Report

Survey and assessment of the status of available nuclear reactor technologies and designs

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CLIENT

The Norwegian Nuclear Commission

SUBJECT

Survey and assessment of the status of available nuclear reactor technologies and designs

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Figure 1.1: Hinkley Point C (EDF, 2021)

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Report

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CLIENT	The Norwegian Nuclear Commission	PROJECT MANAGER	Mette Kristine Kanestrøm
CONTACT	Royal Norwegian Ministry of Energy	PREPARED BY	Kat Culham Aidan Dooley Simon Franklin Simen Karlsen Adrian Worker Mette Kristine Kanestrøm Calum Powrie Hayley-Jo Stephen
RESPONSIBLE UNIT	10105080 Renewable Energy Advisory Services, Multiconsult Norway AS	CHECKED BY	Ian Laidlaw Mark Rumming Mark Lunn Adam Christian Kjersti Rustad Kvisberg Ståle Werner Nielsen Mette Kristine Kanestrøm Sina Haugland Myhrsveen Lewis Roberts Stephen Brauner

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Contents

Glossary of Key Terms and Abbreviations

ABV-6E: Russian 6 MWe PWR SMR by JSC "Afrikantov OKBM"

ABWR: Advanced Boiling Water Reactor

ACP100: Chinese 125 MWe PWR SMR by CNNC/NPIC

AMR: Advanced Modular Reactor

AP1000: Advanced Passive 1000 MWe PWR by Westinghouse

AP300: 300 MWe PWR SMR by Westinghouse

APR1400/APR1000: Advanced Power Reactor 1400/1000 MWe by KHNP (Korea)

ATF: Accident Tolerant Fuel

AVR: Automatic Voltage Regulation

BANDI 60: 60 MWe PWR SMR by KEPCO E&C (Korea)

BIM: Building Information Modelling

BIS: Bid Invitation Specification

BWR: Boiling Water Reactor

BWRX-300: 300 MWe BWR SMR by GE Vernova-Hitachi

CAP1000/CAP1400: Chinese PWRs based on AP1000 technology

CAPEX: Capital Expenditure

CAREM: Argentine 27 MWe PWR SMR by CNEA

CCGT: Combined Cycle Gas Turbine

CEA: Commissariat à l'énergie atomique et aux énergies alternatives (France)

CGD: Commercial Grade Dedication

CGN: China General Nuclear

CNNC: China National Nuclear Corporation

CNSC: Canadian Nuclear Safety Commission

CPFs: Coated Particle Fuels

CSS: Concrete-Strengthened Steel

DOE: Department of Energy (USA)

DTU: Technical University of Denmark

EIA: Environmental Impact Assessment

ENSI: Swiss Federal Nuclear Safety Inspectorate

EPC: Engineering Procurement Construct

EPR/EPR2/EPR1200: French GW type Reactor designs (1.7 GWe/1.65 GWe/1.2 GWe)

EUR: European Utility Requirements

EURATOM: European Atomic Energy Community

FBR: Fast Breeder Reactor

FID: Final Investment Decision

FOAK: First of a Kind

FBNR: Fixed Bed Nuclear Reactor (Brazilian SMR concept)

FBR: Fast Breeder Reactor

GDP: Gross Domestic Product

GDA: Generic Design Assessment, UK Pre-Licensing process

GEV: GE Vernova

GIF: Generation IV International Forum

GFR: Gas-cooled Fast Reactor

GW: Gigawatt (1,000 MW)

GWe: Gigawatt electrical

HALEU: High-Assay Low-Enriched Uranium, typically 10-20% by U235

HEA: High Entropy Alloy

HEU: Highly Enriched Uranium, typically above 20% by U235

HIP: Hot Isostatic Pressing

HLW: High-Level Waste

HPR1000/Hualong One: Chinese 1.1 GWe Gen III PWR by CGN/CNNC

HTGR: High Temperature Gas-cooled Reactor

HTMR: High Temperature Modular Reactor

HWR: Heavy Water Reactor

IAEA: International Atomic Energy Agency

IFE: Institute for Energy Technology (Norway)

IMSR: Integral Molten Salt Reactor (Terrestrial Energy)

INL: Idaho National Laboratory

I&C: Instrumentation and Control

ISDC: International Structure for Decommissioning Costing

ISR: In-Situ Recovery

JAEA: Japan Atomic Energy Agency

JSW: Japan Steel Works

KAERI: Korea Atomic Energy Research Institute

KA-CARE: King Abdullah City for Atomic and Renewable Energy (Saudi Arabia)

KEPCO: Korea Electric Power Corporation

KEPCO E&C: Korea Electric Power Corporation Engineering & Construction

KHNP: Korea Hydro & Nuclear Power Company

KLT-40S: Russian 35 MWe Marine PWR SMR

KTA: Kerntechnischer Ausschuss (German Nuclear Standards Committee)

LEU: Low-Enriched Uranium up to 5%

LEU+: Low-Enriched Uranium Plus (higher enrichment, typically 5-10%)

LF: Load following

LFR: Lead-cooled Fast Reactor

LLI: Long Lead Item, key procurement activity with such a long duration it needs to be procured before certainty of a project final investment decision

LTO: Long-Term Outage

LWR: Light Water Reactor

MC: Multiconsult

ML: Machine Learning

MOX: Mixed Oxide Fuel

MR: Micro-Reactor

MSR: Molten Salt Reactor

MTHM: Metric Ton of Heavy Metal

MW: Megawatt

MWe: Megawatt electric

MWt: Megawatt thermal

NDA: Nuclear Decommissioning Authority (UK body tasked with decommissioning)

NEA: Nuclear Energy Agency of the OECD

NEL: Nel ASA – Norwegian hydrogen company

NEPIO: Nuclear Energy Programme Implementing Organization

NIKIET: Research and Development Institute of Power Engineering

NOAK: N'th of a Kind

NPP: Nuclear Power Plant

NQA-1: Nuclear Quality Assurance Standard

NRC: Nuclear Regulatory Commission

NR: Nuclear Regulator

NSSS: Nuclear Steam Supply System

NWMO: Nuclear Waste Management Organization

ODS: Oxide Dispersion Strengthened (steels)

OEM: Original Equipment Manufacturer

O&M: Operation and Maintenance

OECD: Organisation for Economic Co-operation and Development

ONR: Office for Nuclear Regulation

OTSG: Once-Through Steam Generator

PAEC: Pakistan Atomic Energy Commission

PCI: Pellet-Cladding Interaction

PGP: Power Generation Plant

PPA: Power Purchase Agreement

PPP: Public-Private Partnership

PWR: Pressurised Water Reactor

QA: Quality Assurance

R&D: Research and Development

RCS: Reactor Coolant System

RITM-200S: Russian 53 MWe SMR for Arctic applications

RPV: Reactor Pressure Vessel

RRSMR: Rolls-Royce Small Modular Reactor

SCC: Stress Corrosion Cracking

SCWR: Supercritical Water-cooled Reactor

SE: Slovenské elektrárne (Slovakia)

SiC: Silicon Carbide

SKB: Svensk Kärnbränslehantering AB

SMR: Small Modular Reactor

SNETP: Sustainable Nuclear Energy Technology Platform

SPIC: State Power Investment Corporation

SSR-W: Stable Salt Reactor – Wasteburner (Moltex Energy)

SWU: Separative Work Unit

TRL: Technology Readiness Level

TVA: Tennessee Valley Authority

UAE: United Arab Emirates

UKEPR: UK variant of EPR

UO_2: Uranium Dioxide

USP: Unique Selling Proposition

VBER-300: Russian 300 MWe PWR SMR

VHTR: Very High Temperature Reactor

VVER: Russian Water-Water Energetic Reactor (PWR family)

VVER-TOI: Typical, Optimized, Informatized VVER

WEC: Westinghouse Electric Company

WNISR: World Nuclear Industry Status Report

Executive Summary

This report, prepared by Multiconsult and Amentum for the Norwegian Nuclear Commission, reviews the global status and trends of nuclear reactor technologies, including their readiness, flexibility, supply chains, and costs. The analysis focuses on developments relevant to deployment to the grid on a 2040-2050 timeframe. The Norwegian Nuclear Commission will consider this advisory report as one of many inputs to its process, reporting back to government in 2026.

Reactor Technology Readiness

Globally, 438 reactors are operating and 70 are under construction, most of which are large gigawatt-scale (GW) light water reactors (LWRs). In 2024 these provided 2667 TWh, or about 9% of the world's electricity. Of the reactors being constructed, the dominant types are Russian and Chinese.

There is no doubt that a new generation of light water reactors (LWR) small modular reactors (SMRs) and advanced modular reactors (AMRs) is emerging. The nuclear sector has seen a spike in promotional materials and many bold claims around technology, cost and schedule over the past 3-4 years, combined with hype associated with the energy demands created by Artificial Intelligence. Drawing valid conclusions from this barrage of information is extremely challenging.

While GW reactors are mature and commercially available, SMRs and AMRs are largely in their early stages. Very few SMRs and AMRs are in the advanced stages of licensing. A few are under construction – although typically without a significant degree of modularisation – and very few are operational. Given the nuclear sector’s claims that modularisation will deliver factory-build quality and increase the speed of construction, thereby reducing finance costs, it is not surprising that these technology families are attractive, but the arguments are not yet proven. And many of the 120 or more advanced SMR and AMR designs being promoted today are likely to fail before fruition. It will be crucial to understand whether they can be built more quickly and cheaply to maximise the benefits of modular techniques. Due to a significant number of orders expected in the years to come, more reactors will reach design maturity and regulatory approval over the next 5-15 years, a period during which financial decisions could be expected.

Therefore, by 2040–2050, commercial LWR-SMR and AMR options and further established GW options should be available. New entrant countries will have the opportunity to observe and learn from early, proven operational deployments in the country of origin. As first-of-a-kind risks diminish, these countries can make more informed decisions about domestic implementation, leveraging insights gained through overseas licensing activities. Entrant countries need time to develop nuclear law and a regulatory regime, as well as the necessary regulatory and operator capabilities and capacity for a new build programme. It is also necessary to develop skills and resources at country, region and operator levels before considering design and licensing requirements. We believe that first-of-a-kind licensing risks in a new sovereign location could be reduced through collaboration agreements with overseas regulators.

Flexible Operation

Modern nuclear reactors are being developed to support load following and flexible grid operation, though current capabilities remain constrained by safety margins, transient allowances, and component integrity, as defined in reactor licensing bases. Historically designed for steady baseload generation, GW-scale reactors experienced deep, slow power cycles that created stress on systems when flexibility was first introduced. Additional costs of flexible operation have been estimated as a few percent of operational costs. By 2050, smaller reactors and advances in materials, control systems, and reactor and fuel designs are expected to allow shorter, faster adjustments, enhancing compatibility with variable renewables. For SMRs and AMRs, limited first-of-a-kind data offers little verified evidence of large-scale flexibility, yet engineering assessments suggest that deploying fleets of smaller reactors, each capable of modest, independent and rotating load changes, could collectively deliver greater overall system responsiveness without excessive wear on individual units.

Nuclear generation could complement renewables by providing flexible reliable, low-carbon capacity. Flexibility claims should be validated through operational evidence before considering adoption. The specific role of flexible operations, need for replacement power, as well as other aspects of full lifecycle costing should be addressed in both market modelling and market development.

Supply Chain

The global nuclear supply chain for fuel and the largest reactor components remains concentrated. There is limited manufacturing capacity for the largest components but current overcapacity for standard fuel supply. Capacity growth has been hampered by the relatively small numbers of firm orders for components, despite predictions of a large rise in demand.

Uranium, the most common base for nuclear reactor fuel, is currently mined across the globe in several regions and countries. The key steps of the fuel cycle include mining of uranium ore, uranium conversion, enrichment and fabrication. Kazakhstan accounts for around 40% of worldwide production today. As with mining, a relatively small number of countries and organisations are involved in the specialist fuel cycle processing steps of conversion, enrichment, deconversion and fabrication. Russia plays a strategic role in the nuclear fuel cycle, controlling 14% of uranium concentrate supply, 27% of conversion capacity, and 39% of enrichment capacity. This dominance in downstream services makes Russia a critical supplier, even as Western operators seek alternatives.

Overall, uranium and fuel supply should not be a challenging issue for nuclear strategy, but it needs to be engaged with strategically and tactically at a country level. LWR reactors are the lower risk option, and a combination of early engagement and longer-term contracts can mitigate risks.

The fabrication of reactor pressure vessels (RPVs) and other nuclear steam supply system (NSSS) components are critical enablers of nuclear power deployment. These components require advanced materials, ultra-heavy forging capacity, precision engineering, and compliance with stringent nuclear safety and quality standards. Globally, only a very limited number of specialised firms possess the capability and certifications to produce these components. It is not straightforward to develop a new business manufacturing such large nuclear components. Any business would need to develop new forging and manufacturing capability including the people, processes, tools and very large equipment necessary. Because of the quality framework for these components, non-nuclear companies face significant challenges in meeting the additional codes and standards required. Our research has found that relatively few orders have been placed for LWR-SMR and AMR NSSS components at this time, indicating that the level of design and commercial maturity is not yet there. At present, there are relatively few new orders per year, and the supply chain has capacity. In the future, growth projections indicate the potential for bottlenecks. However, SMR and AMR modularisation and standardisation can create opportunities for new industrial participants. There are many opportunities for local supply chain participation if strategically established from the onset. The most likely opportunity areas are those not linked to items classified as nuclear safety critical and they should be considered within the context and development of a national capacity development plan.

$ Costs

At present, nuclear project costs vary widely depending on openness and consistency of reporting, technology type, financing, governance, national capability, as well as deployment and commercial models. There is plenty of relevant information about GW reactors, where lessons have now been learned and can be applied. Although experience of SMR and AMR reactors is relatively limited at present, we conclude that human and organisational factors are more significant in cost terms than technology. This report identifies significant uncertainty and cost escalation risks but highlights trends and learning effects from ongoing international experience. With financing representing some 67% of project costs due to long schedules with overruns, there is significant scope to secure major cost reductions by focusing on programme and project delivery through robust scheduling and risk management, as well as new operational, commercial and deployment models.

New nuclear power entrants potentially initially face higher overall costs as they address the 19 IAEA infrastructure areas required to achieve readiness for nuclear power development. These include establishing an effective regulatory framework, developing a skilled workforce, and mobilising the domestic supply chain. Additional first-of-a-kind costs may also arise when deploying projects in new jurisdictions where regulations, codes, and standards are not yet fully defined.

A 2040-2050 timescale offers the opportunity to benefit from global cost learning, observe emerging standardised designs, adopt proven financial and delivery models, set up the right governance, and build a positive culture. It also allows time to create an effective project developer, develop and manage robust and defendable schedules and cost predictions, and engage in regulatory harmonisation and acceleration activities. SMRs and/or AMRs could offer more manageable, phased investment and earlier returns compared to traditional large GW plants, although their overnight, operational and waste costs per MW may be higher.

Key Observations

By 2040–2050, new entrants to nuclear power are likely to be presented with a diverse portfolio of proven, licensable nuclear reactor technologies and improved global supply chain capacity, together with new financial, organisational, delivery and commercial models. This timescale could offer new entrant countries the opportunity to:

- Develop harmonised regulatory and institutional frameworks in advance;
- Build industrial and workforce capability;
- Adopt a holistic, full-cost, global energy systems market model, allowing for energy value, capacity, reliability and flexibility, as well as other external costs;
- Engage internationally and regionally to track technology, commercial and cost developments and benefit from inter-governmental agreements;
- Make informed procurement and delivery decisions, with measured, milestone-based controls, underpinned by real project experience; and
- Recognise that it isn't just about the technology but also about the need to set up the right organisations with the right governance, a positive culture, the right people and the best toolsets, to deliver a robust and defendable schedule and manage costs.

1 Introduction

1.1 Context of the Project

The renewed focus on nuclear power technology in neighbouring countries, the ongoing decarbonization of the European energy system and, within Norway, work on specific private projects and intensified public debate, have stimulated the Norwegian Government to seek an updated knowledge base on various aspects of nuclear power technology. The Norwegian Nuclear Commission (the Commission) was appointed by the Norwegian Government in 2024 under a specific mandate to carry out a comprehensive review and assessment of a possible future establishment of nuclear power in Norway. This includes looking into the sustainability of nuclear power as a possible source of electricity production for the national energy system, and what it would entail for Norway to become a new nuclear power country. Such a decision has not yet been made. Multiconsult Norge AS and Amentum were selected by The Royal Norwegian Ministry of Energy on behalf of the Commission to develop a report with an updated overview of the status of various reactor technologies and power plant designs, including technological maturity, estimated timeline for implementation and commercial availability, construction and operational costs, supply chains, capability for flexible operation, and associated costs. The Commission will consider this advisory report as one of many inputs to its process, reporting back to the Government in 2026.

1.2 Project Objectives

The project's key objectives are to provide:

a) an authoritative and comprehensive overview of the state of the nuclear power market based upon publicly available information.

b) information to the Commission that can be published freely to support an open discussion and decision making.

1.3 Project Scope

This study provides an overview of various reactor technologies and power plant designs, including large, small modular and advanced modular reactors, major supply chains and costs. It examines their technological maturity, estimated timeline for implementation and commercial availability, construction and operational costs, and their capability for flexible operation and associated costs. Four main work packages have been delivered under this project, and this report covers the full scope as follows:

a) to undertake a survey of current and future large and medium nuclear reactor technologies that are currently available or could be available for any potential future deployment in Norway in connection with the electricity grid in the period 2040-2050,

b) assess how flexibly different reactor types might operate, specifically regarding the capability to undertake load following operations, and consider the technical and cost implications,

c) consider under what timescales deployment could occur and how much those different technologies do / might cost through their lifecycle, and

d) advise on the supply chain implications to consider for a potential nuclear power programme in Norway for major nuclear components, including the fuel cycle.

This report is not intended to provide a systematic assessment of the feasibility of different reactor types for Norway, or sites in Norway, or the 19 infrastructure challenges that the IAEA recommend that a new entrant nuclear country needs to plan for, and which are noted in this document for ease of reference.

1.4 Methodology & Delivery Approach

A highly experienced multi-disciplinary team was established by Multiconsult, working seamlessly with Amentum, to leverage both local and global expertise and context. The authors have consulted an appropriate range of publicly accessible sources of information to provide expert, impartial analysis to assist the Commission in developing a comprehensive knowledge base on nuclear power as a potential energy source in the Norwegian power system. We have drawn on our previous global experience, such as Hinkley Point C and Sizewell C in the UK, a wide variety of GW, SMR and AMR licensing projects, Vogtle 3 and 4 experience from USA, recent new entrant countries such as Poland and the United Arab Emirates, as well as our work together in Norway to date. We have considered regional and international guidance, engineering journals, regulator reports and submissions, and other relevant sources of information to provide a balanced data set. This is just the start of a potential journey that new nuclear power nations such as Norway might need to undertake, if a decision to proceed is taken, before moving towards formal market consultation and or engagements with vendors. This process has not involved contacting reactor vendors at this stage, to maintain both independence and a holistic overview of the market, as agreed with the Commission. This report, produced in English only, has gone through appropriate quality assurance processes and review and challenge by the Commission. This is a non-nuclear safety, reference review document. It is based on publicly accessible information and has been checked to ensure that none of the contents could be subject to export controls (in any countries) and that it does not contain any sensitive nuclear or commercially protected information.

1.5 Acknowledgements & Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

- This work was carried out under contract from the Norwegian Ministry of Energy.
- In Multiconsult all authors involved in this work are salaried members of staff and who hold no financial or personal relationships with any of the potential vendors.
- Amentum is working as a sub-contractor to Multiconsult on this project. Amentum undertakes a wide range of work at all levels for a wide variety of Generation III/III+ GW (Gigawatt Large Reactor) and light water SMR (Small Modular Reactor), Generation IV AMR (Advanced Modular Reactor) and Micro-Reactor (MR) reactor technologies and associated projects. Work is managed through conflict-of-interest management processes. All authors involved in this work are salaried members of staff and who hold no financial or personal relationships with any of the potential vendors.

2 Reactor Technology Assessment

2.1 Chapter Summary

This chapter gives an overview of nuclear reactors that can be delivered in today's market and the most promising conventional GW, SMR and AMR reactor designs that are under development.

Globally, 438 reactors operate and 70 are under construction, primarily large Gigawatt-scale (GW) light water reactors (LWRs). In 2024 these provided 2667 TWh, or about 9% of the world's electricity. Of the reactors being constructed, the dominant types are Russian and Chinese. A new generation of Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) is emerging. While the GW reactors are mature and commercially available, the SMRs and AMRs are in early stages. The level of advertising of the status of many of these reactors, particularly Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs), is bullish, such that decision making is extremely difficult for anyone without access to detailed and largely unpublished industry information. Currently, a small number of large GW reactors are available to procure. Of the many SMRs and AMRs designs being developed, very few are mature enough at this time for contract. With a significant number of orders expected in the years to come, the next decade should see the emergence of a range of realistic potential options with developing track records. A suitable but narrower range of technologies will be available in time to start deployment in 2040-2050. This is expected to include some promising designs not yet operational. We believe that the window being considered for connecting to grid is more realistic than earlier dates. Very few SMRs and AMRs have yet started to be built, a few are under construction, a few in advanced stages of licensing, and a very small number operational but typically yet without the levels of modularisation. The attractiveness of these technologies is based on the claim that modularisation and factory-build quality will increase speed of construction and therefore reduce finance costs. The next decade will determine whether this claim can be proven. However, many of the more than 120 advanced designs being promoted today are likely to fail before fruition. Over the next 5-15 years, more reactors will reach design maturity and regulatory approval to the levels where final financial decisions could be taken, so by 2040-2050 the market for deployment could look very different.

2.2 Introduction

The Commission has requested a high-level overview of the current and future large and medium nuclear fission reactor technology market for technologies that could be deployed today, *if* a decision was made by the Norwegian Government to introduce a policy to prepare for nuclear power. We should highlight that this work does not suggest any form of commitment by Norway to move to nuclear or any commitment to any technologies and only has been compiled to support a feasibility assessment by the Commission. At this stage, no work has been requested looking at site suitability or alignment of technology types, the Norwegian nuclear regulatory context or other areas of regulation or preparation for a country decision. There has not been analysis of alignment to grid code, codes and standards, or to address the feasibility of current projects proposed in Norway. This work assumes that any future infrastructure and skills required at country and or municipality levels would be secured, but we have not been asked to define this or address its maturity. We have been asked to review the leading reactor designs available, even if those come from countries where geopolitics currently prevents procurement. The Commission has provided a key assumption that the window for future deployment of reactors providing power to the grid is 2040-2050. This report has not assessed or commented on what type or group of reactors would be most suitable for Norway. That work would likely be undertaken in the future if a policy decision was made to pursue nuclear power

This report has identified 5 groups of reactors to help understand the maturity of different sub-sectors of the market:

1. GW level electrical power producing reactors currently widely deployed.
2. GW level electrical power producing reactors currently foreseen coming on to the market.
3. Medium 75-470 MW electrical power producing reactors based upon GW level technologies expected to be coming on to the market.
4. Other advanced electrical power producing reactor technologies that might come on to the market in time. This includes a limited number of test reactors that are being deployed in the next few years.
5. A fifth group of reactors – of older designs that would not be recommended for a future global procurement cycle, or where the design is below the power scale for this exercise – will not be reported on.

Group 1 is essentially electricity producing Gigawatt (GW) power level Light Water Reactor (LWR) technology that is predominantly in use today. These are the leading reactor technologies globally which have already been designed, licensed and constructed and operated. Reactor vendors and operating organisations have developed around them, with specific construction and operating experience. This report presents an overview of technology options and basic details to inform business case development but does not rank and rate them.

Group 2 reactors are evolutions from Group 1, and typically within the licensing and construction phases, but informed by evolving from previous generations of reactors. Key examples are present to illustrate the global nuclear reactor market, highlighting what types of reactors are being built, who the main developers are, where construction is taking place, and the techniques being used. Key risks and opportunities for each high-level type of reactor are summarised.

Group 3 largely comprises medium size LWRs or Small Modular Reactors (SMRs), which are currently broadly in a design and licensing phase. They are not yet operating but are designed to leverage very significant historic and current general technology operating experience from broader families of larger reactors. We have broadened the definition to a slightly higher power level than that assumed by the IAEA.

Finally, for Group 4, the Commission has requested a global overview of the medium-sized advanced technology types or Advanced Modular Reactors (AMRs) that may have lower technology commercial readiness levels currently but might become available as future viable options in the longer term. Again, these are typically in early-stage design, and some are in pre-licensing and early-stage licensing activities. Most have some limited operating experience for the base technology. For the latter two SMR and large-medium AMR Groups 3 and 4, we have been asked to assume bulk electricity production to grid starting in 2040-2050 as the potential prescribed use case. Small reactors focused on heat production only have been excluded from this study. This work has all been undertaken on a technology neutral basis, without contact with the reactor vendors, and completely outside of any procurement exercise. This chapter is based on publicly available information, supplemented by Amentum's global market experience.

This chapter provides an expert overview of the current and future likely market status of large GW reactors and medium to small SMRs and AMRs. We have used judgement to tease out which are the more important reactors to watch and discuss processes used to monitor the market. This report focuses on options that have the realistic potential for grid generation deployment in a theoretical window of 2040 to 2050, as requested by the Commission. It explores some of the lessons learned, a review of technology readiness, and an appraisal of risks and opportunities for each class. Some aspects of reactor technology selection processes and criteria are explored and put into the context of a theoretical broader programme of infrastructure readiness. This shows that the 2040-2050 deployment window is achievable and identifies timescale risks and opportunities.

2.3 GW Technology

2.3.1 Current Deployment and Construction of Nuclear Power Plants

Today there are 438 nuclear power reactors operating in 31 countries, with a combined electrical capacity of about 400 GWe. In 2024 these provided 2667 TWh, or about 9% of the world's electricity (World Nuclear Association, 2025a).

About 70 reactors are under live construction across the world. Most reactors that are under construction or planned are in Asia. Chinese and Russian organisations are the leading reactor vendors, whether this is selling indigenous technologies or variants of overseas technology not for further export. New plants coming online in recent years have largely been balanced by old plants being shut down. Over the past 20 years, 106 reactors were retired, offsetting 102 starting operations. This has resulted in current overcapacity in fuel supply, as will be seen in Chapter 4. The new plants are largely GW LWR reactors, with a few exceptions. These include demonstrator plants, the restart of construction on older designs, and some specialised technologies such as research reactors being tested by certain countries or reactors undergoing long-term operation extensions (World Nuclear Association, 2025a)

2.3.1.1 Key GW Technologies

This section will briefly introduce each of the main large scale or GW reactors in the market.

Table 2.1: Key Features of the GW Reactor Family

Key Features	
Technology Classification	Generation 3 (Water Based Reactors)
Reactor Types	Pressurised Water Reactor (PWR) Boiling Water Reactor (BWR) Pressurised Heavy Water Reactor (PHWR)
Cooling Method	Water
Siting	Mostly remote or semi-rural deployment, coastal or major body of fresh water
Turbine Interface	Rankine Cycle – 33% Efficient use of Nuclear Heat
Cooling	Open Circuit Water Loop Closed Circuit Cooling Towers
Operating Temperature	~ 300- 350°C
Unique Selling Points USPs	Provider of large building blocks of low whole lifecycle carbon electricity Strong track record for earlier phases of deployment Track record of construction now rebuilding Supply chain exists
Primary Use Cases	Baseload Grid Power

Key Features	
	Some flexible operation
Technology Readiness Level (TRL)	TRL 9 – see Appendix A: Definition of Technology and Manufacturing Readiness Levels for details of the scale
Technology Risk	Risks related to the basic GW reactor technologies are generally well managed: • Large body of lessons learned over many decades of operation. Early lessons learned have been addressed for more recent technology variants from experience in both construction and operation; • There is a residual licensing risk related to deployment across borders, particularly related to the lack of harmonisation between regulators internationally. Significant risks related to country and site-specific licensing remain, and new entrant countries can benefit from a specific approach to leverage assessments that other countries have made. Ongoing initiatives to refocus regulatory processes may benefit future deployment; • New risks have been introduced related to modifications modularisation and other forms of advanced manufacturing, but experience from other sectors should mitigate this; • New risks may be introduced with new supply chain entrants, who lack the heritage of being original equipment manufacturers for nuclear. This can be managed through robust quality assurance and control oversight, and rigorous specification and acceptance processes.

The basic concepts of the two most widespread types of LWR are shown below in Figure 2.1: and Figure 2.2 for the generic Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR)

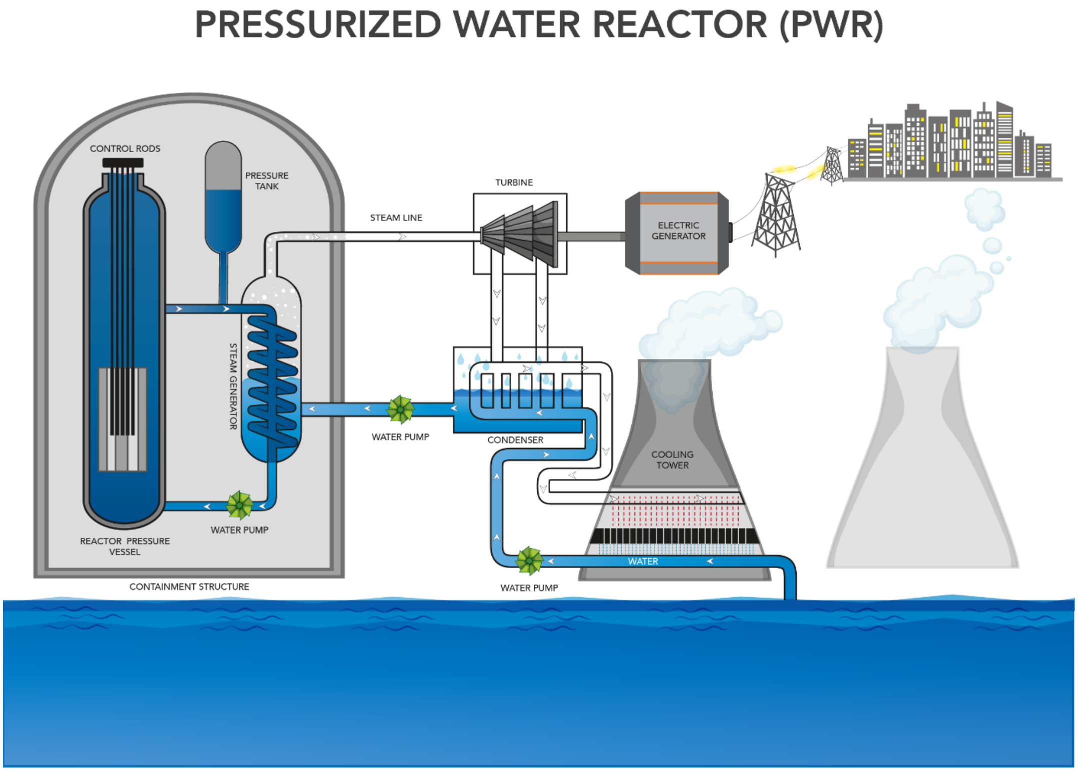

Figure 2.1: Schematic of a PWR Reactor Generating Power (U.S Department of Energy, 2019a)

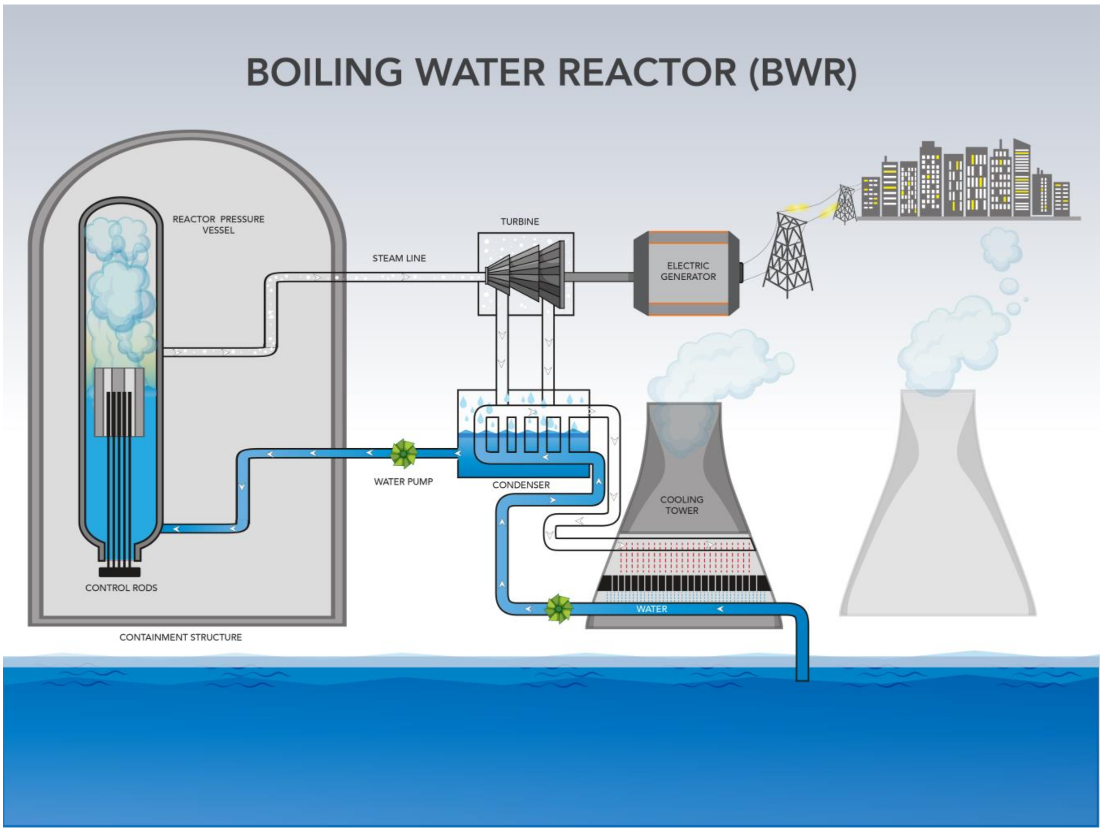

Figure 2.2: Schematic of a BWR Reactor Generating Power (U.S. Department of Energy, 2019b)

We will now explore the main types of GW reactor in the market today.

AP 1000 (also UK-AP1000, CAP1000 and CAP1400): The AP1000 is a Generation III+ advanced GWe PWR utilising passive technology, with a key selling point of reducing size, number of bulk materials and moving parts. Developed by Westinghouse Electric Corporation, the originator of PWR technology, it was scaled up from a 600 MW plant design that was never built. It was originally designed for the 60Hz market. Two units were deployed at Vogtle in the USA after extensive licensing and construction delays, as shown in Figure 2.3. A separate project for two AP1000 units at V.C. Summer in South Carolina was abandoned in 2017 after years of delays and cost overruns. As of 2025, there is renewed interest in potentially completing the project given projected increases in demand for power.

Two variants, including a further uprate to 1400 MW have been deployed in China with increased indigenous technology, and are planned to be further deployed in a major expansion in nuclear. An earlier 50Hz variant has also gone through pre-licensing in UK, and a variant addressing construction and operating experience is now planned for deployment at a few locations including Poland and Bulgaria as well as Ukraine, where contracts have been signed, as well as further locations subject to competition such as the Netherlands. This plant now has significant positive high availability operating experience and incorporates mega-module technology to speed deployment.

A settlement agreement between Westinghouse Electric Company and Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Company (KHNP) has resolved their intellectual property dispute, allowing both parties to move forward with certainty in the pursuit and deployment of new nuclear reactors. The agreement also sets the stage for future cooperation between the parties to advance new nuclear projects globally. The terms of the settlement remain confidential, as agreed by all parties.

Figure 2.3: *AP1000, Unit 3 at Vogtle, US* (Westinghouse, 2023)

APR 1400 (also EU-APR1400, APR1000): The Korean KHNP APR1400 is also a traditionally built multi-train[1] 1400 MW point Generation III PWR technology, which evolved through a combination of technology transfer from the System 80+ design owned by Westinghouse and indigenous design. The APR1400 reference plants are Shin Kori, Units 3 and 4, located in South Korea, as shown in Figure 2.4. What is particularly notable is the level of operating and construction experience; Shin Kori 3 began commercial operation in December 2016. A set of four reactors have been successfully deployed by a Korean consortium in Barakah, United Arab Emirates, a new-to-nuclear country, through a process that included competition for finance. The reactor was also assessed positively by the US regulator, although not constructed. An APR1000 1000 MWe European variant is proposed.

This variant, addressing construction and operating experience, is now planned for deployment at several locations including the Czech Republic, where contracts have recently been signed, as well as further locations subject to competition. The settlement agreement between Westinghouse Electric Company and Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Company (KHNP) is also relevant for this technology option. The APR1000, as the APR1400 nuclear power plant, has some features based on original technology from Westinghouse, so this settlement is an important consideration for potential customers.

This plant now has significant positive availability operating experience. A variant to compete at the GW level is now being proposed as an alternative. European variants, including one targeted for potential deployment in Finland, have been assessed favourably against the European Utilities Requirements (EUR) process, the European Union's framework for nuclear energy. The deployment model for these plants is based on a group of Korean companies.

Figure 2.4: Side view of UAE Barakah Nuclear Power Plant Unit 3 APR1400 (ENEC, 2025).

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[1] A train in reactor technology is a complete, functionally independent set of systems that perform a required safety function. These are for the purposes of delivering safety functions in relation to shut-down, residual heat removal or containment isolation. The goal is to achieve high reliability through redundancy and independence. Thus, if one train fails, others can still perform the same function.

ABWR: The Advanced Boiling Water Reactor (ABWR) is a Generation III boiling water reactor designed by GE Vernova (GEV) Hitachi Nuclear Energy and Toshiba at the 1.4 GWe power point. BWRs are the second most common reactor in the world after PWRs. Slightly different versions of the ABWR are offered by GEV-Hitachi, Hitachi-GEV, and Toshiba. It features a single-cycle, force-circulation design with a rated power of 3926 MWt and incorporates advanced technologies from BWR designs from a series of evolutions across Europe, Japan, and the United States. The ABWR is also notable for its significant deployment and operational experience, with the reference plants Kashiwazaki Kariwa Nuclear Power Generation Station, Units 6 and 7, by the Tokyo Electric Power Company dating back to 1996 and 1997, see Figure 2.5. The ABWR led the way with modularisation and open top construction. Improvements include the use of internal recirculation pumps, control rod drives that can be controlled by a screw mechanism (rather than a step process), microprocessor-based digital control and logic systems, and digital safety systems. The design also includes safety enhancements, such as protection against over-pressurisation of the containment, passive core debris flooding capability, an independent water makeup system, three emergency diesels, and a combustion turbine as an alternative power source. The plant went through licensing in the US. It also completed pre-licensing and underwent extensive licensing in the UK but was not constructed.

A further evolution of the BWR from ABWR, the ESBWR, was licensed in the US, marketed in Europe, and pre-licensing started in the UK before being paused. This has yet to be built. The BWRX-300 SMR is an evolution of the ESBWR GWe design.

Figure 2.5: Units 5 BWR and 6+7 ABWR of the Kashiwazaki-Kariwa plant (TEPCO, 2025)

EPR (also UK-EPR, EPR2, EP1200), The EPR is an advanced 1.7 GWe PWR. The EPR is a large 4 train Generation III+ pressurised water reactor design utilising active and passive safety systems, two-layer concrete containment, developed by the EDF group of companies in France, and by Siemens in Germany, evolving from reactors operating in both countries. In Europe, this reactor design was called European Pressurised Reactor, and the internationalised name was Evolutionary Power Reactor, but it has been simplified to EPR. Due to construction delays in Finland and France, the world’s first operational EPR unit was China's Taishan 1, in late 2018. Operational problems related to fuel were experienced. Finland and France now have single operating units as of 2023 and 2024, following extensive construction delays and significant manufacturing and licensing challenges. Some operational challenges have been experienced. An example is shown in Figure 2.6. Nuclear construction of the UK-EPR variant in a twin unit deployment has been ongoing at Hinkley Point C in the UK since 2016, although the project commenced much earlier. Generic Design Assessment (GDA) pre-licensing was completed in 2012. This project has revealed that challenges in licensing in different counties and against a design that was still under development can create significant pressure on project lifetimes and costs. A further twin unit deployment is planned for the UK Sizewell C project, with a license granted and consent to construct recently granted. Following a final investment decision, full financial close was secured in November 2025. The UK variant has seen an introduction of some elements of modular construction, but it remains largely a conventionally built plant. A European wide supply chain has been created for the projects, including extensive collaboration with UK businesses.

