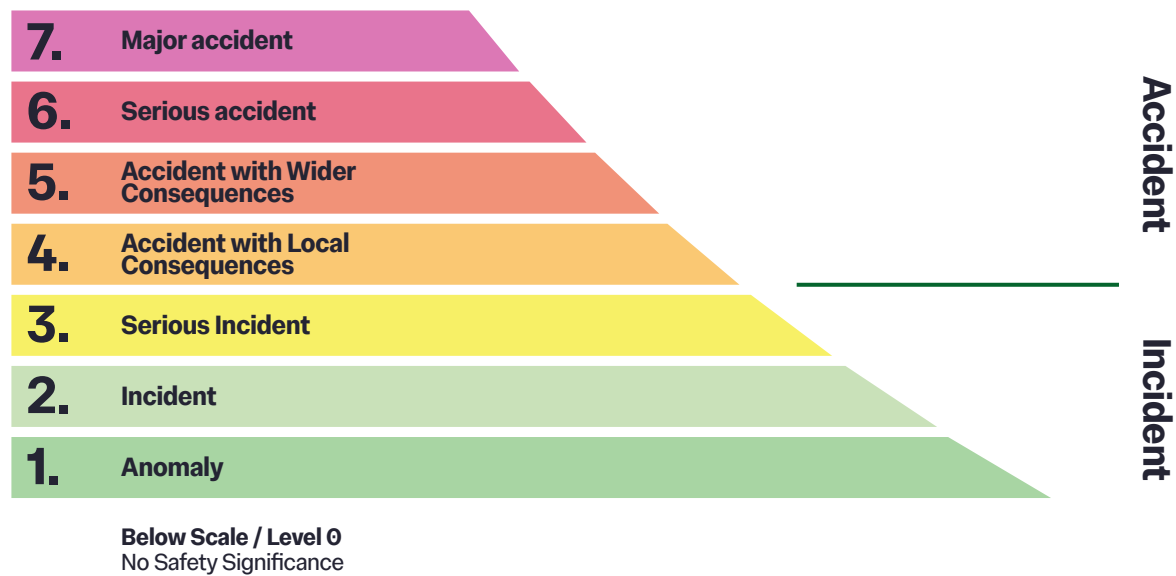


Figure 4-1: International nuclear and radiological event scale (INES) (US NRC 2017)

4.1.2 Regulators

Regulators are required to ensure that nuclear power stations are supervised correctly throughout their whole lifetime, from construction to operation and then to decommissioning. In the UK, the Office for Nuclear Regulation (ONR) is an independent body, which regulates safety, security, and safeguards of nuclear sites in the UK. This currently includes operating reactors, fuel cycle facilities, decommissioning sites, and new sites that will come online in the future. The ONR states that five statutory purposes need to be fulfilled to ensure safe nuclear operation. These are 1) safety, 2) site health and safety,

3) security, 4) safeguards, and 5) transport of nuclear and radioactive materials (ONR, 2023). The ONR has also agreed to commit to European and International agreements to ensure high levels of nuclear safety. The ONR has stated that works conducted by the IAEA and EC directly impact how the ONR regulates nuclear licensed sites.

The ONR regulates under four main points (ONR, 2023).

- **Permissioning inspection**

Safety cases provided by licensees are assessed critically to ensure that hazards have been understood and adequate controls are put in place.

- **Compliance inspection**

They ensure license conditions are adhered to, depending on the safety case and operational intelligence.

- **Enforcement**

By providing advice, warnings, notices, and other legal activities to ensure that nuclear sites comply with regulation.

- **Influence**

Influencing to improve areas such as safety culture, leadership, and vision.

Other countries also employ a regulatory body to monitor their nuclear sites (World Nuclear Association, 2019). Some of these bodies are:

Canada

The Canadian Nuclear Safety Commission (CNSC) oversees most of Canada's nuclear activities. The CNSC provides guidance on license applications and on requirements for conducting licensed activities (i.e., nuclear power station) (Government of Canada, 2024).

China

The National Nuclear Safety Administration (NNSA) of China is the national nuclear and radiation safety regulator of China. Regulation of nuclear power plants and radiation safety is conducted by implementing numerous policies, regulations, laws, systems, and standards to ensure safety is ensured. The NNSA also provides protection and emergency responses (NNSA, 2020).

Japan

The Nuclear Regulation Authority (NRA) of Japan regulates nuclear activities in Japan. The NRA was formed after the Fukushima Daiichi accident in 2011, to improve safety and learn lessons from the accident. The NRA realized that gaining public confidence again was crucial, and therefore considered necessary to hold all nuclear power stations to a high safety standard. NRA's mission is to "protect the general public and the environment through rigorous and reliable regulations of nuclear activities" (NRA Japan, 2013).

Sweden

The Swedish Radiation Safety Authority (SRSA) was established to cover all aspects of nuclear topics, including nuclear safety, radiation protection, security, and nuclear non-proliferation. Protection of the environment and humans is key to the SRSA mission, and this is accomplished by ensuring that nuclear activities meet its standards and regulations (SRSA, 2023).

United States of America

The USA Nuclear Regulatory Commission (NRC) was formed to allow the safe use of radioactive materials. The NRC's main mission is to ensure that people and the environment are protected while safely using nuclear materials. The NRC provides rules, guidance, and participates in communication, and in developing nuclear standards (NRC, 2024).

4.2. Security and Safeguards

4.2.1 Security

Nuclear security acts to prevent hazards from occurring. Security of nuclear facilities is procured by the governments of the countries where nuclear facilities are. Regulators, authorities and operators have a responsibility in ensuring that nuclear facilities are always secure. The security of nuclear facilities can be threatened for a variety of reasons. Some of these are terrorism, military action, and cyberattack.

Terrorism

This can occur due to vulnerabilities at facilities including people gaining unauthorized access. To prevent such acts, additional measures have been put in place such as restrict access and control to authorized users only, use of physical barriers, identification badges, surveillance cameras, and X-ray scanners (World Nuclear Association, 2022e).

Military Action

Plants may be a subject of attack during military action. However, the Additional Protocol of 1979 in the Geneva Convention contains Article 56, in which it is stated that “nuclear power plants shall not be made the object of attack, even where these objects are military objectives”. This is an agreement to guarantee that any release of radioactive materials due to an attack can be mitigated (World Nuclear Association, 2022e).

Cyberspace

Use of digital systems may be problematic in terms of cyberattacks. Mitigation strategies to such attacks, such as encryption of data storage and transmission can be implemented. Additional laws and regulations also exist at national and international levels to ensure that systems are safe to use (World Nuclear Association, 2022e).

The Convention on the Physical Protection of Nuclear Material (CPPNM) was established in 1979. The CPPNM focused on safe international transportation of nuclear material, to make sure the material was not sabotaged or interfered with in any way during transportation. Countries who signed the convention had to adhere to this method of safe international transport of material. The key aspects of the CPPNM were to protect nuclear material in transit, to return stolen material to the country of origin, and to protect the confidentiality of communicated information. In 2005, an additional aspect which contemplated protecting nuclear facilities and material used for peaceful purposes during storage, transport, and at facilities was added (IAEA, 2023a).

4.2.2 Safeguards

Safeguards are applied on nuclear facilities and materials. The IAEA can use technical measures to ensure that agreeing countries are not misusing their nuclear facilities and that materials' safeguards are assessed yearly. The assessments are implemented using four key processes as described below (IAEA, 2022b).

1. Collecting and evaluating information

The IAEA collects relevant data for safeguarding purposes. This data is processed and reviewed to ensure it is consistent with the Member State's declarations about its nuclear activities.

2. Development of safeguards

Safeguards are developed for a Member State to ensure that the State meets its technical objectives.

3. Planning, conducting and evaluating activities

A plan that specifies the safeguard activities is developed. The IAEA then evaluates the extent by which the activities reach the technical objectives, identifying any inconsistencies at this stage.

4. Conclusions

Conclusions are made by the IAEA based on independent verification and findings. These conclusions provide guarantees to the other Member States that safeguard obligations are being adhered to.

4.3 Conclusions

Safety, security, and safeguards are essential cornerstones of nuclear power generation. The definition and development of a safety culture within the nuclear industry has been strengthened over time, using international standards, governing bodies, and regulatory presence. Safety issues have been taken seriously, such as those observed from past accidents, and changes have been made to the industry accordingly. Security and safeguarding of nuclear sites are paramount, ensuring that nuclear sites operate as intended and that they can be protected by any internal or external

threats. Ensuring such sites are consistently safe is essential to ensure that the technology can be used in a peaceful and appropriate manner. Furthermore, new reactor designs are coming online, which requires uniform standardization and international regulation to share best practices and standards.

5. Decommissioning and Waste Management

5.1 Decommissioning

At the end of the reactor lifetime, the nuclear power station is closed and therefore must be decommissioned. Three different options for decommissioning can be implemented, as defined by the IAEA. (IAEA, 2023c)

Immediate dismantling

Upon the end of operational lifetime and regulatory activities, the facility is removed from regulatory control. Dismantling or decontamination activities begin. This method of decommissioning was used in Germany, at the Greifswald nuclear power station. Five reactors were operating at this site and were immediately dismantled upon ceasing operation.

Deferred dismantling

This option considers the postponement of the final removal of controls from a few months to years. Until dismantling and decommissioning takes place, the site is placed into a safe storage configuration. Deferred decommissioning can be beneficial when considering the radioactive decay of shorter-lived isotopes. It can also be used as an option when there are constraints on waste management infrastructure. An example of a deferred dismantling decommissioning strategy was used on the Berkely site when decommissioning the Magnox reactor (NDA, 2014).

Entombment

This is a method of encasing the facility with all its on-site radioactive material, but it is different to dismantling, because no waste products are removed from the site. The waste is

then encased in a safe, radioactive resistant structure such as concrete. This method of decommissioning was put in place when securing the Chernobyl site.

Different methods for decommissioning are chosen depending on the country and region. Countries may not have adequate storage facilities and therefore cannot immediately dismantle their reactors, resulting in a deferred dismantling approach. Different methods also have advantages and disadvantages associated with them. Decommissioning can provide advantages to the existing workforce and newer generations, by training people to move from an operational expertise to a waste management one. Deferred dismantling enables residual radioactivity to decrease, reducing the risk when eventual decommissioning takes place. Entombment structures may be unfavourable due to the occupation of land after operations have ceased.

For immediate or deferred dismantling, Figure 5-1 shows the typical stages required to dismantle and decommission a nuclear site. The process of decommissioning requires the removal of radioactive elements, securing the site, before dismantling the power station.

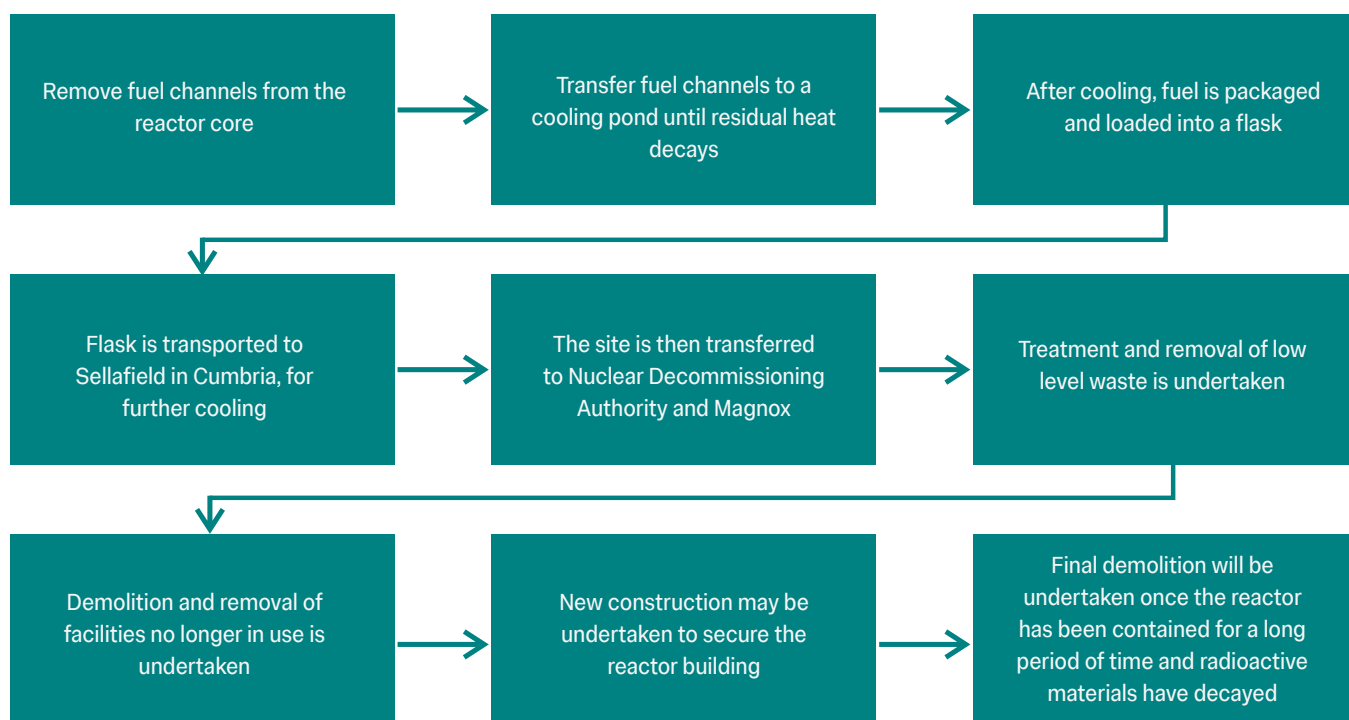


Figure 5-1: Typical nuclear power station defuelling and decommissioning process.

Decommissioning is considered at the initial stages of implementing a nuclear reactor to ensure that there is a plan for the waste upon ceasing operation. This is true for newer reactors, however, some older Generation I reactors may not have this plan set in place. Newer reactor generations took this into consideration as a safety aspect involved with the plants (NDA, 2021).

In the UK, the Nuclear Decommissioning Authority (NDA) is responsible for ensuring that older reactors are decommissioned safely, securely and in a cost-effective manner. The NDA is focused on five key themes in terms of decommissioning, which include addressing spent fuels, nuclear materials, integrated waste management and site decommissioning and remediation, as well as providing critical enablers. The following description highlights how the NDA aims to address the five key themes (NDA, 2021).

Spent fuels

Ensure safe, secure and cost-effective lifecycle management.

Nuclear Materials

Ensure safe, secure and cost-effective lifecycle management.

Integrated Waste Management

Ensure waste is managed to protect people, the environment, comply with policies, and is cost effective.

Site Decommissioning and Remediation

Decommission and remediate sites and release them for other uses.

Critical Enablers

Ensure that a stable and effective operative environment is provided.

Environmental remediation is the process of protecting the surrounding land of the nuclear power plant against radioactivity. This is especially important during the decommissioning process whereby spent fuel and nuclear material waste may be transported off site. Factors to consider when planning environmental remediation include nuclear material exposure to contaminated soil, waste storage facilities, contaminated infrastructure, groundwater, or surface water (IAEA, 2016)

The IAEA states that there are four major elements that must be considered when implementing environmental remediation.

- 1. The level of radiation exposure from contamination**
- 2. Reduction to radiation doses and risks.**
- 3. Accepting that, while acceptable contamination levels can be achieved, the original state of the site may not be possible to attain.**
- 4. The overall well-being of the local community regarding the final state of the site.**

In relation to point 4 of this list, the NDA has a legal duty set out in the 2004 Energy Act regarding local communities living by NDA owned sites, i.e. those that are under decommissioning. Socio-economic and social impact programmes have been developed to benefit areas surrounding NDA sites (IAEA, 2020). For instance, the Magnox socio-economic fund can be awarded to projects which directly benefit areas surrounding Magnox sites (Magnox, 2022). This includes helping to fund the Engineering Education Scheme Wales Ltd., a project in partnership with STEM Cymru, targeted towards Sixth Form (Year 12/13) projects in North Wales. It can also be noted that decommissioning can have both positive and negative socioeconomic effects (Engineering Education Scheme Wales, 2024). Decommissioning can provide additional jobs to those in the area. However, areas may become deprived once the decommissioning process ends if the NDA site was the main source of employment in an area.

5.1.1 Decommissioning Costs

Usually, the owner or operator pays for the decommissioning costs of the nuclear power plant. Costs can vary from country to country and are dependent on the type of decommissioning implemented. For instance, if the deferred decommissioning method is used, costs may be reduced due to handling of less radioactive material. Different costs may also arise due to a variety of decommissioning challenges at different power stations. This makes having a global coherent and reliable source of information on decommissioning costs difficult to obtain (NEA, 2016).

General estimates of decommissioning costs can be generated by using the 'International Structure for Decommissioning Costing (ISDC) for Nuclear Installations' project, which is a joint venture between the IAEA, European Commission (EC) and Nuclear Energy Authority (NEA). Some cost estimation techniques include parametric techniques, which use previous estimates, cost review and update techniques, which in turn use historical databases and statistical analyses. They may also use specific analogy techniques, where a new estimate is created based on old estimates, and expert opinion techniques, used when other techniques are not available.

There is no accepted standard for developing decommissioning cost estimates, as factors influencing the cost estimates vary from plant to plant. Cost estimates mainly depend on the plan adopted, the predicted end state of the power plant, and differences between assumptions and real-time scenarios. The NEA has suggested that a standard reporting template should be developed to map national cost estimates, enabling international comparisons to be made. For this purpose, the ISDC provides a method to report decommissioning costs effectively and is used internationally. The data provided can be separated into high-level and low-level cost data, depending on the importance

of their processes. Examples of high-level processes include facility shutdown, waste processing, storage, and disposal, and research and development.

The source of funding that facilitates decommissioning is different depending on the country considered. Generally, money to support decommissioning is set aside from the revenue obtained through electricity sales from nuclear power, by taxes on sales of electricity of any origin, or by a levy on net profits from the operator on other goods or services (Nuclear Liabilities Fund, 2024). In countries such as the USA, Canada, France, and Sweden, the operator of the nuclear power station is solely responsible for covering costs of decommissioning. For old reactors in the UK, the Nuclear Decommissioning Authority was responsible for decommissioning activities, and government funds covered the cost of decommissioning. Currently, a change to the policy is being made for newer reactors, which are now covered by the Nuclear Liabilities Fund (NLF). The NLF operates through payments made by the nuclear power station operators to the fund, which are then used for decommissioning activities. It is important to ensure that necessary funds are available at the required times for decommissioning. Therefore, risks to funding must be identified to ensure that appropriate measures are put in place to avoid financial issues. Some countries have also set review mechanisms, which analyse calculated liabilities, fund growth, assess market conditions, and evaluate decommissioning timings. These reviews can enable funds to be monitored, preventing the risk of inadequate funding.