Figure 2.6: EPR in foreground of 2 older units at Flamanville, France (EDF, 2025a)

Figure 2.7: EPR1200 (see Section 2.3.1.2 for further details) (Nuclear Engineering International, 2023)

Hualong-1 (HPR1000): advanced 1.1 GWe Generation III PWR designed in China and offered by both CGN and CNNC, with variations in active and passive technology, following earlier French and US technology transfer agreements as well as full indigenous development. The Hualong One is an indigenous, three-loop PWR, more recently deployed with reference units operational in 2021 and 2023, by a joint venture of one of the vendors. It incorporates elements of CNNC's ACP1000 and CGN (China General Nuclear) ACPR1000+ reactor designs. According to IAEA data there are 18 Hualong One units under construction in China and five operating units. Outside China, two plants are operational in Pakistan, with one under construction. In November 2021, the European Utility Requirements (EUR) organisation formally certified the Hualong One (HPR1000) as compliant after a four-step process which began in August 2017. In 2022, UK regulators announced that the UKHPR1000 had passed the then four-step pre-licensing GDA. Licensing started for the UK Bradwell project but was suspended. Examples are shown in Figure 2.8: Fangchenggang unit 3 HPR-1000 and Figure 2.9.

Figure 2.8: Fangchenggang unit 3 HPR-1000 (World Nuclear News, 2023)

Figure 2.9: Zhangzhou-1 is the first of four Generation III Hualong One units planned for the site in eastern China (CNNC, 2025)

VVER-1200 (TOI etc) a family of advanced GWe Pressurised-water reactors. VVER-1200 and VVER-TOI are both Russian PWR designs. A few VVER-1200 variants are being constructed and planned, and the VVER-TOI, an evolution of the VVER-1200, is being trialled at Kursk, Russia. There are an additional 11 VVER-TOI units planned. VVER-TOI, standing for "typical, optimized, and informatized," aims for increased power output, improved technical and economic indicators, and enhanced active and passive safety features compared to the VVER-1200. VVERs are unique in having a hexagonal fuel design. This evolution also targets a reduction of 40 months in nuclear construction time. VVER-1200s are being deployed in a variety of export markets including China, Egypt, Turkey, and India. What is noticeable about these projects is that they generally bring large quantities of finance, and have a degree of turnkey delivery, including into operation. VVER-TOI has been successful in its EUR assessment.

Figure 2.10: Inside a VVER-1200 Reactor Building During Construction (Atommedia, 2025)

Table 2.2 presents a list of types or model names and site names for reactors currently being constructed globally by country and developer or operator where appropriate, including plants where construction has been suspended, with group numbers assigned and electrical power output.

Table 2.2: Reactors currently being constructed by country and operator where appropriate, including plants suspended (World Nuclear Association, 2025)

Latest announced / estimated year of grid connection	Country / Developer, Supplier Country if Applicable	Reactor Site Code Name	Reactor Model	Assigned to Group	Gross Electrical Power Output MWe
2025	Bangladesh, Russian supplier	Rooppur 1	VVER-1200	1	1200
2025	China, CGN	Taipingling 1	Hualong One	1	1200
2025	China, CNNC	Xiapu 2	CFR600	4	600
2025	China, Guodian & CNNC	Zhangzhou 2	Hualong One	1	1212
2025	China, SPIC & Huaneng	Shidaowan Guohe One 2	CAP1400	1	1500
2025	India, NPCIL	Kalpakkam PFBR	FBR	4	500
2025	India, NPCIL	Kudankulam 3	VVER-1000	5	1000
2025	Korea, KHNP	Saeul 3	APR1400	1	1400
2025	Russia, Rosenergoatom	Kursk II-1	VVER-TOI	1	1255
2025	Slovakia, SE, Russian supplier	Mochovce 4	VVER-440	5	471
2025	Turkey, Russian supplier	Akkuyu 1	VVER-1200	1	1200
2026	Bangladesh, Russian supplier	Rooppur 2	VVER-1200	1	1200
2026	China, CGN	Cangnan/San'ao 1	Hualong One	1	1150
2026	China, CGN	Taipingling 2	Hualong One	1	1202
2026	China, CNNC	Changjiang SMR 1	ACP100	3	125

Latest announced / estimated year of grid connection	Country / Developer, Supplier Country if Applicable	Reactor Site Code Name	Reactor Model	Assigned to Group	Gross Electrical Power Output MWe
2026	China, CNNC, Russian supplier	Tianwan 7	VVER-1200	1	1200
2026	China, CNNC	Xiapu 2	CFR600	4	600
2026	China, Huaneng & CNNC	Changjiang 3	Hualong One	1	1200
2026	India, NPCIL, Russian supplier	Kudankulam 4	VVER-1000	5	1000
2026	India, NPCIL	Rajasthan 8	PHWR-700	5	700
2026	Korea, KHNP	Saeul 4	APR1400	1	1400
2026	Russia, Rosenergoatom	Kursk II-2	VVER-TOI	1	1255
2026	Turkey, Russian supplier	Akkuyu 2	VVER-1200	1	1200
2027	Argentina, CNEA	Carem	Carem25	5	29
2027	China, CGN	Cangnan/San'ao 2	Hualong One	1	1150
2027	China, CNNC	Sanmen 3	CAP1000	1	1250
2027	China, CNNC, Russian supplier	Tianwan 8	VVER-1200	1	1200
2027	China, CNNC & Datang, Russian supplier	Xudabao 3	VVER-1200	1	1200
2027	China, Huaneng & CNNC	Changjiang 4	Hualong One	1	1200
2027	China, SPIC	Haiyang 3	CAP1000	1	1250
2027	China, SPIC	Haiyang 4	CAP1000	1	1250
2027	India, NPCIL, Russian supplier	Kudankulam 5	VVER-1000	5	1000
2027	India, NPCIL, Russian supplier	Kudankulam 6	VVER-1000	5	1000
2027	Turkey	Akkuyu 3	VVER-1200	1	1200
2028	China, CGN	Lufeng 5	Hualong One	1	1200
2028	China, CNNC	Sanmen 4	CAP1000	1	1250
2028	China, CNNC & Datang, Russian supplier	Xudabao 4	VVER-1200	1	1200
2028	China, CNNC & Datang	Xudabao 1	CAP1000	1	1250
2028	China, SPIC	Lianjiang 1	CAP1000	1	1250
2028	Egypt, NPPA, Russian supplier	El Dabaa 1	VVER-1200	1	1200
2028	Iran, Russian supplier	Bushehr 2	VVER-1000	1	1057
2028	Russia	Cape Nagloynyn 1	RITM-200S	5	53
2028	Russia	Cape Nagloynyn 2	RITM-200S	5	53
2028	Russia	BREST-OD-300	BREST-300	4	300
2028	Turkey, Russian supplier	Akkuyu 4	VVER-1200	1	1200
2029	China, CGN	Lufeng 6	Hualong One	1	1200

Latest announced / estimated year of grid connection	Country / Developer, Supplier Country if Applicable	Reactor Site Code Name	Reactor Model	Assigned to Group	Gross Electrical Power Output MWe
2029	China, CGN & Datang	Ningde 5	Hualong One	1	1200
2029	China, China Huaneng & CNNC	Shidaowan 1	Hualong One	1	1200
2029	China, CNNC & Datang	Xudabao 2	CAP1000	1	1250
2029	China, CNNC & Guodian	Zhangzhou 3	Hualong One	1	1214
2029	China, CNNC & Guodian	Zhangzhou 4	Hualong One	1	1214
2029	China, SPIC	Lianjiang 2	CAP1000	1	1250
2029	Russia, Rosatom	Leningrad II-3	VVER-1200	1	1200
2030	China, CGN	Lufeng 1	CAP1000	1	1200
2030	China, CGN	Taipingling 3	Hualong One	1	1200
2030	China, China Huaneng & CNNC	Shidaowan 2	Hualong One	1	1200
2030	Egypt, NPPA, Russian supplier	El Dabaa 2	VVER-1200	1	1200
2030	Egypt, NPPA, Russian supplier	El Dabaa 3	VVER-1200	1	1200
2030	Egypt, NPPA, Russian supplier	El Dabaa 4	VVER-1200	1	1200
2030	Pakistan, PAEC, Chinese supplier	Chashma 5	Hualong One	1	1200
2030	Russia, Rosatom	Leningrad II-4	VVER-1200	1	1200
2031	UK, EDF NNB GenCo (HPC) Ltd	Hinkley Point C1	EPR	1	1720
2032	Korea, KHNP	Shin Hanul 3	APR-1400	1	1400
2032	UK, EDF NNB GenCo (HPC) Ltd	Hinkley Point C 2	EPR	1	1720
Late 2030s	UK, Sizewell C Limited	Sizewell C1	EPR	1	1720
Late 2030s	UK, Sizewell C Limited	Sizewell C2	EPR	1	1720
Suspended	Brazil, Eletrobrás	Angra 3	Pre-Konvoi	5	1405
Suspended	Japan, J-Power	Ohma 1	ABWR	1	1383
Suspended	Japan, J-Power	Shimane 3	ABWR	1	1373
Suspended	Ukraine, Energoatom	Khmelnitski 3	VVER-1200 V-392B	1	1089
Suspended	Ukraine, Energoatom	Khmelnitski 4	VVER-1200 V-392B	1	1089

In total, there is approximately 73-78 GW of new nuclear capacity being constructed worldwide, excluding the suspended projects. Of the reactors being constructed, the dominant types are Russian and Chinese with the Russian VVER-1200 (16800 MW), and Chinese Hualong One (16730 MW) and CAP-1000 (11200 MW) models. World Nuclear Association projects nuclear capacity of 746 GWe by

2040, with capacity reaching as high as 966 GWe in the upper scenario and 552 GWe even in the less likely lower scenario (World Nuclear Association, 2025c).

2.3.1.2 GW Reactor Designs Foreseen Coming to Market (Group 2)

Although there is a great market and media focus on small modular reactors, vendors are still developing GW scale reactors that could potentially come to market. These are discussed here in turn.

EPR2/EPR1200: EDF has acknowledged the difficulties in building the original EPR designs and the "New Model" large EPR (later named EPR2) has been progressed towards licensing with ongoing regulatory challenges. The ambition is to simplify some aspects of the design while retaining robust severe accident mitigation features. It incorporates design, construction and commissioning experience feedback from the EPR reactor, as well as more general operating experience from the French fleet of nuclear reactors currently in service. EDF has expressed a desire to deploy the EPR2 at Penly/Gravelines/Bugey sites with Penly targeted in ~2035-2037, noting these dates are the programme timeline, not a licence from the French regulator, ASNR.

The main differences between the newer medium capacity EPR1200 variant and EPR2 are the power level (1200 MWe versus 1650 MWe respectively) and the number of steam generators (three versus four). The vendor documentation highlights constructability optimisation, resistance to external hazards, and continuity with EPR/EPR2 safety case lineage. EPR1200 is targeted towards countries with smaller grid capacities or specific site constraints. In February 2023, The French regulator issued a positive pre-licensing opinion on the safety features of the EPR1200, as shown in Figure 2.7.

CANDU MONARK: The CANDU (Canadian Deuterium Uranium) design, a Pressurised Heavy Water Reactor (PHWR), initially developed by Atomic Energy of Canada Limited (AECL), and subsequently managed by Candu Energy Inc. (a subsidiary of Atkins Realis). This is entering a new phase with the CANDU MONARK, a Generation III+ 1000 MWe unit that leverages proven CANDU features (natural uranium fuel and a heavy water moderator) while integrating modernisations in safety, modularisation and operability. The design was announced in November 2023, and at the time of writing, the vendor is entering into a pre-licensing design review planning stage with the Canadian regulator, the CNSC.

The MONARK design has ~480 fuel channels utilising modularisation and aims to improve maintainability over existing CANDU plants (which have a very strong operational record). The heavy water heat transport system building on prior CANDU lineage has been modernised to meet Generation III+ expectations by demonstrating enhanced safety margins.

The vendor is aiming to complete preliminary engineering design by ~2027 and expects first build to commence before ~2030 with completion by the mid-2030s. These timescales are very ambitious, and although the MONARK is based on proven technology, first-of-a-kind risks remain. In addition, heavy water systems involve specific supply chains which are not as well established in Europe as those for light water reactors. Procurement and supply chain issues would require special regulatory oversight and the MONARK design would need to demonstrate that its heavy water architecture meets the modern safety reference levels (e.g. external hazards, PSA, severe accident management) comparable to LWR Generation III + designs.

SRZ-1200: This is a 1200 Mwe advanced light water reactor developed by Mitsubishi Heavy Industries (MHI) in collaboration with Japanese utilities, announced in September 2022. As of June 2024, MHI claimed that the concept design is nearly complete with commercialisation targeted for the mid 2030s for the first units. Site selection in Japan is still pending with the site at Mihama NPP under survey as a candidate for a replacement unit, with SRZ-1200 as the leading option.

From MHI's published material, a major design objective sets core damage frequency and containment failure frequency to ten times better than Japanese regulatory standards with increased redundancy and diversity. The design is claimed to have enhanced resistance to external hazards, improved severe accident management (noting the design basis was widened post Fukushima) and security against terrorism. It claims increased flexibility for grid operation with load following, variable output and the capability for hydrogen production.

With the design still being at a concept design stage, first-of-a-kind risk is significant from a cost, schedule, manufacturing and regulatory licensing perspective. While the design includes flexibility, those features add complexity and may pose additional reliability and regulatory challenges. The export market for this design is not yet evident and although Japanese utilities are involved even at the early design stages, any international uptake will depend on a proven track record, which will only be possible once a handful of units have been constructed and operated in Japan.

2.3.2 The Global Market: Nuclear Reactors Currently Planned and Proposed

In addition to those reactors under construction, about 100 power reactors with a total gross electrical capacity of about 100 GWe are planned[2], and over 300 more are proposed[3]. Relatively few of these reactors have received final investment decision, and most are subject to aspiration or intention expressed in memoranda of understanding. Most reactors currently planned or proposed are in countries in Asia, characterized by fast-growing economies and increasing demand for electricity. Many countries with existing nuclear power programmes either have plans to, or are building, new power reactors. There is also an increasing trend for countries without a nuclear power programme or new entrant countries, such as Norway, to consider nuclear. With a very large number of reactors planned already, any new programme would potentially be competing with them for external finance resource, design capacity, construction capacity and so on.

Table 2.3 presents a global overview of reactors under construction, plus those known to be in planning and those known at the time of this report to be already proposed by country, to give an idea of the scale of overall market growth.

Table 2.3: Reactors Under Construction, Plus Planned and Proposed by Country (World Nuclear Association, 2025)

Country	Reactors under construction		Reactors planned		Reactors proposed	
	No.	MWe	No.	MWe	No.	MWe
Argentina	1	29	0	0	4	1200
Armenia	0	0	0	0	1	1060
Bangladesh	2	2400	0	0	2	2400
Belarus	0	0	0	0	0	0
Belgium	0	0	0	0	0	0
Brazil †	1	1405	0	0	0	0
Bulgaria	0	0	2	2500	0	0

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[2] 'Planned' means that definitive decisions have been made around reactor projects and that detailed planning has been completed.

[3] 'Proposed' means that sites have been provisionally assigned, but there has been no site characterisation (e.g. seismic response via boreholes) or site-specific engineering completed for deployment of a reactor design

Country	Reactors under construction		Reactors planned		Reactors proposed	
	No.	MWe	No.	MWe	No.	MWe
Canada	0[4]	0	2	400	12	6400
China	32	36,790	39	43,506	154	184,450
Czech Republic	0	0	5	5270	0	0
Denmark						Policy under review
Egypt	4	4800	0	0	0	0
Estonia	0	0	0	0	2	600
Finland	0	0	0	0	0	0
France	0	0	0	0	6	9900
Germany	0	0	0	0	0	Policy under review
Hungary	0	0	2	2400	0	0
India	6	5200	14	9400	26	30,800
Indonesia	0	0	0	0	2	500
Iran	1	1057	2	1417	4	5000
Italy						Yet to declare
Japan †	2	2756	0	0	1	1385
Kazakhstan	0	0	0	0	2	2400
Korea RO (South)	3	4200	1	1400	0	0
Mexico	0	0	0	0	0	0
Netherlands	0	0	0	0	2	2650 + SMRs
Pakistan	1	1100	0	0	0	0
Poland	0	0	3	3750	26	10,000
Romania	0	0	2	1440	6	462
Russia	7	5290	23	21,655	9	754
Saudi Arabia	0	0	0	0	2	2800 + SMRs
Slovakia	1	471	0	0	1	1200
Slovenia	0	0	0	0	1	1200
South Africa	0	0	0	0	2	2500
Spain	0	0	0	0	0	0
Sweden	0	0	2	2500	0	0
Switzerland	0	0	0	0	0	0
Turkey	4	4800	0	0	8	9600
Ukraine †	2	1900	2	2500	7	8750

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[4] The first BWRX-300 is being built at Darlington; however, nuclear safety-related construction has not yet begun, which is why the site does not yet appear to be under active construction.

Country	Reactors under construction		Reactors planned		Reactors proposed	
	No.	MWe	No.	MWe	No.	MWe
UAE	0	0	0	0	0	To be confirmed
United Kingdom	2	3440	2	3340	3	1410 (GBN)*
USA	0	0	0	0	21	4680
Uzbekistan	0	0	6	330	2	2400
Vietnam	0	0	0	0	4	1000
WORLD	69	75,638	107	101,808	310	295,501
	No.	MWe	No.	MWe	No.	MWe

*Additional UK projects are also in early stages of planning at Teesside in the UK, potentially seeing deployment of 12 Xe-100 AMR reactors and a group of AP300 SMR reactors. Deployment of other SMR and AMR and Micro-Reactor technologies are also in early stages of development.

† Under Construction figures include a number of units where construction is currently suspended or has suffered from suspension: Angra 3 (Brazil, now believed to have resumed); Ohma and Shimane 3 (Japan, ABWRs under application to restart construction); and Khmelnitski 3&4 (Ukraine, paused, considering recertification of components manufactured for the Bulgarian Belene NPP).

2.3.3 GW Reactor Technology Assessment Processes

These statistics presented above in Table 2.2 and Table 2.3 highlight that the nuclear energy sector remains very active globally, particularly in terms of GW projects, but with some smaller SMR and AMR plants moving ahead. There is and will be increased competition for vendors and technology, resources and money. Time horizons for additional programmes introduced in this timeframe could be affected, as existing vendors might struggle to cope with demand, but this can be mitigated by prompt action, such as entering into technology support contracts, technology assessment and then early works contracts, and leveraging sovereign wealth funds.

In terms of main GW reactor technology suppliers there are about 10 main designs that are currently commercially available, with a number of additional options dependent on the market, and in some cases slightly different alternative vendor options for slightly different versions. From Table 2.1 above, most designs under construction and planned are Chinese or Russian, or Chinese-adapted technologies where very large numbers of reactors are being built in parallel.

The technical maturity of different reactor technologies cannot be assessed or compared in isolation (see Figure 2.11). With finance costs forming some 67% of the investment cost of new western GW projects, and the procurement of the project itself just 11%, it is very important to keep an open mind about technology procurement and evaluation processes. It should also be noted that the cost of the fuel cycle makes up some 9% of the levelised cost of nuclear electricity for GW reactors. Reactor vendors are keen to both build reactors and then to supply fuel. Fuel supply is arguably a much lesser financial risk for the vendors, especially over a period of 60 to 80 years, so the construction of reactors is often not the primary business case.

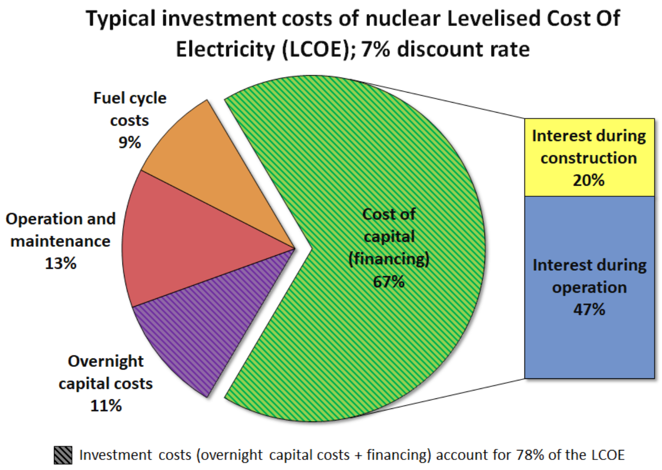


Figure 2.11: Typical Key Components of the Investment Cost of Construction of New Nuclear Highlighting Significance of Fuel (Bodel, 2022).

In full reactor procurement exercises, reactor vendors are typically asked to provide very large amounts of data on many delivery, technical, financial and commercial aspects. This is part of a multi-attribute proposal assessment process that often takes place over a number of years. The IAEA refers to these documents as Bid Invitation Specifications (BIS). They take a long time to prepare, require many different skill sets, and need to be managed by a large customer team, often with supplier support. Vendors must then invest significant effort to respond, and the evaluation process is also lengthy and complex. It is also worth highlighting that the European Utilities Requirements (EUR) assessment process, created by European developers and utilities, sets common standards for new nuclear plants to reduce regulatory and procurement risks. For each reactor design, it reviews more than 5,000 data points just for the nuclear island component of a nuclear power plant - the core heat producing hub. (EUR, n.d.).

2.3.4 Simplistic GW Reactor Comparison

Comparing GW technologies at the highest level to review opportunities and risks provides the following summary in Table 2.4.

Table 2.4: A High-Level Comparison of Opportunities and Risks for a Range of GW technologies

Technology	Opportunities	Risks
ABWR	Evolution of a long line of earlier BWRs. Nth-of-a-kind construction and operating experience in Japan (e.g. Shika 2 was constructed and commissioned in ~48 months although it is noted that this timescale was partially due to unique Japanese working practices that may not be acceptable in Europe). Parallel construction techniques used. For example, the lower plant rooms are equipped and fitted whilst civil construction continues above. This enables quicker construction to be achieved and there is less wait time for some disciplines (e.g. C&I) versus traditional methodologies. Some modularisations through factory assembly and testing of some plant components that were subsequently sent to site for installation. Supply chain exists.	Regulatory risk - potential for change due to lack of global harmonisation of codes, standards and regulations. Track record from deployment within a Japanese environment. Transition to a global workforce is uncertain. Site assembly for some systems.

Technology	Opportunities	Risks
AP1000	Legal settlement between Westinghouse and Korean organisations provides clarity for purchasers and should also provide clarity in the supply chain. Some significant modularisation was used through factory assembly of large components that were subsequently sent to site for installation (but still much less than proposed for SMRs). Examples include the containment vessel. Lessons learned such as refining module and long lead item procurement, fabrication and assembly processes, optimisation of welding sequencing, supporting rebuilding a supply chain, including expanding the international, vetted supplier base, overhauling and focussing supply chain quality data collection and report generation, implementing changes to transportation systems for the largest components to addressing regulatory changes to a design in flight. FOAK design issues that were resolved included reactor coolant pump and specialised valves. This also included navigating US project overrun costs and delays that at one point took Westinghouse into bankruptcy proceedings before restructuring. Construction and largest operating experience (reactor-years) in multiple geographies. Proposed projects often include significant US Government investment through export credit and other means. US NRC licence valid until 2046.	Track record of FOAK challenges of twin unit at Vogtle USA, and halted construction at VC Summer. Repeat build in Western countries to come. Potential for change from US design due to lack of harmonisation, use of Imperial units and different grid frequency. Experienced Workforce in China with projects ongoing. Experienced workforce in the US has now dispersed. Deployment of workforce in Europe may be a risk. Site assembly for some systems.
APR1000/1400	Legal settlement between Westinghouse and Korean organisations provides clarity for purchasers and should also provide clarity in the supply chain. The APR1000 is specifically targeted on Europe but has not yet been built. Repeatable, predictable construction schedule for APR1400 should provide lessons learned, and supporting evidence for some systems. 4 operating in South Korea, 4 operating in UAE. Repeatable, predictable construction schedule. Supply chain exists. Proposed projects often include significant Korean Government investment through export credit and other means.	Lack of operating experience for APR100. Some licensing experience outside Korean and UAE. Limited construction experience Korean and UAE. Supply chain may have reduced opportunity for localisation. Workforce outside of Korea – typically large workforce is deployed from Korea. Site assembly for some systems Potential for change from current design due to lack of harmonisation.
EPR	Construction and operating experience in multiple geographies. Later versions have a few modules. Supply chain exists. Provable but challenged ability to run parallel projects.	Highly complex design Lengthy construction periods. Potential for change due to lack of harmonisation. Large workforce demand. Site assembly for some systems.
HPR-1000	Programme of repeat build starts showing repeatable construction schedule. Supply chain exists.	Chinese technology. Limited licensing experience outside China.

Technology	Opportunities	Risks
	Provable ability to run parallel projects.	Limited construction experience outside China. Limited opportunity for localisation. Potential for change due to lack of harmonisation. Workforce outside China. Site assembly for some systems.
VVER-TOI	Programme of repeat build starts showing repeatable construction schedule. Supply chain exists. Proven ability to run parallel projects.	Russian technology. Limited licensing experience outside Russia. Limited construction experience outside Russia. Limited opportunity for localisation. Potential for change due to lack of harmonisation. Workforce outside Russia. Site assembly for some systems.

Table 2.5 below sets out a smaller set of parameters that might be of interest for Norway to consider in an early-stage overview of currently available technologies before making any commitment, and to understand the current marketplace for GW reactor technologies outside of a formal exercise.

Table 2.5: High-level GW Reactor Evaluation Criteria

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
1. Reactor Vendor	Historical experience with development and deployment of technology, reliability of equipment, impact of preferred supply chain or deployment model etc.
2. Reactor Technology Name / Code	The reactor vendor will have a ‘reference design’ (the technical basis of the plant design recorded in design documentation such as a design control document) used as a basis to bid against, but it does not account for variations that may be required for implementation within different regulatory jurisdictions. For example, a US reactor origin design already licensed by the United States Nuclear Regulatory Commission may require modifications to be licensed in a European country that has different standards. An example of this is a 50 Hz variant needed for Europe which may require design changes to accommodate not only different plant, but changes in structural loads and space requirements. This can become more challenging in a country whether regulatory experience and capabilities are still emerging.
3. Thermal Power MWt	Correlates with parameter 4, Electrical Power, with efficiency determined through the house load of supporting the plant operations, which can be 30-40 MW. This can also be impacted by the type of cooling chain selected and the specifics of the site.
4. Net Electrical Power MWe net	This is the power exported to the grid after considering deductions from house load.
5. Number of Primary Coolant Loops	Basic comparison in the number of major heavy components with forgings for main reactor components. Due to the size and complexity of manufacture, these are often considered “long lead items” that may need to be speculatively procured before project final financial investment decisions are

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
	made in the project. The lead time is necessary as they need to be installed relatively early in the fit out of the main reactor building. These large components of what is called the Nuclear Steam Supply System (NSSS) are discussed further in Chapter 4.
6. Reference fuel supplier	Consideration of security of supply and geopolitical constraints, as well as performance experience of the fuel due to proprietary fuel cladding and manufacturing differences. Some reactors can take fuel from multiple suppliers, but typically the reactor safety case will reference a specific design. Not all reactor designers make fuel.
7. Fuel Cycle Length (months)	This is how long the reactor can continuously operate before it must be shut-down and nuclear fuel replaced. About a third of the fuel is exchanged for fresh unirradiated fuel, with the remainder moved to a different position in the core. Fuel can be present for up to three cycles depending on how the reactor is operated. Reactors tend to operate on either 12, 18 or 24-month fuel cycle durations.
8. Fuel Type and Accident Tolerant Fuel (ATF) Features	Level of competition in fuel market available. Some reactors can be supplied with fuel from multiple fuel vendors, some are far more restricted, which can create a commercial constraint. ATFs are being designed to improve performance under any severe accident conditions but may have a cost premium and may have much less operating experience. These are explored further in Chapter 4.
9. Maximum Fuel Rod Burn-up (MWD/MTU)	Efficiency of use of fuel and impact on fuel cycle costs is an important consideration, and the burnup, or specific power output can give a good indication of how efficient the reactor is. This is also impacted by fuel cycle length with higher burnup normally requiring a greater variety of core positions leading to shorter fuel cycles with less new fuel and more location shuffling.
10. Country of Origin of Technology	Consideration of security of supply and geopolitical constraints, impact of export controls. This may present a binary choice, and in fact could exclude reactors from the procurement and selection process with the most significant current construction experience.
11. European Utilities Requirements (EUR) Assessment Outcome	The missions of the EUR Association are to a) come to common European positions on design requirements to be proposed by vendors for future Nuclear Power Plants (NPP) and b) to promote harmonisation in requirements towards standardisation bodies across Europe and worldwide. This does not mean that there won't still be country to country differences within Europe, but this does aim to create a basic common position and has been used to set a common basic standard for reactor vendors to meet. Differences in regulatory standards and expectations may drive specific differences in design between countries. There are many organisations involved in promoting international harmonisation, but the goal of a standard or reference design that is not modified for different countries is a longer-term objective. The aims are to ensure new reactors will comply with the safety and technical requirements established by regulators, and to facilitate NPP vendors and designs to enter the European market by making the design requirements harmonised and more transparent. On request of vendors of nuclear power plant designs, a detailed assessment of their designs is performed against the EUR Document. The EUR document, is structured over 3 relevant volumes: Volume 1 "Main policies and objectives"

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
	Volume 2 "Generic and nuclear island (NI) requirements" contains all the generic requirements and expectations of the sponsoring utilities for the NI or for both NI and Power Generation Plant (PGP), often called the Turbine Island and Balance of Plant, covers the entire plant up to the grid interface. Volume 4 "Specific Power Generation Plant requirements" contains the generic requirements related to the PGP. To give an idea of the complexity ~ 5000 requirements for the NI alone have been refined and updated over 25 years to reflect changes to European regulations and to incorporate engineering and operating experience from existing plants and new build projects. The document applies to both large PWRs and BWRs, with a variation to address SMRs in development. It's important to note that although EUR compliance can be a useful differentiator in selecting a design for deployment, there are potential options available for addressing the situation of non-compliance (derogations are an example). At the earlier stages of technology selection, a review against vendor information may in itself be sufficient to provide an informed view.
12. Revision of EUR GW Technology Assessed Under	Various revisions have been issued over the course of approximately 15 years, as views of what a Generation III reactor have developed. The higher the letter of the revision of EUR requirements, the more likely that the assessment aligns to current regulatory requirements.
13. Any EUR Reservations?	When EUR awards an assessment certificate, there may be some requirements which are not or partially met, and these are recorded as reservations. This information is not publicised, although occasionally this will be referred to in publication of the announcement.
14. Has a version of this technology been licensed in Europe?	Licensing of nuclear technology is an individual sovereign state responsibility. Each regulator has a different approach, through informal and formal phases increasing regulatory certainty on approvals. There are ambitions to harmonise regulatory standards and expectations in licensing reactor designs (e.g. the Cooperation On Reactor Design Evaluation and Licensing (CORDEL) committee), the ideal standard being that when a design is licensed in one country, a full re-assessment is not required in a 2nd country with the latter regulator being able to 'take credit' for what has been previously assessed. So far, the timescales for any significant changes across regulatory regimes are in the future. Proof of formal licensing in an individual state remains however, a significant factor in determining level of risk of deployment. Costs prior to construction start are rarely considered but can be significant, particularly those related to licensing, including costs of the vendor team and regulator fees.
15. Has a version of this technology undergone pre-licensing in Europe?	Pre-licensing or informal regulatory engagement processes like the UK Generic Design Assessment process have been designed to allow a technology to be assessed in terms of future licensing risk, but experience of Hinkley Point C EPR in the UK shows that major design changes can still be experienced during and after GDA. If a technology has gone through this process successfully, it gives some indication that the level of risk related to licensing and potential for delays may decrease or regulatory engagement can be more predictable.
16. Selected by European Utility (Live Project)?	This builds on parameter 11. If a technology has been selected and is being deployed within Europe, this suggests that risks related to deployment in Europe as a region have been considered, that the design can stand up against competition both from a technical and commercial standpoint. This does not mean that further changes will not be experienced however, but it means that the impact of European standards and regulations will have been or start to

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
	have been considered beyond the design requirements stage. Selection may also have been facilitated through use of Export Credit and may increase investor confidence or reduce investor risk.
17. Number of plants operating	Number of operating plants (units) worldwide is an important consideration. By building fleets, instead of individual reactors, they benefit from economies of scale and learn by doing. Construction becomes cheaper as a result, with valuable lessons learned gained for every build. Whilst at a global level this is less significant, in one country this may be very beneficial. This goes beyond the vendor. Supply chain, provided this remains largely the same, are able to invest in skills and equipment over the long term.
18. Reactor operating years' experience total	The track record of a vendor to have put into operation that runs reliably is an extremely important consideration. Some experience may translate from historical projects, but there is also a technology specific element here, as design specifics can significantly impact reliability.
19. Any reported reliability problems?	This is a key parameter to understand, as often the asset will be depreciated over the first 20 years, and will impact availability, and remedial expenditure, which could impact cost of electricity. Such problems can also undermine regulatory confidence. Very few of the options currently have extended reliability figures, although reliability of earlier variants can provide some insight.
20. Early Life Availability %	GW reactors have a range of existing operating experience from 0 to nearly 100 reactor years of operations. Understanding early life availability figures can give a good indication of plant commercial performance and future lifetime. This could be merged with parameter 19. The key difference is that in parameter 19, more detail is placed on understanding the learning points and how they were addressed, rather than looking at a single figure.
21. Claimed Availability %	It is important to compare claimed availability % with actual availability figures.
22. Construction experience	The track record of a vendor to have designed and then constructed a plant to time, cost and quality is an extremely important consideration, although this can be impacted by different construction standards, how rigorous the regulator is, how influential the Licence Holder is, and how open the lessons learned are. Some experience may translate from historical projects, but there is also a technology specific element here, as generic and site-specific elements of design can significantly impact constructability, time and cost, whether through use of novel construction techniques, new materials, components without operating experience or a new or adapted supply chain, using proven or novel manufacturing or inspection techniques. Over a long construction period, during which there are usually no income streams from the project, the interest on funds borrowed, if that is appropriate, can compound into very significant amounts. In a business plan, the cost of capital is often calculated at various discount rates to discover whether capital expenditure can be recovered. If the cost of capital is high, then the capital expenditure rises disproportionately and may undermine the viability of the project.
23. Major delays in construction experienced	It is important to tease out the reasons for such major delays in construction, which are often highly convoluted. Recently COVID has had a significant, but often over flagged, impact, but factors in causing delays can include political and geopolitical changes, design immaturity at the start of the project, programme design features, funding problems, weather, industrial relations, licensing uncertainty and regulatory challenges, quality and supply chain challenges, investor confidence, delivery model, etc

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
24. Under Construction (Live)	The track record of a vendor to have designed and then constructed a plant to time, cost and quality in recent times is an extremely important consideration, as codes and standards change, regulatory requirements change, skills availability changes, teams develop lessons learned and optimise processes etc. However, the ability of a vendor to support parallel construction projects is something to explore in detail in terms of capacity, capability, location. This can even impact design teams depending on the design detailing strategy taken and design maturity.
25. Claimed construction time (months from commencing nuclear construction to online)	With size of project hotel costs and loss of generation, this construction time metric can have a very big impact on CAPEX costs and financing. This is a snapshot when activity on site is highest, staff costs are largest. Whilst it ignores time to design, licence, plan and prepare the site, and undertake large earth movements it is an important comparator. Section 5 focuses on costs for nuclear.
26. Open top construction approach?	Related to modular construction, the ability to load major components through heavy lift. This can allow projects to proceed more smoothly with construction.
27. Level of Modular Build	Increasing the amount of the construction that can be undertaken in weatherproof factory conditions could increase quality and certainty of production.
28. Footprint scale m^2/MWe	Physical land area required for plant in construction and operation may be a driver for certain countries and projects.
29. Key Safety Features (list)	Safety considerations are vital of course. Some reactors on the market can be shown to have a slightly different offer when it comes to the range, number and breadth of safety systems. This can be in the form of passive safety features that rely on physics (e.g. natural circulation of water to cool the fuel) and the dependency upon the reactor operator to undertake action in the event of a fault condition arising on the plant and the timescales where this is necessary (some designs claim no action required for up to 72 hours).
30. Design features and components that have been proven in currently operating plants or are based on such proven components	Important consideration for newer designs that haven't been constructed but are based on existing designs
31. Any Operational Features Supporting Potential Life Extension	Reactor lifetime has a potentially significant impact on cost, although this diminishes over time. This category is to identify any features worth noting to understand the ability to extend beyond the standard 60 years planned lifetime. Also notes any features where major components have had to be replaced in the past, but current experience hasn't reached this point to determine whether new designs with new materials will see the same challenges e.g. Reactor Pressure Vessel (RPV) head and or steam generator replacement
32. How plant deals with black out from grid	Information gathered to support the assessment of a plant addressing impact of grid stability.

High Level Parameter for Comparison	Specific Considerations for Comparison Between GW Technologies
33. Flexible operations (How is load following and frequency balancing capability maintained)	General information gathered to understand load following
34. Flexible operations limits (load following limits (% power changes, power ramp rates etc)	Specific information gathered to understand load following in more detail
35. How does plant deal with a steam dump (possible overlap with 34)	Where applicable to understand how plant deals with dumping steam that would otherwise go to the turbine

2.4 Future Availability of GW Designs and Technology Selection

2.4.1 Certainty of Technology Availability

This chapter considers future availability of GW designs for new reactors available between 2040 and 2050, the potential time frame for connecting new reactors to the grid *if* Norway decides a strategy for nuclear deployment. With the rapid emergence of SMR and AMR markets drawing significant global attention, the nuclear industry is increasingly shifting toward smaller, modular, and more flexible reactor technologies. At the same time, simplified versions of existing large-scale designs are being explored to enhance cost efficiency and construction timelines. However, it remains uncertain whether reactor vendors will continue investing in or maintaining their current portfolios of gigawatt-scale reactor designs for future commercial deployment, or whether these larger systems will be sidelined as focus and funding move toward modular and advanced concepts. At present, most organisations are developing both strands in parallel.

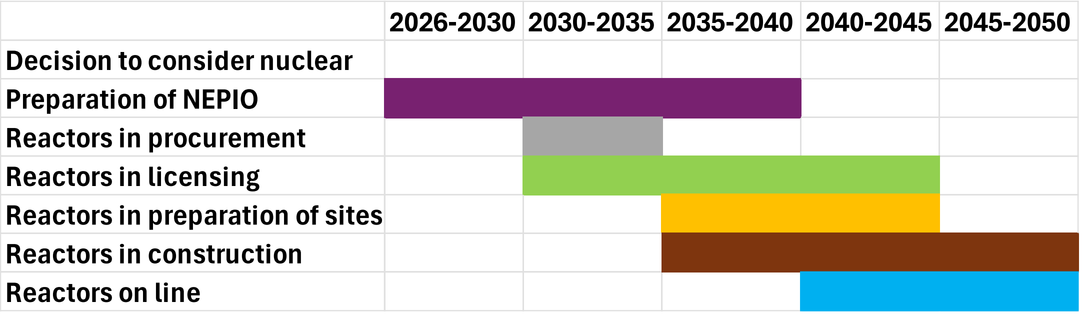
A rough, high-level schedule working back from these dates suggests that any reactor procurement exercise would likely have to be run between 2030-2035, and this is shown below in Figure 2.12 for completeness. This is based on the IAEA requirements for establishing a credible Nuclear Energy Programme Implementing Organization (NEPIO) in a new entrant country. It is reasonable to assume that a wide enough range of reactors is likely to remain on the market for any formal selection processes.

2.4.2 Considerations for Timing of Future Deployment

Figure 2.12 presents a very coarse outline assessment to provide context around market availability and the timing of a potential deployment in Norway, subject to any decision being made. This is a very rough assessment, based upon engineering judgement. A robust programme, involving market engagement, would need to be developed to underpin these dates but this is outside the scope of this report. Some SMR and AMR designs with full modular design and manufacturing capability appear potentially ready for first-of-a-kind home country nuclear construction starting in 2026-2032. Some of these projects have recently started, but typically with non-nuclear construction only. There is also a strong programme of secured GW deployment, and some ambitious plans for additional projects. This will mean a potential dash for skills and resources, which may not be available for new projects, particularly ones that could be seen as higher risk in a new-to-nuclear country. If a NEPIO starts to be established in Norway early, this presents an opportunity to understand in detail the lessons learned as projects progress and engage with the vendor and broader supply chain marketplace. Based upon the history of nuclear power development, the SMR and AMR marketplaces are all likely to undergo significant lessons learned and feedback on technology development, commercial readiness, licensing, selection, price, delivery and schedule. We would expect to see some examples of completed SMR projects, starting in the period 2030-2036, with AMRs perhaps a little later. As essentially a new entrant, it would be essential for Norway to benefit from both home country first-of-a-kind licensing, project risk reduction, and lessons learned. Even in nuclear countries, programmes have faced steep uphill challenges where nuclear construction has been paused.

Crucially, we believe that Norway would need time to develop both nuclear law and regulatory regime, as well as the necessary regulatory capabilities and capacity for a new build programme. It would also need to build skills and resources at country, region and operator levels, before considering design and licensing requirements to support procurement for any Norwegian project. There are accelerators that could be considered, such as a regulatory skills programme, secondments to other regulators, and seeking support organisations to bolster legal and technical resources. A programme of work could be established to stimulate setting up a NEPIO team to gather lessons learned, to undertake logistics studies, and to develop a shadow operator to support selection and procurement and then delivery. Norway may decide that it can partner with another regulatory regime, aligned to the chosen reactor technology, which could greatly accelerate any type of programme, and engage strongly with international bodies such as the IAEA. It may alternatively decide to develop independently based on selecting relevant good practice from different regulatory regimes. This approach allows for partnerships with expert organisations, including experienced secondees from both regulator and regulated alike, and then a strong parallel programme to develop indigenous capability. A focus on using milestones and independent peer review from international experts can support this approach. This would also need focused academic, apprenticeship and educational programmes to develop the necessary skills, together with retraining from similar industries. This is essentially what happened in the UAE on the Barakah programme.

Based on an ambitious 3–4-year construction programme starting in 2036, the earliest date that reactors could be ready for connection to the Norwegian grid is around 2040. By adopting a relatively cautious approach, Norway has an opportunity to potentially capitalise on reactor designs being further developed by the time of short-listing for procurement in time for the 2040-2050 window.



	2026-2030	2030-2035	2035-2040	2040-2045	2045-2050
Decision to consider nuclear					
Preparation of NEPIO	🟪	🟪	🟪		
Reactors in procurement		▨			
Reactors in licensing		🟩	🟩	🟩	
Reactors in preparation of sites			🟨	🟨	
Reactors in construction			🟫	🟫	🟫
Reactors on line				🟦	🟦

Figure 2.12: Earliest Reactor Short-List Planning

This chart shows that there could be sufficient time to progress the start of the development of the required Nuclear Energy Programme Implementing Organization (NEPIO) as defined by the IAEA, and this could be well aligned to technology availability. There is also the potential opportunity to accelerate the timeline in Figure 2.12 by starting procurement earlier than shown and shortening this phase to 36-48 months. Similarly, there are also possible opportunities from early commencement of initial site preparation, such as earth works, non-nuclear infrastructure and site characterisation.

2.4.3 Formal Technology Assessment and Milestone Readiness Exercises

If a member state (ME) makes a policy decision for nuclear power, the IAEA recommends that it adopts a milestone approach with thorough readiness reviews at each milestone to develop a nuclear power programme (IAEA Nuclear Energy Series, 2015). The MS should have a thorough understanding of the consequences of moving into procurement with outstanding infrastructure issues. This is especially true when it comes to an underdeveloped nuclear regulatory framework. If the regulatory framework is not sufficiently defined for a new build project, as is the case currently in Norway, then the risk of project delays or other issues is increased, and it creates a situation where the costs could change, and delays could be caused. Obligations for interface with the European Union should also be considered.

The IAEA recommends a set of 19 infrastructure assessment areas to be developed and tracked through a milestone-based readiness process to support a new nuclear programme. Reactor selection by procurement is the last item in the list.

1. National position
2. Nuclear safety
3. Management
4. Funding and financing
5. Legal framework
6. Safeguards
7. Regulatory framework
8. Radiation protection
9. Electrical grid
10. Human resource development
11. Stakeholder involvement
12. Site and supporting facilities
13. Environmental protection
14. Emergency planning
15. Nuclear security
16. Nuclear fuel cycle
17. Radioactive waste management
18. Industrial involvement
19. Procurement

Whilst this document can inform some considerations made under topic 19 (Procurement) this is not intended or required to be a replacement for a full systematic assessment.

Figure 2.13 illustrates Milestones 1, 2 and 3:

1. Ready to make a knowledgeable commitment to a nuclear power programme
2. Ready to invite bids/negotiate a contract
3. Ready to operate

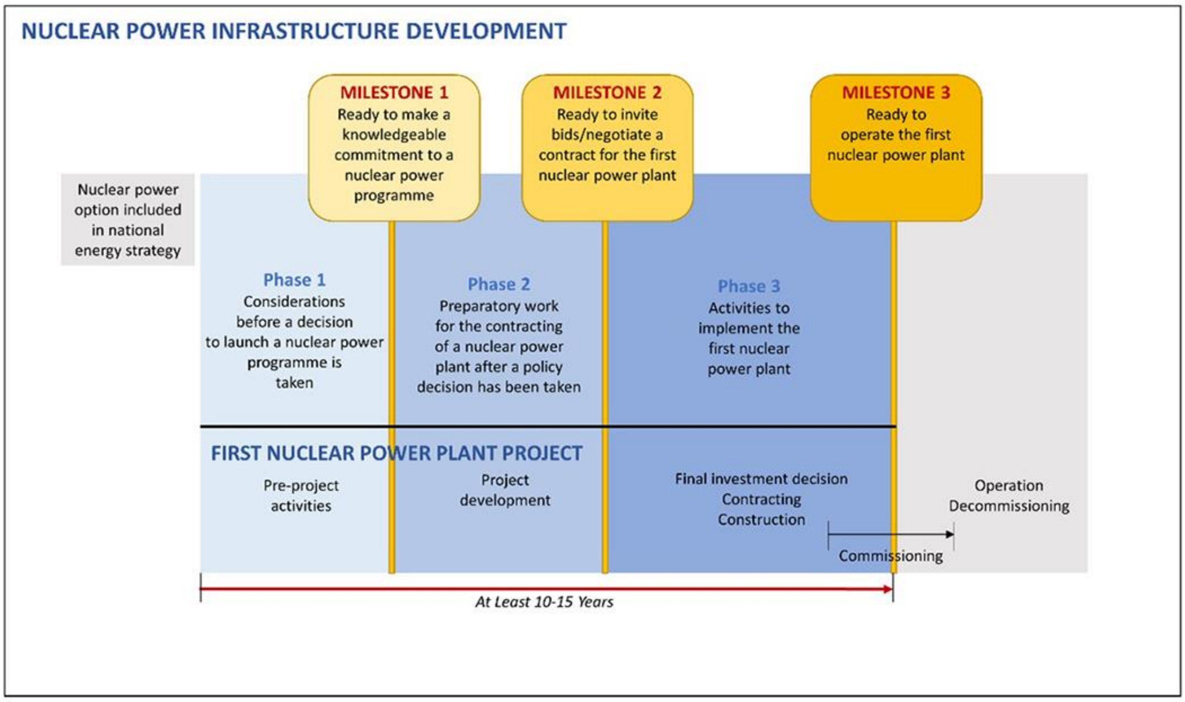


Figure 2.13: Milestones in Nuclear Power Infrastructure Development (IAEA, 2024a)

The bid invitation specification (BIS) document suite is designed to contain all the information that bidding reactor vendors and consortium members need to prepare their bids. Its development will be a culmination of a lengthy pre-development phase. The BIS will be updated to provide the most up to date and complete procurement specification and thus be the sole document that vendors will rely on in preparing their formal bids and managing future claims. Any specific owner or licensee's requirements for the project need to be clearly defined in the BIS. The IAEA indicates that a reasonable timescale for this activity to get into contract with a nuclear reactor vendor is range from 1 year and 8 months to 3 years and 5 months, but recent experience has shown that this may be an underestimate – see Figure 2.14 for the IAEA view of the BIS schedule.

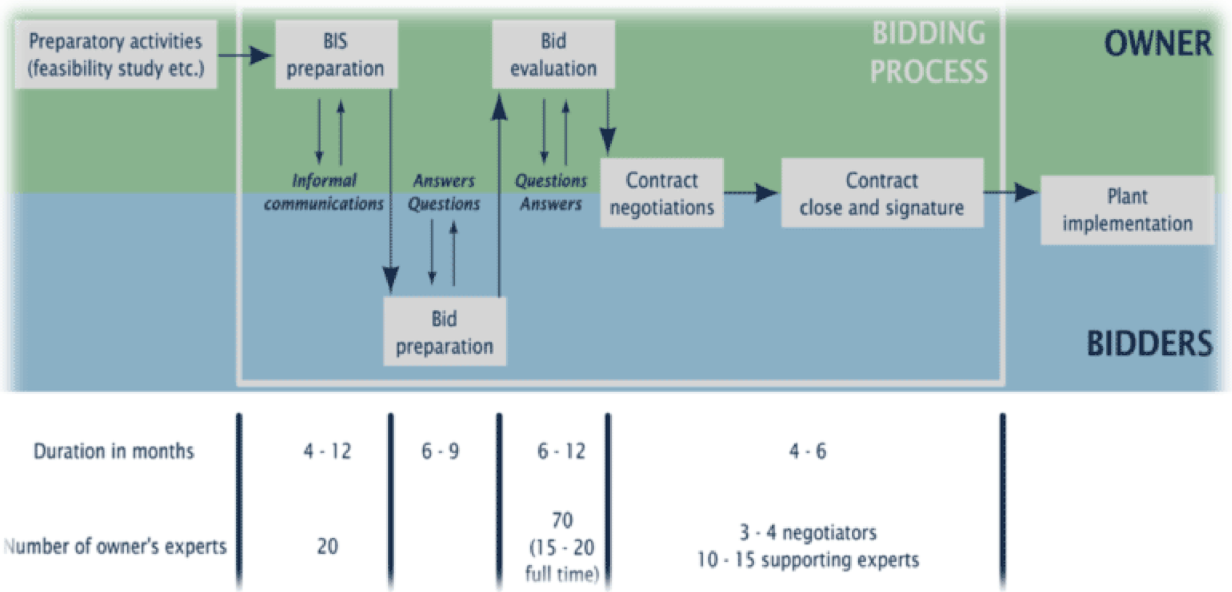


Figure 2.14: Outline of the Procurement Phase for Selecting a Reactor Technology (IAEA, 2011).

BISs are useful even for sole-source purchases or intergovernmental agreements. They allow the purchaser to clearly specify the scope and requirements for the project (including any specific owner's requirements), and for the bidder to provide a clearly scoped and costed bid. The purchaser can then compare the received bid against other options (e.g. other energy supply options, do nothing option, etc.), and ensure that the proposal received represents good value. A quality, independently produced, owner's estimate of reasonable project costs is a key starting point for such a sole-source comparison.

2.4.4 Additional Future GW Reactor Technology Options

Other GW reactors are being marketed based on existing plants, but they are in earlier phases of design, are not yet fully licensed and do not have construction experience. We believe that with the current desire to consider SMRs and AMRs, it is unlikely that additional GW reactors will come on to the market in the timescales suitable for connection to the grid in 2040-2050. Variants of current designs have already been covered in the description of each reactor family in Section 2.3.1.1. These reactors are currently being marketed for potential future deployment on a timescale that could make them credible for consideration in any future programme in Norway. These reactors are typically being marketed as a simplification or slimming down of existing GW reactor designs, and an evolution, rather than a step change in safety or construction performance. However, much less information is available in the public domain about these designs. With the emergent focus on SMRs, it remains to be seen which reactor vendors will continue to develop and offer their current and future GW reactor designs for future deployment by 2040.

2.4.5 Conclusions from GW Reactor Technology Review

The wide variety of GW reactors negotiable for potential deployment, together with live experience of design, manufacture, construction, operation, and future pipeline, means that there should be sufficient choice if Norway makes a policy decision to pursue nuclear power. We have not eliminated any designs from the list at this pre-decision-making stage, as exclusions would be political decisions and/or subject to formal procurement processes. A future review and update of market status would form part of any pre-engagement process in future steps.

A lack of harmonisation is likely to remain a significant challenge for most if not all designs to some greater or lesser extent. For example, currently a US reactor design cannot simply be licensed in the EU "as is". Whilst there is much work on cross-border harmonisation and significant political challenge being made to regulators to make licensing easier, it remains to be seen how this progresses. There is a large body of lessons from recent mega projects including from construction of GW reactors and so, before any procurement process, Norway could learn how to do things differently to avoid the same mistakes.

As with all reactor types, if a decision was made to pursue nuclear in Norway there would need to be significant investment against all of the IAEA infrastructure task areas, including scaling up the nuclear regulator and introducing of new regulations and guidance, as well as development of an NEPIO and operator/licence holder (if separate from the NEPIO).

SMR and AMR technologies could change market dynamics considerably, with small reactors becoming more dominant if their claimed benefits are delivered in future deployment and operation. The current range of GW reactors may not be sustained in the focus turns to SMRs and AMRs, although this is not to say that large scale GW reactors will not continue to be viable in countries with centralised energy planning, robust financing capacity and long-term decarbonisation goals. In other words, SMRs and AMRs will be complementary technologies, not direct replacements. This view is generally shared by the IAEA, which expect SMRs to make a meaningful but not dominant contribution to nuclear generation. The 2024 publication “Small Modular Reactors: Advances in SMR Developments 2024” details technology development, design status, lifecycle, non-electric applications and cautions that deployment still has challenges (IAEA, 2024b). The OECD-NEA Nuclear Energy Agency (NEA) offers a similar perspective and according to its 2024 annual report “for some, there will be a need to build numerous large nuclear units, for others, a distribution of small modular reactors…” (NEA, 2024). In other words, the technology must fit the context.

Reactor vendors might struggle to maintain GW and SMR and or AMR, 60 and 50Hz variant product lines for global deployment, each requiring country and site-specific designs, with the number of projects foreseen. It is of course not possible to be certain what may happen in the future around the timescales being considered for potential deployment in Norway, but a cautious delivery programme could allow Norway to consider how the market is changing.

We will now explore SMR and AMR reactor types in the next sections.

2.5 SMR Technology

2.5.1 What are SMRs?

Small modular reactors (SMRs) are deployable either as single or multi-unit plant, typically 3-10 units, together comprising a fleet of reactors. They offer the possibility to combine nuclear with alternative energy sources, including renewables. The IAEA definition limits the power level to 300 MWe, around one third the level of a typical GW plant, but there some notably larger designs up to 470 MWe such as the Rolls-Royce SMR from the UK. These reactors are typically digital first designs, have advanced engineered features, and are designed to be substantially built in factories and shipped to site for installation, using a variety of advanced manufacturing features. Depending on the source, whether IAEA or NEA, there are some 80-130 advanced reactors in a wide variety of states of readiness for market but the majority of them are at the concept stage. This list is growing weekly. (NEA, 2025)

With such a large and diverse range of designs and concepts globally, it is very uncertain how many of each design will be constructed. Many are adopting advancements on basic light water reactor technology. Most are at low technology readiness levels of developmental and a few are claimed as being near-term deployable. Very few have progressed significantly in licensing. There are currently four smaller SMRs in advanced stages of construction in Argentina, China and Russia. There is again a dominance of Chinese and Russian reactors in current and planned deployments. As these examples are below the power level assumption set by the Commission, we will not discuss them further.

For this report, we deal with AMRs from SMRs separately to mark the differentiation from LWR reactor fuel technology. Light water reactors (LWRs) are the most common NPPs worldwide and for the SMR scale are again divided into two general sub-types: PWRs, which produce steam for the turbine in separate steam generators; and BWRs, which use the steam produced inside the reactor core directly in the steam turbine. All LWRs require fuel that is enriched in the fissile isotope, U^{235}, typically in the form of UO_2 pellets in cladded fuel pins set out in a fuel assembly array of various sizes and geometries. Smaller versions of Heavy Water Reactors (HWRs) use “enriched” water, the molecules of which comprise hydrogen atoms that are made up to more than 99 per cent of deuterium. A heavier hydrogen isotope is also being developed. This heavy water, used as a moderator, improves the overall neutron economy, allowing fuel to be used that does not require enrichment (IAEA, 2025a).

Note that the main potential differentiator for SMRs is speed of deployment which is closely linked to a predicted lower cost of finance, as most of these reactors are significantly more compact than the GW plants previously described. Speed of deployment and quality assurance from factory-based module manufacturing means that the first units could start to generate power and bring in income to service debt while additional capacity is constructed. SMRs also typically introduce additional forms of passive safety systems compared with GW reactors, although some GW plants such as AP1000 and ESBWR already have some passive design features.

Table 2.6: Key features of LWR SMRs

Key Features	
Technology Classification	Generation 3 (Water Based Reactors)
Reactor Types	• Pressurised Water Reactor (PWR) • Boiling Water Reactor (BWR)
Cooling Method	Water
Siting	Flexible Deployments, Closer to Industry (but still semi-rural locations with access to cooling water).
Turbine Interface	Rankine Cycle – 33% Efficient use of Nuclear Heat
Cooling	• Open Circuit Water Loop • Closed Circuit Cooling Towers
Operating Temperature	250 ° C to 350 ° C
USP’s	Factory built, modular assembly, passive safety.
Primary Use Cases	• Grid Power • Micro Grids • Low Temperature Steam Electrolysis
Technology Readiness Level (TRL)	TRL 7/8 for basic LWR technology elements TRL-5-6 for specifics of the SMR designs and technologies being implemented
Technology Risk	Relatively low – Based on existing basic aspects of technology from GW LWR, deployed projects live by 2026 (China).

Key Features	
	However, typically, many are in a concept or preliminary design phase with a higher risk. Most SMRs are first-of-a-kind technologies, albeit with evolution from proven designs. Risks relate to licensing, maturity of supply chain and infrastructure, maturity of the delivery teams etc.
Commercially Available	Now – Existing sales of technology agreed, with first projects in construction, and a wider family coming to market around 2035.

2.5.2 Concept of Flexibility

SMRs are often referred to as "more flexible", which is an ambiguous term. They can potentially be sited in places that aren't feasible for full-scale nuclear plants and can also be added incrementally or scaled, as energy demand grows. Some SMRs can be built partially or fully underground to further increase safety. They may be suitable to directly meet the energy needs of a greater range of end users, from industrial applications requiring a mixture of electricity and also heat by private wire and pipe, to both national and decentralised grids. SMRs may also have a degree of flexibility when it comes to load following which will be discussed in Chapter 3.

2.5.3 How Can Different SMRs be Compared?

This section describes a number of high-level parameters that could be used to support a more detailed evaluation of different SMR designs, explaining which remain relevant for the SMR market and highlighting areas where information is yet to become available. What the reader will see is that the parameter list is to a large extent very similar to that for the GW designs.

Table 2.7: A Summary of a Number of Key Parameters to Assess When Exploring Different SMR Technologies

High Level Parameter for Comparison	Commentary on applicability of GW Parameters. Specific Considerations for Comparison Between SMR Technologies
1. Reactor Vendor	Remains relevant for SMR. Historical experience with development and deployment of technology, reliability of equipment, impact of preferred supply chain or deployment model etc. This remains relevant to consider when reviewing risks around SMR technologies coming to market and being deployed. However, there is a considerable number of new technology disrupters, and it is sensible to consider whether a fresh approach could reduce some risks. There are also additional risks and opportunities related to deploying multiple reactor types at the same time.
2. Reactor Technology Name / Code	No difference for SMRs. Comments for GW reactors apply here.
3. Thermal Power MWt	Correlates with 4., Electrical Power, with efficiency determined through house load, cooling chain performance etc. Note that many SMR designs have around one third of the power output but are not one-third scale physically.
4. Net Electrical Power MWe net	No difference to GW reactors, unless the plant is being considered for co-generation, tapping off heat and electricity to make hydrogen for example.
5. Number of Primary Coolant Loops	As with GW, basic comparison in the number of major heavy components with forgings for components considered long lead items that may need to be speculatively procured before project final financial investment decisions are made. It may be the case that some SMR or AMR technologies are able to move away from traditional large heavy forgings, but that is still to be agreed with regulators.

High Level Parameter for Comparison	Commentary on applicability of GW Parameters. Specific Considerations for Comparison Between SMR Technologies
6. Reference fuel supplier	Consideration of security of supply and geopolitical constraints, as well as performance experience of the fuel due to proprietary fuel cladding and manufacturing differences. This remains important to consider. The primary or reference supplier may not be the same as the vendor. Not all SMR vendors are designing their own fuel. Some SMR fuels will be identical to GW plants; some may have some changes including length; some may have very significant complexity.
7. Fuel Cycle Length (months)	SMR designs considering LEU+ or HALEU fuel may appear to offer the prospect of higher burnup and operations for much longer periods between refuelling outages and better fuel utilisation which has economic and waste management benefits. SMR core designs may be more complex than GW cores, and this is worthy of assessment of the potential impacts. It may also make more sense to phase outages across a fleet so that they can cycle around in a joined-up way.
8. Fuel Type and Accident Tolerant Fuel (ATF) Features	Some SMRs are being designed with ATF as a basis. Level of competition in fuel market available. Some reactors can be supplied with fuel from multiple fuel vendors, some are far more restricted, which can create a commercial constraint. ATFs are being designed to improve performance under any severe accident conditions but may have a cost premium and may have much less operating experience. Some SMRs are being designed and licensed with ATF as a basis, but this carries FOAK risk although this is somewhat being mitigated by testing programmes of ATF in existing operational reactors.
9. Maximum Fuel Rod Burn-up (MWD/MTU)	Efficiency of use of fuel and impact on fuel cycle costs is an important consideration. For SMRs, front end fuel cost could be a more significant fraction of the overall cost (versus GW reactors) for traditional UO_2 fuel-based designs. That said, some SMRs and AMRs are considering very different fuel types (such as HALEU) which could extend burnup to a different range and longer fuel cycles and improve the economics to make such fuel types attractive.
10. Country of Origin of Technology	No difference to GW reactors
11. European Utilities Requirements (EUR) Assessment Outcome	EUR aims and purpose are described in Table 2.5. Not yet appliable for SMRs until December 2026 when a variation will be published. It is noted that any such assessments will be likely to be several years in duration which depending on the timescales for any possible technology selection in Norway may make EUR assessments of limited use for SMRs. As noted for GW reactors, it's important to note that although EUR compliance can be a useful differentiator in selecting a design for deployment, there are potential options available for addressing the situation of non-compliance (derogations are an example). Due to the constraints of deploying EUR for SMRs, at the earlier stages of technology selection, a review against vendor information will be necessary to provide an informed view.
12. Revision of EUR Technology Assessed Under	N/A No assessments of SMRs have yet occurred.
13. Any EU Reservations?	N/A No assessments of SMRs have yet occurred.
14. Has a version of this technology been licensed in Europe?	Commentary for GW reactors apply here. In addition, it is noted for SMRs, that there are some factors related to codes and standards where if there is a pan-European approach, that if considered previously, can be a mitigator of risk. For US origin reactor designs, CE conformity is an important consideration.

High Level Parameter for Comparison	Commentary on applicability of GW Parameters. Specific Considerations for Comparison Between SMR Technologies
15. Has a version of this technology undergone pre-licensing in Europe?	Very few SMR reactor designs have progressed through all stages of Pre-licensing, and this should be a factor to be considered, as there is a learning curve for vendor engagement in this phase that is useful to understand. Pre-licensing or informal regulatory engagement processes like the UK Generic Design Assessment process have been designed to allow a technology to be assessed in terms of future licensing risk. If a technology has gone through this process successfully, it gives an indication that the level of risk related to licensing and potential for future delays may decrease.
16. Selected by European Utility (Live Project)?	If a technology has been selected by an organisation somewhere in Europe, this suggests that some risks related to deployment in any European state may have been considered, that the design can stand up against competition both from a technical and commercial standpoint. Selection may also have been facilitated through use of Export Credit. This must be taken with caution as all projects are very early in due process. Worth noting whether there has been selection by the EU Industrial Alliance as a project-based technology.
17. Number of plants operating	N/A. This criterion is not yet appropriate for an emergent market like SMRs or AMRs at this stage.
18. Technology type operating years' experience total	In the absence of a track record for a specific technology, the track record of a technology type such as evolution of a specific technology from a basic PWR or BWR, and the related track record is an important consideration. Some experience may translate from historical projects, in terms of shared components and manufacturing experience for example, but there is also a technology specific element here, as design and manufacturing specifics of the same component but in the context of implementation in a different reactor, perhaps including advanced manufacturing techniques, can significantly impact the safety case. For LWR SMRs this is essential.
19. Any reported reliability problems?	Not fully relevant due to lack of SMR operating experience. Nevertheless, how reliability information has been interpreted from other existing plants, including assessment of adaptations of components or new components will be important to determine, however.
20. Early Life Availability %	This criterion is not appropriate for an emergent market like SMRs or AMRs at this stage. Information from GW plants may also be relevant, however.
21. Claimed Availability %	Whilst there is lack of operating experience for SMRs generally, it is important to ask for predicted plant generating availability by % and ask how vendors can be confident to meet it. However, vendors may be reluctant to provide any such guarantees.
22. Construction experience	Commentary from Table 2.5 applies here and in addition, Norway has an important opportunity to review the lessons learned across a number of SMR and AMR projects that are starting globally and address those in future plans should policy decisions be made. Understanding how the risks and opportunities of advanced construction have been assessed will be a vital step. Whereas with GW this is likely to be more site based, the experience from the factory-based supply chain will be important.
23. Major delays in construction experienced? Y/N and details	N/A as very few plants constructed – see 22.
24. Under Construction (Live)	Very few SMR vendors have experience in this area, and those that are building are typically not building a high modular variant or are focussed on non-nuclear construction. This is discussed further later, as it will be vital to understand on what conditions and when the full economics of SMRs could be delivered. The

High Level Parameter for Comparison	Commentary on applicability of GW Parameters. Specific Considerations for Comparison Between SMR Technologies
	track record of a vendor to have designed and then constructed a plant to time, cost and quality in recent times is an extremely important consideration, as codes and standards change, regulatory requirements change, skills availability changes, teams develop lessons learned and optimise processes etc. However, the ability of a vendor to support parallel construction projects is something to explore in detail in terms of capacity, capability, location. This can even impact design teams depending on the design detailing strategy taken. It will be important to ask vendors how they would address a future pandemic. With modular factory environments increasing, this may require some additional attention to understand how a project may continue in such circumstances.
25. Claimed construction time (months from nuclear construction to online)	Commentary for GW scale reactors applies here. With the economics of SMRs dependent on the time to generation coming down to reduce financing costs, this will be a crucial piece of evidence to explore, and detailed evaluation of the schedule, risk analysis and contingency budget is required. There is clear advantage to factory build and site assembly, and it may be a differentiator between some SMR vendors where some are really modularised civil construction followed by a traditional installation and some are factory built and then assembled on site. The latter approach will significantly reduce the numbers of personnel on site reducing the financial significance of any site-based delay.
26. Open top construction approach?	Related to modular construction, the ability to load major components through heavy lift. Would expect further use of advanced construction techniques for SMRs. This criterion is more focussed on movement of large modules into buildings, which we expect to increase in SMR designs.
27. Level of Modular Build	Increasing the amount of the construction that can be undertaken in weatherproof factory conditions. Understand whether this applies to factories and or site.
28. Modular Build Readiness	This will be a major piece of work. Impact of modular build on licensing needs to be assessed. New SMR Parameter. Modular Factory status.
29. Footprint scale m^2/MWe	For SMRs, physical land area required for plant allows comparison and consideration on a bulk civil construction / bill of quantities basis. Need to understand how this changes for both the site, the laydown and site factory area and also impact on off-site development. The claims around emergency planning zones and secure areas need to be fully understood and challenged. The attention needs to be placed on the layout of the fleet, not just the generic unit, and consider how issues like potential for turbine disintegration have been considered.
30. Key Safety Features (list)	Safety considerations are vital of course. Some reactors on the market can be shown to have a slightly different offer when it comes to the range, number and breadth of safety systems. Understanding any novel features and their validation status or use in GW plants will be vital.
31. Details of Passive safety systems	This may become a specific area of focus depending on the technology and whether regulators are looking for both passive and active safety systems. Again, looking for validation evidence.
32. No operator action required in event of accident for x hours?	Some SMRs vendors state that no operator action may be needed for example up to 72 hours. These will need detailed assessment, including understanding how support from offsite will be provided, including access to water supplies.
33. Design features and components that have been proven in currently operating plants or are based	Important consideration for newer designs that haven't been constructed but are based on existing designs. This may include use of advanced materials, including composite or hot isostatic pressed components, novel inspection techniques, as well as considering aspects where commissioning and site acceptance might be undertaken in a factory environment.

High Level Parameter for Comparison	Commentary on applicability of GW Parameters. Specific Considerations for Comparison Between SMR Technologies
on such proven components	
34. Any Operational Features Supporting Potential Life Extension	Category to identify any features worth noting to understand the ability to extend beyond the standard 60 years planned lifetime. Also notes any features where components have had to be replaced in the past, but current experience hasn't reached this point e.g. RPV head and or steam generator replacement. Whilst some suppliers may be bullish that large components won't need replacing, this should be considered as a risk. Some SMR and AMR plants have been designs with different use cases in mind compared with GW plants, and in some cases a shorter life. It is noted that GW scale plants tend to focus on major plant wide refurbishments and licence renewal programmes due to their large capital investment and long-established practices. SMRs, with their modular, factory-built nature, may not emphasise life extension in the traditional sense, instead favouring replacement modules at end-of-life. This remains somewhat speculative until actual SMR units operate long enough to assess real world ageing behaviour. SMRs would be expected to offer the use of greater instrumentation to understand the ongoing state of the plant.
35. How plant deals with black out from grid	General information gathered to understand how the impact of loss of grid has been allowed for.
36. Flexible operations (How is load following and frequency balancing capability maintained)	General information gathered to understand load following. There can be expected to be very bold claims in this area, and they will need to be assessed in detail to understand impacts on cost and availability, as well as fuel utilisation.
37. Flexible operations limits (load following limits (% power changes, power ramp rates etc)	Specific information gathered to understand load following.
38. How does plant deal with a steam dump	Specific information gathered to understand load following and islanding.

2.5.4 Which SMR Reactor Designs Should be Considered?

The IAEA currently has 122 "new" reactor designs listed in its Advanced Reactor Information System (ARIS) (IAEA, 2025b). Some of these are reactors that have been registered for many years and have not been developed. Of the 122, 68 have a power level greater than 30 MWt and less than 1000 MWt, and all are listed as active under design or later phases. Of these, just 22 are LWR reactors. It should be noted that this report focuses on medium to large SMRs as agreed with the Commission. Micro-reactors, plants that have a power too low to consider for making a major impact on grid wide electricity generation or are aimed at district heating are shown in grey in Table 2.8 above, and will not be considered further at this stage, as specified with the Commission, leaving 10 SMR reactors for potential consideration.

Some additional judgement has been applied to understand the more realistic options for widespread potential deployment. Although the small Russian KLT-40 reactor is operational, it has been designed for a very specific purpose for icebreakers and to be moored in marine environments. The HAPPY200 reactor is a concept for a scaled-up district heating only reactor, and this has not been explored further as agreed with the Commission.

Table 2.8: An Extract of IAEA SMR Database Showing Water Reactors & a Shortlist to Consider for Medium to Large LWR SMRs

Acronym/ Power MWe	Design Organisation	Type	Purpose	Design Status	Country
ABV-6E **6**	JSC "Afrikantov OKBM"	PWR	Commercial – Electric/Non-Electric (Arctic)	Detailed Design	Russian Federation
ACP100 **125**	CNNC/NPIC	PWR	Prototype/ FOAK	Under Construction	China
AP300 **300**	Westinghouse	PWR	Commercial – Electric/Non-Electric	Basic Design	United States of America
BANDI 60 **60**	KEPCO E&C	PWR	Prototype/ FOAK Floating	Conceptual Design	Korea, Republic of
BWRX-300 **300**	GE Vernova-Hitachi	BWR	Commercial – Electric/Non-Electric	Moving to detailed Design Approved for non-nuclear start of construction	United States of America
Calogena **30 MWt**	Calogena S.A	PWR	Commercial – Electric/Non-Electric	Conceptual Design	France
CAREM **27**	CNEA	PWR	Commercial – Electric/Non-Electric	Under Construction	Argentina
FBNR Fixed Bed Nuclear Reactor **70**	FURGS Federal University of Rio Grande do Sul	PWR + TRISO	Commercial – Electric/Non-Electric	Conceptual Design	Brazil
HAPPY200 **District Heating**	SPIC	Low pressure PWR	Commercia Non-Electric	Concept Design	China
i-SMR **170**	iSMRDA, KHNP	PWR	Commercial – Electric/Non-Electric	Detailed Design	Korea, Republic of
KLT-40S **35**	JSC "Afrikantov OKBM", Rosatom	PWR	Marine	Operational	Russian Federation
NuScale Power Module **6x77**	NuScale Power LLC.	PWR	Commercial – Electric/Non-Electric	Licence Approved	United States of America
NUWARD™ **300-400**	EDF with major contributions from CEA, Naval Group, Framatome,	PWR	Commercial – Electric/Non-Electric	Conceptual Design	France

Acronym/ Power MWe	Design Organisation	Type	Purpose	Design Status	Country
	TechnicAtome, and Tractebel-Engie				
PWR-20 **20**	Last Energy	PWR	Commercial – Electric/Non-Electric	Early stages of Design	United States of America
RITM-200M **55**	JSC "Afrikantov OKBM"	PWR	Commercial – Electric/Non-Electric	Conceptual Design	Russian Federation
RITM-200N **55**	JSC "Afrikantov OKBM"	PWR	Commercial – Electric/Non-Electric	Detailed Design	Russian Federation
Rolls-Royce SMR **470**	Rolls-Royce SMR Ltd	PWR	Commercial – Electric/Non-Electric	Detailed Design; in Pre-Licensing	United Kingdom
SHELF-M **10**	NIKIET	PWR	Commercial – Electric/Non-Electric	Detailed Design	Russian Federation
SMART **100**	KAERI	PWR	Commercial – Electric/Non-Electric	Detailed Design Licence Approved	Korea, Republic of
SMR-300 **300**	Holtec International	PWR	Prototype/FOAK	Early stages of Design; in pre-licensing	United States of America
VBER-300 & V-478 325 optional **295-325**	JSC "Afrikantov OKBM" and Gidropress	PWR	Marine / Commercial – Electric/Non-Electric	Under Regulatory Review	Russian Federation

2.5.5 Current SMRs Close to Market

This section describes a number of the key LWR SMRs identified in the table above, their designers, technological maturity, any unique features, and details of planned deployments.

2.5.5.1 ACP100, CNNC, China

The ACP100 is an integrated PWR design developed by China National Nuclear Corporation (CNNC). It represents the first truly integrated small modular pressurised water reactor to reach full construction. The ACP100 generates a gross electric power of 125 MWe and ~385 MWt of thermal output.

Its hallmark is a fully integrated design, as shown in Figure 2.15, the reactor core, steam generators, and coolant pumps are contained within a single pressure vessel. This eliminates the large external piping and, in turn, the possibility of large break, loss-of-coolant accidents. Safety systems are dominated by passive mechanisms, gravity driven cooling, passive residual heat removal and natural convection. The ACP100 is also designed to provide district heating, desalination and industrial steam, which CNNC claim makes it versatile for off-grid or islanded applications.

Construction began at the Changjiang site on Hainan Island in 2021, the first SMR project in the world to reach this stage. The design received IAEA review and endorsement under its SMR initiative and commissioning is expected later this decade. For CNNC, the ACP100 is a key step forward for China's goal of exporting modular, factory built nuclear systems. The key challenges ahead will be scaling up manufacturing efficiency and proving lifecycle cost competitiveness.

Figure 2.15: The Integrated RPV for the ACP100 SMR (CNNC, 2023)

2.5.5.2 AP300, Westinghouse, USA

Westinghouse AP300 SMR is a 300 MWe class (990 MWt core thermal power), Generation III+, one-loop light water PWR. It is a direct derivative of the licensed AP1000 plant technology together with existing fuel technology, which has demonstrated industry leading reliability. The design includes passive safety systems and extensive plant simplifications to enhance safety, construction, operation, and maintenance. Safety systems use natural driving forces such as pressure, gravity, natural circulation, and convection. The plant has self-pressurising behaviour that allows 72 hours of safety without operator action. Active components such as pumps, fans, or diesel generators are not required, and the plant is designed to function without safety-grade support systems such as AC power, component cooling water system, service water system, or HVAC. A rendering of a cross section of the main containment building and adjacent buildings, showing main components is shown below in Figure 2.16.

Announced in 2023, Westinghouse is now pursuing design certification with the U.S. Nuclear Regulatory Commission (US NRC), aiming for approval around 2027 and deployment in the early 2030s. The company markets the AP300 as a “mid-sized, low-risk reactor” that leverages an existing supply chain, offering the familiarity of an LWR with smaller siting and capital requirements. Its main strength lies in technical maturity. Its main challenge, as with other designs, is cost and the need to demonstrate that smaller truly means cheaper when using conventional PWR technology.

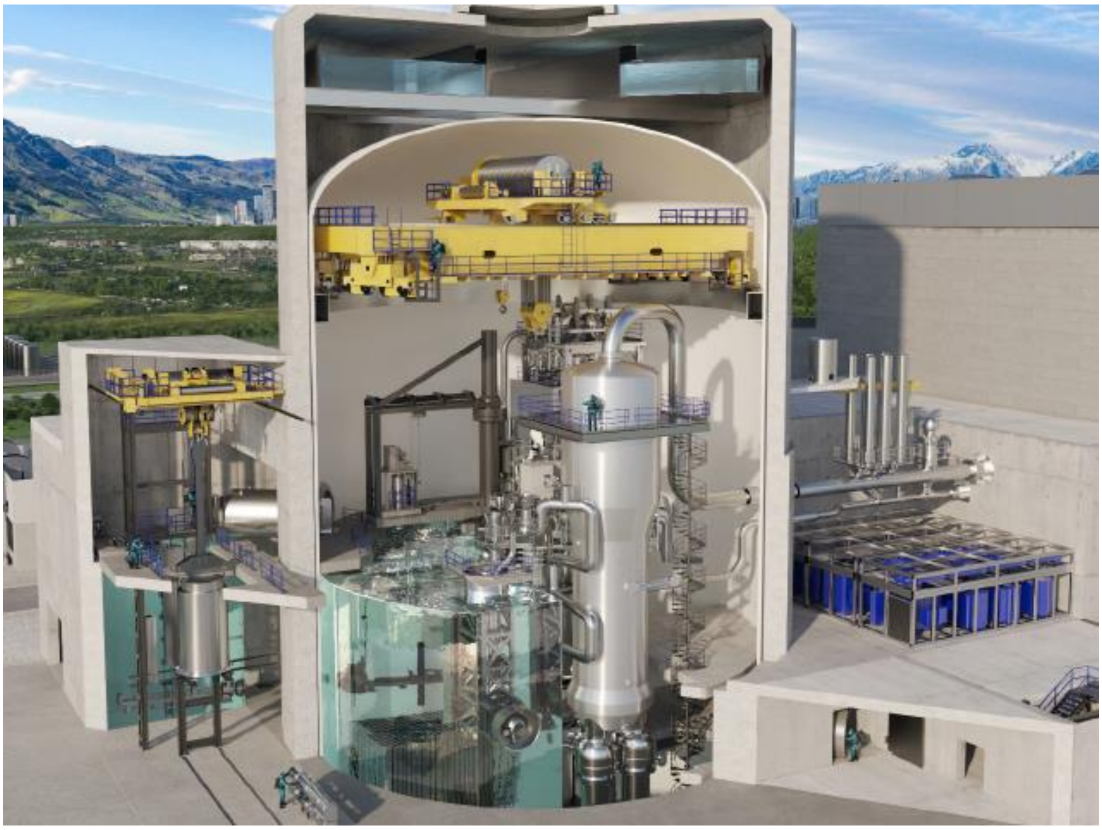


Figure 2.16: Cross Section Model of the AP300 (Westinghouse Sweden, 2025)

2.5.5.3 BWRX-300 USA/Canada

The BWRX-300 is a Boiling Water Reactor (BWR) that employs natural circulation and passive emergency cooling features and is rated at approximately 300 MWe. The passive design features of the BWRX-300 provide decay heat removal capability using only installed systems with no reliance on operator actions or external resources for at least 72-hours. For the BWRX-300, a safe stable condition (“stable shutdown”) is defined as safe shutdown with average reactor coolant temperature ≤ 215.6°C. Following 72 hours post-accident, on-site or off-site resources are used to power non-safety equipment for proceeding to cold shutdown conditions, as needed. The BWRX-300 design applies a defence-in-depth process for safety assessment and safety analysis to ensure that radiological acceptance criteria are met. The leveraging of passive design features greatly simplifies the design and results in a significant reduction in the total number active SSCs compared to conventional nuclear power plants.