In the UK, there are currently three different financing methods for nuclear reactor decommissioning, depending on the age of the reactors. For the older Magnox reactors, the NDA is solely responsible for decommissioning activities. The transfer of ownership of older nuclear reactors from British

Energy to the NDA was conducted in 2005. The NDA's budget for decommissioning was set by the UK's Department for Energy and Climate Change (DECC) and the HM Treasury. This budget consisted of government funding and income from the NDA's assets.

For newer reactors owned by EDF energy, decommissioning costs are covered by the NLF. The NLF was initiated in 1996, to provide funding for nuclear power stations decommissioning. Initially, it was set to support British Energy power stations but was then transferred to support the decommissioning of EDF energy stations. The NLF is owned by the Nuclear Trust, whose aim is "to protect and to preserve, for the benefit of the nation, the environment of the United Kingdom". The fund has five trustees, from which three are appointed by the Secretary of State for Energy and Climate Change, and two by the owners of the EDF energy power stations. Payments are made into this fund to contribute to the overall decommissioning costs of the remaining EDF energy power stations (Nuclear Liabilities Fund, 2024).

For new reactors which have not yet been built, decommissioning financing arrangements must be secured before building. These include decommissioning costs, waste

management costs and disposal costs of the reactor. New nuclear power stations are required to set in place a Funded Decommissioning Programme (FDP) which requires approval by the Secretary of State for Energy and Climate Change before construction commences. In the UK, Hinkley Point C has had conditional approval for decommissioning using the FDP. The FDP consists of two main parts as described below.

Decommissioning and waste management plan

Indicates how decommissioning, waste management, and waste disposal will be undertaken by the operator. The plan is reviewed and updated every 5 years.

Funding arrangements plan

Indicates how money will be provided to ensure that decommissioning, waste management, and waste disposal is conducted correctly. It is a contract between the operator and the independent funding company for decommissioning activities. The fund's roles and responsibilities and additional payments details are also contained in the funding arrangements plan.

5.2 Waste Management

Waste from nuclear power stations can be classified into four main categories: very low, low, intermediate, and high-level waste (NDA, 2024).

Very low-level waste (VLLW)

Waste with very low levels of radioactivity is a subcategory of low-level waste. Items considered very low-level waste can be disposed of in a standard way i.e., household, or industrial

waste at permitted landfill facilities. An example of very low-level waste would be building rubble from a nuclear facility that has been decommissioned.

Low-level waste (LLW)

Waste with low levels of radioactivity is classified depending on the radioactivity emitted. For alpha radioactivity, the limit is 4 giga-becquerel (GBq) per tonne, and for beta or gamma

radioactivity, the limit is 12 GBq per tonne. Low-level waste is generated during decommissioning of nuclear power stations, and includes items such as scrap metal, paper, and plastic. Out of the total radioactive waste generated while decommissioning a nuclear reactor, 94% is classified as low-level waste. Low level waste is disposed of in the Low-Level Waste Repository (LLWR) in Cumbria. The waste is secured in metal containers or flasks, before being inserted into concrete-lined vaults. There are limits on the number of radionuclides accepted at LLWR, and thus some LLW may be disposed of as higher level waste (NDA, 2024).

Intermediate-level waste (ILW)

Intermediate level waste has a higher activity than the limit stated for LLW (greater than 4 GBq per tonne of alpha radiation and greater than 12 GBq per tonne of gamma or beta radiation). However, ILW does not generate a lot of heat, contrary to higher level waste. Typical items classified as ILW include nuclear reactor components and graphite from the reactor core. ILW is disposed of in a different way to LLW and VLLW. Treatment of ILW including compacting, cutting, or drying the waste may occur. The waste is packaged in a container and immobilised in cement-based materials, which prevents the radionuclides from leaving the container. The waste can be packaged into stainless steel, concrete, or ductile-cast iron containers, enabling its safe storage, transportation, and disposal.

High-level waste (HLW)

High-level waste may undergo a temperature increase due to the presence of a large concentration of radioactive elements. Spent fuel from the nuclear reactor, with less than 1% of the waste from nuclear power stations are classified as HLW. HLW is often liquid, and undergoes a process called vitrification, whereby a liquid is converted into a glass or glassy substance and forms an essentially solid product. The liquid waste is vitrified in stainless steel canisters, enabling long-term storage and disposal. The canisters are then

deposited in an air-cooled store for at least 50 years. Over this time, a large amount of the radioactivity and heat from the HLW decays. The process of treating and storing HLW takes place at the Sellafield site in Cumbria.

Current efforts are focused on how to permanently store the fuel after HLW storage. Although overground storage is safe, and remains safe for approximately 100 years, overground storage is not a final solution. Waste in overground storage facilities requires constant monitoring and refurbishment to ensure that its integrity is not compromised. One option under investigation is the creation and use of a geological disposal facility (GDF). GDFs enable radioactive waste to be stored safely, deep underground and out of human reach. Other waste such as ILW and small amounts of LLW may also be disposed in a GDF. Waste associated with radioactive materials and nuclear power stations takes precedence over storage in a GDF.

GDFs operate by storing the waste at depth, within a volume of rock that surrounds the waste and ensures that the radioactivity does not ever reach the environment. This depth is below the water table, so that there is no risk of underground water radioactive contamination. A multi-barrier approach, involving both isolation and containment of the waste, is used for GDF storage to ensure that the radioactivity does not reach the environment and impacts life. Isolation and containment activities are described in more detail below.

Isolation involves removing the waste from people and the environment, and is achieved by choosing an appropriate GDF site and depth. The GDF depth varies between 200 – 1000 metres below the surface, under a stable rock. The location of the site is also important, and it must ensure that no mining activities may occur nearby (RWM, 2017).

Containment results in the waste kept safe in the designated area. Containment involves surrounding the solid waste in a metal or concrete waste container, surrounded by a buffer or backfill material. The tunnels or vaults, which form pathways or access points to the GDF, lead to a stable underground environment to store the waste safely. This area is then closed off by secure seals to guarantee that the waste is contained safely.

The containment surrounding the waste may differ depending on its classification. Figure 5-3 shows how intermediate and high-level waste are contained. Main differences include the waste form material and buffer/backfill material. As discussed, HLW must be vitrified, and thus is an essentially solid material. Clay acts as a buffer or backfill material for HLW due to its improved properties compared to concrete. To contain HLW

securely, the material used as a buffer or backfill requires self-sealing properties; clay supersedes concrete in this respect (Sellin & Leupin, 2013).

Waste from nuclear sites is regulated by the Office for Nuclear Regulation (ONR). The ONR ensures that waste is managed effectively by ensuring that the public and workers are protected from radiation emitted by the waste. This involves controlling where and how waste is stored. The ONR is the UK's independent nuclear regulator who ensures that safety and security is upheld at the 35 licensed nuclear sites in the UK. This includes operating reactors, fuel cycle facilities, waste management and decommissioning sites, and authorized defence sites. The ONR is also involved in the regulation of new nuclear facilities (ONR, 2020).

5.2.1 Potential Reuse

Some materials considered waste from nuclear power station decommissioning or some structural materials such as concrete or steel, may be reprocessed and reused for other purposes. Often, the procedure to repurpose and reuse such materials depends on the political stance and public viewpoints of the country in question. Countries must decide whether this is in the public's interest, and whether negative public perception of nuclear waste is too great when considering recycling materials.

Not all structural materials from nuclear power stations can be recycled, it depends on the condition of the material in terms of radioactivity. A few options can be considered when recycling waste. Firstly, uncontaminated materials can be unconditionally released, secondly, metal materials can be melted in a regulated manner and then recycled, thirdly, short

half-life products can be melted and then refabricated and reused, and lastly there are some materials which cannot be released from regulatory control or recycled to be reused.

Reuse of nuclear fuel is also becoming a re-emerging field of interest. Spent nuclear fuel can be reprocessed and recycled, extracting the fissile materials remaining, which can then be reused as fuel. Reusing spent fuel will be of great relevance to newer reactor generations, such as Generation IV reactors. Reprocessing and reusing spent fuel is advantageous, because it reduces the amount of high-level waste to be stored. It also reduces reliance on uranium reserves, diminishes the environmental impact through uranium mining, and fully closes the nuclear fuel cycle. Many countries such as China, Japan, and France have adopted this method of reprocessing fuel. Currently, reprocessed uranium is converted and enriched for

reuse in LWRs, and many reactors in Europe use recycled fuel. Other reuse options include using reprocessed uranium as fuel for pressurized heavy water reactors (PHWR). CANDU reactors use this type of reprocessing.

5.3 Conclusions

Various decommissioning methods can be used, depending on the country. Immediate dismantling is often used, allowing the outer part of the nuclear power station building to be removed as soon as possible. Authorities in different countries, such as the NDA in the UK, are responsible for ensuring that decommissioning is conducted in a safe manner. Cost of decommissioning has been discussed and can vary depending on the funding mechanisms of each country.

Waste from decommissioned sites can be separated into four categories, depending on the level of radioactivity. HLW storage is of further interest. Geological disposal facilities (GDFs) aim to safely store waste for the foreseeable future,

which is being discussed in several countries. The potential reuse of waste for other means, such as new fuel, can limit the amount of waste to be stored. Different manufacturing processes would need to be conducted to ensure that the reprocessed fuel is appropriate for use in different reactors, alongside ensuring that changes to the reactor core are approved.

6. The Future of Nuclear Power in the UK

6.1 The Current Landscape

Nuclear power stations in the UK

Active, decommissioned and planned nuclear reactor sites.



Figure 6-1: Map of reactor sites in the UK [Office of Nuclear Regulation, 2024b].