The BWRX-300 is based on the US NRC-licensed, 1520 MWe Economic Simplified Boiling Water Reactor (ESBWR). The ESBWR is an evolution of the 600 MWe Simplified Boiling Water Reactor (SBWR) and has a significant testing and qualification program directly applicable to the BWRX-300. The BWRX-300 is the tenth generation of the BWR that incorporates the lessons learned in design, construction, operations, and maintenance from more than 100 previous BWRs previously built, operated, and in some cases, decommissioned. The BWRX-300 is specifically designed to enhance safety through simplification and reduce dependence on human intervention. This is achieved through increasing its reliance on natural circulation and natural phenomena-driven safety systems. These safety enhancements, in combination with its reduction in scale and complexity, enable reductions in operating staff, maintenance, and security requirements as well as being easier to decommission.

At the time of writing, the Canadian Regulator, CNSC, has issued a licence to construct (LTC) by OPG for the first-of-a-kind BWRX-300 at Darlington, Ontario. Broadly speaking, this allows the utility to prepare the site, but it does not allow construction of nuclear significant plant on site for which further permission is required from CNSC. The design has completed GDA Step 2 in the UK, but a site is yet to be announced. The Tennessee Valley Authority (TVA) has submitted a first construction permit application to the US NRC for the Clinch River site in Oak Ridge, Tennessee. The reactor has already been shortlisted in other countries such as Sweden, Estonia and Poland. A visualisation of the outside of the plant is shown below in Figure 2.17.

Figure 2.17: Rendering of the Outside of A Unit of BWRX-300 (GE Verona, 2025)

2.5.5.4 SMR 300 SMR Holtec International, USA

The Holtec SMR-300 is an advanced, passively safe, pressurized light water nuclear power plant with a rated net electric output of 300-320 MWe, targeting an 80-year lifetime from the start. It features forced circulation utilizing two cold legs each with a vertically mounted reactor coolant pump, two hot legs, and a single once-through steam generator (OTSG) with an integral pressurizer. This allows for a compact containment with the goal of factory fabrication and installation by heavy lift methods. The design employs passive, gravity-driven safety systems that do not rely on pumps, external water, external power, or operator action. The annular reservoir inside containment serves as the ultimate heat sink and is a key safety innovation of the design for station blackout and loss of coolant events. Innovative modularized concrete-strengthened steel (CSS) has been developed for efficient construction of structures needed in the SMR-300 plant.

The U.S. Nuclear Regulatory Commission (US NRC) is involved in the pre-application activities with Holtec International regarding the SMR-160 and its uprated design, the SMR-300. The design has undergone significant changes, including an increase in reactor power output from 160 MWe to 300 MWe and the introduction of two reactor coolant pumps for use during normal operation. Holtec’s first SMR-300 deployment is planned to be at Palisades, Michigan, in the USA.

In the UK, the GDA is in Step 2, based on a twin unit design, comprising two SMR-300 reactors and associated plant. The design is stated in the GDA paperwork to be at an advanced concept stage of development, although other databases refer to detailed design. One of the challenges we have identified for the SMR market as a whole is that the level of design detail is often not visible until detailed commercial arrangements are in place. This subject is discussed further in section 2.5.6.

Holtec, nuclear utility EDF UK and real estate partner Tritax Management announced on 15th September 2025 their intent to work together to develop Holtec's SMR-300 small modular reactors at the former Cottam coal-fired power station in Nottinghamshire in the UK, to provide clean, secure power to new, advanced data centres on the site. A rendering of what a complete generic twin unit site might look like when constructed is shown below in Figure 2.18.

Figure 2.18: Rendering of a Twin SMR-300 Plant Courtesy of Holtec (Holtec, 2023)

2.5.5.5 i-SMR, KEPCO, Korea

The "integral" or "innovative" SMR" is a 170 MWe SMR with 69 fuel assemblies developed by a Korean consortium led by KEPCO (Korea Electric Power Corporation) on behalf of the Korean Government. It is an integral PWR design with a focus on passive safety, economy, and flexibility compared with traditional nuclear power plants. The i-SMR utilizes a boron-free operation to simplify the reactor control systems, it is claimed that this improves load following capabilities, although varying boron concentration is a relatively slow technique for adjustments to reactor power. In comparison with traditional PWR plants, the proposed boron free design is not a commonly deployed approach. The i-SMR features an integrated primary coolant system, with major components such as the reactor vessel, steam generators, and primary coolant pumps being housed within a single unit. This eliminates the need for large external piping, simplifying the design and enhancing safety, but potentially creates challenges around inspections (to be able to comply with ASME codes and standards for example) and reliability through life. The i-SMR project is ongoing, with the goal of completing the design by the end of 2025 and obtaining standard design approval by the Korean regulator by 2028. The consortium envisages the i-SMR as a multi mission reactor, capable of not only electricity generation, but potentially producing hydrogen, district heating or desalinated water, and as a major export candidate for Asia and Europe.

There is also a Korean conceptual integral SMR targeted at Middle Eastern and Southeast Asian countries, the passively cooled 110 MWe/365 MWt SMART100, that was subject to a positive licensing decision in Korea in 2024. It was proposed by The Korea Atomic Energy Research Institute (KAERI), Korea Hydro & Nuclear Power (KHNP) and Saudi Arabia's King Abdullah City for Atomic and Renewable Energy (KA-CARE), based upon slightly lower powered Korean SMART technology that at a basic design level passed licensing in 2012, based upon separate nuclear components.

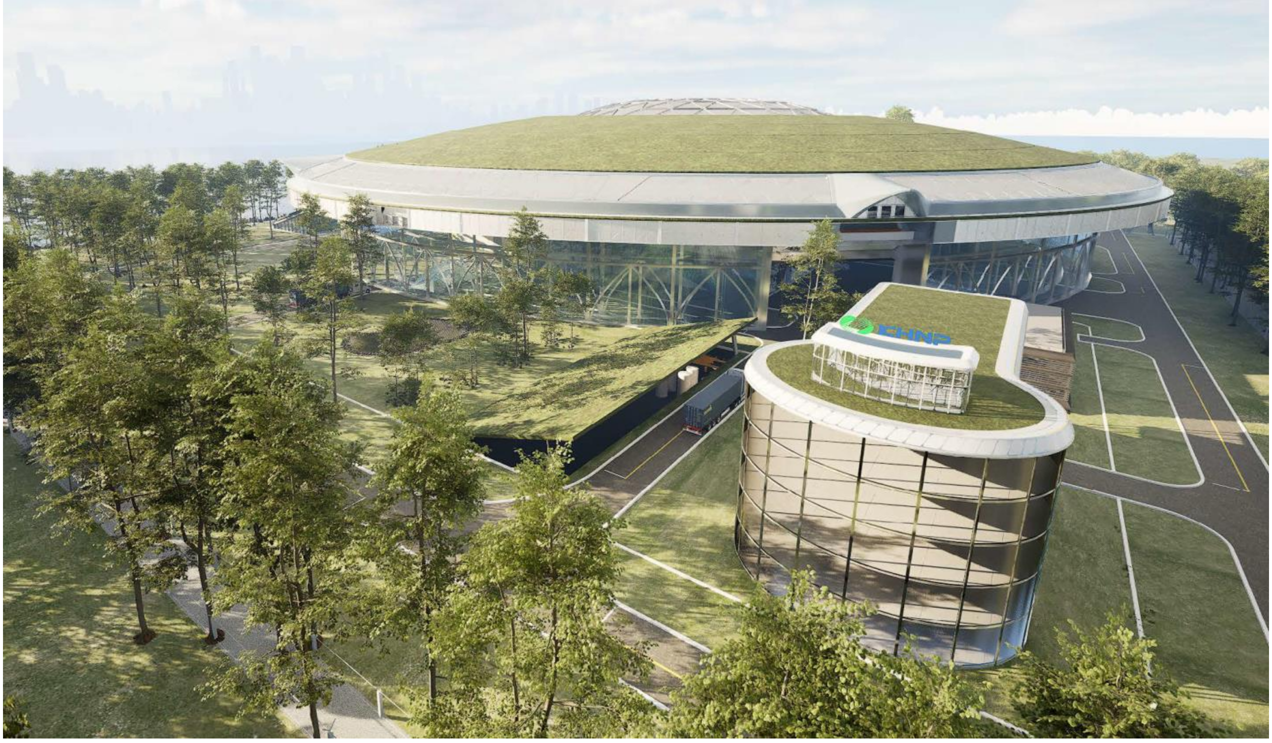


Figure 2.19: Rendering of an iSMR Campus (World Nuclear News, 2025)

2.5.5.6 NuScale Power Module, NuScale Power Corporation, USA

The 77 MWe/250 MWt NuScale Power Module™ (NPM) is currently the only small modular reactor (SMR) to receive design approval from the US NRC. Such a unit would not be deployed in isolation, so it merits assessment here. The NPM's design is based on proven pressurized water-cooled reactor technology using natural circulation (no reactor coolant pumps) and a steel containment vessel submerged in a large water pool. In loss of coolant or station blackout events, decay heat removal occurs entirely by passive means and without external power or operator intervention.

The design has been developed to supply energy for electrical generation, district heating, desalination, commercial-scale hydrogen production and other process heat applications. Theoretically, modules can be added incrementally, with the first module generating electricity while additional modules are being installed. Standard light water reactor (LWR) fuel in a 17 x 17 configuration, each assembly 2m in length, is used at a conventional enrichment. Two steam generators are integrated into each module. Approval is being sought in the US for deployment of up to 12 modules per unit.

In September 2025, a 12-unit project was proposed in concept for deployment in Tennessee, USA. In Europe, RoPower Nuclear intends to deploy six NuScale Power Modules in Romania, with FID planned for 2026-7 at the site of a former coal plant. It is noted that a previous NuScale project with Utah Associated Municipal Power Systems was cancelled in November 2023. The proposal was to deploy six NuScale SMRs at the Idaho National Laboratory site to generate ~462 MW of power. The project received significant US federal support, but rising costs, financing uncertainties and insufficient customer commitment led to cancellation. It’s important to note that the cancellation of this project does not mean that NuScale’s design or the concept of SMRs is invalid. Rather, the major lesson here is around deployment risk (cost, financing and market commitments) rather than technical readiness alone.

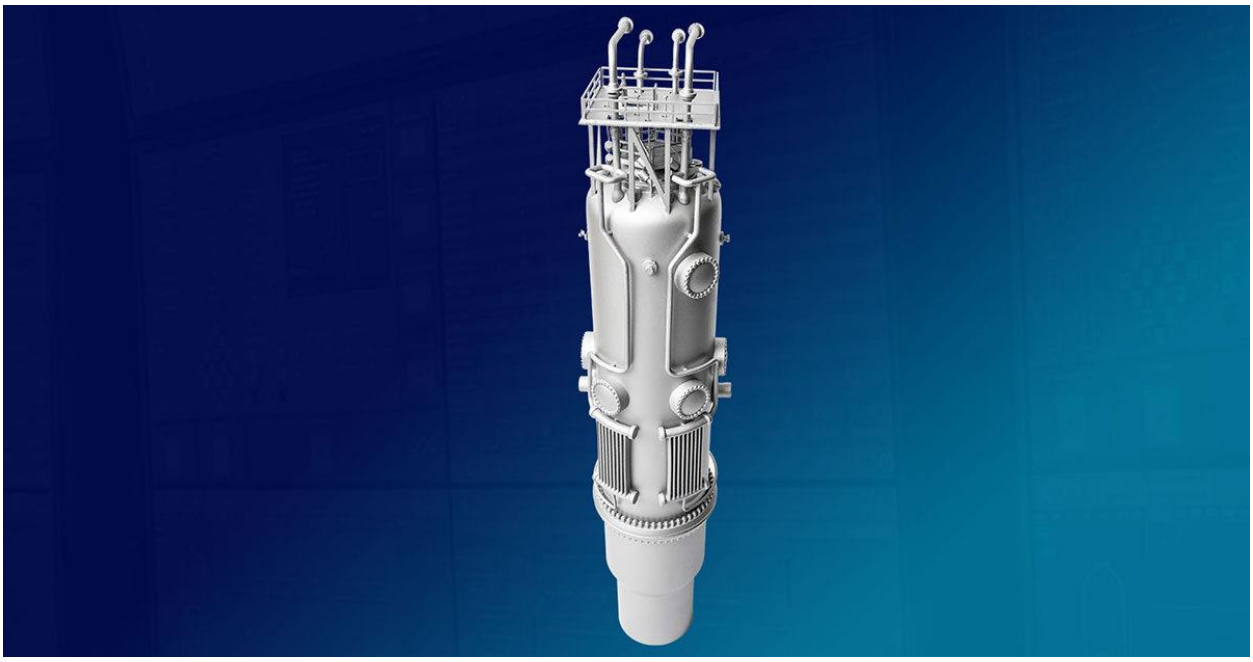


Figure 2.20: Rendering of NuScale Power Module™ (NPM) and supporting plant (NuScale, 2025)

2.5.5.7 Nuward, EDF Nuward, France

Little is known publicly about the current status of the Nuward SMR reactor being developed by a consortium led by CEA and EDF since 2019. EDF has indicated that this is based upon PWR technology aimed at load following as a complementary solution to renewable energy sources, to replace coal-fired plants in the 300-400 MWe range, and to supply remote municipalities and energy-intensive industrial sites, as shown in Figure 2.21.

In January 2025, Nuward relaunched its SMR design after dropping out of UK Great British Energy - Nuclear’s (GBE-N) competition, focusing on existing and proven technologies. The updated concept is said to aim for an output “up to about 400 MWe” with the design concept to be finalised by mid-2026. The updated roadmap shows Nuward in the basic design phase, with engineering work underway and industrial partnerships forming.

By leveraging EDF’s large reactor experience and France’s domestic nuclear industry, Nuward potentially benefits from strong institutional backing and supply chain potential in France and Europe. The shift to proven technology reduces technical risk which could improve cost and schedule confidence compared to more exotic SMR designs.

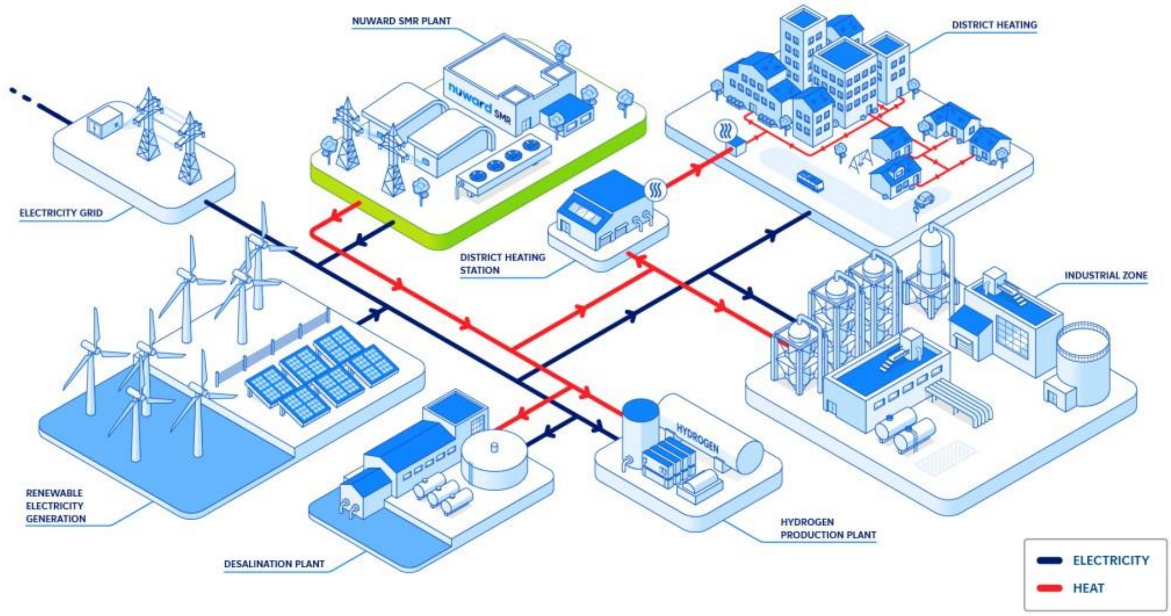


Figure 2.21: A Visualisation of an Energy Hub Utilising a Nuward Reactor by EDF (EDF, 2025b)

2.5.5.8 Rolls-Royce SMR (RRSMR), UK

The R-R SMR is a symmetrically arranged, three-loop, close coupled PWR reactor producing 1358 MWt of heat, using standard PWR fuel. The design is essentially a conventional PWR in that the heated water from the reactor core then flows through to one of the three steam generators that passes the heat to the lower pressure secondary side, which is allowed to boil. It is then driven through a turbine generator set that powers the generator exporting 470 MWe electricity through to the grid, which is at the upper end of the scale for an SMR (Rolls Royce SMR, 2025).

The plant design provides multiple layers of safety, redundancy and back-up systems - meeting the highest standards of safety, security, safeguards and environmental protection, such that it can operate independently of any human intervention so that the core is put into a safe state with no external intervention for up to three days. The R-R SMR, like i-SMR, has a boron-free primary circuit design (for a PWR), which has allowed toxic and corrosive boric acid to be eliminated from all duty systems - reducing overall plant water consumption and eliminating a hazardous waste source from daily operations. As with i-SMR, a boron free circuit is also likely to improve load following capabilities.

The R-R SMR adopts a high level of factory-build with approximately 90% of the plant planned to be prefabricated, tested and delivered to site as ~1500 modules, where they are proposed to be assembled and commissioned by the R-R SMR team. Seismic isolation devices protect the reactor core from external risks and the impact of any ground movement. The level of modularisation proposed can be seen in the graphic below in Figure 2.22, showing a cross section of the reactor building and adjacent turbine building.

The R-R SMR has been selected as the preferred bidder for Great British Energy-Nuclear in the UK for three units, and by CEZ, the government-owned utility in the Czech Republic, which is investing in the project. The R-R SMR has also been down-selected in Sweden.

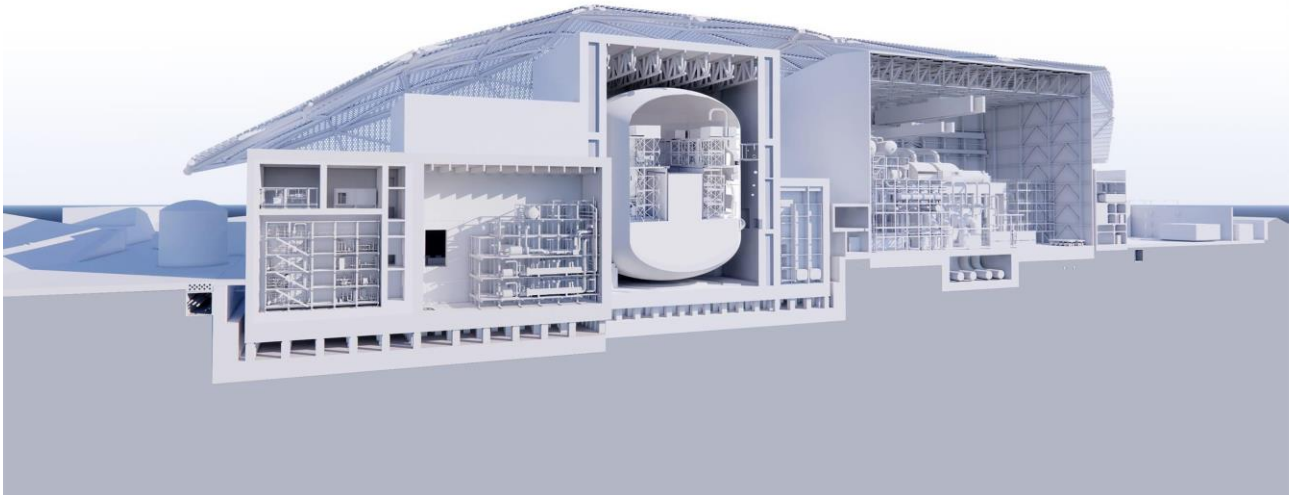


Figure 2.22: Rendering of a Cross Section of the RRSMR Plant (Rolls Royce SMR, 2025)

2.5.5.9 *Technical Risks for SMRs*

Although many basic technology risks have been mitigated for LWR SMRs, any potential future SMR project still faces several significant **technical risks** that could significantly impact project timelines and costs. These risks arise from the innovative features of SMR technology, and some technologies planned to underpin fleet production of SMRs. Below is an outline of the key technical risks of typical SMRs:

Table 2.9: Summary of Key Risks & Challenges for LWR SMRs

Risk	Challenges	Potential Impact
Design Maturity and Validation: Although basic reactor technology such as the physics of LWRs is well known, and there are many years of operational experience to draw upon, many SMR designs are still in the concept or preliminary development or prototype stages, and some lack operational experience on features introduced.	Potential for unforeseen design flaws or inefficiencies during testing or early operations. Delays in completing design certification or updates to meet regulatory requirements due to lack of design detail and substantiation. New risks introduced by “design for modularisation”.	Licensing risks. Increased costs for re-engineering and delayed project milestones.
Manufacturing and Supply Chain Complexity: SMRs rely on modular construction and advanced manufacturing techniques, which may face supply chain constraints or quality issues.	Limited availability of specialized components, such as reactor vessels or heat exchangers although the constraints on the supply chain may not be as onerous as GW scale due to the smaller size of forged components. Need for precision in manufacturing and assembly to meet safety and operational standards.	Licensing risks. Delays in component delivery, increased costs for quality assurance, and potential project bottlenecks.

Risk	Challenges	Potential Impact
	Lack of factory-build capacity. Introduction of less well proven advanced manufacturing techniques.	
Integration of Innovative Technologies: SMRs incorporate advanced technologies, such as passive safety systems, zero boron, or fuels outside of standard norms, which may introduce unexpected challenges.	Existing codes and standards may be applicable in SMRs (e.g. for BWRX-300, GE are approaching the design of the RPV via the ASME B&PVC which is highly likely to be acceptable) for some technical areas where the design is very similar to a large GW scale plant. It is possible that alternative or new standards may be needed for areas of novel technology, particularly in thermal hydraulics where new computer codes could be necessary requiring extensive validation. This does carry risk, as regulatory authorities can take a considerable amount of time to accept standards, they are unfamiliar with or which have not been previously licensed. Testing and validating new materials under extreme conditions such as high temperatures and radiation exposure. Integration of innovative features like natural circulation cooling, which may behave differently under real-world conditions. Test rigs could be required to verify and validate associated computer models. As an example, GE-Hitachi have built a mock up isolation condenser system for the BWRX-300.	Whilst modelling codes for SMRs are well developed and are in many cases the same as for GW reactors, the adequacy of their use needs to be well demonstrated. We believe that there remain a number of SMR vendors using codes designated for research purposes which may have reduced applicability. Further validation is likely. Additional time and resources are required for extensive testing and validation, including irradiation testing and thermal hydraulics rigs. Limited access to materials test reactors and associated post irradiation examination facilities. Lack of data to support emergency planning zone claims. Delays in licensing where codes and standards are proposed that have not been previously used. Risks of re-design or additional justification being necessary.
Construction and Modular Assembly: While modular construction is intended to reduce costs and timelines, the process introduces unique risks.	Underground construction – some designs employ this philosophy in terms of improving resilience of the major plant components to external events, including aircraft impact, adverse weather and earthquakes. As an example, the BWRX-300 has a large part of the reactor building constructed in a cylindrical shaped structure embedded in a vertical shaft, to a	Delays in assembly, increased costs for rework, and potential misalignment of project timelines.

Risk	Challenges	Potential Impact
	depth of approximately 34 m below-grade. The reactor pressure vessel, steel-plate composite containment vessel and other important systems and components are located in the deeply embedded shaft. First-of-a-kind challenges around this approach include the potential for contamination of ground water and seismic qualification. Coordination among multiple suppliers and contractors for off-site fabrication and on-site assembly. Quality control issues during transport and installation of prefabricated modules. Lack of factory-build and assembly capacity.	
First-of-a-kind challenges: Although reduced for LWRs, where supply chains are pivoting to make different size components or different construction techniques, it could be five units or so before an equilibrium design is reached.	Advanced manufacturing. Lack of / stretched prior data or benchmarks to predict operational performance. Delays in establishing operational procedures, training, and supply chains.	Higher costs for initial projects and delays due to troubleshooting during construction and commissioning. Regulations tuned to SMRs
Waste Management and Fuel Supply: LWR fuel is very mature. Only if designs plan to move to advanced fuel cladding which then leads to Low Enriched Uranium+, which is typically 5-10% enrichment) or other features may this become a significant risk. Data to support fuel disposability is well known.	Limited irradiation data for accident tolerant fuels.	Small licensing and permitting risk LEU+ supply risks and costs. Plans to dispose of whole cores for some reactors may present a larger challenge.
Operational ramp-up and reliability: Again, this risk is reduced for LWR SMRs as they are generally evolutions of existing designs. Ensuring reliable operations and achieving expected performance metrics during initial years can be challenging.	Load following and grid code compliance Addressing teething issues such as extended commissioning periods, unanticipated downtime, maintenance needs, or performance deviations.	May be able to apply for exception Increased operational costs and delays in achieving full capacity and availability.

Risk	Challenges	Potential Impact
	Training and retaining skilled personnel to operate and maintain the reactors. Offset by opportunity to make a heavily instrumented plant and take benefits of a digital twin	

2.5.6 Conclusion on LWR SMR Reactor Technology Assessment

A wide variety of SMR reactors of different sizes are being marketed by mature reactor vendors and new entrants. The realistic design maturity of SMRs varies significantly by technology and developer and current assessments point to a mixed picture. Some SMR designs, such as the NuScale Power Module have reached high TRL status, by receiving US NRC design approval. Other designs are progressing through licensing and pre-licensing stages but are not yet fully deployed. It's important to understand the context of different regulatory regimes and what the individual stages of approval mean. A good example of this is the BWRX-300, which despite receiving licence to construct approval from the CNSC at Darlington, is limited in scope to site preparation. The site licensee, Ontario Power Generation, in conjunction with vendor GE-Hitachi, is seeking full justification via an updated safety analysis report to obtain consent for construction of the main nuclear plant design elements through three regulatory hold points. The decision by the CNSC does not yet authorize the operation of a BWRX-300 reactor at Darlington.

It is therefore imperative that before signing binding commercial agreements, any potential new-to-nuclear country such as Norway gains clarity as to the maturity of the design and safety case in other regulatory regimes. For example, in the UK, completion of a Generic Design Assessment process, reduces risk but does not allow the licensee to proceed with on-site activities. Permissioning initial construction of a new nuclear power plant requires the site licensee to self-assess, approve and submit to the regulator a site-specific safety case that has the initial elements of the design substantiated to a very high degree of design detail. These are nominally the civil structures. For a GW scale plant utilising an open top construction method, the traditional approach generally agreed between the licensee and regulator is that the remainder of the design can be at lower levels of maturity, with subsequent permissions via mutually agreed licensee/regulatory hold-points. For more modular SMRs or AMRs, a similar approach is likely to be used, with outputs from the UK's Regulatory Taskforce due later this year, although with modularisation at scale it is not yet clear how this would be undertaken (UK Government, 2025).

It is noted that the International Nuclear Safety Advisory Group (INSAG) and IAEA guidance emphasise that for a design to be considered mature, it must demonstrate operational data, verified design tools and methods, and full-scale prototype testing or equivalent experience. For many SMRs, full-scale prototypes are still under development and there is no operational history at present, meaning these designs are, in reality, still at a lower level of technical readiness. However, some of these designs do possess strong elements of proven technology from GW scale reactors.

SMR vendors make bold claims of faster construction, increased safety and reliability. Such claims, particularly around licensing, modularisation and factory build are yet to be substantiated, and it will be crucial to understand whether they can be built quickly to maximise the benefits of modular techniques. It is noted that, like GW scale reactors, SMRs are subject to multiyear licensing processes under national regulations, and these processes can take 5-10 years depending on the completeness of the design, level of novelty and regulatory maturity.

All SMRs, regardless of national origin are being marketed on the same premise

- Small size with shorter build and lower absolute capital cost
- Modularity enabled by factory production with economies of multiples rather than scale, and
- Passive safety leading to simpler systems and lower operating costs

The FOAK units of each design face nearly identical cost and market risks in that there is no previous construction learning curve, no supply chain maturity and there are extensive regulatory and qualification costs front loaded into the first projects. It is imperative that the economics of any design are looked at through a FOAK perspective where they have not been constructed elsewhere. It is only when multiple units have been constructed and operated that 'Nth-of-a-kind' gains credibility. In a new nuclear power plant project, cost savings are only achieved after supply chain repetition. But this is a circular problem because repetition does not occur until investors see proof of cost savings.

Traditional GW reactors enjoy large economies of scale, but SMRs, being smaller, depend on economics of *multiples*, i.e. savings from serial modular construction. The risk is that if few units are ordered, the per unit cost remains high. Without high production volume, modularisation can't overcome the loss of scale.

SMRs depend on precision manufacturing, modular assembly, and certified transport logistics, all of which need industrial scaling. The absence of serial fabrication means that every first plant faces custom manufacturing with associated cost and schedule unpredictability. For example, qualification of welds and materials in small batches is expensive. During on-site construction, the integration of modules can cause delays if not executed seamlessly. This happened at Vogtle and also on successful projects involving ABWR construction.

SMRs introduce new design and safety paradigms through passive systems, modular layouts, and shared containments that existing regulatory frameworks were not developed to assess. The potential impact is that licensing takes a long time and duplicate licensing in multiple countries increases costs. Each design must finance and justify its own safety case.

Assuming a FOAK unit operates successfully by the early to mid-2030s, fleet deployment (i.e. multiple units at multiple sites) would realistically not occur before about 2040 at the earliest. This timeline depends on performance and safety validation of the FOAK design(s), investor and utility confidence, supply chain procurement and crucially the standardisation and licensing by reference for any follow-up units constructed. Experience gained in FOAK construction will provide an opportunity for a new entrant country to understand which vendors to engage with in a future procurement process and will enable a risk-informed decision.

As with GW evaluation, we have not eliminated any designs at this stage, as this would be a political decision and subject to a formal procurement process. A future review and update of the SMR market status would form part of any pre-engagement process in future steps.

2.6 AMR Technology

2.6.1 What Are AMRs?

Advanced Modular Reactors (AMRs) use a range of alternative fuels and cooling media to generate heat using nuclear power compared with the SMRs and the GW technologies that have been discussed so far in the report that use water as a coolant and uranium dioxide as a fuel. Many are based upon early research that has been undertaken since the 1950s-1970s, but where such designs did not enter full commercialisation. So, in some senses, AMRs are both the newest and most advanced class of modular reactors. They plan to use advanced technologies to improve safety, reduce waste, and increase efficiency. They are being designed to be more flexible than traditional reactors, with the ability to operate at different power levels and use different types of fuel, and supply heat and electricity.

AMRs may be able to provide the high-temperature heat and stable power required to decarbonize industrial sectors like oil and gas (electrification of platforms) and production of petrochemicals, hydrogen, ammonia, synthetic fuels, cement, steel and fertilizer, which are technically challenging to interface with intermittent renewables. Key features of the AMR family are shown in Table 2.10.

Table 2.10: A Summary of Key Features of the Advanced Modular Reactor (AMR) Family

Key Features	
Technology Classification	GenIV (non-water-based reactors)
Reactor Types	Including main AMR technologies being deployed such as • Very High Temperature Gas Reactor (VHTR) and High Temperature Gas Reactor (HTGR) subset • Lead Fast Reactor (LFR) • Molten Salt Reactor (MSR) • Sodium Fast Reactor (SFR)
Cooling Method	Novel Coolants (Gases, Liquid Metals, Molten Salts)
Siting	Flexible Deployments, Close to Industry, Semi-urban (medium density population locations).
Turbine Interface	Brayton Cycle – 50% Efficient use of Nuclear Heat
Cooling	Dry Cooling Systems – Zero Water Hybrid Cooling Systems – Minimum Water (secondary circuit)
Operating Temperature	550°C to 950° C
USP’s	Factory built, modular assembly, enhanced passive safety, reduced exclusion zone, reduced re-fuelling intervals, reduced moving parts, reduced infrastructure, site anywhere concept (claimed).
Primary Use Cases	Combined Heat & Power (Brayton Cycle + Heat Recovery) Hydrogen / Synthetic Fuel Production Direct Process Heat (Industrial Heat)
Technology Readiness Level (TRL)	TRL 2-7
Technology Risk	Medium to high- Some are loosely based on existing prototypes technology, FOAK being developed, deployed projects live by 2030/35 or likely later. Note many of these technologies were operated on research sites away from the constraints of modern regulatory environments. Although there are major programmes of work, the modelling codes and data used to substantiate the safety of designs of reactors and fuels are often for research purposes and may require further work to verify and validate them to a level suitable for licensing of the designs. In some cases, further irradiation testing may be needed or test rigs built.
Commercially Available	Starting to see potential in period 2025/2026 for the first designs to be available for orders to be placed in a broader market in order to secure finance. Some FOAK projects are progressing. However, full proven

Key Features	
	commercial availability suitable for a new entrant country to order is unlikely until mid-2030s.

2.6.2 Example Use Cases for AMRs

Whilst the Commission has asked us to consider nuclear electrification, it is worth noting that AMRs in particular present significant potential opportunity to explore deployment of both heat hubs and private heat lines. In some cases, business cases are being developed predominantly around heat. A network of multiple potential use cases can be considered, both in series and parallel depending on temperature of heat needed, as shown in Figure 2.23, which would widen the number of reactors that could be suitable for deployment.

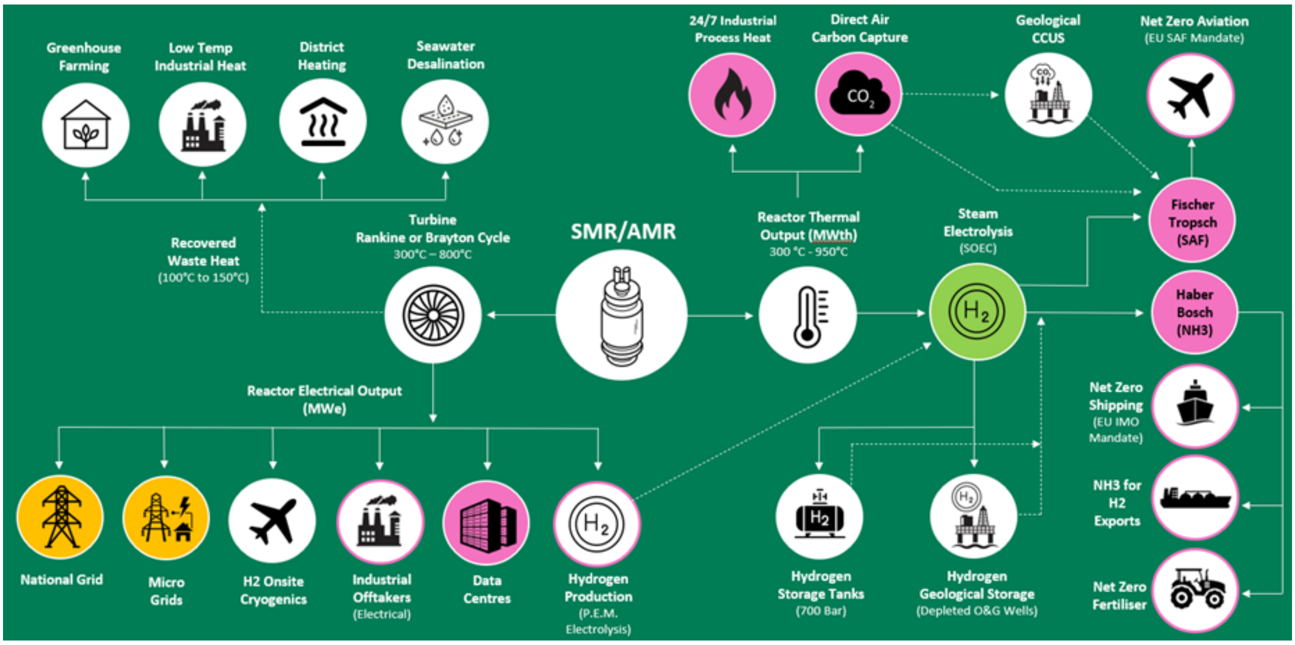


Figure 2.23: Chart Showing Alternative Potential Use Cases for SMRs and AMRs

Key:

🟧 = Traditional Use of Nuclear
🟪 = Applications that require high-capacity factor, reliable 24/7 energy

2.6.3 The Role of International Collaboration in bringing forward AMRs

The Generation IV Forum (GIF) brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the UK and USA), as well as Euratom – representing the 27 European Union members – to co-ordinate research and development on these systems. In principle, if Norway was to decide to pursue a programme of reactor deployment, including AMRs, it could participate in the GIF as new member. To do this successfully, it would need to establish capabilities in these areas:

- **Political**: Sign the GIF framework agreement, which is a legal agreement outlining the terms for international collaboration in R&D on Generation IV systems and show political will to support advanced nuclear R&D and share in the associated responsibilities.
- **Technical**: Possess or plan to develop substantial technical expertise in areas like reactor physics, thermal-hydraulics, materials science, fuel cycle analysis, safety assessment and

waste management. Develop or have partnerships with advanced test facilities for irradiation, materials testing, thermal-fluid studies etc.

- **Nuclear Regulatory Infrastructure:** Establish a credible and independent nuclear regulatory authority aligned to IAEA standards with the capacity to evaluate innovative and non LWR reactor designs. Engage in regulatory dialogue on harmonisation of safety frameworks for Gen IV systems.
- **Non-Proliferation:** In addition to being a signatory to the NPT, must have a comprehensive safeguards agreement and ideally, the additional protocol in force with the IAEA.
- **Active Contribution:** Join and actively contribute to System Steering Committees (SSCs) and Project Management Board (PMBs) for specific reactor types. Share R&D findings and engage in joint experiments, modelling efforts and technical meetings.

These capabilities can be progressively developed, and it is noted that a new entrant to Gen IV and start with observer status or bilateral agreements with Gen IV members to build experience and credibility before full accession to member status.

AMR technologies are being developed with a number of agreed, specific goals in mind to target economically feasible designs. For more than twenty years, GIF has supported global cooperative initiatives to develop advanced nuclear energy systems addressing future global energy requirements. These goals guide the cooperative R&D efforts undertaken by GIF members. The focused aim is now for some of these reactor designs to be fully demonstrated with commercial deployment beginning in 2030. Several goals have now been set to support a focus on commercialisation which are covered next.

2.6.3.1 GIF Goals Sustainability

Sustainability 1

Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production.

Sustainability 2

Systems will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.

2.6.3.2 GIF Goals Economics

Economics 1

Systems will have a clear life-cycle cost advantage over other energy sources.

Economics 2

Systems will have a level of financial risk comparable to other energy projects.

2.6.3.3 GIF Goals Safety

Safety & Reliability 1

Systems operations will excel in safety and reliability.

Safety & Reliability 2

Systems will have a very low likelihood and degree of reactor core damage.

Safety & Reliability 3

Systems will eliminate the need for offsite emergency response.

2.6.3.4 Proliferation Resistance & Physical Protection

Systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism.

2.6.3.5 The Role of Non-EURATOM Members In GIF

Euratom, or the European Atomic Energy Community, is an international organization established in 1958 to create a common market for the peaceful uses of atomic energy. Its primary purpose is to promote the development of nuclear energy and ensure the safe use of nuclear materials among its member states. Euratom operates separately from the European Union, outside the regulatory control of the European Parliament, focusing on establishing a single market for nuclear materials and technology. The European Commission is empowered to issue bonds on behalf of Euratom to finance back-to-back loans to investment projects related to nuclear power generation and the nuclear fuel cycle in EU countries. Euratom can also finance investment projects related to nuclear safety improvements or the decommissioning of nuclear installations in certain EU neighbourhood countries. The total amount of lending for these activities is limited to $4.66 billion, of which $4.28 billion has already been allocated.

Euratom is a community established under the Euratom Treaty establishing the European Atomic Energy Community. Parties to the Euratom are the EU Member States.

The EU and Euratom share a common institutional framework, a common budget and common financial provisions. Liabilities of Euratom are covered by the EU budget and Euratom. Loans to third countries are in addition covered by the Guarantee Fund for External Actions.

The UK ceased to be a full member of the European Union (EU) on 31 January 2020. However, under the terms of the UK–EU Trade and Cooperation Agreement, the UK participates in Euratom as an Associated State following the end of the transition period. Since 2014, Switzerland has also participated in Euratom programmes as an Associated State, as well as through the direct GIF route.

Norway could explore one of these options for collaboration on advanced nuclear technologies. Norway is not currently a member of EURATOM, the European Atomic Energy Community, which means it does not automatically benefit from shared nuclear safeguards, fuel supply agreements, or regulatory harmonization with EU member states. It sets a European-level regulatory framework for ionising radiation and is a major funder of nuclear research. Nevertheless, it could join. An analysis of the benefits and risks of EURATOM membership would be sensible, but overall it is certainly something that should be considered as it would promote a harmonised approach, access to teaching, research and development programmes, a consistent approach to safeguards and much more.

2.6.4 Examples of Medium to Large AMR Technologies

Summaries of international AMR activity often focus on the development of six groups of reactor technologies. These are down-selected from a longer list of more than 130 designs which are undergoing further research and development and are moving towards supply chain engagement and commercialisation by the mid-2030s, based on nuclear technologies where original concept development was undertaken in the in 1950s-1980s. The types now being explored for commercialisation are shown in Figure 2.24.

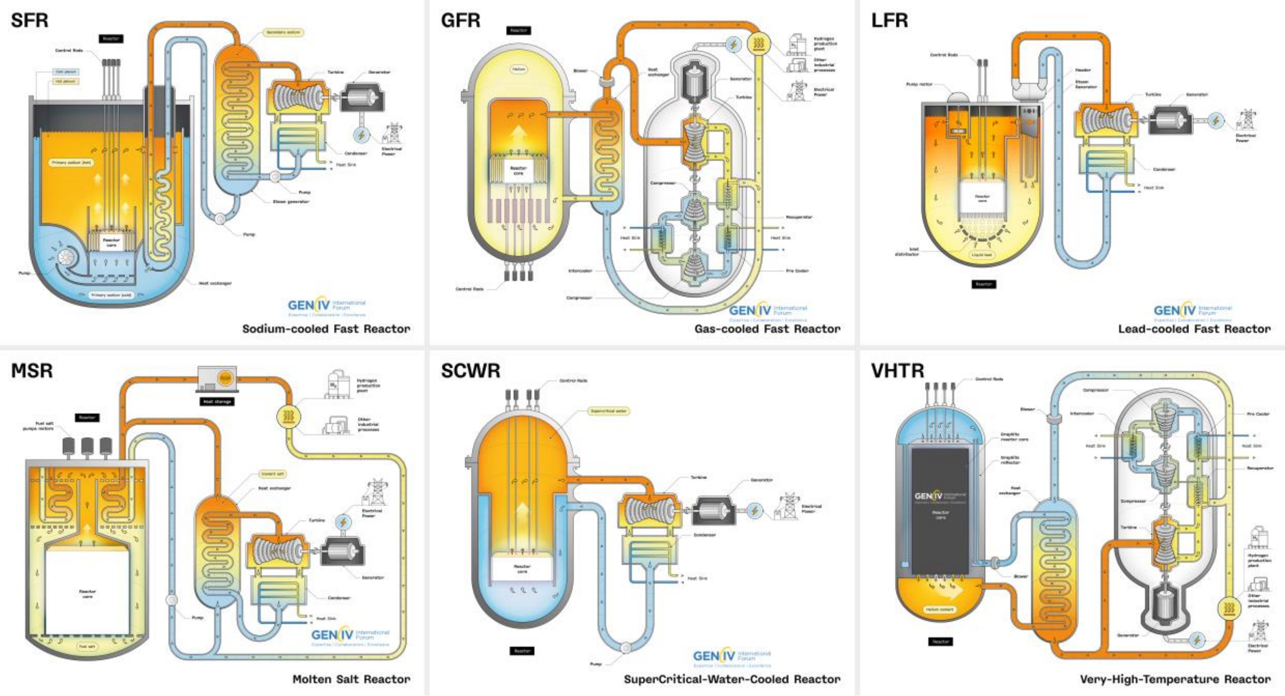


Figure 2.24: The Types of Reactor Being Developed Through GenIV International Collaboration (Gen IV International Forum, 2025)

Such Generation IV (GenIV) technologies are reactors designed to operate at much higher temperatures, typically between 550 °C and 800 °C (with novel test reactors having delivered +950 °C). They use novel cooling media such as high temperature gas, molten salt or liquid lead, have upgraded materials engineered to cope with high-temperature, high-pressure environments and feature passive cooling that further increases their design safety. Table 2.11 shows a high-level view by Gen IV Technology Type of the sorts of designs being developed.

Table 2.11 Summary of the 6 Types of Gen Reactor with Key Parameter Ranges (Gen IV, 2025a)

Gen IV System	Neutron Spectrum	Coolant	Outlet Temperature °C	Fuel Cycle	Size (MWe)
VHTR (Very-high-temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (Sodium-cooled fast reactor)	Fast	Sodium	500-550	Closed	50-150 300-1500 600-1500
SCWR (Supercritical-water-cooled reactor)	Thermal /Fast	Water	510-625	Open/ Closed	300-700 1000-1500
GFR (Gas-cooled fast reactor)	Fast	Helium	850	Closed	1 200

Gen IV System	Neutron Spectrum	Coolant	Outlet Temperature °C	Fuel Cycle	Size (MWe)
LFR **(Lead-cooled fast reactor)**	Fast	Lead	480-570	Closed	20-180 300-1200 600-1000
MSR **(Molten salt reactor)**	Thermal/ Fast	Fluoride salts	700-800	Closed	1000

The 6 reactor types are briefly discussed here in turn:

Very-High-Temperature Reactor (VHTR): This is an advanced, graphite moderated, helium cooled reactor designed to operate at outlet temperatures of 900-1000 °C (or higher) and uses TRISO coated particle fuel in either prismatic block configuration (hexagonal graphite blocks with fuel compacts) or pebble bed configuration (spherical fuel elements). The IAEA describes VHTRs as an “evolution of high temperature gas-cooled reactors” (HTGRs) which have the most operating experience of any of the Generation IV designs. As they have been operational for some years, HTGR base technology is at a very high technology readiness level (TRL). But often new fuels, structural materials and/or systems are in development which reduce the TRL of very high temperature variants to around 5-6, compared with the HTGR TRL of 7. Fuel supply is currently very limited, with a number of pilot plants in development. Reactors can be optimised for both electricity generation and or high temperature process heat. Power conversion is via a helium turbine (direct Brayton cycle) or indirect via heat exchangers with a thermal efficiency theoretically approaching 50%, operating at relatively low pressures.

VHTRs embody several inherent safety principles that are cornerstones of advanced nuclear safety thinking:

- High temperature margin. The fuel can withstand >1600 °C without failure with normal operation ~1000 °C, implying a large margin before fuel damage.
- Strong negative temperature coefficient: reactivity naturally decreases as temperature rises which is inherently self-regulating.
- Passive decay heat removal: Core power density is low, and graphite conducts heat well. In the event of a complete loss-of-coolant-flow scenario, VTHRs are demonstrated to be capable of not exceeding fuel failure temperature (demonstrated in experimental reactors like HTTR in Japan and HTR-10 in China).
- No coolant phase change: Helium remains gaseous which avoids issues like void coefficients, boiling or coolant reactivity effects.
- Simplified Source Term: Core inventory is smaller, radionuclides are more tightly bound and accident source term is lower than in water reactors.

The challenges with VHTRs are with materials performance at >900 °C (vessel steels, heat exchangers, turbine blades), graphite oxidation control (air ingress fault scenarios), TRISO fuel fabrication and quality assurance at industrial scale, complex power conversion system (helium Brayton cycle), economic competitiveness and the licensing frameworks, which are built around LWRs. HTGRs planned for deployment at present are mostly exploring outlet temperatures around 560 °C with more benign conditions for structural integrity.

Commercially designed and operated HTR-PM HTGR reactors in China are believed to have had some significant operational problems (Gen IV, 2025b).

Sodium-Cooled Fast Reactor (SFR): This a fast neutron spectrum reactor that uses liquid sodium as the coolant instead of water or gas. Its primary goals are to achieve high neutron economy and breeding (if desired) to convert U^{238} to Pu^{239}, allow closed fuel cycle operation (recycling plutonium/actinides) and to deliver a high-power density with passive safety. Prior to Gen IV, SFRs have a long history, with examples built in the UK, France, Japan and notably in Russia, where the BN-600/BN-800 designs have been operating commercially for quite some time (since 1980 and 2016 respectively).

Gen IV SFRs employ the following key nuclear safety features:

- Low-pressure, non- boiling primary circuit: Sodium has a boiling point of 883°C, well above typical core outlet temperatures of ~550 °C, so there are no boiling or pressurisation issues. This situation eliminates a 'loss of coolant accident' from the design basis.
- Large thermal margins and high heat capacity: Sodium has excellent heat conductivity allowing for passive heat removal and long grace periods in loss-of-flow scenarios.
- Negative reactivity feedback: Core expansion and fuel Doppler feedback provides inherent power limitation; modern metallic fuel cores are designed for passive shutdown on overheating.
- Passive decay heat removal: Natural circulation systems remove decay heat without operator action or AC power.
- Pool type configuration: Most current designs use a pool type layout consisting of a core plus primary pumps and heat exchangers in one vessel which minimises pipe rupture risk.

There are safety challenges, particularly around sodium water reactions, sodium air oxidation, fuel handling and more responsive reactivity control systems. Optical inspections of the core being impossible due to coolant opacity. However, a major advantage of an SFR from a procurement perspective is that large, expensive pressure vessels are not required and that in terms of economics, a long core life with high efficiency is possible. TRL for commercial deployment is assessed at around 7 (Gen IV, 2025c).

Supercritical-Water-Cooled Reactor (SCWR): This is an advanced reactor concept that uses light water at supercritical pressures and temperatures, above 22.1 MPa and 374 °C (the critical point of water). At these conditions, water becomes a single-phase fluid. This enables simplified coolant systems (no boiling, steam separators or recirculation pumps), higher thermal efficiency (~45%) and the potential for compact designs.

System pressure is broadly similar to conventional PWRs, and the high heat capacity allows efficient energy extraction. However, the smaller coolant inventory can lead to rapid transients if flow or pressure are lost. The concept designs incorporate passive emergency core cooling using gravity driven injection or isolation condensers with decay heat removal by natural circulation of water after depressurisation. As coolant density changes smoothly with temperature, reactivity coefficients are stable and negative over normal ranges.

There are safety and materials challenges associated with SCWR particularly around materials corrosion (supercritical water is highly oxidising), fuel cladding interaction (new cladding is required as zirconium is not suitable in the temperature range), control and shutdown at supercritical conditions, loss of pressure scenarios and high outlet temperature materials. TRL for commercial deployment is assessed at around 2 (Gen IV, 2025d).

Gas-Cooled Fast Reactor (GFR): This is one of the most technically ambitious and least mature Generation IV concepts, merging fast spectrum fuel cycle (like SFR), plutonium breeding and waste minimisation, and high temperature gas coolant technology of helium cooled systems (as in VHTRs). This enables a system that promises high efficiency, closed fuel cycle sustainability, and inherent safety, but also introduces formidable materials and cooling safety challenges.

The design concept includes helium coolant, high heat capacity at temperature with the potential for passive decay heat removal by natural convection, low pressure drop and no coolant phase change (stable flow, predictable thermal hydraulics), fast neutron spectrum allowing actinide transmutation and breeding which can close the fuel cycle and large temperature margins between operating temperature (~850 °C) and fuel melting (> 2000 °C).

There are several design challenges, mainly around high-power density and low coolant density (if forced flow stops, decay heat removal by natural convection is limited, requiring passive heat exchangers), fuel and cladding materials need to withstand high neutron flux and elevated temperatures, loss-of-coolant accidents (helium leaks quickly) and faster reactivity control. TRL for commercial deployment is assessed at around 2-4 (Gen IV, 2025e).

Lead-Cooled Fast Reactor (LFR): The Lead-Cooled Fast Reactor is a promising Generation IV design for both safety robustness and fuel cycle sustainability. It represents a hybrid of proven fast neutron reactor physics (like SFRs) with chemically inert, high density, high boiling liquid metal coolant (lead or lead-bismuth). Russia has experimented with several lead-cooled reactor designs and used lead-bismuth cooling for 40 years in reactors for its Alfa class submarines. Pb^{208} (54% of naturally occurring lead) is transparent to neutrons.

LFRs have no pressurised water or steam systems inside containment which minimises the risk of pressure transients. They have low flow rate, high density coolant which allows natural circulation for decay heat removal combined with long thermal inertia enabling the coolant to remain molten for hours after shutdown, preventing freezing. The designs offer high boiling point which means there is no risk of coolant boiling within the design basis, excellent heat capacity and conductivity, passive decay heat removal via natural convection in primary pool and air heat exchangers, negative reactivity coefficients and chemical inertness (no violent Na-water or Na-air fires).

There are design challenges, particularly around lead corrosion and erosion of steels, polonium production (from bismuth activation) which causes radiological handling issues, high density of lead causing structural loads and seismic considerations, and long-term fuel qualification where metallic and nitride fuels are still being validated. TRL for commercial deployment is assessed at around 5-6 (Gen IV, 2025f).

Molten Salt Reactor (MSR): The MSR represents the most radical shift from traditional reactor concepts in that the fuel is dissolved directly into the coolant in the form of a salt, with fission occurring in the liquid. The absence of fuel rods and cladding eliminates risks of rod rupture or fuel melting. The design concept has beneficial physics from core density and temperature feedback in that the expansion of salt reduces reactivity with a strong negative temperature coefficient. There is single phase flow, so no boiling or pressurisation is possible. A large heat capacity with excellent thermal inertia and inherent damping of transients, combined with passive natural circulation, enables heat removal by stable natural convection decay.

Despite these strong advantages, there are many challenges to be overcome in MSRs, notably around salt chemistry and corrosion which is a key issue for materials in terms of maintaining vessel integrity, fission product retention (off-gas of noble gases and removal of volatile species), radiation and contamination control, and a freeze/solidification risk (electric heating and salt circulation management is needed).

IAEA and GIF treat MSRs as unique due to their elimination of high-pressure failures, intrinsic negative feedback and innovative decay heat removal via drain tanks.

Globally, many tens of each of the reactor designs within the GIF framework are being developed. It is not possible to include all designs that are in various stages of development. By including these designs here in this report, or excluding others, this does not provide an investment rating, and this does not represent an implication that such designs are right for Norway or will be viable options going forward. We have tried to identify designs which appear to be current front runners. With many claims and counter claims about AMR technology, it is not possible to provide firm advice. Table 2.12 shows a high-level view by Gen IV Technology Type of the sorts of designs being developed, and examples where vendors are working to commercialise them. TRL for commercial deployment is assessed at around 3-5 (Gen IV, 2025g).

Table 2.12: Technology Readiness for AMRs by Gen IV Reactor Type (Adapted from Gen IV International Forum, 2025)

Gen IV System Family Sub-Type	Lead Reactor	Power MWe	Lead Vendor (other vendors)	Lead Country	Technology Readiness	Licensing Readiness	Commercial Readiness
VHTR (Very-high-temperature reactor	Xe-100	100, built as a 4-pack	**X-Energy** (also smaller variants such as Radiant, Jimmy, KRONOS, and ZettaJoule. JAEA and UKNNL (with Amentum) have been exploring a larger variant, also related to heat pipe reactors such as e-VINCI)	USA	Well-grounded in base technology Preliminary design	First project in licensing in USA	FOAK Grand Gulf, USA. Second project for 12 units proposed for Hartlepool UK in September 2025
SFR (Sodium-cooled fast reactor)	Natrium	345	**Terrapower** (also ARC, Hexana)	USA	Well-grounded in based technology Preliminary to Detailed Design	First project secured final safety evaluation for construction permit December 2025 in USA	FOAK Wyoming, USA. Planned to deploy in UK Linked to experienced vendor GE Vernova
SCWR (Supercritical-water-cooled reactor)			No designs commercially offered		Builds on LWR		

Gen IV System Family Sub-Type	Lead Reactor	Power MWe	Lead Vendor (other vendors)	Lead Country	Technology Readiness	Licensing Readiness	Commercial Readiness
GFR (Gas-cooled fast reactor)			No designs commercially offered		Builds on VHTR		
LFR (Lead-cooled fast reactor)	LFR-AS-200	200	**Newcleo** (also Westinghouse, Ansaldo Nucleaire/EAGLES-300)	France	Base technology has operated in Russian submarines Concept design	Licensing in France	Progressing both an inactive and active demonstrator reactor
MSR (Molten salt reactor)	KP-FHR	75, built as twin	**Kairos** (also Terrestrial, Naarea, Copenhagen Atomics, Stellaria)	USA	Limited base technology has operated Detailed design	In licensing in USA	Progressing furthest with both inactive and active demonstrators' beds and reactor

2.6.4.1 Xe-100, X-Energy, USA

X-Energy is a private USA nuclear reactor and TRISO fuel design engineering company. It is developing a Gen IV high-temperature gas-cooled pebble-bed thermal spectrum nuclear reactor design but with lower temperatures than the VHTR. It has received funding from private sources and US government grants and contracts, notably through the Department of Energy's (USDOE) Advanced Reactor Concept Cooperative Agreement in 2016 and its Advanced Reactor Demonstration Program (ARDP) in 2020. The Xe-100 is an 80 MWe/200 MWt reactor that can be scaled into a twin unit or a 'four-pack' 320 MWe power plant pebble bed high temperature gas reactor, where HALEU 20% enriched coated particle TRISO fuel is loaded in pebbles, which migrate through the core over a number of cycles to high burnup, which is a relatively unique feature with on-load refuelling. High temperature helium is the coolant medium, and graphite is the moderator. The design, highlighted in Figure 2.25 showing the flow of pebbles though the reactor pressure vessel and flow of heat through the heat exchanger, aims to maximize the use of off-the-shelf components manufactured and shipped to site using existing road and rail, with a 60-year life. This reactor provides heat as steam at 565°C.

X-energy and Dow, a global chemical company announced the selection of Dow's Seadrift manufacturing facility in Texas as the site for the first Xe-100 plant, providing Dow's site with power and steam. A construction permit application has been issued to the US NRC.

XENITH, a variant of the Xe-100, is proposed for defence sites in the USA and for use in space.

X-Energy, Amazon, Korea Hydro & Nuclear Power, and Korean NSSS manufacturer Doosan Enerbility announced a Partnership to Scale Advanced Nuclear Energy for AI Infrastructure in August 2025. In September 2025, UK utility and investor Centrica and X-energy signed a Joint Development Agreement to deploy what could be the U.K.'s first AMR targeting 6 GW of new nuclear capacity in the UK in total, initially at the Hartlepool site where Generation II AGRs are running.

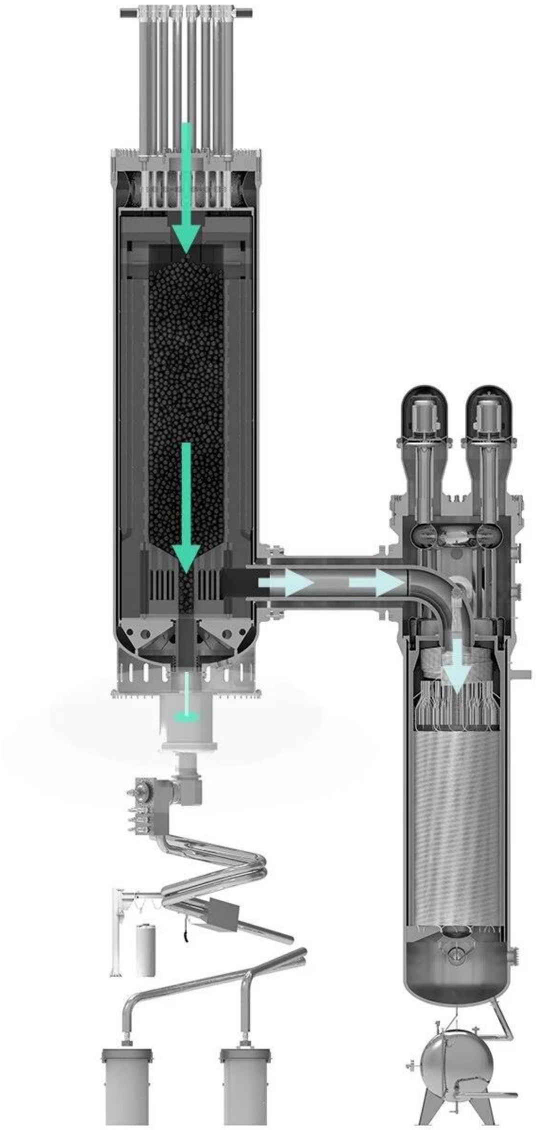


Figure 2.25: Xe-100 Reactor Courtesy of X-Energy (X-Energy, 2025)

2.6.4.2 Natrium, Terrapower, USA

The Natrium reactor is a 345 MWe/840 MWt low pressure, sodium fast reactor, using TerraPower and GE Vernova Hitachi technology. It produces 500°C heat, coupled with a molten salt energy storage system, providing built-in gigawatt-scale energy thermal storage, which has the potential to boost the system's output to 500 MWe of power for more than five and a half hours when needed. The Natrium reactor uses HALEU metallic fuel (TerraPower, 2025).

TerraPower is building its first plant through a public-private partnership with the U.S. Department of Energy's (DOE) Advanced Reactor Demonstration Program (ARDP). This program authorizes a 50/50 cost share and authorizes up to $2 billion for the Natrium project in Wyoming, USA. TerraPower, through its subsidiary, US SFR Owner (USO), submitted the demonstration plant's construction permit application in 2024. The US NRC recently announced that it has completed its final safety evaluation (SE) for the construction permit application for Kemmerer Power Station Unit 1. The NRC plans to provide both its SE and final environmental impact statement for the last phase of the licensing process, after which the NRC will make its final deliberations and vote on whether or not to issue the permit to USO. The schematic for the site development is shown in Figure 2.26.

Figure 2.26: Rendering of the Site Arrangement for Deployment of the Natrium Reactor (TerraPower, 2025)

2.6.4.3 LFR-AS-200, Newcleo, France

Large French headquartered start-up Newcleo is designing lead-cooled fast reactors using MOX fuel in a fast neutron spectrum. They operate at atmospheric pressure, providing high temperature heat, meaning that significant energy release does not occur in case of vessel failure. Lead is chemically relatively inert, meaning extra safety provisions and intermediate loop are not necessary. Coolant boiling is practically eliminated meaning safety injection systems are not needed. The reactor holds significant thermal inertia if a loss of heat sink occurs. Newcleo is developing MOX fuel designs, MOX fuel plant technology and reactor technology. An inactive demonstrator is being constructed in the Brasimone centre in Italy, with plans for a 30 MW test reactor before launch of the 200 MW full scale reactor. Corrosion and erosion testing is already in operation, with static and moving lead. Newcleo is working on the basic design of the LFR AS-30 reactor and the MOX plant and is engaged in the pre-licensing phase on both with ASNR, the French nuclear regulator (Newcleo, 2025a). A cross-section sketch of the reactor pressure vessel and reactor core is shown in Figure 2.27.

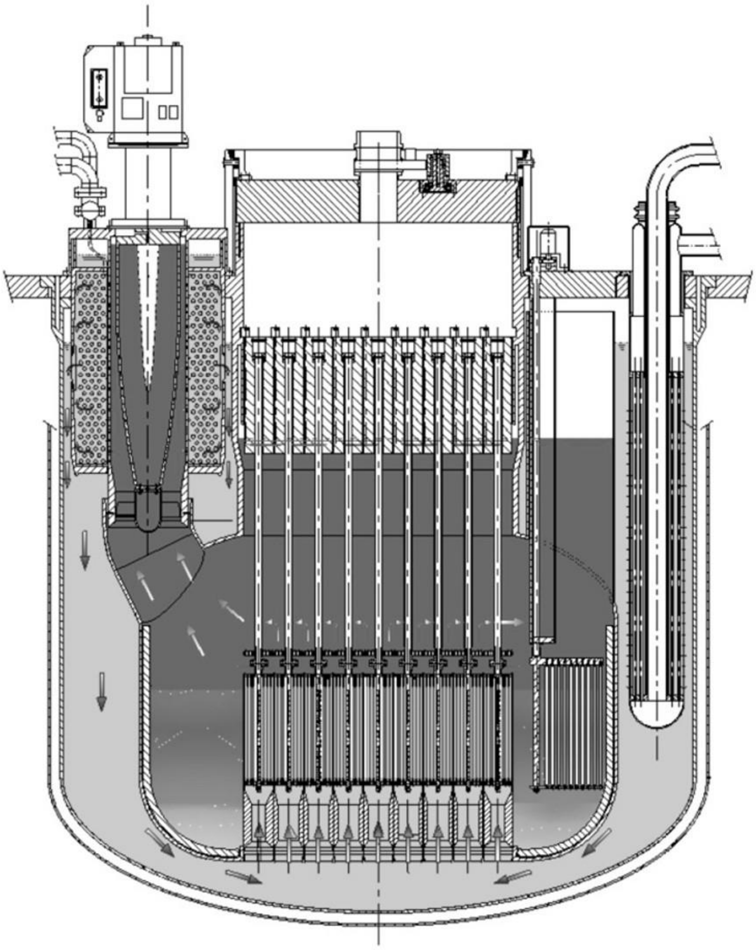


Figure 2.27: LFR-AS-200 Reactor Vessel Courtesy of Newcleo (Newcleo, 2025b)

2.6.4.4 KP-FHR, Kairos Power, USA

The Kairos Power FHR (KP-FHR) is an advanced reactor technology that leverages HALEU TRISO fuel in pebble form with on load refuelling using conventional reactor pressure vessel materials, combined with a very low-pressure molten fluoride salt coolant and heavy ET-10 graphite reflector from IBIDEN of Japan. Twin 75 MWe units are foreseen, providing reactor outlet temperatures of 650°C, but can be connected to a steam cycle through an intermediate heat exchanger to reduce risk of steam contacting core molten salt. A high-level schematic of the future KH-FHR is shown in Figure 2.28. Kairos Power is differentiated by its adoption of a “model-to-learn" process that supports ongoing planning, designing, building and testing, with a phased test plan through inactive salt loops, in active reactor to the 50 MWe HERMES-2 active test reactor, and are well advanced in US licensing.

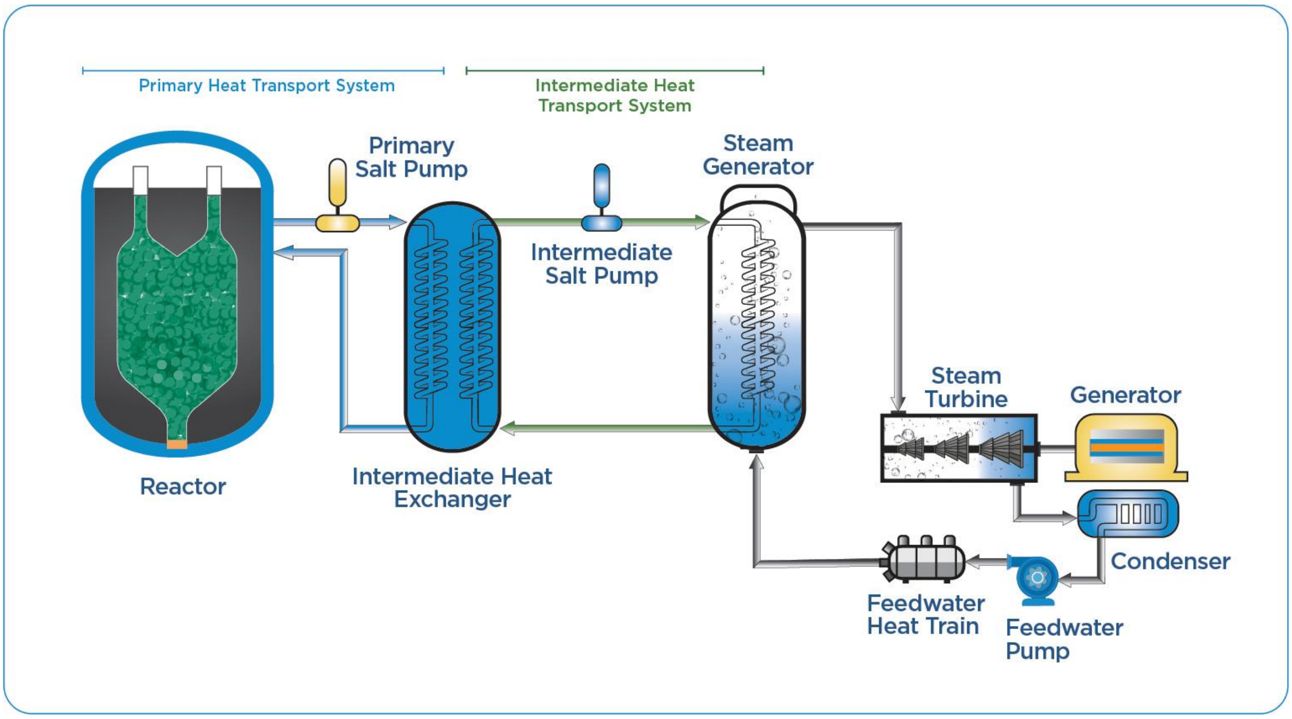


Figure 2.28: Schematic of the KH-FHR Courtesy of Kairos Power (Kairos, 2025)

2.6.4.5 ***Integral Molten Salt Reactor (IMSR), Terrestrial Energy Inc, USA***

The Integral Molten Salt Reactor (IMSR) is an AMR developed by Terrestrial Energy. It utilizes molten salt reactor technology based on the denatured molten salt reactor (DMSR) design from Oak Ridge National Laboratory and incorporates elements from the small modular advanced high temperature reactor (SmAHTR). Unlike other technologies, the IMSR is a "burner" reactor, employing a liquid fuel which contains the fissile nuclear fuel and also serves as the primary coolant. The reactor is designed to have low pressure operation.

Unlike many other designs which are based around refuelling a reactor which stays within the reactor building through its lifetime, the IMSR core unit can be lifted out for replacement, making it a compact and replaceable nuclear reactor unit. The IMSR is being designed to have a capacity of 442 MWt and 195 MWe.

Terrestrial Energy is currently engaged in preapplication activities with the US regulator regarding the IMSR design. The company has an ambitious target of a commercial fleet by “the early 2030s”.

In terms of deployment risk mitigation, it is worth noting that the company has partnerships and agreements with notable organizations such as Westinghouse Fuels, Energy Solutions, Schneider Electric, the U.S. Department of Energy (DOE), and US Argonne National Laboratory, among others.

2.6.5 Technical Risks for AMRs

Any potential future Advanced Modular Reactor (AMR) project faces several significant technical risks that could significantly impact project timelines and costs. These risks arise from the innovative nature of AMR technology, some technologies shared with SMRs, reliance on new designs, and integration challenges. Below is an outline of the key technical risks of AMRs in Table 2.13. All of the SMR risks also apply to SMRs but there are also some major risks to understand across all designs.

Table 2.13: A Summary of Risks and Challenges for AMR Reactors as a Group

Risk	Challenges	Potential Impact
Design Maturity and Validation: Many AMR designs are still in the concept or preliminary development or prototype stages, and some lack operational experience or are stretching experience well beyond existing data.	New equipment, new materials, new suppliers of design, high temperature impacts on materials, new higher temperature heat exchangers with lack of operating experience, volatile coolants. Potential for unforeseen design flaws or inefficiencies during testing or early operations. Delays in completing design certification or updates to meet regulatory requirements due to lack of design detail and substantiation Reduce base technology experience Many new entrants	Licensing risks of entering licensing without mature designs and design processes. Increased costs for re-engineering and delayed project milestones. Risk of gaps in materials properties or lack of validation evidence. Licensing has to pause whilst testing occurs. Delays.
Manufacturing and Supply Chain Complexity: AMRs like SMRs rely on modular construction and advanced manufacturing techniques, which may face supply chain constraints or quality issues.	Limited availability of specialized components, such as reactor vessels or heat exchangers. Need for precision in manufacturing and assembly to meet safety and operational standards. Lack of factory-build capacity. Introduction of less well proven advanced manufacturing techniques Limited materials availability	Licensing risks. Delays in component delivery, increased costs for quality assurance, and potential project bottlenecks.
Integration of Innovative Technologies: AMRs incorporate advanced technologies, such as passive safety systems, high-temperature materials, or novel fuels, which may introduce unexpected challenges.	Testing and validating new materials under extreme conditions (e.g., high temperatures, radiation exposure). Integration of innovative features like natural circulation cooling, which may behave differently under real-world conditions.	Additional time and resources required for extensive testing and validation, including irradiation testing. Limited access to materials test reactors and associated post irradiation examination facilities. Lack of data to support emergency planning zone claims.

Risk	Challenges	Potential Impact
Construction and Modular Assembly: While modular construction is intended to reduce costs and timelines, the process introduces unique risks.	Coordination among multiple suppliers and contractors for off-site fabrication and on-site assembly. Quality control issues during transport and installation of prefabricated modules. Lack of factories for manufacture and assembly	Delays in assembly, increased costs for rework, and potential misalignment of project timelines.
First-of-a-Kind (FOAK) Challenges: As many AMR projects are in reality the first deployment of their kind, vendors and developers face a steep learning curve.	Lack of / stretched prior data or benchmarks to predict operational performance. Delays in establishing operational procedures, training, and supply chains.	Much larger list of FOAK risks. Higher costs for initial projects and delays due to troubleshooting during construction and commissioning. Additional costs of validation programmes. Risks of specific delays if validation has been based upon in silico predictions. Additional challenge around licensing if traditional containments are not included.
Waste Management and Fuel Supply: Sourcing advanced nuclear fuels and managing storage and disposal of spent nuclear fuel (e.g., HALEU TRISO or molten salt) can be challenging.	Limited or no availability of fuel supply chains for novel reactor types. Data to support fuel disposability Development and licensing of waste storage or disposal facilities and disposal containers	Limited source of HALEU. Limited source of fuel. Fuel supply cost and delays. Waste routes lacking cannot secure permit to operate Licensing and permitting risk Increased costs for waste management and fuel logistics. Uncertainty on decommissioning costs. Additional waste costs if components fail.
Operational Ramp-Up and Reliability: Ensuring reliable operations and achieving expected performance metrics during initial years can be challenging.	Load following and grid code compliance, if relevant Performance of heat as a service. Challenges on plants constructed where data does not support initial licensing case. Addressing teething issues such as extended	Apply for exception. Plant cannot be operated to supply heat and or electricity. Low availability, challenging commercial models.

Risk	Challenges	Potential Impact
	commissioning periods, unanticipated downtime, maintenance needs, or performance deviations. Training and retaining skilled personnel to operate and maintain the reactors. Offset to an extent by opportunity to make a heavily instrumented plant and take benefits of a digital twin (a digital twin will not offset the risk of a proper validation and testing programme). Combined efforts of due diligence by Operator and Regulator will be required to assess more novel technologies.	

2.6.6 Conclusion on AMR Reactor Technology Assessment

A wide variety of AMR reactors of different sizes are being marketed, a few by mature reactor vendors but mostly by relatively new entrants. Compared with SMRs, this sector is characterised by even bolder claims of design and safety case detail, faster construction, and cheaper cost of finance, as well as increased safety and reliability, with additional claims that the reactors can be sited anywhere. As with SMRs, the claims being made around licensing, modularisation and factory build are yet to be substantiated, and it will be crucial to understand whether they can be built faster. With time, construction experience will be forthcoming by 2035 to provide an opportunity for a new entrant country to understand which vendors to engage with in a future procurement process. AMRs have many additional technical challenges to overcome, and we have identified some of these. It is likely that several of the designs presently being developed will disappear from the market over the next 10 years, and some designs will start to show feedback from construction. Operational experience will follow.

As with GW and SMR evaluations, we have not eliminated any designs at this stage, as this would be a political decision and subject to a formal procurement process. A future review and update of the AMR market status would form part of any pre-engagement process in future steps.

3 Flexible Operations

3.1 Chapter Summary

This chapter considers how nuclear reactors of various types provide different aspects of flexible operation, and what flexible generation means for their operation. Traditionally, nuclear plants primarily operate at constant output to maximize fuel efficiency and minimize mechanical stress. However, as energy systems integrate more intermittent renewables, the ability of nuclear plants to adjust power output becomes increasingly valuable.

Flexible operations impact the structural integrity of reactors and fuel, and typically a mechanical budget is set for such transient operations over the lifetime. In the past, adaptations were made to allow for flexible operation with relatively small cost impacts of a few percent.

Whilst nuclear reactors already contribute significantly to a more stable power system, the design maturity and proof of performance of SMRs and AMRs are at too early a stage to form a firm view on how much flexibility they will introduce. There are claims of attractive flexible operations capability from many reactors in development.

Although individual units (GW/SMR/AMR) will no doubt provide significant flexible operation capability for the majority of each fuel cycle, the greatest benefits are likely to come from flexible operations rotating around a fleet of medium to small reactors, each with mechanical spinning reserve and smaller power contributions that can be changed.

The approach in any future reactor deployment would no doubt be strongly informed by the terms of the energy market and the energy system as a whole. Market mechanisms could address full lifecycle costing, carbon accounting, land use, the benefits of supporting flexible operations, recognition of high availability factors and not needing backup power sources to support more intermittent forms of generation.

3.2 Introduction - What is Flexible Operation and Why is it Typically Needed?

The term load following (LF) is used to describe operation of a power plant where generation is adjusted to match fluctuations in demand for energy in the system. Most nuclear power plants are traditionally and routinely operated at their full base load badged power output, i.e. operating constantly at maximum or close to maximum thermal and electrical power output, outside of maintenance or outage windows, to maximise fuel use efficiency. There are some exceptions to this, particularly the French fleet, where load following operation is spread and rotated across a large fleet of plants. Additionally, Swedish plants also load-follow, and German plants extensively load-followed before closure.

Load following is avoided primarily to minimize mechanical stress on major components and reduce process equipment costs, and because staffing and other operational expenses remain fixed regardless of output. However, the majority of modern NPPs, which are predominantly GW-scale plants, are actually designed to provide for flexible operation, or load following power operation, as well as to enable fault ride-through and frequency control of the transmission grid system (i.e. to support the 50 Hz AC frequency baseline (or 60 Hz for certain regions), which ensures the efficient and reliable operation of electrical equipment and prevents potential damage, malfunctions, and blackouts).

European power system frequencies are typically maintained within a very tight tolerance of 50 Hz, with targeted deviations of less than +/- 0.1Hz and, in extreme cases, +/- 0.5Hz. The balance between supply and demand impacts frequency. If there is more demand for electricity than there is supply, frequency will fall, but if supply is higher than demand, frequency will rise. The generators' ability to frequency-follow against the target is particularly important in countries with a high share of certain forms of renewable power generation which provide electricity through inverters and are susceptible to large scale temporal variation. Spinning heavy turbine and generator sets reduce deviations in frequency, since their spinning weight is inertia that must be counteracted to impact them. As countries move away from traditional large thermal and hydro power generation to more decentralised and intermittent solar and wind renewables, the system experiences more rapid changes in the supply and demand balance. If an electricity grid relies on intermittent wind generation and operates with lower inertia from reduced numbers of spinning heavy generator sets, faster-acting frequency response becomes more important than ever. Nuclear power could support existing hydropower to provide long term inertia but, in common with hydropower, does not provide an ultra-fast frequency response.

According to IEEE, NERC and IAEA, ultra-fast frequency response is defined as "*the autonomous delivery of active power within 1 to 2 seconds of measurable frequency disturbance, sustained for several seconds to stabilise system frequency before primary frequency control fully responds*".

The inertial response counteracts any change in system frequency and is attained via the inherent physical inertia of a rotating plant. This is a passive benefit of the grid-synchronized rotating mass. For fast frequency response, this is not normally within the capability of a nuclear power plant (GW scale or SMR) because of the inherent thermal hydraulic and reactor physics constraints. For AMRs, molten salt and liquid metal designs with very different reactor physics and a high thermal inertia could allow for an operating regime where one could decouple power output from immediate reactor power and allow coolant temperature to increase or decrease and respond with control rod or similar activation.

Nuclear plants can change their power output over time (i.e. ramping or load following) and contribute to power system stability and reliability needs, including frequency regulation and providing operating reserves. Load following can help manage both daily and seasonal variability in demand and renewable energy output or respond to the impact of changing market prices or grid system operator dispatch, which is heavily dependent on the electricity market mechanisms chosen.

In fact, there are three different types of flexible operation for NPPs whose terms are often used interchangeably:

- Frequency responsive operation, where the plant is set to operate at less than full nominal power, and its output varies automatically in response to changes in the system frequency.
- Profile operation in which the operator offers periodic load changes to create a profile which varies across the day (typically this involves "two shifting" over a 24-hour period with reduced output overnight).
- Load following, where the operator is instructed by the grid system operator to carry out manoeuvres at short notice to change the output in accordance with changing system requirements.

Although flexible operation from nuclear power plants has potential value, the focus has mostly been on providing this flexibility through directing the fixed power generation from nuclear plants towards other energy vectors than output to grid, such as local production of hydrogen through electrolysis, water desalination, or energy storage.