At present, there are 8 reactor sites (Dungeness B, Hartlepool, Heysham 1, Heysham 2, Hinkley Point B, Hunterston B, and Torness, and Sizewell B) housing a total of 14 reactors. However, only 9 are still operational at present. Hunterston B, Hinkley Point B, and Dungeness B have come to the end of their operational lifetime and are due to be decommissioned (Office for Nuclear Regulation, 2024b). The UK Government has recently committed to a new nuclear roadmap, setting out how the UK will achieve 24 GW of nuclear power by 2050 (DESNZ, 2024b). New large nuclear power stations would be situated at Hinkley C and Sizewell C, alongside the development of small modular reactor technology and fuel production (DESNZ, 2024b).

In May 2024 it was announced that the next nuclear new build will be situated at the previous Wylfa Newydd site on Anglesey, North Wales.

With an influx of investment in nuclear technologies, the nuclear workforce is another focus of the UK Government. Destination Nuclear, a programme to recruit people into the UK nuclear sector has been launched. Using this programme, people can find a variety of roles available in the nuclear sector, which will be required to support the UK Government’s mission of developing a new nuclear strategy (Destination Nuclear, 2024).

Table 6-1: Status of nuclear power plants in the UK (Office for Nuclear Regulation, 2024b)

Plant name	Reactor type	Capacity (MW)	Status
Dungeness B	AGR	520	In decommissioning since June 2021
Dungeness B	AGR	520	In decommissioning since June 2021
Hartlepool	AGR	595	Operational
Hartlepool	AGR	585	Operational
Heysham 1	AGR	585	Operational
Heysham 1	AGR	575	Operational
Heysham 2	AGR	610	Operational
Heysham 2	AGR	610	Operational
Hinkley Point B	GCR	435	In decommissioning since August 2022
Hinkley Point B	GCR	435	In decommissioning since July 2022

Plant name	Reactor type	Capacity (MW)	Status
Hunterston B	AGR	460	In decommissioning since January 2022
Hunterston B	AGR	460	In decommissioning since January 2022
Sizewell B	PWR	1191	Operational
Torness	AGR	595	Operational
Torness	AGR	595	Operational

6.2 Net Zero Innovation Portfolio and Advanced Nuclear

The UK Government has developed the Net Zero Innovation Portfolio (NZIP) in order to support net zero projects and commit to the target of meeting net zero carbon emissions by 2050. NZIP aims to decrease the costs of decarbonisation, along with innovating and bringing new technology to the UK. The NZIP project has been funded up to March 2025, enabling industries to focus on progressing their technologies through technology readiness levels (TRLs) to be used successfully in the future (DESNZ, 2023).

The NZIP is divided into ten technology-focused themes: Energy Storage and Flexibility, Future Offshore Wind, Advanced Nuclear, Bioenergy, Industry, Hydrogen, Advanced Carbon Capture Usage and Storage, Greenhouse Gas Removal, Homes and Buildings, and Disruptive Technologies (DESNZ, 2023).

The Advanced Nuclear theme in NZIP is funded through the Advanced Nuclear Fund in order to develop modern nuclear technologies. The Advanced Nuclear theme aims to shorten the timescales of new nuclear builds, alongside increasing investor confidence in pursuing new nuclear construction (DESNZ, 2023). The theme is also focused on developing Advanced Modular Reactor (AMR) technologies, alongside scaling up the development of coated particles fuel, also known as TRISO (TRi-structural ISOtropic) fuel. The commercialization of coated particles fuel is within the remit of the Nuclear Fuel Fund (NFF) (Office of Nuclear Energy, 2020). The NFF was developed to ensure that fuel demands of future nuclear power stations could be met. This involves ensuring that there is a feasible supply chain, alongside developing the capability to produce new fuel products.

The Advanced Fuel Cycle Programme (AFCP) was established as a part of the Department for Business, Energy & Industrial Strategy' (BEIS) Energy Innovation Programme. The AFCP focuses on next generation fuels, including accident-tolerant fuels and advanced nuclear fuels. Accident-tolerant fuels are those which increase both overall performance and performance in severe accident conditions (DESNZ & National Nuclear Laboratory, 2021). Advanced

nuclear fuels are those which can improve the economic performance of a reactor (AFCP, 2024). The AFCP consists of over 100 UK and international collaborators, with 90 of the collaborators based in the UK. These collaborators are based both in industry and academia, to ensure that research can be implemented in real reactors (AFCP, 2024).

6.3 Advanced Modular Reactors

The UK Government is also running an AMR Research, Development and Demonstration (RD&D) Programme to understand the technology and provide an AMR demonstration by the 2030s, in an effort to meet net zero by 2050 (BEIS, 2022). AMRs are Generation IV reactors, which can use novel coolants and novel fuels, and also have higher temperature outputs, lower power outputs and are fabricated in a factory environment

The UK Government has confirmed that the AMR technology of interest will be focused in high-temperature gas-cooled reactors (HTGRs). Other reactor types will continue to be investigated, but the AMR Programme, will be mainly focused on HTGRs (BEIS, 2022). The AMR RD&D Programme will be focused on developing and demonstrating an HTGR technology that can support the UK's net zero target by 2050. To succeed, the programme will focus on four main aspects (BEIS, 2022).

- 1. Maximising the impact of HTGRs on achieving net zero by 2050**
- 2. Minimising the cost of energy produced by HTGRs**
- 3. Encourage private investment to develop HTGRs**
- 4. Maximise economic benefits from HTGR deployment in the UK**

Phase A of the AMR RD&D project ended in 2022. Phase A was able to fund 4 pre-FEED (Front End Engineering Designs) across 2 key technology lots, which included reactor demonstration and fuel demonstration. Pre-FEED work focused on reactor design, costs and risks, to make a justified decision on which designs to take forward.

6.4 Conclusions

Nuclear power generation has been on the decline in the UK without substantial new investment, with many operating reactors due to close soon. The UK Government has now highlighted their current plans to develop and construct new nuclear facilities. The UK's NZIP and Advanced Nuclear theme directly targets this, with funding set aside for AMR and SMR projects to be developed. The development of Great British Nuclear will hopefully help to assist these new technologies to

be developed and deployed, ensuring that the UK has access to energy generation from advanced nuclear technologies in the future. However, as with any technological development, there are uncertainties and challenges when transitioning from research and development to full-scale deployment.

7. Economic Analysis

7.1 Government Debt and Fiscal Constraints

Navigating the landscape of private investment and funding mechanisms for nuclear power projects entails a comprehensive exploration of various factors influencing financial feasibility. The high debt levels of the UK government, amounting to 101.2% of Gross Domestic Product (GDP) in 2023 (Office for National Statistics, 2023), hinders its capacity to invest substantially in large-scale nuclear initiatives. This constraint raises concerns about the government's ability to allocate funds to the nuclear energy sector and underscores the importance of innovative financing models. Beyond the specific case of the UK, examining fiscal constraints is paramount, considering potential limitations on government resources globally.

Moreover, inflation emerges as a crucial factor with implications for the financing of nuclear power projects. The destabilizing effect of inflation on the financing landscape

requires strategic measures to mitigate risks and ensure the viability of nuclear projects. Additionally, the threat of a banking crisis is a significant concern, potentially restricting the availability of investment in nuclear power projects. An exploration of these challenges shows intricate relationships between fiscal constraints, inflation, banking crises, and the long-term financing needed for the development of nuclear power plants.

It is important to note that these are complex issues, and while they have been touched upon, a comprehensive analysis of their full implications is beyond the scope of this white paper. The forthcoming economic analysis will highlight the effect of discount factors and project delays amongst other aspects, providing valuable insights into key aspects of nuclear project financing.

7.2 Funding Mechanisms

Whether a country is starting its first nuclear project or enhancing an existing program, government funding is crucial. This financial support is needed for setting up the necessary nuclear infrastructure, including legal frameworks, regulatory bodies, workforce development, emergency readiness, and funding for waste disposal and facility closure. However, financing nuclear projects has become more complex in recent decades. Deregulation in utility markets, where energy generation is separated to encourage competition, has introduced challenges which result in an increased risk for nuclear operators. To overcome these hurdles, the nuclear sector is exploring new financing approaches, such as government-backed investments and loan guarantees. Simultaneously, in global financial markets, innovative tools are being developed to ensure returns on investments and attract investors by spreading risks across project phases. This section delves into the changing landscape of nuclear project financing, exploring the connection between government funding, market changes, and novel financial tools.

Nuclear power plants are characterised by a high upfront capital cost and long construction periods, low and stable operational costs, and prolonged return on investment timelines. Hence, the financing cost becomes a key determinant of the cost of the electricity generated, due to the investment profile and risks associated with construction. Nuclear power plants secure their financing through a combination of debt and equity, and while assessing investor risk is a common practice in any project, there are distinctive factors that must be considered for investors in NPPs. These factors include the technical complexity and risk present during the construction phase due to delays and cost overruns. For instance, an NPP takes more than five years to construct and often over a decade (Carajilescov & Moreira, 2011), whereas natural gas-fired plants are frequently built

in around two years (Necoechea-Porras et al., 2021). This impact is amplified given the absence of project revenue streams during the construction period, which can result in a significant compounding interest on borrowed funds. The liabilities related to waste management and decommissioning also contribute. Furthermore, the evolving and costly nature of permitting and licensing regimes in the policy and regulatory landscape introduces an imperative element of risk. Adding to that, the construction timespan of nuclear power plants often spans multiple parliamentary periods, exacerbating uncertainties and risks for investors. Fortunately, once the NPP is commissioned, the high capital costs are offset by low and stable variable costs.