Nuclear load following operation has been performed in many geographies including Belgium, Canada, France, formerly in Germany, Nordic countries, Slovakia, the USA and others for several decades now, always with full safety assessment and related regulatory approvals.

The minimum requirements for the load following capabilities of modern reactors have collaboratively been set by European utilities, which are in turn based on the requirements of the grid operators. The main parameters for an NPP's load following capacity are as follows: power gradient (rate of change in % of rated power Pr), power increment (amount of power change), and minimum power output. As an example, the European Utilities Requirements (EUR) state that a GW NPP must at least be capable of daily load cycling operation between 50% and 100 % Pr, with a rate of change of electric output of 3-5% of Pr per minute. Most of the modern designs implement even higher manoeuvrability capabilities, with the possibility of planned and unplanned load following in a wide power range and with ramps of 5% Pr per minute. Some designs are capable of extremely fast power modulations in the frequency regulation mode, with ramps of several percent of the rated power per second, but in a narrow band around the rated power level. Generally, smaller reactors can adjust power levels more readily than large GW scale plants.

Using a turbine bypass enables the reactor's power level to be maintained constant, with the 'reserve' power (steam) rejected to the main condenser (U.S. Nuclear Regulatory Commission, 2007). The speed of operation of the bypass valves would be critical, particularly in fault ride-through and mandatory frequency response. The generator's governor and automatic voltage regulation (AVR) systems would also be critical in this.

Flexibility in terms of meeting the requirements of international grid codes, e.g. ENTSO-E and The Nordic Grid Code for Flexible Operations is understood to be challenging for any SMR or reactor technology. Typically, this is in the areas of frequency response, fault ride-through and islanding operation. Although SMRs and other reactors can offer some load following capability, this requires them to be operated below their maximum output to allow headroom for increased demand by a grid system operator. This load following is a slower response which differs from grid code frequency response, fault ride-through and island mode requirements, and places a far lesser burden on the plant, nuclear fuel, and turbine-generator system. For SMRs and other NPP reactors, a disproportionally over-sized turbine bypass (steam reserve), may be required, particularly for BWRs in island mode, to meet these more demanding requirements. This is unattractive to investors and affects plant thermal efficiency. Also, more complex reactor and generator control systems are required, which additionally decreases attractiveness to investors. The key challenge at present remains the level of design maturity to enable assessment with grid codes (EU grid code based on ENTSO-E), although ambition is strong.

3.3 Focus on an Example SMR

Broad claims have been made against grid compliance by SMR and AMR vendors, but at present, these have yet to be fully substantiated and clear gaps remain. The Rolls-Royce SMR is stated as being designed for full compliance with the U.K. Grid Code, provides load following between 50% and 100% power at a rate of 3-5% per minute, and can deliver stable operation for at least two hours:

The Rolls-Royce SMR documents claim a ramp rate target[5] of 3-5% of full power per minute which is ambitious for a larger reactor and indicates design for flexible operation, for example by adjusting to grid demand or backing off when renewables are high. The target includes operation down to targeted ~20% of full power as a lower bound, though routine operation may focus on the 50-100% range. The literature claims the ability to drop to minimal power (supplying internal loads only) or operate in an islanded mode if needed, rather than automatic full shutdown on grid loss, which adds resilience. This is an existing capability of marine reactors (Rolls Royce SMR, 2023).

The IAEA's SMR catalogue 2024 emphasises that SMRs are increasingly required to provide flexibility for balancing grids, integration with variable renewables, and dispatchable power. In particular, the IAEA note that SMR designs are claimed to have enhanced manoeuvrability compared to large GW scale reactors, partly because the smaller size mean reduced thermal inertia and better ramping. The R-R SMR specification for ramp rate and turndown appear aligned with the broader market/industry expectation that future SMRs will support grid flexibility rather than being strictly baseload.

This is, however, a new design of SMR NPP, and the proof will only be fully secured once the plant is commissioned and connected to a grid. Further information would be required to independently assess whether this SMR can fully comply with the ENTSO-E requirements or other grid code requirements, including mandatory and optional ancillary services over and above what is in the public domain. However, being a relatively large PWR reactor, this should be relatively low risk. There is significant experience in developing the PWR design codes, thermal and reactor models, and significant effort has been made to validate them. Final proof will be in the operation but there is reason to accept models that are subject to major regulatory scrutiny. Whilst it is technically possible for a fast-responding reactor to be developed to manage the grid's frequency response, the economics of how this is paid for need to be addressed, such as through a levy on low inertia/intermittent generators.

3.4 Load following Considerations for Norway

This report does not primarily address the Norwegian grid or energy market, but for context it is necessary to describe how the electricity system works to deliver base load and flexible operation in Norway. Hydropower plants are the main source of electricity as well as the main source of both market and frequency balancing. The fleet consists of around 1800 plants, ranging from micro-power plants to Kvilldal Kraftverk's 1,240 MW of installed power and yearly power generation of 3,231 GWh (Statkraft, 2025).

Energy storage primarily comes in the form of approximately 1,100 reservoirs, totalling 87 TWh capacity. Additionally, there is a smaller contribution from 10 pumped storage hydro plants with a combined capacity of 1369 MW.

In other words, Norway currently has an unusually high degree of flexibility on the generation-side, which has been leveraged in tandem with foreign transmission connections (to Sweden, Finland, Denmark, Germany, the Netherlands, and the UK) to absorb some of the fluctuations from intermittent renewables and slow-regulating thermal generation.

However, it is sensible to consider what potential role nuclear generation could play in supporting future flexible operations because of a range of factors including predicted growth in electricity

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[5] It's important to note that at a target specification are desired characteristics and are not yet proven through operational experience. The plant is still in GDA pre-licensing phase, so actual performance will depend on commissioning tests.

demand for decarbonisation of industry, climate change and the effect of drought on reservoir levels, introduction of additional wind and solar power, direct or indirect customers making decisions depending on energy price through a variety of market mechanisms, and the reliance on interconnecting cables across Europe. This report focuses on the technical ability to perform load following and the costs of load following but does not consider the broader implications of energy pricing.

3.5 Technical Implications of Load following

There are three potential approaches to load following by NPPs: (1) the direct approach by reactivity control and/or (2) turbine control; and (3) the indirect approach through energy offtake for district heating or flexible electricity consumption such as production of hydrogen.

Load following nuclear reactors face technical challenges related to variations in basic reactor physics of the different designs, such as balancing neutron populations, maintaining heat removal, and designing fuel and structural components to withstand temperature and therefore mechanical load variations (impacting fatigue strength). Intermittency or increased load following would cause nuclear reactors to cycle power and temperature more often and could lead to earlier retirement of the plant as the transient or number of plant power cycles is used up earlier. Such transient budgets are often set for different ranges of power level change as laid down in the approved safety analysis reports and reviewed at each periodic safety review, with some examples shown in Table 3.1.

Table 3.1: Example fatigue life transient budgets for previously operating German nuclear plants (NEA OECD, 2011).

Load Change Cycle (by % Power)	Number of Transient Cycles Within Plant Design Basis
10% (step change)	100 000
100%-80%-100%	100 000
100%-60%-100%	15 000 (i.e. daily cycling for 40 years)
100%-40%-100%	12 000

In order to improve flexible operation performance, plant design changes have been implemented. These include different control rod drive and rod designs that can be moved faster and easier, fast boric acid removal from the primary coolant, instrumentation and control (such as in-core measurements of the state of the core and better power regulation), automatic launching of the turbine, and so on. The components are designed for stress associated with load cycling, but this can mean additional costs for replacement parts such as control rod drive mechanisms. Continuous monitoring of equipment fatigue is performed (temperatures measured and recorded, non-destructive testing and so on), especially on the safety-class components. It has been shown that basic load following operation regimes do not decrease the fatigue strength of the equipment. One of the most important overriding requirements for load following is to maintain fuel cladding integrity in order to retain fission products within the fuel. The manoeuvrability of the reactor could be limited by fuel cladding failure due to pellet-cladding interaction (PCI), stress corrosion cracking (SCC) and other effects. Sometimes restrictions are placed at the start and end of the fuel cycle to limit such effects for traditional UO_2-based fuels. AMR reactors and fuels may be more resilient.

3.5.1 Load following in PWRs

A load change of the PWR is mainly performed by means of the control rods to achieve the required thermal reactor power. Fine adjustment of the reactivity within the reactor core is performed by use of less intense or grey control rods and controlling the boric acid concentration within the primary water circuit (in some designs, where it is used to balance through cycle reactivity). The coolant temperature stays constant in the range of 60-100% load and thus reduces thermal stress in the main mechanical components. Adjustments in boric acid concentration is not suitable for faster adjustments in reactor wear and therefore control rods are utilised. Previous summary reports of research have shown that Generation II and III commercial GW PWRs have had relatively slow regulation, and do not participate as well in frequency control as BWRs (Nonbøl, 2013) and (IAEA Nuclear Energy Series, 2018).

3.5.2 Load following in BWRs

The power output of a Boiling Water Reactor (BWR) can either be controlled below 60% of the NPP's design load by means of the control rods, or by means of change of coolant water flow rate (change of power input of the recirculation pumps) in a range of 60 to 100% nominal full power. Adapting the recirculation flow rate through the reactor core affects the moderation through changing the void fraction and therefore the reactivity – essentially power feedback mechanisms inherent from the physics. This is the preferred method for load following as it does not stress the fuel rods, and power distribution in the core stays almost constant. A BWR can change its power output faster than a PWR in the upper load range.

However, it is important to understand that a BWR typically does not have a high rate of frequency change capability and is highly unlikely to participate well in frequency control. There are a number of reasons for this due to the control of reactivity via the recirculation of water through the core with any change in turbine load immediately affecting reactor pressure, void fraction (BWRs rely on void reactivity feedback as a method of control) and neutron flux. In some BWRs, frequency disturbances on the grid therefore directly perturb reactor power, risking power oscillations and instability if not tightly controlled. Thus, rapid frequency excursions are inherently undesirable for BWR operation and load rejection limits are tighter than in a PWR in order to minimise the risk of fast transients that would be concerning for the reactor pressure vessel and steam line load. It is entirely possible for BWRs to operate in a frequency-sensing mode if additional fast acting turbine bypass valves are added and the condenser redesigned, allowing for the reactor power to change at a different rate to the generator output.

3.5.3 Load following - Comparison of Nuclear with Fossil Fuel

Studies have shown that nuclear outperforms combined-cycle gas turbine (CCGT) and coal stations for load following in terms of typical power change and power rate response.

The study from Sustainable Nuclear Energy Technology Platform (SNETP) compared the ability of former German nuclear power plants with gas- and coal-fuelled plants, resulting in power gradients of 63 MW/min, 26 MW/min and 38 MW/min, respectively, when the load following characteristics was considered. Similar results were found to be true French nuclear power plants (SNETP, 2020).

The NEA study considered French and former German nuclear power plants and examined both the regulatory and economic considerations of load following (Lokhov, 2011). Participation in both primary and secondary frequency control is discussed, and some units follow a variable load programme with one or two large power changes per day. In France, this makes sense, noting the daily and weekly power variations and the predominance of nuclear energy in the national mix. Before shutdown in Germany, load following became increasingly important when a large share of intermittent sources of electricity generation (e.g. wind) was introduced to the national mix. The study concluded that although load following has limited impact on ageing of large plant components, it does have some influence over components such as valves, which can lead to an increase in maintenance costs and outage durations.

3.5.4 Load following and Cycle Length

An interesting feature has been identified in the BWRX-300 specification, which notes that the fuel cycle length is 12 months for load following duty and 24 months for base load operation. It is not clear whether this is an isolated instance of such a restriction. The BWRX-300 will have limited capability for load following and frequency response, as ramp rates will be in the order of minutes.

3.6 Interim Conclusions on SMR Flexibility Compared with GW Stations

3.6.1 Design Features of SMRs and AMRs

Due to the importance of load following, most recent SMRs and AMRs claim to be designed with the capability and flexibility to vary their output power, but there is very limited information in the public domain to allow claims to be interrogated or validated. Very few have been fully designed and licensed, let alone constructed and operated, and none are deployed as a full fleet. Further information will be required if the decision is made to go ahead with a nuclear policy to assess whether SMRs and AMRs can fully comply with the ENSTSO-E requirements or other grid code requirements, including mandatory and optional reserve services.

3.6.1.1 SMRs

LWR SMRs have been designed with load following capabilities in mind, with attempts to introduce European Utility Requirements for SMRs from the early 2020s. These reactors nominally have several features that allow them to adapt to changing power demands with minimal impact on their performance and safety. Some of these generic features include:

Smaller size: SMRs have a smaller thermal mass and shorter coolant loops compared to large-scale reactors, whilst retaining heavy rotational inertia. This feature could result in faster response times when adjusting power output. However, they typically use more reactor fuel per power generated than GW stations, so any additional fuel needs because of load following may increase costs.

Modularity: A strategic aim of SMRs is that they can be installed in modular configurations, with multiple units operating together on a site, and potentially connected as a broader distributed fleet, subject to licensing. This allows for easier and more precise control of power output by adjusting the operation of individual modules. If the generator is based upon a fleet of SMR units, the power output can be adjusted by the disconnection of some units during periods of low demand for scheduled maintenance, or when significant amounts of high-priority energy become available from intermittent renewable energy sources. Disconnection on a regular basis is not ideal as it would last for several days. Such actions also have potential consequences for transient budgets and the lifetime of the plant. A distributed fleet of SMRs could be better at balancing the load impact on a country or wider network with an increased number of connection points, thus reducing risk of transmission grid congestion. In general, a site with several nuclear power plants could load-follow in a small interval of down-rated power, say from 100 % to 70 %, starting with one reactor, and then the other units in series. Most claims around increased flexibility for SMRs are accounted for by this fleet management effect, assuming that the fleets are each in the order of 10 reactors, compared with 2-4 typically seen for existing stations.

Advanced control systems: Again, subject to licensing, SMRs will incorporate advanced digital control systems with higher fidelity in-core and ex-core instrumentation that enable real-time monitoring and control of reactor conditions, as well as digital protection systems. This potentially provides for more accurate and responsive load following capabilities. The combined impact on component lifetime of load following and more straightforward reactivity balancing would need to be assessed.

Passive safety systems: SMRs are designed with passive safety systems that rely on natural processes like convection and gravity rather than active mechanical components. This potentially enhances their stability and resilience during load variations.

Steam Bypass Systems: Details on the level of steam bypass systems would need to be reviewed. Using a turbine bypass enables the reactor's power level to be maintained constant, with the 'reserve' power (steam) rejected to the main condenser. The speed of operation of the bypass valves would be critical, particularly in fault ride-through and mandatory frequency response. The generator’s governor and automatic voltage regulation systems would also be critical in this.

For the SMR designs discussed in 2.5.5, Table 3.2 lists a summary of the claimed characteristics for these designs.

Table 3.2: A Summary of claimed load following capabilities for SMR designs discussed

Design	Ramp-Rate	Minimum Power (Turndown)	Special Operating Modes	Primary Flexibility Approach	Fuel / Thermal Hydraulic & Structural Considerations
RR SMR (Rolls Royce SMR, 2025)	3-5% per minute	20% of rated power	House load, islanded mode	Direct throttling via control rods+ turbine valves, designed for frequency cycling	Must manage xenon transients, core thermal stress, fuel mechanical fatigue assessed
AP300 (Westinghouse, 2025)	Not published but may inherit AP1000 ramping (~2-3% per min)	Likely to be ~30-50%	Capable of frequency control	Throttling, grey control rods, boron control adjustments	Proven AP1000 fuel, mechanical fatigue and xenon transients shown to be within AP1000 envelope
SMR-300 (Holtec International, 2025)	Steady state operation	N/A (steady core)	Black start and islanded capability	Uses thermal storage for grid flexibility	Reduces in core xenon and fatigue cycling, steady thermal output improves thermal performance
i-SMR (i-SMR, 2025)	Daily cycles 100% to 20% (implied 3-4%/min)	20%	N/A	Deep throttling	Fuel enrichment and control algorithms chosen to minimise

Design	Ramp-Rate	Minimum Power (Turndown)	Special Operating Modes	Primary Flexibility Approach	Fuel / Thermal Hydraulic & Structural Considerations
					reactivity oscillations, structural analysis includes low-load creep/fatigue
NuScale (NuScale, 2025)	~40%/hour	Each module can be shutdown	Multi module staging; sequential module shutdown and startup	Staggered module dispatch	Staging minimises transient cycles on fuel, lower power per module fatigue
ACP100 (CNNC)	Not published, expect typical PWR ~2-3%	Not specified	N/A	Thermal co-use for flexibility (divert heat rather than throttle)	Stable thermal output, fewer xenon issues, fatigue managed by steady NSSS
Nuward (EDF)	Not published, expect typical PWR ~2-3%	Not specified	Unknown	Not specified but likely to be direct throttling	Not specified but will be similar to AP300/RR SMR

R-R SMR and i-SMR explicitly target operations down to ~20% and both are designed for rapid throttling, which is suitable for daily cycling. NuScale is claiming system level flexibility by dispatching or idling modules. Holtec SMR-300 uses thermal energy storage as a buffer instead of reactor throttling, which is ideal for renewables integration without core cycling penalties. The AP300 will inherit the AP1000's flexible turbine and reactor control system, but Westinghouse is not yet publishing specific performance characteristics. The ACP100 is flexible mainly by diverting heat to district heating/desalination.

In terms of common technical issues faced:

- Rapid temperature gradients stress fuel cladding, vessel internals and piping welds.
- Fuel management must include burnable absorbers and extended cycles to tolerate more frequent ramps, but this is just an extension of good core design performed for modern reactors.
- Reactivity (xenon) transients must be smoothed by control rods or soluble boron, although such transients are relatively slow.

3.6.1.2 Advanced Modular Reactors

As discussed earlier in this report, six Advanced Modular Reactors AMR types are proposed, four of which have a commercial offering. Each of them has unique characteristics, particularly suited to alternative uses of nuclear power, such as the high-power volumetric density of lead-based reactors aligned to marine power, and the potentially higher outlet temperature of the VHTR, which aims to deliver direct process heat at volume for industry. At the current stage, these reactor designers often make claims that power can be changed quicker than traditional GW or SMR designs or that the reactors are designed to balance heat take off in addition or instead of electrical generation.

All four AMR developers highlighted earlier in this report recognise the importance of flexibility, given increasing use of renewable energy and evolving grid dispatch needs (more dynamic load/production). As an example, the “Flexibility of advanced nuclear reactors” brief lists TerraPower’s and X-Energy’s designs explicitly in the context of load following (Nuclear Innovation Alliance, n.d.). Some of the flexibility is achieved not by rapid reactor power change, but by coupling with heat storage (as in Terrapower) or by modularity or high temperature process integration (industrial heat) that allow flexible net output. Despite such claims, detailed technical parameters such as ramp rate, response time to frequency deviations etc. are not publicly disclosed. Because AMRs face the same reactor physics constraints (xenon transients, thermal hydraulic limits) as SMRs, the extent of potential load following in these designs remains to be seen.

3.6.2 Cost Implications of Load following

Load following operations in nuclear are inherently inefficient as nuclear power cost structure is composed almost entirely of sunk or fixed costs; therefore, lowering the power output, does not significantly reduce operating expenses and the plant is thermo-mechanically stressed as previously described. If the fuel cycle is planned for load following there will in theory be no additional fuel costs. However, it is likely very difficult to predict the exact amount of load following that will take place during the upcoming operating periods. It is therefore reasonable to assume a certain additional cost for non-optimal fuel usage through having to replace some fuel earlier than required. A more attractive option for load following in a more holistic sense could be to maintain the primary circuit at full power and use the excess power for cogeneration to provide heat to produce hydrogen, which many nuclear operators are exploring globally. This also has benefits in preserving the full lifetime of the plant.

Despite these technical factors, interest in operating NPPs with load following capabilities has grown because, in principle, nuclear reactors can contribute significantly towards grid stability. Vendors of modern power plants have built considerable load following requirements into their reactor designs. NEA advises that “no additional significant investment into the equipment would be needed to use the manoeuvring capabilities of the recent designs”. However, this may require additional specific safety analyses.

With nuclear power, a lower power rate does not translate into an equivalent fuel saving. Consequently, running a power plant at 50% of its power does not save more than few percent of its operating cost, while the loss of revenue is proportional to the electricity not produced (assuming the operator is not paid a premium for providing this service, or that low inertia generators do not pay [6]). Where it has been implemented, load following typically provides for lower power production during nights and weekends. Whilst NPPs have high initial capital costs, they have significantly lower fuel costs when compared with other sources of power due to the vast energy density of uranium, allowing them to deliver electricity at a lower marginal cost when their load factors are kept high. Flexible NPPs operating in a successful load following mode have in the past borne additional but limited costs related to retrofit and design conversion, inspection and maintenance due to the wear and increased

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[6] Balancing and settlement agreements under grid codes may compensate generators when asked to reduce or increase power at relatively short notice.

frequency of replacement of components. This is especially true for control rod drive mechanisms, some fuel costs, staff costs, intensified safety measures and additional support to licensing.

Reliable and consistent data on the cost impacts of load following is relatively sparse. In 2011 and 2012 respectively, NEA and Elforsk reported that it has been estimated that typical load following patterns experienced in highly adapted older French GW PWR plants had led to cost increases of circa 1.2-1.8% compared with baseload generation. The largest contribution to the increase comes from loss in load factor and reduction in fuel efficiency (Lokhov, 2011). It is, however, difficult to assess the current monetary value. Whilst uranium prices have increased, fuel manufacturing costs have decreased, fuel performance and reliability have increased, and cycle lengths have increased on average, so this figure provides only an indication of the order of magnitude of impact of real-world load following. In fact, this figure may be less representative for a renewable-heavy grid of the 2050s. Today's evolving power system, with ever increasing fluctuations in demand and prices (including the emergence of negative prices), add to the uncertainties around load following, and may require more from flexible operation than the typical approach of lower power production during nights and weekends.

The loss due to load following was estimated in 2012 monetary terms at 135,000-250,000 €/day for a nuclear plant of 1,400 MW operating in Europe (NEA, 2012a, Andgren, et al., 2012). Others have assessed that a viable model of baseload operation in front of renewables is possible only if nuclear plants co-generated power and heat as well, such as for district heating, desalination and hydrogen production (Locatelli, et al., 2017), or support biomass conversion into liquid transport fuels (Forsberg, 2009).

3.7 Opportunities of Potential Flexible Operations with Nuclear

Nuclear load following is constrained by the transient budgets of regulator-assessed reactor safety cases and relates to the mechanical integrity of major safety-significant plant items.

Load following had long-lasting deep cycles in GW reactors when first introduced and could have shorter cycles with fast changes by 2050 with new reactor designs.

The progress on the FOAK designs and analyses for SMRs and AMRs, at least in the public domain, does not so far give sufficient indication of the progress of design changes to provide widespread flexible operation, but it is our judgement that the claims for increased flexibility using a fleet of SMRs or AMRs are not unreasonable.

Intermittency or flexible operation, if adopted to a more significant extent, will likely still make nuclear reactors cycle more often and therefore retire earlier if component fatigue life is the limiting factor and cannot be replaced, compared with a baseload operation. However, this could be offset by reactors where component replacement is more straightforward.

Claims of increased nuclear flexibility related to small, slow changes to a larger number of smaller reactors could provide an overall enhanced flexibility in operations.

Flexible operation could be more attractive for nuclear operators if they could create additional revenue streams beyond operating as a baseload provider, although further assessment of this is not the subject of this report.

4 Supply Chain - Global Suppliers of Critical Nuclear Components

4.1 Chapter Summary

This Chapter 4 provides an overview of specific aspects of the global supply chain, focusing on:

- Nuclear fuels addressing the fuel cycle, typical fuels used today, capacities and developments; and
- Large, specialised components of a nuclear reactor for GW and SMR LWR reactors.

Nuclear Fuels

Uranium is the basis for most common nuclear reactor fuels. This is manufactured through a fuel cycle into various forms and fabricated into fuel assemblies that are used within the nuclear reactor. Uranium is a tradeable commodity mined in several regions with plentiful supply from at least 14 countries through 10 companies. Dissolved or entrained uranium in seawater from natural geological processes provides a vast untapped future resource. As a commodity it is traded on markets and with increasing demand, prices are anticipated to increase. These increases may be offset by reprocessing, which is likely to develop more capacity.

Uranium is processed through conversion and enrichment leading to fuel fabrication. There are five enrichment companies and about 20 fuel fabrication companies globally, indicating sufficient capacities now, with new organisations and facilities beginning to be developed.

Supply of uranium and fuel cycle services comes with significant geopolitical considerations that need to be addressed to ensure fuel security.

Should Norway choose to progress with the deployment of nuclear power, a nuclear fuel strategy should be developed to enable continuous, secure supplies. Such a strategy could simply acquire fuel services or procure uranium along with fuel enrichment and fabrication services.

Nuclear Power Plant Supply Chain

Within the nuclear power supply chain, there are significant components in the reactor referred to as the nuclear steam supply system (NSSS), which include the reactor pressure vessel, steam generators, reactor coolant pumps, valves and lines, and pressuriser. These are high nuclear grade components of significant size that demand the highest quality and controls. There are about 12 companies globally that have capabilities in these areas, but few are capable of producing the largest components.

This report does not address the broader nuclear supply chain but notes several considerations to bear in mind:

- The choice of supply chain or delivery model, including how Government and industry participate.
- How supply chain critical items can be secured in a timely manner including possible early commitments.
- How a country wishes to benefit economically and strategically from the significant investment in a nuclear program.
- What capabilities and capacities could be developed locally to support the deployment of nuclear power.

There are plentiful opportunities in construction, supply and services if addressed in a timely manner with clear strategies.

Should Norway choose to adopt nuclear power, consideration should be given to:

- The supply chain risks in any technology choice.
- If early investment would be necessary to secure appropriate manufacturing slots.
- How quality in these critical components will be achieved and ultimately confirmed.

4.2 Introduction

This chapter provides an overview and status of some specific aspects of the global supply chain. It focuses on:

- Nuclear fuels – addressing the fuel cycle, typical fuels used today and developments; and
- Large, specialised components of a nuclear reactor covering the nuclear steam supply system for GW and SMR LWR reactors that dominate the market today.

The NSSS includes the components that provide heat and transfer that heat to turbine generators. It comprises, typically in LWR GW or SMR reactors, the reactor pressure vessel, steam generators and other forms of heat exchangers, valves and pumps, major pipework and other large vessels. They typically make up some 15% of the cost of a nuclear power station. The report provides information on supply lines, sources, capacity issues, trends, impacts driven by SMRs, potential risks and opportunities for Norway.

The report is not required to or intended to cover all parts of a nuclear power station. However, for context these are considered briefly. Nor does it cover supply chains for AMRs, as this has hardly begun to develop, other than some advanced fuels that are covered. Thorium based reactors are also excluded.

4.3 Nuclear Fuels

Most reactors around the world use Low Enriched Uranium (LEU), and most of the global enrichment and fuel manufacturing capacity is geared toward this. Typical fuels used include:

- Depleted uranium - the residual left after enrichment and used in fast reactors.
- Unenriched or natural uranium as used in CANDU reactors – about 0.7% U^{235}.
- LEU up to 5% U^{235} that is the basis of conventional fuel for GW and LWR SMRs.
- Low Enriched Uranium+ (LEU+) 5 to 10% U^{235} for advanced fuels, which is increasingly relevant for advanced reactor designs and longer fuel cycles, offering a middle ground. LEU+ reduces refuelling frequency and improves reactor economics, but its production requires regulatory updates for fuel plants and reactors alike, and specialized enrichment capacity.
- High Assay Low Enriched Uranium (HALEU) to 20% U^{235} for advanced reactors and research reactors.
- High Enriched Uranium (HEU) which is typically 80% and above for defence programmes, and some unconverted research reactors.

The market continues to develop alternative nuclear fuel technologies to the zirconium-clad LEU UO_2 widely used in PWR and BWR reactors. At present this new market is relatively immature and at the start of its path to commercialisation. Due to very good performance statistics, current fuels licensed and in commercial operation undergo only relatively small tweaks to pellet additives, fuel cladding materials, structural components, and burnable poisons, and enrichments typically remain below 5% U^{235}.

Advanced manufacturing techniques are being explored for structural components. There is however, a very active research and development community. A few pilot plants are exploring advanced and even more accident tolerant and higher burnup nuclear fuels, which typically lead to a higher enrichment. Significant redesign and licensing amendment is under way for both fuel manufacturing plants and reactors. Most SMRs plan to utilise conventional zirconium-clad LEU UO_2 fuels. Some lower technology readiness level SMRs and AMRs are adopting more exotic fuels. Features of such advanced fuels include:

- **Reprocessed uranium (REPU)** That requires some additional shielding and minor licensing changes. Although not widespread, its use is increasing. Westinghouse Springfields in the UK is exploring a large investment in conversion of reprocessed enriched uranium, with final decisions due shortly. This is an area worth watching, noting that reprocessing of spent fuel is likely to make a re-emergence in the next 20-40 years if fresh uranium ore becomes rarer and more expensive to extract.
- **Plutonium-based fuel** These fuels, such as Mixed Oxide Fuel (MOX), are already in commercial use. Small quantities of MOX fuel rods have been irradiated in Swedish reactors. The Orano Melox recycling plant, located in Marcoule, Gard, France, produces MOX fuel assemblies made from a blend of uranium oxide and plutonium developed from spent fuel. UK MOX plants have been closed down, and the UK Government has recently confirmed that its stocks of plutonium will be disposed of. There is emerging interest in the USA and Russia already undertakes MOX fuel production. Newcleo, the lead fast reactor designer, has also signalled an intention to build a MOX plant in Europe. Not all MOX fuels require uranium enrichment, which can make them more attractive, although there are other costs associated with this type of fuel. Japan is re-entering this market. Newcleo is exploring MOX fuel manufacture in Europe.
- **More radically different fuel matrices** These include uranium metal and uranium nitride and are being developed by Westinghouse and Idaho National Laboratory (INL) in the USA. Also in the USA, uranium–zirconium metal fuels are under low TRL development by Lightbridge and INL.
- **Coated particle fuels (CPF)** These fuels use kernels of UN, UO_2 or UCO fuel at enrichments of up to HALEU levels or 20% U^{235}. BWXT produces CPFs such as TRISO as a commercial small batch product, including nitride kernels, and pilot plants are under development by TRISO-X and General Matter, all in the USA. TRISO fuel is the most widely explored and more commercialised of the more advanced fuels, where the base for a future licensed fuel has been identified and agreed with regulators, following a long running major research and development campaign in the USA, building on early work in the UK, Germany, Japan and elsewhere. The market for this fuel, and others like it, is highly dependent on demand from deployment of advanced reactors.

- **Additional dopants to traditional zirconium cladding** Chromium-doped materials have enhanced protection against high temperature steam corrosion. Chromium-doped fuel cladding for LEU+ nuclear fuel is being developed by several companies, including Framatome in France and Rosatom in Russia.
- **Alternative and more transformational fuel cladding materials** These include ceramic silicon carbide (SiC), oxidation dispersion strengthened (ODS) steels, metal composites such as FeClAl, and irradiation resistant high entropy alloys (HEAs). Mo or Mo alloys are under consideration and examination.

Fuel manufacture typically follows the nuclear fuel cycle as discussed below.

4.3.1 Nuclear Fuel Cycle

This sub-chapter explores aspects of the nuclear fuel cycle as shown in Figure 4.1. It is a series of industrial processes to support the production of power from uranium in nuclear power reactors. Uranium is a relatively common element in Earth's geology that is found throughout the world in several different forms or ores. Uranium is also present in sea water due to geological erosion processes. It is mined in several countries by a range of different radio-chemical and mechanical processes and must be processed before it can be used as fuel for nuclear reactors. The nuclear fuel cycle starts with the mining of uranium and ends with the disposal of nuclear waste. With reprocessing of used fuel, the stages form a true cycle as shown below (World Nuclear Association, 2025d).

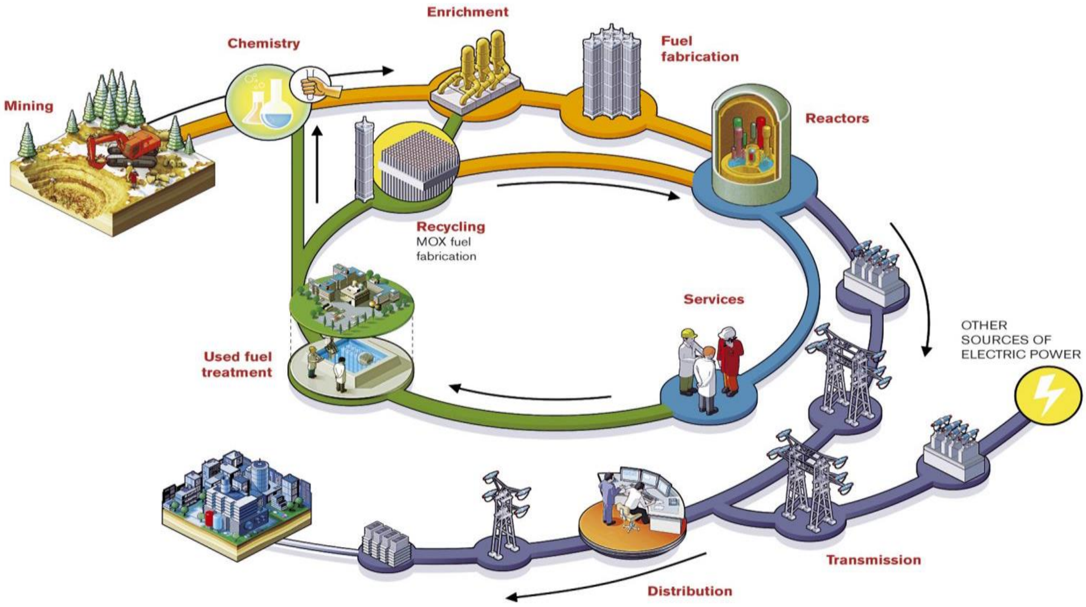

Figure 4.1: The Main Stages of a Generic Nuclear Fuel Cycle (World Nuclear Association, 2025d).

4.3.2 Uranium Mining

The generic nuclear fuel cycle for GW and SMR and most AMR reactors, as shown in Figure 4.1, begins with the extraction and processing of uranium-bearing ores to produce a concentrated form of uranium known as uranium concentrate (U_3O_8), or 'yellowcake'. This is the foundational material for nuclear fuel. The mining and milling stages provide the raw material required for conversion to a fluoride salt of uranium hexafluoride UF$_6$, enrichment in the U^{235} isotope, conversion to uranium dioxide, and ultimately fuel fabrication. AMRs have a slightly different set of end steps depending on the fuel form used.

Uranium naturally occurs in a variety of forms, and the choice of mining method depends on the depth, ore grade, and geological characteristics of the deposit, as well as environmental and economic considerations. There are three primary methods of uranium extraction: open pit mining, underground mining and in-situ recovery. Once mined, uranium ore is processed at a mill to extract and concentrate the uranium into a transportable and stable form.

Ground-based uranium deposits are estimated at 8-12 million tonnes for accessible regions. The amount of ultimately recoverable uranium is essentially linked to economics and market conditions. However, it is widely distributed with many large low-grade deposits not considered economically viable. Open pit and underground mining techniques are typically used, with an increasing proportion (52%) now coming from in-situ leach (ISL) mining. This is where oxygenated groundwater is circulated through a very porous orebody to dissolve the uranium oxide and bring it to the surface. The recovery process involves crushing the ore, leaching it with acid or alkaline solutions, and extracting uranium into a purified oxide form suitable for enrichment and fuel fabrication. Some 4% of uranium comes as a byproduct from extracting copper and phosphate.

4.3.2.1 Uranium Producing Countries

Table 4.1 presents data for uranium mining for the past 10 years. It shows that after a period of oversupply, the market has become more balanced, but with some room for growth. There is geopolitical complexity – for example, China's CGN has a joint venture mine in Namibia, while French company ORANO is investing in Mongolia, backed by investment from both countries, with the aim of producing 2500tU per year by 2029.

Table 4.1: Uranium Production from Mining by Country (tonnes U) (World Nuclear Association, 2025f)

Country	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Kazakhstan	23,607	24,689	23,321	21,705	22,808	19,477	21,819	21,227	21,109	23,270
Canada	13,325	14,039	13,116	7,001	6,938	3,885	4,693	7,351	11,001	14,309
Namibia	2,993	3,654	4,224	5,525	5,476	5,413	5,753	5,611	6,986	73,33
Australia	5,654	6,315	5,882	6,517	6,613	6,203	4,192	4,553	4,693	4,598
Uzbekistan *	2,385	3,325	3,400	3,450	3,500	3,500	3,516	3,561	4,000	4,000
Russia	3,055	3,004	2,917	2,904	2,911	2,846	2,635	2,508	2,710	2,738
China *	1,616	1,616	1,692	1,885	1,885	1,885	1,600	1,700	1,600	1,600
Niger	4,116	3,479	3,449	2,911	2,983	2,991	2,248	2,020	1,130	962
India *	385	385	421	423	308	400	600	600	485	500
South Africa *	393	490	308	346	346	250	192	200	200	200
Ukraine *	1,200	808	707	790	800	744	455	100	340	288
USA	1,256	1,125	940	582	58	6	8	75	19	260
Others	357	277	85	116	116	131	95	108	161	155
World total tU	60,342	63,207	60,462	54,154	54,742	47,731	47,805	49,614	54,433	60,213
% of world demand	98%	96%	93%	80%	81%	74%	76%	76%	83%	90%

*Estimated figures

4.3.2.2 Uranium Producing Companies

Over half of uranium mine production is from state-owned mining companies and is focused on the strategic security of supply. Table 4.2 shows a breakdown of production by the top ten companies, equal to 90% of supply. Kazatomprom, the world's largest supplier, is 63% owned by the Kazakh National Wealth Fund, the Kazakh Ministry of Finance holds 12% of the shares, while the remaining 25% is in free float on the Astana and London stock exchanges.

Table 4.2: Uranium producers by company 2024 (World Nuclear Association, 2025f)

Company	Tonnes U	% of World Total
Kazatomprom	12,463	21%
Cameco	10,193	17%
Orano	6,815	11%
CGN	5,761	10%
Uranium One	5,829	10%
Navoi Mining	4,000	7%
CNNC	3,286	6%
ARMZ	2,738	5%
BHP	2,693	5%
General Atomics/Quasar	1,808	3%
Other	4,627	8%

4.3.2.3 Uranium Mine Ownership

The ownership of individual mines is far more complex than may be expected, with multiple ownership typical, as can be seen in Table 4.3 below.

Table 4.3: The largest-producing uranium mines in 2024 (World Nuclear Association, 2025f)

Name of Mine	Country	Main Owner	Type of Mine/ Production	Production (tonnes U)	% of world
McCarthur River/Key Lake	Canada	Cameco	Underground	7,808	13%
Cigar Lake	Canada	Cameco/ Orano	Underground	6,501	11%
Husab	Namibia	Swakop Uranium (CGN)	Open pit	4,437	7%
Karatau (Budenovskoye 2)	Kazakhstan	Uranium One/ Kazatomprom	ISL	3,299	6%
Inkai, sites 1-3	Kazakhstan	Kazatomprom/ Cameco	ISL	2,992	5%
Akdala & South Inkai 4	Kazakhstan	Uranium One/ Kazatomprom	ISL	2,803	5%
Olympic Dam	Australia	BHP Billiton	By-product/underground	2,693	5%
Moinkum & Tortkuduk	Kazakhstan	Orano/ Kazatomprom	ISL	2,388	4%
Rössing	Namibia	CNNC	Open pit	2,205	4%

Name of Mine	Country	Main Owner	Type of Mine/ Production	Production (tonnes U)	% of world
Khorassan 1	Kazakhstan	Kazatomprom/ Uranium One	ISL	2,030	3%
Top 10 total				37,156	62%

The World Nuclear Association (WNA) has noted that the top producing mines are expected to be depleted in the 2030s, which means investment decisions will need to be made now. While the world currently has plenty of uranium, getting it out of the ground in time to meet the growing demand is not so straightforward. The expected uranium mine development timeline has changed from eight to 15 years to between 10 and 20 years. The good news is that WNA believes that there are significant recoverable resources available to meet even the high demand scenario (World Nuclear Association, 2025f).

4.3.3 Uranium Supply Outlook

WNA predictions indicate that a nuclear renaissance could create opportunities for new entrants and new sources, while increasing prices and pressure on the availability of supply (World Nuclear Association, 2025c). Global reactor requirements for uranium in 2025 are estimated at about 68,920 tU. In the reference scenario, these are expected to rise to just over 150,000 tU in 2040, with requirements rising to over 204,000 tU in the upper scenario and over 107,000 tU in the lower scenario by the same date.

Global uranium production in 2024 reached approximately 71,000 tonnes of U_3O_8 (equivalent to 60,200 tonnes of uranium), a concentrated form of uranium produced through the milling and chemical processing of mined uranium-bearing ores. Kazatomprom (Kazakhstan) remained the dominant supplier, contributing ~39% of global output, followed by Cameco (Canada), Orano (France), Uranium Energy Corp (USA), and NexGen Energy (Canada) (World Nuclear Association, 2025e). Despite strong production figures, supply remains vulnerable due to geopolitical risks and logistical challenges, such as Kazatomprom's sulphuric acid shortages, which disrupted operations.

Kazakhstan's South Tortkuduk mine (a joint venture with Orano) adds 46,000 tonnes of reserves, while Canada's Athabasca Basin and Australia's untapped deposits offer significant potential for future expansion.

Meanwhile, China's claimed breakthrough in uranium extraction from seawater, reportedly achieving 100% recovery in trials, could if proven and scaled unlock access to the ocean's estimated 4.5 billion tonnes of uranium at lower dilutions, much larger than ground-based sources, potentially reshaping long-term global supply dynamics (Guidez & Gabriel, 2016). We believe that this technology is at a lower TRL than media speculation has suggested, but this does reduce concerns about claimed shortage of uranium for future reactors.

4.3.4 Uranium Conversion

This next stage, shown in Figure 4.1, involves converting the natural enrichment level U_3O_8 ore through chemical processing with nitric acid and then fluorine, often in the form of hydrofluoric acid, converting the uranium into uranium hexafluoride (UF_6) such that the fissile isotope U^{235} can be enriched or concentrated in a later stage. This process also removes impurities. Wet and dry processes are used, depending on the location, with a number of interim steps involved before reaching UF_6, a chemically reactive gas which is a tradable commodity on the enrichment market. This gas is cooled under pressure into a liquid and then a solid and is stored in special tankers to transfer to enrichment companies for the next stage of the fuel cycle.This process is often undertaken by the fuel manufacturer, as addressed later, although there are examples of standalone conversion plants.

4.3.5 Uranium Enrichment

The enrichment stage of Figure 4.1 involves the preferential separation of the U^{235} fissile isotope of uranium to leave enriched uranium for fuel use, and depleted uranium or tails, using gaseous UF_6. The international landscape of uranium enrichment services is limited and includes several major organisations that have both the facilities and technological capabilities, generally now based upon centrifuges. The levels of enrichment align with the fuel required, as discussed earlier.

Table 4.4 below summarises the major global enrichment providers, their technological capabilities, strategic roles in the HALEU and LEU+ supply chain, and their compatibility with Norway's regulatory and geopolitical context, particularly in relation to AMR deployment.

Table 4.4: Global Enrichment Providers for LEU+, HALEU and AMR Fuel Supply (Ashkeboussi, 2025; Rosatom, 2024)

Provider	Major Facilities	Technology	Strategic Role	Capacity and Orders	Risks & Challenges
Orano (France) Also investing in US	Tricastin	Gas centrifuge	EU supplier; supports EDF and Nuward reactors	~12% global share	Ageing infrastructure, now investing, including HALEU; dependency on Kazakh feedstock
Urenco (UK/NL/DE/US)	Capenhurst (UK), Almelo (NL), Gronau (DE), Eunice (USA)	Gas centrifuge	Western-aligned supplier; LEU for EU & US	~15% global share; expanding HALEU capabilities	Limited current HALEU output; regulatory constraints
Rosatom (Russia)	Angarsk, Zelenogorsk, Novouralsk, Seversk	Gas centrifuge	Largest global supplier; key for LEU & HALEU	~40% of global enrichment	Geopolitical risk; sanctions; Western phase-out
JAEA (Japan)	Rokkasho (pilot – not operational, but currently being restarted)	Gas centrifuge	Strategic reserve; limited commercial role	Minimal exports; domestic focus	Earthquake risk; public opposition
CNNC (China)	Lanzhou, Hanzhong, Shaanxi	Gas centrifuge; R&D on laser	Strategic autonomy; supports domestic reactor fleet	~17% global share; growing rapidly	Transparency; export limitations

WNA assessments show that global scale enrichment supply exceeds demand through to at least the early 2030s. However, there are capacity issues for HALEU and LEU+ that are essential for some AMRs. Currently, only a few facilities, primarily Centrus Energy (USA) and Rosatom (Russia), produce HALEU UF_6 at scale, with geopolitical factors limiting access to Russian supply. It is worth noting that despite the high level of interest in AMRs, there are very few firm orders for fuel.

There are several emerging fuel providers, including:

- **General Matter**, a California-based startup, was selected by the U.S. Department of Energy in October 2024 to help establish a domestic supply of HALEU. The company is developing a private-sector uranium enrichment facility on a 100-acre site at the former Paducah Gaseous Diffusion Plant. It will use existing uranium hexafluoride stockpiles for re-enrichment. Operations are expected to begin by the end of the decade. Nano Nuclear has also acquired a laser enrichment company.
- **Centrus Energy** is competing for a share of $2.7 billion in U.S. Department of Energy funding, alongside European fully or partially state-owned entities like Orano and Urenco (U.S. Department of Energy, 2025).
- **Quantum Leap Energy** announced in November 2025 that it has started early regulatory engagement with the UK ONR to explore the deployment of uranium and other isotope enrichment technologies in the UK.
- **Global Laser Enrichment (GLE)** is expected to be a future HALEU supplier with facilities at Piketon, Ohio (HALEU demo plant) using Gas centrifuge; SILEX (JV) currently at small-scale but aiming to expand to 600 Mt/yr.

Several enrichment suppliers are working hard to offer alternative HALEU sources. Excluding Russia or China, HALEU TRISO fuel supply at significant levels is limited outside of BWXT. However, stimulated by US and UK investment, work proceeds at pace and should not concern a 2040-2050 potential deployment horizon. Recent progress is being made by manufacturers such as X-Energy, for example, which started construction of a fuel manufacturing plant and irradiation of trial fuel in November 2025.

Given the maturity of enrichment technology and the speed of construction, it is possible to design, build and put into operation an enrichment facility in a timely manner.

HALEU enrichment capacity is largely being driven by the AMR market, and in particular, coated particle fuelled reactors. Fuel manufacture of HALEU coated particle fuel is at a lower level of readiness. However, investment driven by the US Government is stimulating growth in the availability of feedstock, HALEU enrichment and HALEU coated particle fuel manufacturing to support global delivery. The UK Government has also invested in enabling HALEU enrichment and in UK research into coated particle fuel production. US and Canadian regulators issued a joint statement on the value of the evidence base for coated particle fuel from the Advanced Gas Reactor programme, which the UK regulator also engaged with. Framatome and ORANO are moving ahead with investments in this area.

4.3.6 Fuel Fabrication

The first step in the fuel fabrication stage of Figure 4.1 is deconversion. This is where the enriched UF_6 must be reconverted to uranium oxide or metal for fuel fabrication. This is done in a Deconversion plant, typically following a three-stage process. The first step is to react the UF_6 with water to form UO_2F_2, which is exothermic and must be controlled to avoid hydrogen fluoride release. The UO_2F_2 is reduced in a high temperature furnace using hydrogen gas, converting it to the key tradeable product, UO_2, a fine black powder suitable for pressing and sintering into fuel pellets.

The subsequent step of fuel fabrication transforms the UO_2 powder into ceramic pellets, into tubes or fuel pins, and then into finished nuclear fuel assemblies suitable for reactor use. Fuel assemblies are the robust, dimensionally precise fuel elements designed to operate safely and reliably under the demanding conditions of an LWR. The process begins with powder conditioning, in which the UO_2 powder is blended and processed to achieve the specified particle size distribution, density and chemical purity. Impurities such as fluorides are limited to prevent adverse effects on fuel performance and cladding interaction during irradiation. The powder is compacted into pellets that are slightly larger than their finished specification in anticipation of shrinkage during sintering, the next step in which the pellets are densified to provide the required mechanical strength, thermal conductivity and fission gas retention characteristics. Once sintered, the pellets undergo grinding and finishing to achieve precise dimensional tolerances and surface quality. These operations are critical to ensuring uniform heat transfer, minimising cladding wear, and maintaining proper pellet-to-clad clearance during reactor operation. A comprehensive inspection and quality control programme follows to verify compliance with specifications.

The qualified pellets are loaded into cladding tubes fabricated typically from zirconium alloys, and the pellets are stacked to a prescribed height within each tube, leaving a plenum volume to accommodate fission gas release. A stainless steel or zirconium alloy spring may be inserted above the pellet column to maintain axial restraint forming fuel rods. Fuel rods are sealed by welding end plugs with each rod inspected by non-destructive examination. Individual fuel rods are assembled into fuel assemblies, with completed assemblies subjected to mechanical integrity and hydraulic tests to confirm flow characteristics, structural stability and dimensional accuracy.

The supply market capacity for powder, pellets and finished fuel is summarised in Table 4.5 below. Some fabricators do not have conversion facilities and buy such services, whilst others provide UO_2 powder for pelletizing elsewhere.

Information has been removed from Table 4.5 for Orano Malvési, as this plant converts to uranium tetrafluoride (UF_4). The plant has increased production by 50%, which gives an idea of the investments taking place. French company Framatome has announced its intention to construct a new nuclear fuel fabrication facility in the UK. Terrestrial Energy Inc signed an AMR manufacturing and supply contract in November 2025 with Westinghouse subsidiary Springfields Fuels Limited for the design and construction of an Integral Molten Salt Reactor fuel pilot plant for 5% salt-based fuel. Westinghouse and JSC “NNEGC “Energoatom””, Ukraine’s national nuclear power company, signed an agreement to jointly pursue final fuel assembly capability in Ukraine. Westinghouse is creating LEU+ fuel manufacturing capacity at its Columbia Fuel Fabrication Facility and has also produced LEU+ fuel in the UK.

Figures for mining volumes and fuel differ because mining is based on natural uranium, and fuel manufacture uses enriched fuel, while some uranium is destined for other reactor designs. The current fabrication capacity oversupply needs to be contrasted with demand, which currently sits at about 10,000 tU but is about to change. A WNA report in September 2025 suggests that existing fabrication capacities are sufficient to cover the need for several years, but rising demand from 2027 onwards, especially for new reactor types, will require technological investment, capacity expansion, and market adaptation. Whilst market trends indicate the potential to add significant reactor capacity, the impact on new fuel will be offset by older reactors closing.

Table 4.5: World LWR fuel fabrication capacity, tonnes/yr (WNA, 2025)

Country	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Brazil	INB	Resende	160	120	400
China	CJNF Jianzhong	Yibin	800	800	800
	CBNF	Baotou	0	0	400
	CNNFC	Baotou	200	200	200
France	Framatome-FBFC	Romans	1,800	1,400	1,400
Germany	Framatome-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	383	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global Nuclear Fuel – Japan	Kurihama	0	620	630
Kazakhstan	Ulba	Ust Kamenogorsk	0	108	200
Korea	KNFC	Daejeon	700	700	700
Russia	TVEL-MSZ (including RBMK fuel)	Elektrostal	1,500	1,500	1,560
	TVEL-NCCP	Novosibirsk	450	1,200	1,200
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	787	600	600
UK	Westinghouse (including AGR fuel)	Springfields	950	600	860
USA	Framatome Inc	Richland	1,200	1,200	1,200
	Global Nuclear Fuel – Americas	Wilmington	1,200	1,000	1,000
	Westinghouse	Columbia	1,600	1,594	2,154
Total			12,645	13,913	15,476

4.3.7 Reprocessing

The market for reprocessed fuel is currently poor due to low prices for fresh uranium. Given the demand that may materialise, uranium prices are expected to rise. This may lead to a revival in interest in the future, with a projected large increase in nuclear power globally and depletion of natural reserves.

Reprocessing takes place after fuel is removed from the reactor and an initial period of interim storage. The spent nuclear fuel can be sent to a reprocessing facility for the recovery of reusable fissile materials. Reprocessing forms an optional but integral stage of the closed nuclear fuel cycle, designed to extract uranium and plutonium from irradiated fuel, reduce the volume and toxicity of high-level waste, and recycle valuable materials for new fuel fabrication. Reprocessing involves a combination of mechanical and chemical separation steps that dissolve the spent fuel and separate its constituents into recoverable materials (U and Pu), fission products and minor actinides, which are immobilised as waste, and structural materials such as zirconium cladding, which are treated as solid radioactive waste.

Reprocessing capacities are currently limited, but those plants that have capacity, such as La Hague (France) and Rokkasho (Japan), use PUREX (Plutonium and Uranium Recovery by Extraction), an aqueous solvent extraction method developed for large scale operations.

4.3.8 Geopolitical Considerations

Obtaining a secure fuel supply is critical to operations. Other than simply supply issues, there are other geopolitical considerations to consider. Some recent aspects that are being highlighted are presented in Table 4.6.

Table 4.6: Geopolitical considerations for secure nuclear fuel supply.

Russia's Nuclear Fuel Demand and Supply	Russia, through Rosatom, produced approximately 2,598 tonnes of U_3O_8 in 2024, ranking sixth globally. While its raw uranium output is modest, Russia plays a strategic role in the nuclear fuel cycle, controlling 14% of uranium concentrate supply, 27% of conversion capacity, and 39% of enrichment capacity (Cameco, 2023). This dominance in downstream services makes Russia a critical supplier, even as Western utilities seek alternatives due to geopolitical tensions. Russia's domestic nuclear fleet and its export commitments to Soviet-designed reactors abroad (e.g., VVER-440 and VVER-1000 units and their more recent models) drive substantial demand for nuclear fuel. TVEL, Rosatom's fuel subsidiary, continues to supply fuel to European VVER reactors in Hungary, Slovakia, Bulgaria, Finland, and Ukraine, although many of these countries are actively transitioning to Western suppliers of VVER fuel like Westinghouse and Framatome, subject to qualification and licensing of new fuels. Despite sanctions, Russian nuclear fuel exports remained resilient in 2024, with some European countries increasing imports to maintain operational continuity.
General Atomics: ISR Innovation in New Mexico	General Atomics, through its affiliate Grants Energy, is advancing uranium production in New Mexico via the Grants Precision ISR project. This initiative combines in-situ recovery (ISR) with horizontal drilling, aiming to reduce environmental impact and carbon emissions. Production is slated for the early 2030s.
Peninsula Energy Limited: Lance Uranium Project	On the 16th of September 2025, it was announced by Peninsula Energy Limited and its wholly owned subsidiary, Strata Energy Inc., that the Lance Central Processing Plant in Wyoming had produced its first dried yellowcake since 2019, making Peninsula Energy Limited a fully independent, US end-to-end producer of uranium, again using more environmentally sensitive means. The ASX-listed uranium company is now scaling up the production of dried yellowcake, targeting full-scale production of 680 tonnes of U_30_8 from 2028 onwards. Whilst this is not significant compared to global production, investment in US uranium mining exploration has now started to turn back up, in part through some success at this project site.

4.3.9 Opportunities for Norway

In forming thoughts about how Norway may look to secure fuel supplies and use the developing opportunities within the Fuel Cycle, the following should be considered against the potential fuel demand. If Norway should consider deploying nuclear power, a future long-term fleet might consist of five GW reactors and 10 SMRs. In such a case, this would create a fuel demand, depending on fuel type and burnup, of around 1,500 – 2,500 tonnes U_3O_8 annually. It is unlikely to create meaningful economic opportunities for Norway to participate in the fuel cycle other than for strategic reasons. It would represent about 2.5% of current global output, necessitating long-term partnerships and contracts with potential suppliers that are robust. Given the direction of the market, the future availability of uranium or fuel fabrication services is not seen as a major risk. However, it should be kept under review.

- **Uranium Extraction**: Based on available information, Norway does not have substantial uranium deposits, so mining and extraction look unlikely.
- **Fuel Enrichment to Fabrication**: Enrichment is expected to remain international, where Norway could source UF_6 enriched to LEU, LEU+, or HALEU from trusted partners such as Urenco or Orano. Both are aligned with European regulatory frameworks and have scalable infrastructure. Westinghouse Electric Company (WEC) currently operates a major conventional fuel fabrication facility in Västerås, Sweden, supplying up to thirty reactors across Europe. Sweden, like Norway, has no active uranium mining but benefits from EURATOM-aligned sourcing and regional collaboration. Major suppliers like Urenco, Orano, and Centrus already serve Western markets, and expanding enrichment in Norway would offer limited strategic or economic advantage. This may change beyond the 2030s.

Any desire to consider Fuel Enrichment to Fabrication should be addressed through rigorous studies and assessments set against clear goals and objectives that recognise Norway's capabilities. There are several significant barriers to entry requiring substantial investment, advanced safeguards, and international licensing, which are impractical for an emerging nuclear country with no prior commercial nuclear infrastructure. Mid-Term (2030–2040), options could be to evaluate and consider in more detail LEU, LEU+ and HALEU needs for GW, SMRs and AMRs and consider joint ventures or licensing agreements for advanced fuel fabrication. Firm contracts based upon existing suppliers would likely need to be signed in the early to mid-2030s.

Norway's current exclusion from EURATOM complicates integration into shared European enrichment frameworks and safeguards. Assessment of EURATOM membership is considered an important step, as discussed in Chapter 2. Enrichment capabilities are tightly controlled under international treaties, and Norway's strong non-proliferation stance makes domestic enrichment politically and diplomatically complex.

Regardless of the above, should Norway progress to deploy nuclear power, the immediate consideration would be to determine a robust nuclear fuel strategy to support the operation of the plants deployed. To note, the initial fuel supply should be undertaken by the technology vendor to enable confirmation of performance and retain commitment to achieving Commercial Operations Date (COD). The technology vendor should also provide full fuel specifications that enable the future sourcing of fuel. A sourcing strategy should be developed during the early stages of the programme that can consider full fuel services or component procurements and consider sourcing and pricing along with future security needs.

4.3.10 Key Observations

Should Norway choose to adopt nuclear power, it should:

- Develop a fuel strategy that aligns Norway's strategic intent and provides future security of supply.
- Ensure the strategy developed is aligned to the nuclear plant procurement approach.
- Consider whether to become involved in the fuel cycle at a later date.

4.4 Nuclear Power Plant Supply Chains

This sub-chapter explores some key supply chain aspects.

4.4.1 Nuclear Power Plant Components and Key Plant Equipment

Nuclear power plants consist broadly of a Nuclear Island (NI), a Conventional Island (also known as Turbine Island) and the Balance of Plant (BOP) that usually includes several significant structures, including secondary cooling, switch yard and a range of auxiliary buildings and structures, as illustrated in Figure 4.2 for a PWR reactor.

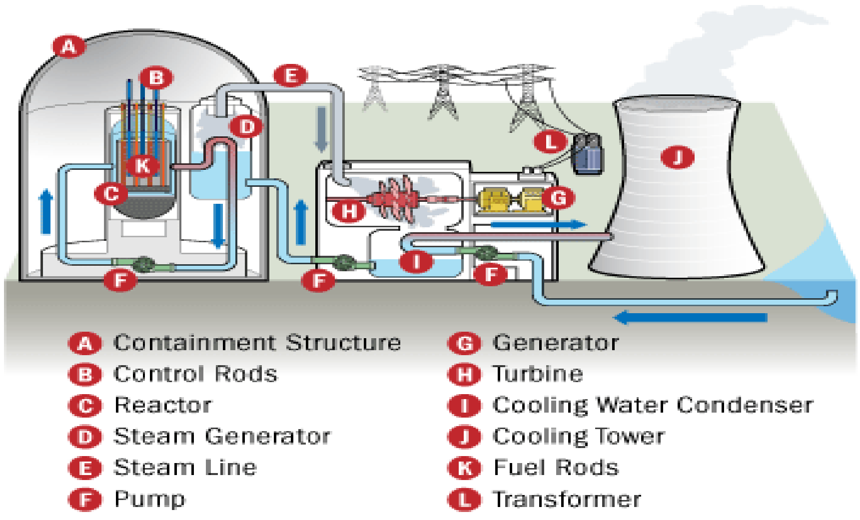

Figure 4.2: Main nuclear power plant components for a PWR reactor (Kiger, 2011).

4.4.2 Typical Nuclear Power Plant Supply Chain Model

In the context of the supply chain, there are several tiers, as shown in Figure 4.3, that will be organised by way of a commercial delivery model of choice, e.g. EPC, EPCm etc. These companies will be charged with the design and construction of the plant and support to commissioning into full operations. In some countries, the Developer will be the same organisation as the Operator-Licensee, but that is not universal. In any case, that aspect of the project will present a major transition, as the future plant has to be capable of being licensed in the context of a specific Operator. Engagement will be through complex contractual mechanisms requiring significant development and agreement.

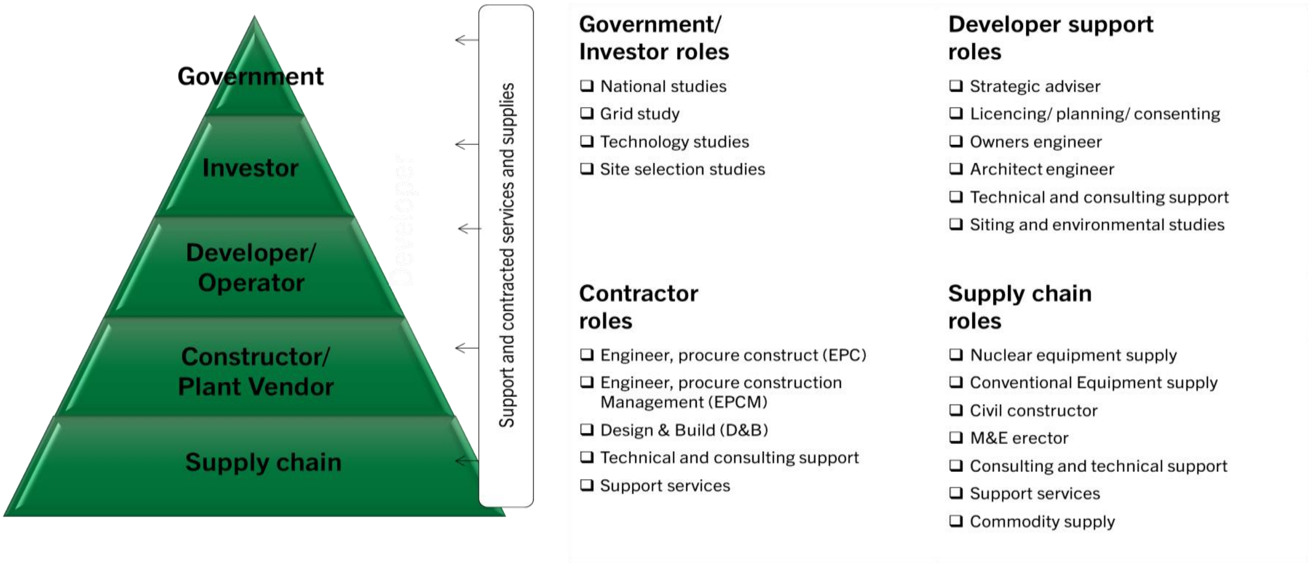

Figure 4.3: Supply chain model for nuclear power.

The supply chain for the construction of the nuclear power plant will comprise a range of programme, technical, engineering and construction services and, equipment supply, including many nuclear safety graded components. It will include the Technology Vendor (TV) or reactor vendor for the NI, and usually a General Contractor (GC) of some sort that will undertake the civil, electrical and mechanical works along with full responsibility for the CI and BOP. Some steam turbine manufacturers provide an integrated TI service. Some TVs provide a full power plant; some focus on the NI. Numerous consultants will also be required to support the activity. This is illustrated in Figure 4.3.

There are many supply chain considerations within this context including how to engage the constructor and technology vendor when selected, and how this will be accomplished. To note, not many technology vendors will perform as an EPC. This means that in selecting technology, the delivery model is also being decided. How the developer will engage with the rest of the supply chain to ensure its obligations are met from a safety and quality perspective is a major consideration. To note, there are severe constraints in gaining a credible supply chain and numerous challenges within the market regarding some key components, such as steam turbine, transformers etc. These have not been addressed, as they are outside the scope of this report, but are noteworthy. This report, therefore, as required, focuses on the major NI reactor components that are largely classified as Class 1 nuclear safety critical components requiring specific treatments throughout design, manufacture and installation. Furthermore, all these aspects will need consideration, along with any Norwegian strategic intent to create local content and capabilities. Norway will need a capacity plan covering all aspects.

4.4.3 Long Lead Items

Committing to Long Lead Items (LLI) prior to Final Investment Decision (FID) will need to be considered in order to secure timely supply on a realistic programme timeline. Typically, these include Reactor Pressure Vessel (RPV), Pressuriser, Steam Generator(s) (SG), Primary Valves and Pumps, Steam Turbines, Protection Systems, Coolant Pump(s) and Main Steam Isolation Valves, Nuclear Grade Cranes and so on. This would represent a considerable commitment. Our knowledge of the market indicates that the program timelines are tightening, and capacity could present a risk. With the SMR market developing, this may open further capacities, but this remains to be seen.

4.4.4 Operator Capability

Fairly early on in any programme, the approach to acquiring operator capabilities will need to be addressed with adoption of a clear strategy. This will need to consider supply chain aspects for support and outages in procurement specifications at the BIS stage onwards.

4.4.5 Preparing for New Entrants to Nuclear Programs

There are many opportunities for local supply chain participation if strategically established from the onset. The areas most likely to feature are those not linked to items that are deemed to be classified as Nuclear Safety Critical. This should be considered within the context of a National Capacity Development Plan that should focus on a set of clear strategic objectives. Opportunities will include performing construction and fabrication tasks and delivering non-nuclear supplies. Supply chain categories for nuclear programs are illustrated in Figure 4.4.

Figure 4.4: Supply chain categories

4.4.6 Major Reactor Components

The major components in either LWR GWR, or SMR technologies include the Reactor Pressure Vessels (RPVs) and Nuclear Steam Supply System (NSSS) components. All have the highest nuclear quality as they form part of a safety critical system. The NSSS components typically include steam generators, reactor coolant pumps and valves, coolant lines and pressurisers as highlighted in Figure 4.5. The number and size are determined by the thermal output and the number of loops included, normally up to four. Components are similar for AMR, but not the same, as AWRs use different nuclear technologies than LWR.

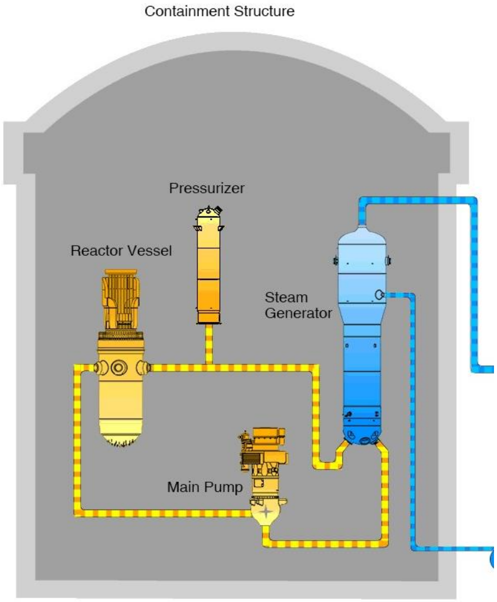

Figure 4.5: Main NSSS Components of a PWR Reactor (Environment Agency, 2023).

The RPV and NSSS components require advanced materials, ultra-heavy forging capacity, precision engineering, and compliance with stringent nuclear safety and quality codes and standards. Globally, there are only a very limited number of specialised companies that possess the capability and certifications to produce these components. This has created capacity challenges in deployment, especially for large-scale reactors requiring larger components. These companies have taken many decades to develop these capabilities in terms of having the skills, capabilities, processes, tools and very large equipment necessary. The quality framework for operating in nuclear, while based on fundamental standards like ISO 9001, presents challenges for non-nuclear companies in adapting to additional codes and standards. Examples include ISO 19443 and ASME NQA-1, as well as requirements to produce defect-free, high-integrity vessels, piping, and pumps with rigorous inspection during and after manufacturing. This work involves both large scale metal forging with very tight materials tolerances, down to fine tolerance machining and high-quality welding. It involves mastery of design codes and interpretation of those codes in terms of component manufacturing quality. The techniques used for inspection for defects and addressing repair are complex. The components themselves are expensive.

4.4.7 Comparison of the Major NSSS components in the Technologies

The challenges between GW and SMR reactor concerning major NSSS components are considered as follows in Table 4.7.

Table 4.7: Challenges concerning major NSSS components for GW and SMR reactors.

Reactor type	Challenges
GWRs	Widely deployed requiring ultra-heavy components: • RPVs forged from steel ingots of 500–600 tonnes. • Forging presses of 14,000–15,000 tonnes. • Complex welding, heat treatment, and inspection facilities. • Increasing levels of mega-modularisation. These capabilities are concentrated in a few firms (e.g., Japan Steel Works of Japan, Doosan of Korea, Framatome, of France), with global throughput limited to 4–6 RPVs per year.
SMRs	Described as modular and scalable. While some components are smaller and more standardized, this does not apply universally, particularly for some Light Water Reactor (LWR)-based SMRs, which still require: • Large RPVs and steam generators. • High-integrity pressure boundaries. • Specialized manufacturing and transport logistics. • Some have stick built nuclear steam supply systems. • Some have extensive equipment modularisation. As a result, LWR SMRs may not benefit fully from factory-based mass production, and their modularity is often limited to site assembly and auxiliary systems, not core reactor components.
Smaller SMRs and AMRs	Potentially offer a more innovative alternatives that could, if proven, have and provide slightly different supply chain opportunities as follows: • Some have lower pressure reactors that may offer alternatives for large components beyond the current NSSS manufacturers. • If there was a fleet, components are smaller and more standardized. Factory-based mass production is feasible. Easier transport and on-site assembly. • Broader family of reactors, some require new materials. • Require specialized components like molten salt pumps, high-temperature materials, and advanced fuel handling systems. • Often involve novel alloys and ceramic composites for high-temperature operation. • Manufacturing is more R&D-intensive, with fewer suppliers currently capable. More versatile, often designed for co-generation (electricity + heat), hydrogen production, and industrial decarbonization.

4.4.8 Nuclear Steam Supply System Market

The global NSSS market is projected to grow from $9.5 billion in 2024 to $14 billion by 2032 (Phapale, 2025), driven by the demand for clean energy, safety innovations, security and the rise of SMRs. In Europe and North America, there are challenges of ageing infrastructure, supplier attrition, and regulatory fragmentation, while advanced economies like China and Russia are expanding their global footprint through state-backed nuclear exports.

The European Industrial Alliance on SMRs focuses on harmonisation and reducing barriers for a potential EU based SMR and includes addressing how to rebuild the supply chain. The Alliance aims to facilitate the development and deployment of SMRs in Europe. Participation is open to various stakeholders, including:

- Project promoters and financial institutions.
- Regulators and researchers.
- Training centres and civil society organizations.
- Policymakers and industry representatives.

This alliance seeks to create a European platform for collaboration to accelerate the deployment of SMRs by the early 2030s. As a European Economic Area EEA state, Norway can provide supporting organisations to work as members of the Alliance (European Commission, 2024).

4.4.9 Industrial Giants in Reactor Component Manufacturing

The global supply of RPVs and NSSS components is dominated by a small group of firms with the necessary forging capacity, certifications, and nuclear-grade quality control. These firms are essential to the deployment of both large reactors and SMRs/AMRs.

- **BWXT (USA/Canada):** A critical supplier of RPVs, steam generators, and heat exchangers. BWXT operates major facilities in Cambridge, Ontario, and Barberton and Mount Vernon, Ohio, and is one of the few North American firms capable of manufacturing large nuclear components. Recently announced as the designer and supplier of steam generators for the R-R SMR. BWXT will produce the RPV for the inaugural BWRX-300 SMR, in construction at Ontario Power Generation’s Darlington New Nuclear Project site in Canada. BWXT announced an expansion in 2024.
- **Doosan Enerbility (South Korea):** Manufactures RPVs, steam generators, and other NSSS components for Korean and international projects. Investing in capability and capacity to support SMR and AMR plants. It supplies NuScale and X-energy.
- **ENSA (Spain):** Has manufactured nuclear large components such as reactor pressure vessels since 1981, supplying nine to Spanish nuclear plants and others in the United States, India and South Africa.
- **Forge Monchieri (Italy)**: Italian Forgemaster operating for over 50 years at the 100t level, with qualifications and track record for some smaller RPVs (or parts of), SGs, Pressurisers, and Reactor Coolant Pumps. It has been estimated that the Italian nuclear industry, which is extensive for a currently non-nuclear country, including FM, could produce 8 SMR RPVs per year (Polytechnic University of Milan, 2023).

- **Framatome (France):** Specializes in NSSS components, especially Steam Generators, main piping, and RPVs, also sourcing the very largest forgings from JSW*. Works within a broader French-German supply chain. Strategic suppliers for EDF designs of reactors.
- **Mitsubishi Heavy Industries (MHI, Japan):** Supplies components for PWRs and advanced reactors, including steam generators and internals.
- **Japan Steel Works (JSW, Japan)*:** One of the few facilities globally capable of forging ultra-heavy RPVs (>500 tonnes). Supplies components for large reactors and some SMRs.
- **Rosatom (Russia):** Through subsidiaries like ZiO-Podolsk and Atommash, manufactures RPVs, steam generators, and internals for VVER and fast reactors. Supplies both domestic and export markets, including floating reactors and SMRs like RITM-200.
- **Shanghai Electric / Harbin Electric / Dongfang Electric (China):** Rapidly expanding capacity for large reactor components, including AP1000-class RPVs and steam generators, as well as indigenous designs. Dongfang Electric has delivered an indigenous steam generator to Fuqing Hualong One GW reactor.
- **Sheffield Forgemasters (UK):** Now owned by UK MoD, this experienced forgemaster with a growing Defence sector mission is investing in a new forge. It is growing and seeking further investment to meet demand from SMR and AMR clients, although without the current capacity to extend in this market beyond the core mission. Involved in several MoUs with SMR and AMR vendors, including Holtec.
- **ŠKODA JS a.s. (Czech):** manufactures a variety of nuclear components, including complete VVER reactors. They claim production of 21 complete VVER-440/V-213 type reactors and three VVER 1000/V-320 type reactors. R-R SMR has signed a memorandum of understanding with Škoda to explore the fleet production of key components. May feature in the delivery of the KHNP scope in Czechia.
- **Reactor Forging Consortium (USA)**: RFC was established to support the NuScale programme, comprising three primary members: **North American Forgemasters (NAF),** which specialises in large alloy and stainless-steel forgings; **Scot Forge,** which provides a range of forging services and products for various industries, including nuclear; and **ATI Forged Products,** which offers advanced forging solutions and materials for critical applications. Capable of producing large, complex forgings with piece weights exceeding 160 tons.
- **Westinghouse (USA):** Nuclear Components Manufacturing (NCM) facility in Newington, New Hampshire has been producing large ASME Code and safety-related NSSS adjacent nuclear components for over 40 years, including core barrel, control rod drive mechanism, reactor coolant pumps.

Despite Westinghouse's U.S. origins, NSSS components for AP1000 and AP300 are often sourced internationally. This is due to limited ultra-heavy forging capacity in the U.S, established manufacturing partnerships in China (e.g., Harbin Electric, Shanghai Electric) for AP1000 deployments, and cost and timeline efficiencies from leveraging existing supply chains in Canada and Asia. Sourcing relies on international partners such as AP1000 NSSS components for Chinese deployments manufactured by Harbin Electric and Shanghai Electric under technology transfer agreements, and for AP300, Westinghouse is expected to leverage existing AP1000 supply chains, with potential sourcing from Europe or Asia, depending on deployment location.

This international sourcing reflects a globalized nuclear supply chain, where technology ownership and component manufacturing are often distributed across regions. The implication for global deployment is that there will be supply bottlenecks because of the limited capacity constraints of global reactor deployment timelines.

Furthermore, geopolitical dependencies mean that countries must navigate strategic partnerships to secure component supply. Firms like Westinghouse have transferred technology to China, enabling local manufacturing for AP1000 technology, for example. Technology transfer on SMRs enables broader participation and IP development.

The move to SMR/AMR with some smaller forgings will enable new entrants into the list and allow current manufacturers to increase their area of supply – for example, a proposed US Reactor Forging Consortium, who signed a collaboration agreement with NuScale.

4.4.10 Supply Chain Risks and Mitigations

The NSSS nuclear supply chain faces a complex and evolving set of risks and constraints that impact both operational reliability and future development. These challenges are particularly acute in Europe but reflect global trends. The main risks and constraints are outlined in Figure 4.6 below.

Figure 4.6: NSSS Component Risks and Mitigation Measures

Risks	Mitigations
Obsolescence of OEMs and Legacy Components	
Many of the original equipment manufacturers (OEMs) have exited the nuclear market or discontinued legacy product lines. Replacement parts for NSSS components (e.g., some OEM reactor pressure vessel heads, steam generators, control rod drives) are unavailable. There is a challenge to ensure that obsolete equipment does not become part of new plant construction. This also means that the remaining supply chain is serving both new build and existing customers.	• Strategic Spare Stockpiling: Maintain inventories of critical NSSS components and materials. • International Collaboration: Share qualification data and component specifications across utilities. • In occasional cases outside the NSSS, Commercial Grade Dedication (CGD): Use of high-quality industrial-grade components with rigorous qualification and dedication processes. Reverse Engineering: Recreate legacy components using modern manufacturing techniques. • The lifetime extension market creates extra pressure on NSSS supply for new build that can only be mitigated through advance procurement and supporting investment in scaling up plant.
Qualification Bottlenecks	
Qualification of NSSS components to nuclear-grade standards is costly and time-consuming. There is a persistent lack of harmonized qualification protocols across countries which delays procurement and increases costs.	• Advance engagement on qualification and adopting approaches already used in other regulatory regimes. • Key mitigations for SMR and AMR design are through the minimisation of safety categorised equipment, such as backup generators for example, and use of passive systems by design. • Graded Approach: Apply risk-informed qualification based on safety significance (e.g., Safety Class 1 being highest vs. Safety Class 2 and

	3. Classification of SSCs drives the level of QA, design rigor, inspection, maintenance and ensuring that the plant can deliver the safety function(s) under all operational and fault conditions. The classification drives the defence in depth required. Higher classification imposes more rigor). • Benchmarking with Non-Nuclear Industries: Leverage standards from oil & gas and aerospace sectors (e.g., API, ISO 9001). • European Harmonization Initiatives: Develop common CGD guidelines and qualification frameworks (e.g., CEN Workshop 64 - a forum of nuclear code experts helping harmonise standards across Europe under CEN (Comité Européen de Normalisation))
Limited Forging and Manufacturing Capacity	
Large forgings for GW and some SMR NSSS components (e.g. reactor pressure vessels, steam generator shells) are only available from a few global suppliers (e.g., Japan Steel Works). The lead times are long, and reservation costs are high (up to 30% of component cost).	• Advance Procurement Planning: Secure forging slots early in project timelines. Check prioritisation of the supplier's orders and pipelines rigorously by asking for evidence to be provided transparently (order book, future contracts etc.) • Diversification of Suppliers: Encourage qualification of alternative suppliers in Europe and North America, even if this may require a small investment. • Advanced Manufacturing Techniques: Explore additive manufacturing and powder metallurgy for selected parts. • Smaller forgings allow for a wider supply chain in some designs.
Regulatory Fragmentation	
Different countries apply different nuclear codes (ASME, AFCEN, KTA), limiting cross-border component use. Regulatory conservatism hinders acceptance of alternative standards or modern technologies.	• Code Reconciliation: Perform structured comparison and justification of alternative codes. • Regulatory Engagement: Involve regulators early in CGD and qualification discussions. • Pilot Projects: Demonstrate successful use of alternative standards in NSSS applications
Cybersecurity and Digital I&C Integration	
There is an increasing use of digital instrumentation and control (I&C) in NSSS which introduces cybersecurity vulnerabilities. The Commercial off-the-shelf (COTS) digital components may lack nuclear-grade robustness. Most regulators now accept digital control and protection systems	• Digital CGD Frameworks: Apply IAEA NR-T-3.31 and Electric Power Research Institute (EPRI) guidelines for digital component justification. • Cybersecurity Protocols: Implement secure development lifecycle and vulnerability assessments. • Redundancy and Diversity: Use diverse I&C architectures to mitigate common-cause failures.
Ensuring quality and compliance with codes and standards	
There have been several observations of critical quality issues including material qualities, quality	• Demand high quality standards. • Ensure compliance.

processes and suspect items that can have prefund impacts on programme timescales and costs	• Incorporate quality controls. • Inspect and observe at all critical stages.