The cost of capital is a critical factor affecting NPPs, and it is influenced by investor assessments of project completion and market risks. The shift from regulated markets, with government oversight and cost guarantees in the 1970s, to deregulated markets with competition and market volatility, transformed the financial risk landscape for investors (Egli, 2020). In competitive markets, investors face uncertainty in their return of investment, especially for technologies with high fixed-to-variable cost ratios. This is especially common among low-carbon energy solutions (Egli, 2020). Regardless of market design, any project needs to be economically feasible to attract finance. There are many different project structures that may be used to pay for upfront capital costs, and finance is raised using both debt and equity. Debt financing involves a bank or lender offering a loan to a project's owner. This loan usually involves the company providing security and is repaid with interest. Equity financing, in comparison, involves an investor providing funding in exchange for a stake in the project and in the case of nuclear power plants, an equity investor will receive returns from the sale of electricity once the plant is operational.

Broadly, there are two main ways in which a nuclear power plant project can be structured - either government or corporate finance, corresponding to public or private finance, respectively. (World Nuclear Association, 2023a). Here, governments directly finance the project through a mix of equity and debt and usually the government is involved in owning and operating energy utilities. Alternatively, private finance is usually handled by a large utility company who arranges for a mix of debt and equity. In some instances, such as in Finland and France, a group of investors chose to cooperatively finance a project and are allowed to purchase electricity at a cheaper price (IAEA, 2018b).

Nonetheless, governments play a crucial role in mitigating investor risks even if they are not direct sponsors. Unclear funding streams (and thus hindering effects on investor confidence in repayment) are a challenge to gain private finance. The capital-intensive nature of nuclear power projects, with high fixed-to-variable cost ratios, poses risks due to significant upfront spending before earning revenues. There are several financing methods already in place including the ones described below.

Contracts for Difference (CfDs) (House of Commons, 2023) were introduced in 2014 in the UK, and are crucial mechanisms for securing competitive financing for nuclear power projects. CfDs are long-term contracts between operators and often a government entity representing electricity customers. The agreement ensures that, over an established period, the difference between the project cost and market price for electricity is shared between the government and the operator. This risk-sharing approach provides revenue certainty for investors and is the current mechanism used. However, the CfD places the entire risk on developers and has led to the cancellation of recent potential projects such as Hitachi's project at Wylfa Newydd in Wales and Toshiba's at Moorside in Cumbria (BEIS, 2021).

Regulated Asset Base (RAB) model (House of Commons, 2022) has been proposed by the UK government for future nuclear power projects. The RAB model allows a nuclear plant developer to obtain a license from an independent regulator, verifying the project's viability. The developer can then recover costs by charging customers for the asset and electricity supply. The RAB model's innovative feature is that it ensures bankable revenue during construction, reducing investor's risk and potentially lowering the cost of capital. The UK government's proposal includes a funding cap to limit investor exposure and incentivize on-budget project delivery. This model has been used and successfully financed other infrastructure projects such as the Thames Tideway Tunnel and Heathrow Terminal 5.

Power Purchase Agreements (PPAs) (Crown Commercial Service, 2020) provide long-term revenue guarantees in the electricity industry. These agreements, common in the UK, involve a contractual commitment between an electricity generator and a purchaser such as a grid operator or wholesaler. The PPA specifies the price, quantity, and duration over which the buyer purchases power from the seller.

Feed-in Tariffs (FiTs) (Ofgem, 2024) are a mechanism currently employed to incentivise investment in renewable energy projects. Under FiTs, electricity generators are paid a fixed, above-market price for the power they produce. In the context of nuclear power, FiTs may play a limited role due to the unique characteristics of nuclear projects, specifically the high upfront capital costs and long construction periods.

7.3 Economic Analysis

The economic analysis presented in this work uses scenario analysis to address the cost of nuclear power plant projects. This is because of the dynamic nature of the energy landscape and the imperative to anticipate various contingencies; scenario analysis becomes a vital tool in elucidating potential outcomes under different circumstances. The International Atomic Energy Agency’s (IAEA) approach (IAEA, 2018a) serves as the methodological approach for this analysis, ensuring a robust and globally recognized framework. This methodology allows for the exploration of diverse factors that could influence the economic viability of nuclear power projects, encompassing variations in discount rates, construction periods, capacity factors, and reactor types. The scenario analysis not only offers a nuanced understanding of potential outcomes but also facilitates informed decision-making for policymakers, investors, and stakeholders navigating the complexities of nuclear energy planning in the UK. The considered reactors and scenarios are shown in Table 7-1 and 7-2, respectively.

Table 7-1: Overview of reactor sites in the UK, including company, location, reactor type, capacity and operational status.

Company	Reactor Site	Location	Reactor	Capacity (MW)	Status
EDF Energy	Sizewell	Suffolk	EPR	1670 x2	Planned
China General Nuclear	Bradwell	Essex	Hualong One	1150 x2	Proposed
Horizon	Wylfa Newydd	Wales	ABWR	2760 x2	Cancelled
GE Hitachi	Sellafield	Cumbria	PRISM	311 x2	Cancelled
Candu Energy	Sellafield	Cumbria	Candu EC6	740 x2	Cancelled
NuGeneration	Moorside	Cumbria	AP1000	1135 x3	Cancelled

Table 7-2: Economic analysis scenarios with varying discount factors, capacity factors, construction periods and years of operation.

	Discount Rate (%)	Capacity Factor (%)	Construction Period (Years)	Years of Operation
Scenario 1	5	92	5	60
Scenario 2	5	92	10	60
Scenario 3	5	85	5	60
Scenario 4	5	92	5	80
Scenario 5	3	92	5	60
Scenario 6	10	92	5	60

The economic analysis of the EDF EPR 1720 MWe (Figure 7-3) reactor provides valuable insight into the cost composition and factors influencing its financial dynamics. Capital costs account for a significant portion, precisely 52%, which underscores the capital-intensive nature of nuclear power projects. This substantial allocation to capital expenses reflects the extensive upfront investments required for construction, including reactor infrastructure and safety features. The breakdown further reveals fuel costs at 11.3%, highlighting the relative cost stability associated with nuclear fuel compared to fossil fuels, a factor contributing to the low and stable operational costs typically observed in nuclear power plants (World Nuclear Association, 2023a). Fixed operations and maintenance (O&M) expenses claim a notable share of 25%, emphasizing the ongoing commitment to ensuring operational reliability

and safety. This allocation reflects the costs associated with routine maintenance, personnel, and other fixed operational expenditures crucial for sustained plant performance. Additionally, the allocation for spent fuel at 4.7% shows the importance of addressing nuclear waste management, with dedicated resources allocated to handle the spent fuel generated during the reactor’s operational life. The decommissioning component, representing 6.7% of the total cost, acknowledges the long-term responsibility and financial provision required for the eventual decommissioning of the reactor. This allocation highlights the industry’s commitment to addressing the entire lifecycle of nuclear projects, from construction to decommissioning, and underscores the need for robust financial planning to meet future decommissioning obligations.

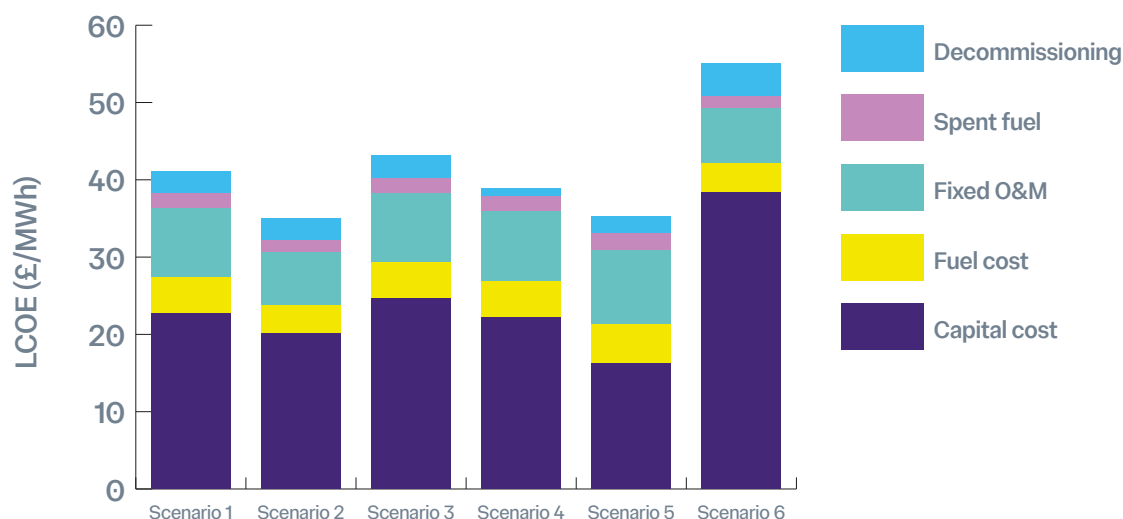


Figure 7-3: Calculated levelised cost of electricity (LCOE) in £/MWh for the different scenarios studied, divided into various cost categories.

The results of the economic analysis yield crucial insights into the potential implications and challenges associated with nuclear power projects in the UK. Firstly, various discount rates were considered because they are used to accurately assess the economic viability and competitiveness of nuclear power projects in the face of changing financial conditions and risk perceptions (Figure 7-4). The scenario analysis with varying discount rates revealed a sensitive relationship between the discount rate and project costs. The substantial increase in

the cost of the EDF EPR by 90% when transitioning from a 3% to a 10% discount rate underscores the financial significance of discount rate choices. Higher discount rates, reflecting increased economic risk or opportunity costs, significantly amplify the economic hurdles faced by nuclear projects. This underscores the need for careful consideration of discount rate selection in the context of broader economic conditions and policy frameworks.

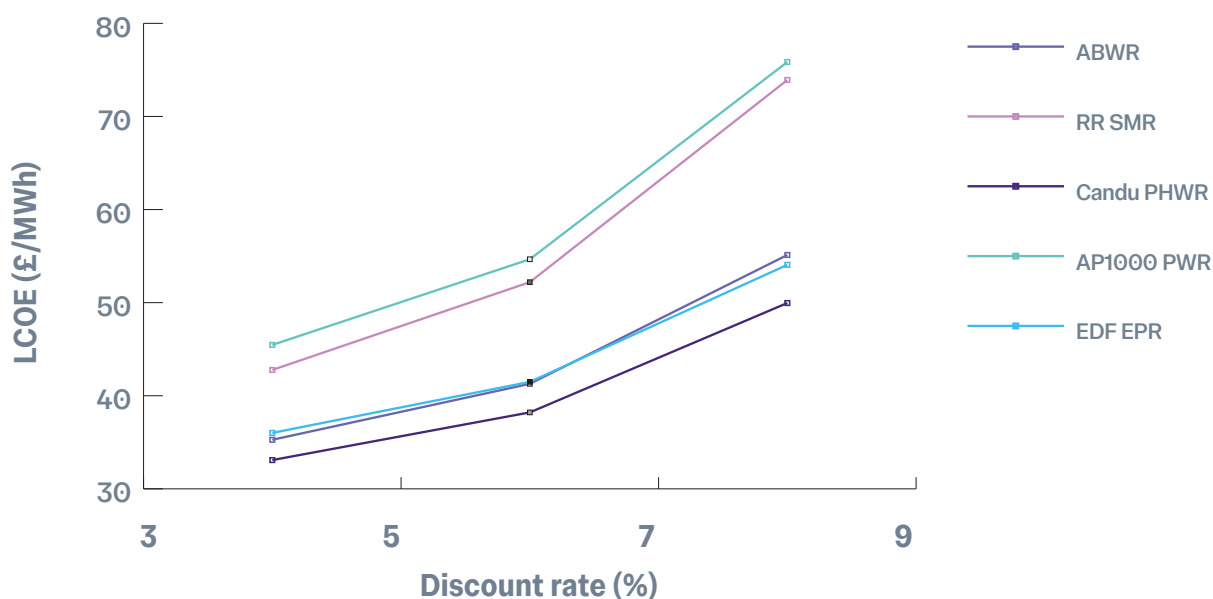


Figure 7-4: levelised cost of electricity (LCOE) in £/MWh vs. discount rate for different reactor types.

The costs of nuclear power reactors under all scenarios are shown in Figure 7-5. The extension of the construction period to account for potential delays introduces a trade-off between upfront costs and the levelized cost of electricity (LCOE). While an extended construction period may reduce immediate capital outlays, it also leads to a higher LCOE. This dynamic shows the balance between upfront investment, project timelines, and long-term economic sustainability. It suggests that efforts to streamline construction processes and mitigate delays are essential for optimizing project economics.

The scenario with an 85% capacity factor, although associated with lower total costs, leads to a higher LCOE. This counterintuitive outcome underscores the importance of considering the trade-offs between upfront construction efficiency and the long-term implications for electricity pricing. In essence, a lower capacity factor, indicative of decreased efficiency, would result in a higher electricity price, emphasizing the nuanced dynamics that shape the economic profile of nuclear power projects.

Analysing specific reactor types further accentuates the diversity in cost considerations within the nuclear energy landscape. The Rolls Royce SMR's higher cost highlights potential challenges associated with innovative small modular reactor designs, emphasizing the need for economies of scale, and streamlined construction processes to enhance cost competitiveness.

Despite the design advantages of SMRs such as shorter construction times and lower upfront costs, several factors contribute to their relatively higher costs compared to

conventional nuclear reactor designs. One significant factor is the economies of scale. While SMRs are designed to be smaller and more modular, allowing for easier manufacturing and assembly, they may not benefit from the same economies of scale as larger reactors. The smaller size of SMRs can result in higher costs per unit of electricity generated, particularly during the initial phases of development and deployment.

Additionally, the innovative nature of SMR technology introduces uncertainties and complexities in the licensing, regulatory approval, and supply chain processes, which can lead to higher costs. SMRs may require more extensive research and development efforts to address technical challenges and ensure safety and reliability, adding to their overall costs.

Moreover, the supply chain for SMRs may not be as mature or well-established as that for larger reactor designs, leading to higher procurement costs for components and materials. As a result, while SMRs offer potential advantages in terms of flexibility, scalability, and enhanced safety features, these benefits may come at a higher initial cost, which could impact their overall economic competitiveness. Conversely, the comparatively lower cost of the CANDU reactor points towards the economic advantages of certain reactor designs, providing valuable insights for decision-makers in reactor selection.

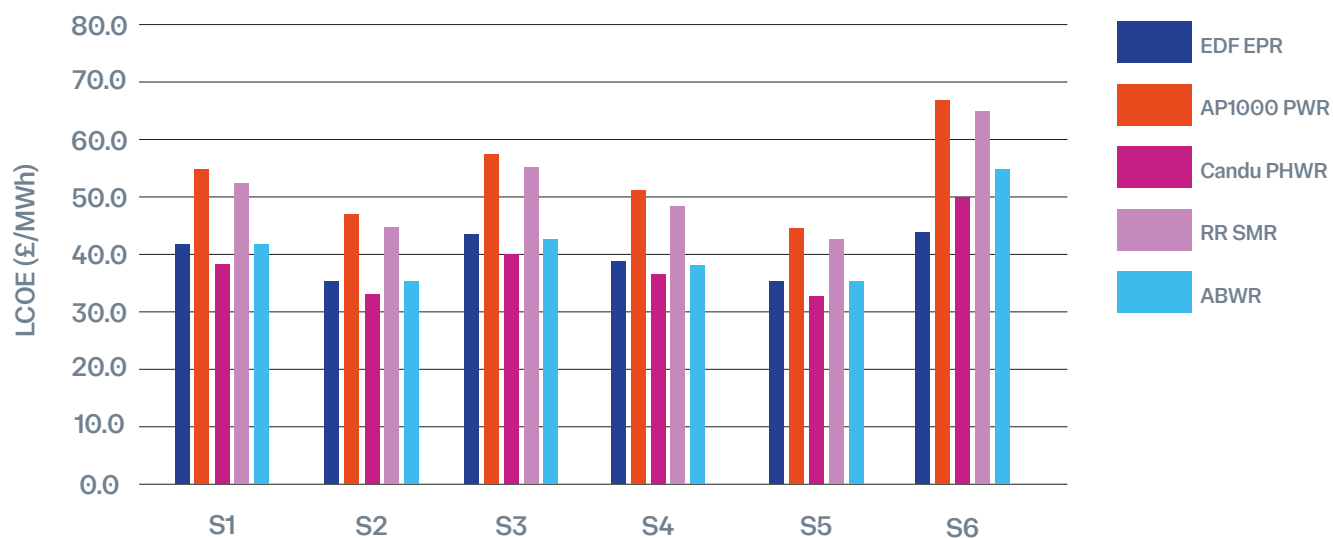


Figure 7-5: levelised cost of electricity (LCOE) in £/MWh for all the reactors studied under various scenarios.

It is important to note that although LCOE is a useful metric for comparing the cost of electricity generation across different technologies, it is also essential to recognize its limitations, particularly concerning the longevity of the asset. Unlike renewable energy sources like wind or solar, which typically have shorter lifespans of around 25 to 30 years, nuclear power plants are designed to operate for much longer periods, ranging from 60 to 80 years.

Therefore, while the LCOE provides valuable insights into the cost of electricity over the project's lifetime, it may not fully capture the economic benefits of nuclear power plants extended operational lifespan. The longevity of nuclear assets allows for extended periods of revenue generation, spreading the initial capital investment over a longer period and potentially reducing the overall cost of electricity over the plant's lifetime. Incorporating this understanding into discussions about nuclear economics underscores the importance of considering nuclear power projects' full lifecycle

costs and benefits, when evaluating their economic viability and contribution to the energy mix.

In the broader context of the UK's nuclear energy aspirations, the identified gap between planned and proposed capacities and the targeted 24 GWe by 2050 emphasizes the financial and strategic challenges ahead. Bridging this gap necessitates substantial investment, with potential implications for public finances, private sector involvement, and policy frameworks. The equivalent budget allocations in the UK serve as a useful benchmark, offering a tangible perspective on the scale of financial commitments required for achieving the outlined nuclear energy goals. Assuming the proposed projects proceed as planned, the calculated cost to produce the remaining required gigawatts (GW) of nuclear power ranges from 5.2 to 10.4 billion pounds per year (Figure 7-6).

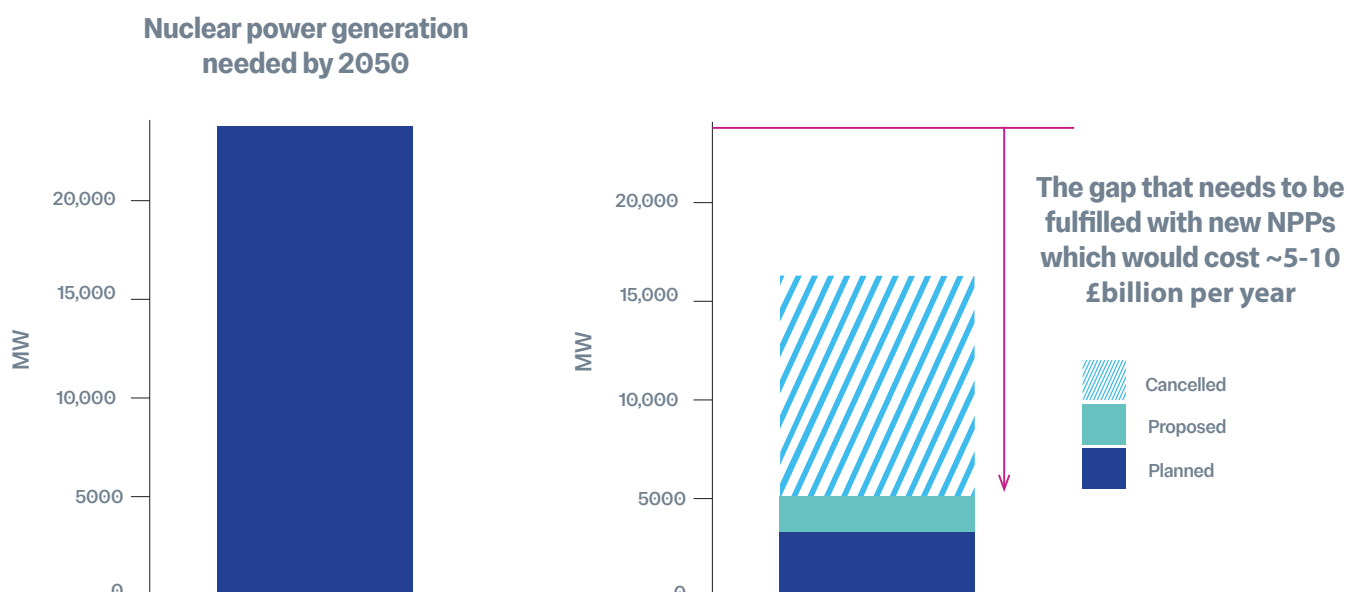


Figure 7-6: Nuclear power generation needed by 2050 compared to planned and proposed capacity, highlighting the gap and estimated costs to fulfil this gap.

7.3.1 Conclusions

In summary, the economic analysis provides an understanding of the multifaceted considerations shaping the feasibility and viability of nuclear power projects in the UK. The scenario analysis showcases the intricate relationship between construction efficiency, operational performance, and the economic metrics used to assess

project viability. The insights are crucial for policymakers, investors, and stakeholders, guiding strategic decisions and policy formulations in the pursuit of a sustainable and economically viable nuclear energy future.

8. Skills and Workforce Requirements

8.1 Required Skillsets

Nuclear power projects are multifaceted and hence require a comprehensive set of skills across various phases, ranging from the initial design and construction to the subsequent operation and maintenance of facilities. The complexity and precision demanded by nuclear power plants requires specialized expertise in several key areas. Some of the critical skillsets required include the ones described below.

Project and Program Management

These are vital for overseeing the entire lifecycle of nuclear projects, from conception to completion, ensuring adherence to timelines, budgets, and regulatory requirements. Project management has a notable effect on the long-term electricity pricing and upfront capital costs, as seen in Section 7.3. Therefore, the roles outlined can significantly impact the outcome of nuclear power projects.

Construction Project Management

Essential for coordinating the complex construction process, managing resources, and ensuring compliance with safety standards.

Engineers with Diverse Skill Sets

Crucial skills to guarantee the structural integrity and safety of nuclear facilities, contributing to the robustness of the construction. Engineering subdisciplines of interest include, but are not limited to, civil, electrical, and mechanical.

Safety Case Authorship

A pivotal role in developing comprehensive safety cases that underpin the secure operation of nuclear facilities, ensuring compliance with stringent safety standards.

Research and Development (R&D)

Continuous innovation and technological advancement are fundamental for the nuclear sector. R&D professionals drive advance in reactor technologies, safety protocols, and waste management.

The mentioned skillsets collectively contribute to the successful implementation, operation, and maintenance of nuclear power projects. Given the industry's emphasis on safety and regulatory compliance, expertise in these areas is paramount for sustaining a resilient and secure nuclear sector.

8.2 Current Workforce

As of the latest available data in 2015, the UK's nuclear workforce consisted of approximately 40,000 employees, indicating a robust and experienced talent pool (HM Government, 2015). However, challenges in the workforce are evident. The UK's nuclear industry is confronting a significant problem as its workforce ages. With a significant portion of professionals in the sector nearing retirement, there are concerns regarding the preservation and transfer of invaluable tacit knowledge. As the industry matures, the retirement of experienced personnel raises questions on the sustainability of the knowledge base that underpins nuclear operations. A critical aspect of this challenge is the nature of tacit knowledge, developed through years of personal experience and involvement in nuclear projects. Tacit knowledge, which is not easily codified or stored, constitutes a substantial part of the expertise held by the retiring workforce. An analysis (Oxford Economics & Atkins, 2013) of the workforce demographics reveals that approximately 53% of the employees are over 45 years old, where 20% under the age of 34, signalling an imminent attrition of skills and expertise over the next decade. This demographic challenge is particularly acute in management and subject matter expert roles, with nearly 70% of those in such roles expected to retire by 2025. This underscores the urgency for strategic workforce planning to ensure knowledge continuity and

the development of a pipeline of skilled professionals. The potential loss of this experiential knowledge poses a threat to the efficiency, safety, and cost-effectiveness of future nuclear activities.

Furthermore, there is a declining influx of recent graduates into the nuclear field (UK Parliament, 2009). Investments in nuclear research and development have experienced a notable decline, further exacerbating concerns about the potential loss of knowledge and competence (IAEA, 2012). There are reported skills deficiencies, particularly in project and construction management, high integrity welding, and safety case authorship (HM Government, 2015). These gaps emphasize the need for strategic interventions to address immediate skills shortages. The urgency to implement programs and measures for preserving, managing, and transferring knowledge to the emerging generation becomes increasingly apparent. Adopting strategic initiatives, considering policy implications, and reimagining workforce structures are essential steps in preserving and transferring knowledge effectively. Policymakers, both at the national and organizational levels, must proactively address these challenges to ensure the continued success and safety of the UK's nuclear industry.

8.3 Workforce Development

To proactively address the workforce challenges that have been identified, a multifaceted and strategic approach is imperative. Investing in education and training programs emerges as a cornerstone for preparing the next generation of nuclear energy professionals. The skills gaps in project

and construction management, high integrity welding, and safety case authorship can be specifically targeted through apprenticeships and higher-level apprenticeships. Initiatives like the "Triple Bar for new nuclear" underscore the industry's commitment to developing specialized qualifications that

align with the unique demands of nuclear projects (NSAN, 2024). Additionally, the establishment of frameworks, such as the Nuclear Education, Skills and Technology (NEST), becomes crucial. Such frameworks aim to preserve and transfer explicit knowledge in critical areas including nuclear science, radioactive waste management, and radiological protection (Nuclear Skills Strategy Group, 2021).

Collaboration with universities and research institutions is essential for aligning the educational curricula with industry needs. These partnerships can facilitate the development of tailored programs that emphasize nuclear-specific skills and behaviours, creating a pool of talent equipped to contribute to the industry’s growth. Apprenticeships and higher-level apprenticeships can be expanded to address the immediate skills gaps identified in construction, welding, and safety case authorship.

Leveraging the existing infrastructure and expertise within national laboratories can provide hands-on experience with nuclear materials, enhancing the practical skills of the

workforce. The comprehensive strategy should also involve addressing the immediate skills gaps while concurrently focusing on long-term workforce planning. This includes measures to attract more talent into the nuclear sector, promoting flexibility and mobility within the workforce, and ensuring a clear career progression pathway.

A comprehensive and strategic approach to workforce development is crucial to secure the future of the UK’s nuclear industry. By investing in education, collaborating with universities, and tailoring training programs to industry needs, the UK can ensure a skilled, diverse, and sustainable nuclear workforce capable of addressing the challenges and opportunities in the evolving landscape of nuclear power. This strategy will not only meet the immediate demands of ongoing projects but also position the industry for long-term success and global competitiveness.

9. International Collaborations

After the Chernobyl disaster, international cooperation on nuclear operations was developed through the World Association of Nuclear Operators (WANO) (World Nuclear Association, 2020). WANO acts to coordinate nuclear power stations in 34 countries and has four main programmes which focus on peer reviews, operating experience, technical support and experience, and professional and technical development. Through sharing experiences, WANO aims to improve safety and operational experience at these power stations moving forward. Power stations in the UK as well as Sellafield are members of WANO (WANO, 2024a).

The development of new nuclear is a global effort. Currently, the UK cooperates internationally with the USA, France, Finland, and Japan, sharing technical information of new nuclear builds (Office for Nuclear Regulation, 2024a). Other organizations that also facilitate collaboration include the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development (OECD). The OECD has a specialist unit for nuclear energy, called the Nuclear Energy Agency (NEA). Through the NEA, the Multinational Design Evaluation Programme (MDEP) aims to enhance multilateral co-operation between member states and to develop future standards and inspection practices for new nuclear builds. Member states of NEA include the UK, Canada, Finland, France, Japan, the Republic of Korea, and the USA. A working group on regulating new builds has also been set up to share best practices. Member states include the UK, Sweden, France, Japan, Spain, and the USA (Office for Nuclear Regulation, 2024a). International

collaboration is a necessity for new nuclear in the UK to ensure that best practices and technologies are adopted and to allow a successful development of the UK's future nuclear fleet.

Often, private, or corporate funding provides the financing for new nuclear builds. In the UK, many international investors have been involved on proposed or current projects. When the Wylfa Newydd site was proposed for construction, the site was owned by Horizon Nuclear Power. However, the reactor was supplied by Hitachi GE Nuclear Energy. For the proposed Bradwell B site, there is potential for a joint ownership between China General Nuclear Power Group and EDF Energy. Both EDF Energy and China General Nuclear Power Group own Hinkley Point C, which is under construction (EDF, 2024a). However, for Sizewell C, the UK Government is still awaiting private investors to come forward to fund the project. Such delays are considered negative for the nuclear industry and increase the overall project costs due to suspensions (Boarin & Ricotti, 2013).

Nuclear security is a major consideration for the national government. However, an international approach is needed. Through the IAEA, the Nuclear Security Series aims to provide guidance on nuclear security to all member states. Frameworks on how to identify sensitive information and secure it, along with sharing and disclosing sensitive information, are provided to its member states (IAEA, 2015). Member states of the IAEA benefit from sharing data in the correct manner, whereas states who are not involved have

less regulations. This can be observed as an issue for nuclear security, where the ideal would be for all nuclear operating countries to share information freely following best practices and materials.

A new threat facing the nuclear community is the digitalisation of nuclear power stations. Newer designs are moving towards digitalisation and away from traditional analogue setups. Power stations may be designed so that they can be operated remotely or autonomously. However, this requires security improvements from a technological standpoint. Security measures around cyber-attacks must be considered, to ensure that nuclear power stations are not vulnerable. Guidance following the IAEA's Nuclear Security Series on computer security is being developed to allow sites to determine the amount of protection they require (IAEA, 2023b).

Geopolitical factors can also influence collaboration decisions. Deciding factors may include location of fuel supply and current collaborations. The Russia-Ukraine war has had an impact on many countries. The USA and some European countries rely on Russia to provide uranium for fuel purposes. If this fuel supply were to be interrupted, it could lead to energy shortages in these countries (Defence News, 2023; The Associated Press, 2023). Because of this, some countries are slowly moving away from obtaining their fuel supply from Russia. The Finnish company Fortum has recently agreed a

deal with the American company Westinghouse Electric to supply fuel for two reactors in the future (Fortum, 2022).

Positive experiences of international collaboration include the UK – India deal. In 2015, the UK and India Prime Ministers signed a Nuclear Collaboration Agreement (NCA) as a part of a wider collaboration on energy and climate change. This agreement encouraged joint training and experience sharing on nuclear research. The agreement was stated to be a “symbol of mutual trust”, aiming to “strengthen safety and security in the global nuclear industry”. This positive experience of knowledge sharing can help develop nuclear industries further, along with adopting best practices and nuclear operations in the future (King's College London, 2015).

10. Research and Policy Recommendations

10.1. Overview

This briefing paper has outlined the prospects of nuclear power as a technology to meet net zero carbon emissions in the UK and globally. Comparisons have been made in terms of the technology used, the global landscape, economics of nuclear power, safety, security, and safeguards for new

nuclear, and decommissioning and waste management. These comparisons have been made to facilitate discussions on the prospective developments in nuclear energy within the UK.

10.1.1 Strengths

The main strength observed both in the UK and globally is the clear appetite for investing in the development of new nuclear technologies. Achieving carbon neutrality necessitates transitioning away from coal, oil, and gas. Consequently, exploring non-carbon emitting energy options, such as nuclear power, is advantageous. Countries whose nuclear strategies were analysed in this briefing paper, (UK, China, US, Canada, Russia, and France) are all investing heavily in developing the technology and ensuring that they have adequate energy generation from nuclear sources. SMRs and AMRs are known to have improved nuclear reactor generation designs, thus increasing safety, efficiency, and economics of power generation. SMRs can also be useful for areas which are more remote or not well connected to the

grid. This enables the technology to be deployed in areas harder to reach, or smaller sites, ensuring flexibility.

Progress in spent fuel storage is also promising. Research and development are being carried out to tackle the problem of overground spent fuel storage, by developing technologies such as geological disposal facilities (GDF). Incentives to store such radioactive material indefinitely allows the future nuclear fleet to be commissioned sustainably, as waste storage will already be accounted for upon decommissioning.

10.1.2 Challenges

Challenges facing nuclear power, in common with many other large-scale engineering projects, include time constraints, construction costs, and political decisions. The main problem in developing major new nuclear generation plants is the time it takes to build them. Larger conventional nuclear power stations can take upwards of 8 years to build, with estimated construction times often increasing during the project. Reducing construction times for these larger power stations through tight project management, resilient supply chains and increasing workforce availability would be key recommendations. SMRs also offer an alternative means of generating fewer GWs using nuclear power, but on a quicker timescale. This trade-off between energy generation and time must be considered when investing in new nuclear energies.

The construction of new nuclear power stations presents significant financial challenges, primarily due to their notorious reputation for high initial costs and the tendency to exceed budgetary allocations. SMRs offer a potential cost-saving advantage due to their reduced size, but they may not always be practical in terms of energy output.

When it comes to financing these large-scale engineering projects, it is crucial for governments to explore various options. The UK Government has faced setbacks with investments in new nuclear projects such as Wylfa Newydd, primarily due to escalating costs. The government has proposed the Regulated Asset Base (RAB) model as a new financing approach. This model encourages low-cost, private investments in public projects, making it more appealing to investors by minimizing initial expenses. While this strategy could lower the barriers to investment, it also transfers the financial burden to consumers, who may see an increase in their electricity bills as a result. The fluctuating costs associated with construction and financing can lead to

consumers ultimately paying higher than anticipated amounts. Therefore, it is imperative for the UK Government to weigh the advantages and disadvantages of adopting the RAB model for funding future nuclear power initiatives, ensuring a balance between attracting investment and protecting consumer interests.

Political decisions play a pivotal role in a nation's commitment to nuclear energy. The UK's journey with nuclear power began in the 1950s, with eleven Magnox reactors becoming operational from 1962 to 1971, signifying a strong national focus on nuclear energy. This was followed by the commissioning of seven Advanced Gas-cooled Reactors (AGRs) and one Pressurized Water Reactor (PWR) between 1976 and 1995. However, since that period, the construction of new nuclear power stations has stalled, with some sites currently under construction, others pending commencement, and some projects being abandoned.

Initially, the UK's nuclear power stations were state-owned. The 1990s saw a shift as the Central Electricity Generating Board (CEGB) was divided into independent entities, leading to the privatization of the nuclear sector under the Conservative Government. This transition necessitated private investments for the development of commercial nuclear power stations, moving away from government-funded projects.

Construction challenges are intertwined with the complexities introduced by political dynamics. In recent times, the Conservative Government has renewed its support for nuclear energy through initiatives like Great British Nuclear. It is imperative for the current UK Government to prioritize the development of new nuclear facilities as a critical agenda, ensuring that new nuclear power stations become operational in a timely manner to meet future energy needs.

11. Policy Recommendations

Nuclear power is an important component of the UK's energy mix, providing low-carbon, reliable, and secure electricity. However, the nuclear industry faces several challenges, such as high costs, skills shortages, and complex waste management. To overcome these challenges and ensure long-term viability of nuclear power in the UK, this report recommends the actions described below.

Diversify Funding Sources

The UK government should establish a mix of funding sources for nuclear projects, including government investment, private sector participation, and innovative financing mechanisms to mitigate economic risks. Additionally, the government should consider long-term contracts such as power purchase agreements to provide revenue certainty to nuclear projects, making them more attractive to investors.

Develop Education and Training Initiatives

The UK government, in collaboration with academic institutions and industry partners, should develop comprehensive education and training programs to cultivate the necessary workforce skills for nuclear projects. These programs should cover the entire nuclear lifecycle, from design and construction to operation and decommissioning, and should target a diverse range of talent, including young people, women, and minorities.

Promote International Partnerships

The UK government should promote strategic international collaborations with countries that possess complementary nuclear expertise, such as France, the US, China, and South

Korea. These collaborations should aim to share knowledge, reduce costs, and enhance security in areas such as reactor design, fuel supply, waste management, and regulatory frameworks.

Participate in Public Engagement

The UK government and the nuclear industry should engage the public in open and transparent dialogues about nuclear power's role in the UK's energy future, addressing concerns and building support for nuclear projects. These dialogues should highlight the benefits of nuclear power, such as its low-carbon footprint, its contribution to energy security and economic growth, and its potential for innovation.

Invest in Research and Innovation

The UK government and the nuclear industry should continue to allocate substantive resource for research and development in advanced reactor technologies, safety improvements, and waste reduction, ensuring the UK remains at the global forefront of nuclear innovation. In particular, the UK should pursue the development of small modular reactors (SMRs) and the storage and reprocessing of spent nuclear fuel, which could offer significant advantages in terms of cost, flexibility, and sustainability.

Consider Safety and Decommissioning

The UK government and the nuclear industry should maintain high security and safety standards, by collaborating internationally with initiatives such as the International Atomic Energy Agency. Furthermore, the UK should consider decommissioning routes which are most economical for site closure, such as immediate dismantling or deferred

dismantling. The UK should also develop permanent storage facilities such as Geological Disposal Facilities or develop pipelines for the re-use of fuel for future reactors, to alleviate pressures of spent nuclear fuel.

capacity, a clear roadmap for the deployment of new nuclear projects, and a consistent policy framework that supports nuclear power.

Develop a Long-Term Plan

The UK government should develop a clear and cohesive long-term strategy for nuclear power that aligns with national energy and environmental goals, providing stability for investors and industry stakeholders. This strategy should include a realistic assessment of the current and future nuclear

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