Despite certification, NuScale's initial flagship project was terminated in November 2023 due to escalating costs (up to $9.3 billion) and insufficient subscription from municipal partners. However, NuScale has signed an agreement with ENTRA1 Energy and Tennessee Valley Authority (TVA) for the deployment of 6GWe of NuScale SMR capacity across TVA's service region. Deployment in Romania is also targeted. The EU faces a fragmented regulatory landscape, with significant disparities in licensing procedures and safety standards across member states. The EU SMR Industrial Alliance has been set up to explore harmonisation at pace and is exploring nine different designs with real projects.

The French Government is investing heavily in AMR projects, several of which have moved into regulatory engagement. We believe that these projects are some distance away from achieving supply chain certainty.

In Poland, two companies have requested "general opinions" from the Polish regulator PAA for SMRs; one related to GEV BWRX-300 and one related to NuScale VOYGR. As these processes progress, it will be important to understand how supply chain opportunities emerge, as early entrants may start to identify localisation opportunities.

Sweden and Czechia have an active focus on SMR deployment. Estonia and Finland are also active. Finland is reviewing its regulatory approach to future reactor deployment.

In Belgium and Italy, it appears that both SMR and AMR opportunities may progress. Italy is just starting to explore how to expand its nuclear regulator.

4.4.11 Current Demands on the Supply Chain

Chapter 2 indicates there are many ongoing orders for projects and overall plants, mostly GW types that should be monitored to understand how this will impact developing supply chains in future. In the SMR and AMR markets, whilst there is much speculation about such designs and related projects, in most cases this has not yet fed into confirmed orders. Where contracts exist, they typically refer to design support, or agreements to work together in principle. With many components being the same or similar to existing components for the SMR market, it will be interesting to see how the global supply chain responds. Projects to watch in terms of how the European supply chain will develop include:

- Westinghouse: AP1000 units in China; selected for Poland, Bulgaria, Slovakia, and Ukraine and possibilities in the USA, including the restart of VC Summer.
- GEV Hitachi: BWRX-300 chosen by Ontario Power Generation and Orlen Synthos Green Energy, with a focus in Poland.
- Rosatom: VVER reactors under construction in Türkiye (Akkuyu), as well as Egypt (El Dabaa), and India.
- Rolls-Royce SMR: UK government-backed deployment with multiple sites in UK and Czechia under consideration. As of November 2025, R-R SMR is negotiating to deploy three units at Wylfa in the UK.

- KHNP: deployment of two APR1000 at Dukovany in Czechia, addressing EU and local requirements, including localisation through Skoda and similar suppliers. The KHNP deal provides an option to have two more units built at the other nuclear plant in Temelín.

4.4.12 Key Observations

Should Norway choose to adopt nuclear power, potential areas to addressed regarding the nuclear power plant supply chain include:

- Choice of supply chain/ delivery model.
- How to secure and lock in supply chain critical items.
- How Norway wishes to benefit economically and strategically from its significant investment.
- What capacities Norway seeks to develop to support the deployment of nuclear power.
- The supply chain risks inherent in any technology choice.
- Whether early investment will be necessary to secure appropriate manufacturing slots.
- How quality in these critical components will be achieved and ultimately confirmed.

5 Costing

5.1 Chapter Summary

As discussed in chapter 1 the global nuclear market is increasing, where 438 reactors operate and 70 are under construction, primarily large Gigawatt-scale (GW) light water reactors (LWRs). About 100 power reactors are planned, and over 300 more are proposed. A new generation of Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) is emerging, where deployment of SMR technology is promising, with lower costs through factory construction and modularisation. AMR technologies are being progressed but these are not addressed they are speculative and a long way from being fully deployable, as discussed in Chapters 2 and 4.

The market is dominated by Russia and China. However, the USA is beginning to wake up as a result of the demand for energy associated with AI-based data centres. We expect that the cost of deploying both GW and SMR technologies will fall, in line with rising volumes and the shift from first-of-a-kind to nth-of-a-kind. This applies to GW and SMR technologies to different extents, with SMRs expected to benefit more.

Other than plant acquisition, costs and timescales are heavily impacted by adaptation of technology to regulation (including codes and standards), site conditions, country readiness, developer capabilities and the infrastructure needed to enable construction and operation. Therefore, there are aspects within Norway that would need to be established to support deployment.

In compiling this report, we explored a considerable amount of publicly available information and have presented credible data to help to inform opinions. However, we should note that available information on programme costs can be sketchy, inconsistent and frequently conflicting. Table 5.1 contains an analysis of costs for delivering 2GWe power plants, both GW and SMR.

Table 5.1: Summary nuclear cost breakdown table extracted from Table 5.17*: Modelling of Nuclear cost breakdown structure.*

Nuclear Cost Breakdown (All costs escalated to 2025 economic conditions unless indicated otherwise set)	Type	GW (2*1GWe = 2GWe)		SMR (6*350 MWe =2.1GWe)	
Type of Cost		Low	High	Low	High
Government Costs		TBD	TBD	TBD	TBD
Developer/Owners Cost (Pre and Post FID)	CAPEX	$8bn	$16bn	$8bn	$16bn
Power Plant Costs	CAPEX	~$13.0bn	~$17.0bn	~$14.5bn	~$19.7bn
Developer/Owners Cost + Power Plant Costs (Overnight costs)	CAPEX CAPEX	~$10.5k/kw ~$21.0bn	~$16.5k/kw ~$33.0bn	~$10.7k/kw ~$22.5bn	~$17.0k/kw ~$35.7bn
Construction Timescales (For first Unit)		*6 years*	*12 years*	*6 years*	*12 years*
Financing Costs @5% Low and 10% High	FINEX	~$8.3bn	~$30.6bn	~$8.6bn	~$30.5bn
O&M Costs/ year	OPEX	~$395m	~$616m	Higher	Higher
Fuel Cost/ year	OPEX	~$81m/yr	~$134m/ yr	~$99m/yr	~$245m/ yr
Waste- Long term disposal	DISEX	~$20m	~$1,400m	Higher	Higher
Spent Fuel	DISEX	~$65m	~$600m	Higher	Higher
Decommissioning (for whole site)	DISEX	~$1.2bn	~$2.0bn	Higher	Higher

Areas to highlight include:

- Only limited information is available about recent GW projects.
- Information associated with SMR projects is published by a wide range of sources and is both variable and speculative. There are forecasts that initial SMR FOAK projects will have a higher cost than GW reactors but will achieve longer-term savings when they reach NOAK, but it is not clear how large any savings would be.
- The costs in Table 5.1 are based on financial information taken from multiple public reports issued between 2018 and 2025, which refer to cost information obtained assumed around 2015. Consequentially, all cost elements, CAPEX, FINEX, OPEX and DISEX, are assumed to have reflected circa 2015 economic conditions. To ensure the information remains current and meaningful, the 2015 cost values have been index adjusted reflect 2025 economic conditions.
- Table 5.18 provides a comparison between the outcomes shown in Table 5.1 with real projects and provides possible explanations for any differences outlined in paragraph 5.26.
- Much of the data does not take a realistic account of location, geology and ground conditions, and associated infrastructure or any changes driven by national regulations and localisation of supply chains.
- There is little published data on developer costs, which can be extensive. Together with operator development costs, they are crucial for understanding the programme costs which underpin any business case.
- Any nuclear programme delivery certainty will require significant amounts of work and should be considered in a structured way, addressing the full scope of the programme, financing needs and achieving financial investment decision (FID).
- Traditional project financing costs, if attainable, can be one of the largest elements of cost influenced by factors such as programme duration, the amount and quality of work delivered, and the extent of supporting guarantees. Alternatives could be considered and should be explored.
- Determining realistic costs requires a lot of work, including studies, technology selection processes and a cost development process that links to key activities.
- It is crucial to engage with the technology providers, initially through a market engagement process.
- Costs to achieve FID will be extensive and will be the same for FOAK SMRs.
- Operational and maintenance costs are influenced by the in-country cost of labour. Fuel costs are globally consistent and stable and account for only 10% of a plant’s whole life costs.
- Waste, spent fuel and decommissioning costs will become the responsibility of the national government and are paid for from funds built up during the operational lifetime of the power plant. These will need to be established and built into any financial model to determine the levies needed to generate decommissioning funds.

5.2 Introduction

This section has been prepared to provide a strategic summary of the global position of costs and cost challenges for building, operating and decommissioning GW and SMR plants. In the section we look to reflect publicly available information concerning all aspects of construction, operation and decommissioning. We also undertake a level of analysis to assist the Norwegian Nuclear Commission to reach suitable and useable conclusions with uncertainty and risk in mind. There is a significant amount of information available publicly, much of which lacks context and content. We have used reputable sources and added our experiences and knowledge to provide sound information. Costs related to SMR deployments remains speculative. We have sought to provide an expert account of what may be possible in their deployment. We have not justified nuclear power in relation to other power generation technologies but simply explored possible nuclear power deployment, operational and decommissioning costs and timelines.

5.3 Context

This chapter evaluates the costs associated with GW (~1GWe) and SMR technology. GW plants have come to dominate the market over the past 50 years and are mainly LWRs (PWRs or BWRs). There is now a near-term trend towards SMRs (350 to 500MWe), which are mostly LWRs but smaller and highly modularised with the intent to reduce costs and progress to multi-plant deployments.

There are now many examples of programmes in the early stages of choosing between GW and SMR deployments. Some FOAK AMR projects are also progressing. There are well known GW technologies available on the market and several SMRs are progressing with first claimed deployments forecast in the late 2020s or early 2030s. Most Western nations tend to favour LWRs, as discussed in Chapter 2.

AMR technologies have a wide range of potential power outputs and deployment use cases, including cogeneration, and further enhanced safety features as discussed in Chapter 2. These have not been considered in this section, as the cost basis of such reactors is subject to widespread speculation. Whilst the US national laboratories and the Gen IV Forum have tried to grapple with understanding the potential cost taxonomies and cost breakdowns, there is limited substantiating information in the public domain.

Additional considerations for a nuclear power plant programme include licencing and permitting, supporting infrastructure and temporary infrastructure to support construction. Financing can be a dominating cost, as we saw in Chapter 2 and the cost to get to a Final Investment Decision (FID) can also be extensive.

As will be seen in the section there is much discussion of FOAK and NOAK costs. The definitions used are:

- **FOAK** (First-of-a-kind) A new technology being deployed for the first time anywhere around the world, including new unproven fuel and reactor technologies and a new supply chain. This would apply to highly modified existing technologies as well.
- **FOAC** (First-of-a-class) A known technology being deployed under a different regulatory regime, site conditions or supply chain (except critical components) where the technology has been demonstrated as a FOAK. Potentially requiring some adaptation and changes in the safety case. This would assume any technology deployment has a reference design and is relevant to emerging nuclear countries following IAEA guidance.

- **NOAK (**Nth-of-a-kind) Later, multiple deployments of a proven technology in the same or similar regulatory regime and similar site conditions derived from either FOAK or FOAC.

With increased harmonisation across deployment sites in the same country, the benefits of NOAK can potentially be realised. For NOAK, there are many claims of potential savings discussed in Section 5.9. However, when established technology is deployed to different sites and regions with different regulatory regime or a new supply chain, this is likely to be FOAC and may even approach FOAK, depending on the location.

For emerging nuclear nations, it is normal for any deployment to be tied to a reference plant and fuel that is proven in the country of origin and licensed to reduce risk. International harmonisation efforts are many and widespread, at global, regional and country-country levels. Such benefits of international harmonisation are probably a decade away. Modular SMRs provide an opportunity to minimise FOAK issues by utilising the same supply chain as the reference plant. If localisation requirements for a country drive a new supply chain, this can be a factor in causing cost and schedule increases. NOAK status provides a programme with the opportunity to learn from others and reduce costs.

Building on the analysis presented in Chapter 2, this report focuses on GW LWRs and SMR LWRs. These technologies are assessed as the most viable and attractive options for Norway, given the potential timeframe of 2040–2050, should the country decide to integrate nuclear energy into its national energy mix. AMRs remain mostly in preconcept or concept development having yet to reach technology readiness of demonstration. We therefore feel, whilst they will offer many advantages, they are not readily deployable to emerging nations at present. Furthermore, information concerning their costs is publicly difficult to obtain and highly speculative.

Costs presented in this report may either be ‘real-time’ costs that consider programme timescales, or ‘overnight’ costs. These are labelled as such throughout the report. In both cases, financing costs are also excluded and addressed separately.

The definition of overnight costs refers to the hypothetical cost of constructing a project, such as a nuclear power plant, if it were completed instantly, without considering the time value of money or financing costs. Overnight cost typically includes expenses like land acquisition, equipment, labour, and construction costs. Crucially, this excludes cost of financing.

Estimated “high-case” and “low-case” costs are summarised in Tables 5.1 and 5.17. The financial information has been drawn from multiple reports issued between 2018 and 2025, which in turn reference cost data developed around 2015. All cost elements (CAPEX, FINEX, OPEX, and DISEX) are therefore assumed to reflect approximately 2015 economic conditions throughout this chapter.

To ensure the information remains current and meaningful, the 2015 cost values have been index adjusted to reflect 2025 economic conditions in Table 5.1 and 5.17.

Evaluations are typically presented as ‘high-case’ and ‘low-case’ ranges based on the information gained. In respect of high-case assessments, these do not normally take significant account of the impact of extreme catastrophic events. However, when compared to several projects the full impact may have been made showing differences between norms and actuals/ estimates.

5.4 Access to Information and its Reliability

This section presents and analyses publicly available information from a variety of sources. Few nuclear new build programmes have progressed significantly in the past 15 years in Europe or the

USA. Both China and Russia have made considerable progress. However, there is extensive commercial sensitivity around costs and its availability in the public domain. Where there is public information, its validity, context and content are often unclear and vary depending upon the source. Therefore, it must be interpreted carefully. The information we present has been carefully considered and analysed to enable some level of useful assessment. Crucially, more accurate information can only be ascertained through a much more extensive assessment, direct market enquiry or procurement competition with vendors, with protection of both the cost and technology data.

It should also be noted that accurate forecasting of GW power plants programmes may be thwarted due to delays and cost overruns. These are discussed further in Section 5.14. SMR data remains unproven and subject to many of the same challenges as GW power plants. Our ability therefore to give an accurate summary of overnight costs for future new nuclear power plants is challenging with numerous studies providing speculative predictions in how they may develop over time and how additional deployments may improve efficiency and produce cost savings.

5.5 Market and Current Projects

According to the WNA, in the past 15 years 107 GW/SMR programmes with a total gross capacity of 102 GW have reached the planning stage worldwide with a further 310 being considered or proposed, as outlined in Table 2.3. Most reactors currently planned are in countries in Asia, characterized by fast-growing economies and rapidly rising electricity demand. Key dominators in this market are clearly China and Russia. Both use state-backed financing to secure political influence. The western world is now looking to progress nuclear power with recent announcements in Europe and the USA, including the influence of Korea.

5.6 Main Overnight Cost Drivers for Power Plant Development and Main Cost Classes

The main overnight costs components of nuclear power plant construction are regarded as CAPEX expenses. This excludes finance and operating costs but includes the development of the operating capability. It also includes elements of generic design costs, procurement and supply chain costs, engineering, generic design licensing, commissioning, land acquisition, site specific and operator licensing, site preparation, and associated infrastructure. Typically, it will also include the first nuclear fuel load. Land costs, associated development costs, access and logistics costs can be substantial. Organisational development costs, including the establishment of a fully operational capability and operating organisation, are rarely considered sufficiently. Costs will vary greatly across different countries, sites, delivery approaches, supply chain and operating models. The typical cost drivers can be summarised as follows:

- **Site acquisition** – role of state, number of owners, land values including potential for competing use of land, mineral rights.
- **Site preparation and excavation** – current use/contamination, type of geology, disposal/reuse of excavation spoil, re-use of aggregate, other site costs such as archaeology and biodiversity related policies and associated costs. Vendor capacity and capability – experience, parallel projects, workforce.

- **Licensing, permitting, planning consenting** – access to licensed intellectual property, licensing starting before design and substantiation complete, government policy, regulatory complexity, level of global harmonisation, support from vendor, phasing, licensing of technology and operator, use of regulatory interface office / programme management techniques, public engagement, nearby high hazard infrastructure, requirements management, regulatory fees, cost of meeting regulatory challenge, export controls delays.
- **Developer organisation and operator organisation development** – phasing and size of, heavily influenced by operator and regulatory choice or action, different delivery and commercial models, access to support from existing operator of nuclear and or generation.
- **Operational capability and facilities establishments** – facilities outside of vendor scope such as office accommodation, security and visitor management, canteen and workforce, spent fuel store, security requirements, storage, use of shared services for temporary use.
- **Permanent and temporary infrastructure and facilities** at location (both on and off site) - existing facilities and upgrades needed, worker accommodation, training centres, off-load and laydown areas, modularisation plant, sea, river, road and rail logistic facilities, land values, grid system connectivity.
- **Power plant procurement** – (Nuclear Island, Conventional Island and Balance of Plant) including full supply chain, different delivery and commercial models, willingness to take full project scope, localisation.
- **Construction delivery** – workforce, quality, weather, supplier viability, union engagement, rates of pay, health and safety, productivity, construction techniques, energy, commodity and material costs, use of construction for safety techniques and logistics.
- **Governmental** – policy and regulatory certainty, change of ruling party, geopolitical action, legislative or political changes affecting taxes and wages, requirement for localisation and other forms of social value, nuclear indemnity regime.

Figure 5.1 illustrates a typical distribution of the main cost types in a typical GW power plant construction. The contributions are influenced by many factors including the delivery model/ strategy and design status in relationship to the siting of the power plant. It should be noted that the detailed publicly available data is frequently limited. Figure 5.1 below is based on summary information supporting GW projects Hinkley Point C, Vogtle 3 and 4, and Flamanville 3 (adapted to a twin power plant unit).

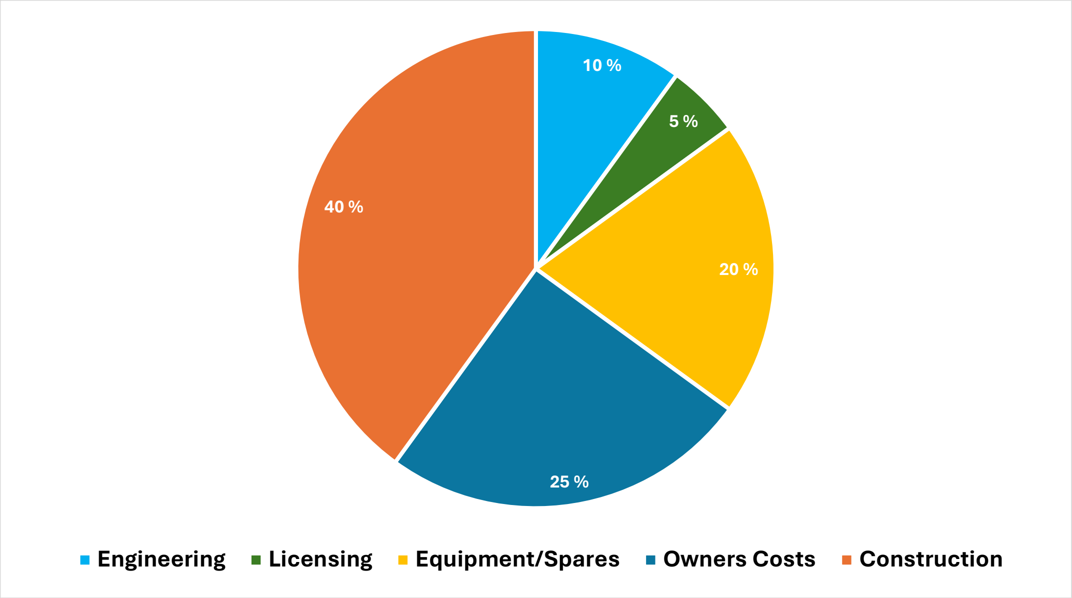

Figure 5.1: Overnight Cost Class Contributors to Power Plant Construction for GW (twin power plant unit)

Financing is usually an extensive and a potential limiting factor for most programmes. The NEA suggests that as much as two-thirds of total project costs could be associated with financing. This problem is particularly acute in the UK.

Among cost drivers, items that can have the largest impact include:

- Labour costs (blue and white collar).
- Need for foreign nationals with expertise (deployment driven costs, connected both with the reactor technology and addressing skills shortages).
- Commodity and material costs.
- Location.
- Regulatory-related costs.
- Technology selection.
- Economics.
- Cost of finance.
- Productivity (this can be influenced significantly by union labour and should be addressed as soon as possible in the discussions).
- Inflation.
- Exchange rates.

The typical demonstration of labour types and costs is indicated in Figure 5.2, and they vary considerably in each region/country, these have a significant impact on power plant development and construction costs. Additionally, workforce accommodation and associated welfare standards vary considerably by region, and this will have an impact on costs.

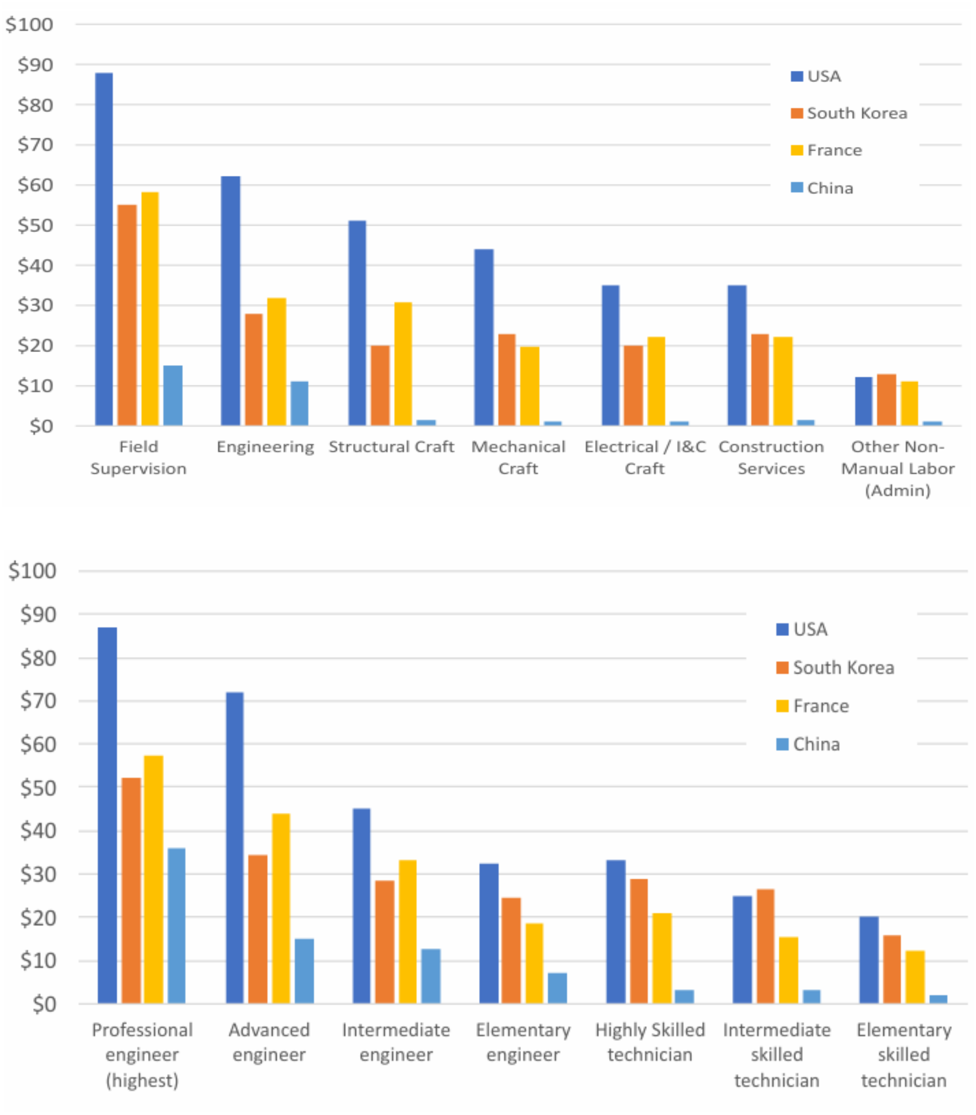

Figure 5.2: Labour related costs in various countries (Massachusetts Institute of Technology, 2018)

Typical commodity volume usage by various technologies is shown in Figure 5.3 and has significant impact on power plant construction (Massachusetts Institute of Technology, 2018). To note also, nuclear power plants use largely ultra-high-performance concrete (UHPC) and high strength steel in reinforced concrete at high density levels.

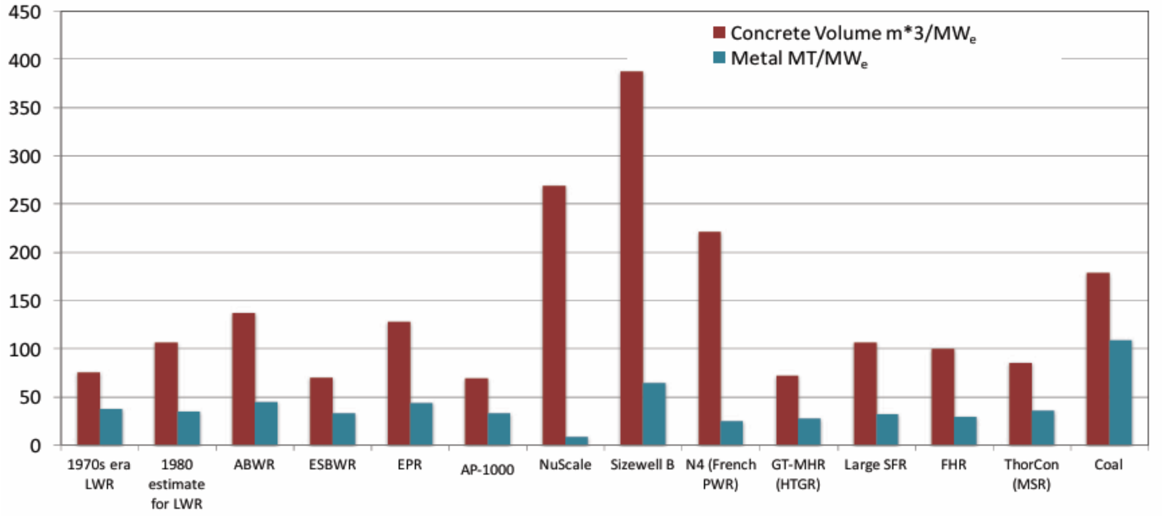

Figure 5.3: Commodity Volumes for Various Technologies (Massachusetts Institute of Technology, 2018)

Both these diagrams seek to illustrate relative differences for comparison only.

Table 5.2: Typical Power Plant Cost Class observations (% of project capital costs)

Engineering	Typically, technology venders will generally have some form of generic design for the nuclear technology aspects of the power plant. This can be well progressed and frequently built upon past designs. Most LWR plants are technological derivatives of previous plants with either power upgrades or reductions. There is always a significant level of engineering to be done to define the design basis (site and developer requirements) and adapt the design to site, regulatory requirements and address codes and standards. Depending on the level of adaptation required, engineering costs would typically represent 5–10% of project capital costs. This is consistent with Figure 5.1. It would also include feasibility studies, concept, preliminary and detailed design, and its project management. Each vendor has its own convention for developing the design of the plant but broadly speaking they follow a process of ever-increasing levels of detail from plant level to system, sub-system (and this can have multiple layers) down to component level (e.g. individual valves). These are progressively unpacked during the phases of concept design, preliminary design, detailed design and construction design with stage gate reviews at each phase. These design phases can span for several years, influenced by the technology maturity and customization (notably for construction design on a specific site).
Licensing	Construction and operation of nuclear plants are generally licensable activities i.e. requiring a permission, licence or consent from several regulatory bodies. Licensing costs are a cover term for meeting all regulatory requirements. This includes the areas of nuclear and conventional safety, security, safeguards, environment, decommissioning planning, and development consenting. This may or may not include informal non-binding pre-licensing and early engagement activities. We believe that the costs of licensing category cover many other costs than the pure licensing costs themselves. The licensing cost will typically be around 5% of project capital costs as shown in Figure 5.1. But licensing costs vary by technology, jurisdiction, site and project and the maturity and experience of the regulator, the efficiency of the owner's interaction with the regulator and public engagement requirements, and other factors such as level of early engagement, use of pre-licensing, maturity of the design, reactor vendor, and operator/licensee. It should be noted that there are costs associated with licensing of the base technology, and costs associated with licensing of a project construction and operation. The phrase licensing costs is often used without definition. There is the cost of paying for regulators to both assess and inspect projects, and the costs of support to licensing from both the reactor vendor and the operator/licensee. In most cases this involves the development of large bodies of information which explain why a plant and its operating organisation is safe for example, how it is safe, and the evidence that underpins the claims. Some jurisdictions are very precise, with rules-based regulation, such as the US, some are goals based such as UK. Early engagement and pre-licensing, if undertaken as risk mitigation activities can take 2-6 years. Licensing can take 3–10 years, depending on maturity of the technology, national frameworks and stakeholder engagement along with the maturity of the regulator and crucially maturity of the proposed operator and pathway to grow capability. Aspirations of dramatically shorter licensing periods are not at this stage realistic.
Construction	Construction costs dominate total expenditure as Figure 5.1 shows at 40% of project capital costs. It includes labour, materials etc. Outcomes can be impacted by project delays and significant scope changes. The major factors that commonly influence cost growth are; poor requirements definition, management and evidence of substantiation of requirements, poor design process, managing design changes and erosion of margins, early justification of design elements outside of regulatory regime (that needs to be justified within the context of the intended country for deployment), incomplete design, ground conditions, inefficient integration and coordination, unrealistic schedule durations without appropriate time risk allowances, skilled workforce availability. The limited Nuclear New Build projects in Europe and the USA have adversely impacted production and constructability which has impacted labour norms. These factors are expected to improve in SMR forecasts as the workforce should become more efficient with an increased frequency of projects, more stable design and increased modularisation.

	Construction durations for GW-scale plants are planned to range from 6-8 years from the pouring of first nuclear concrete. Figure 5.5 indicates some projects where the schedule overruns have looked to double these durations. There is evidence of shorter and consistent timescales in Japan where they were beginning to achieve 3.5 years. Durations should be reduced by improved workforce performance generated by repeat work and increased modularisation approaches particularly in SMRs. Some designs such as RRSMR look to create a site factory environment to reduce impact of weather and allow 24/7 working if needed.
Major Equipment inc. Spares	Key components such as the NSSS or equivalent, including reactor pressure vessels, steam generators, and turbines account for 20% to 25% of project capital costs that is consistent with Figure 5.1. Contracts may include all or some of unit and site-specific design, licensing support, manufacture, test, transport, storage, installation, and commissioning. Including initial spares holding.
Owner's Direct Costs	Includes land acquisition, insurance, legal, and internal staffing to manage project as owner to build the plant and develop the operator as a Licensee. Expected to be 25 to 30% of project capital cost aligning to Figure 5.1. This will include establishing and developing the operating organisational and facilities prior to going operational. This can include a significant amount of construction that the reactor vendor is not willing to and may not be the best organisation to build. This element will also be influenced by the delivery strategy, for example workforce accommodation, warehousing, simulator and administration buildings may be part of the Owner's cost. The choice to develop a Programme Management Office internally or contract this out will be important.

5.7 Pre Final Investment Decision (Pre-FID) Costs

Based on our experience, achieving a Financial Investment Decision (FID) for GW plants and, where applicable, reaching financial close, presents numerous challenges along the way. The process can take between five and 10 years and typically costs between $2 billion and $5 billion USD in 2015 economic conditions. Based on evidence from the market, as shown in Table 5.8, not all programmes get through FID and some end up being cancelled or delayed. To expedite the overall programme, an Initial Investment Decision (IID) is often made to begin site preparation and fund early activities such as site-specific and non-vendor design work, early engagement contracts, and supply chain establishment. The FID also supports developing the operator’s capabilities, including people, processes, tools, and culture, advancing licensing activities, and procuring long-lead items (LLIs, as described in Chapter 4). This initial phase can require investment in the range of $1 billion to $2 billion USD.

Similar challenges remain for SMRs but the drive to standardise SMR designs, and progress towards multi-plant deployment would potentially have a beneficial effect in both time and costs as SMRs move towards NOAK status. For modular reactors, these costs could include the cost of the factories to make modular-build components.

5.8 Potential Government Related Costs

When developing nuclear power programmes, national, regional and local government bodies can have, and likely will have, a significant role to play. This is regardless of government engagement with or stake in any nuclear power plant development organisation. The key activities include:

- Establishing or maintaining governmental nuclear development bodies.
- The development or maintenance of regulatory frameworks and bodies including policies and legislation.
- Regulatory assessments and inspections sometimes borne by the developer/ technology vendor as license.
- Planning and permitting regimes.
- Signing enabling country-country agreements, including access to export credit.
- Managing an export controls regime and organisation to manage export licence applications to and from country.
- Establishing the security and safeguards regimes.
- Government, regional and local level emergency planning, including establishing the nuclear indemnity regime.
- Investment in teaching, research and development.
- Supporting the development of in-country capabilities, skills and industry (capacity planning).
- Strategies for, and ability to, disposal of nuclear waste including spent nuclear fuels.
- Engagement at the IAEA and regional level.
- Setting localisation and other sustainability targets.

- Provision of potential infrastructures to support the construction and operation of the power plant.

Estimating costs for these is challenging. It would require scoping and estimating and that could be accomplished in future work.

5.9 GW Construction costs (Overnight construction costs)

The ability to provide an accurate summary of overnight costs for future new nuclear power plants is challenging. There are numerous studies that contain predictions on these costs and how they may develop over time with additional deployments expected to improve efficiencies and offer cost savings. These are summarised in a Columbia University Report, *The Uncertain Costs of New Nuclear Reactors*-December 2023 (Bowen, et al., 2023). The studies summarised in the report have been produced by MIT, USDOE, SMR Start, The Breakthrough Institute, National Renewable Energy Laboratory, and Nuclear Innovation Alliance.

For each technology, the study used two FOAK costs (upper and lower) and then applied two learning curves for later deployments to estimate efficiencies (5 percent and 12 percent, which were applied as cost reductions achieved after a doubling of deployed capacity. No learning was applied to traditional nuclear costs). The deployment ranges vary widely in the reports with some determining that NOAK overnight costs may require up to 20 reactors to achieve the optimum cost. We would also point out that GW reactors have sought to modularise some elements of their designs including the AP1000 and the ABWR that has extensive integrated modularisation.

There are numerous challenges when trying to turn learning into cost reductions for a NOAK fleet. This includes harmonisation of regulations, codes and standards, use of metric versus imperial units and related standards (relevant for US reactors), challenge from governments to introduce localisation (to gain benefit from the economic activity), as well as site specific conditions.

The information gathered concerning overnight construction costs provides a significant range that is significantly region specific. These are typically LWR and are as follows:

- It is estimated that future US reactor costs range from $3,000/kW to $6,200/kW, depending on the reactor design and a variety of cost reduction curves assumed for subsequent years (Bowen, et al., 2023).
- An IEA international study indicates reactor costs in other countries can range from $2,500/kW to $6,600/kW (International Energy Agency (IEA), 2025). The report also references a study which estimates the FOAK cost for four categories showing traditional GW to be between $4,783/kW and $6,338/kW[7]. The difference between the two can be characterised as labour costs and construction efficiencies, material costs and regulator influence.
- A further study listed predicted overnight costs for follow on GW nuclear reactor builds in various countries as shown in *Table 5.3: Estimates of Overnight Costs for NOAK nuclear reactor builds by country (excluding cost of finance) Table 5.3*

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[7] Used in evaluation

Table 5.3: Estimates of Overnight Costs for NOAK nuclear reactor builds by country (excluding cost of finance) (Bowen, et al., 2023)

Country/Year (Cost $/kW)	2020	2030	2050
China	$2,800	$2,800	$2,500
United States	$5,000	$4,800	$4,500
European Union	$6,600	$5,100	$4,500

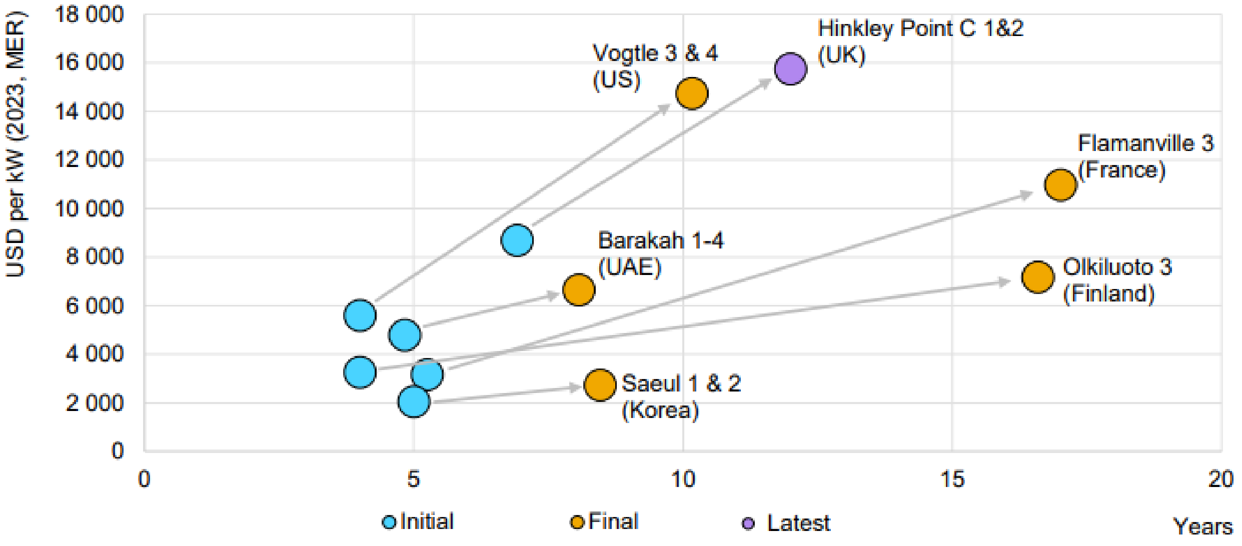
There is substantial variation in assessments from governmental, academic and industry sources on the cost of new nuclear reactors with a further variance between different countries. Some comparisons of overnight costs to real time costs are illustrated in Section 5.26.

Overnight costs in China and in India are substantially lower than in the US and EU due to repeat copy build and less design modification. Planning and regulatory processes also occur on shorter timescales. The cost of land, labour and basic materials are much cheaper, partly due to lower salaries and partly due to the state stimulation of many jobs and investment in manufacturing. Typically, these builds have much larger workforces.

There is an inconclusive view of different regulatory standards and levels of compliance, but this no doubt has a significant impact in terms of both licensing time and cost. There has also been a major investment in research and development and test facilities to provide information to substantiate designs in China and India, although more recently the US and EU have been investing more.

The IEA 2025 (International Energy Agency (IEA), 2025) has compiled a graph, provided here as Figure 5.4, that shows a summary of recent programmes cost and schedule growth on the most recent reactor builds in Europe, Korea, Middle East and USA. It includes the most recent projects where there is available data showing the extent of substantial delays and cost overruns experienced.

Even for current GW power plants, an overall trend of cost reductions is expected as progress is made through NOAK deployments as intended. This will mainly be with equipment and construction processes and times, given the focus towards modularisation, which reduces site-based work hours.



IEA. CC BY 4.

Notes: kW = kilowatt; MER = market exchange rate. The cost estimates do not include interest. Gross installed capacity is considered. Construction time refers to the time period between the start of the construction until grid connection. For plants shown here with multiple reactors, the average construction time is taken. The construction of Hinkley Point C is ongoing.

Figure 5.4: Summary of Cost and Schedule Variances (International Energy Agency (IEA), 2025)

Another important aspect is that even in the host countries that were not newcomers to nuclear energy, no new reactors had been built over the last 10 to 20 years, which meant that the nuclear industrial base and skills had depleted with time and had to be rebuilt. This extends to labour skills and productivity, constructability efficiencies and manufacturing norms and techniques. Additionally, supply chains had to be rebuilt. These factors have played a significant part in the cost overruns.

Outside Europe and the USA, other recent nuclear projects have been completed with comparatively more moderate delays and cost overruns. For example, Korea's Saeul 1 and 2 reactors became operational after delays of two and five years, respectively, with construction costs rising by about 30% compared with initial estimates, with cost per capacity reaching $ 2,700/kW. Similarly, Barakah nuclear power plant in the United Arab Emirates was completed with comparable schedule delays to those experienced by Saeul 1 and 2, while incurring lower cost overruns. Furthermore, Saeul Units 3 and 4 are reporting delays from 134 months to 147 months. Table 5.4 provides a summary from publicly available information for the projects listed in Figure 5.4 and other.

Table 5.4: Summary of project CAPEX costs (Realtime) Published Data for GWs (Massachusetts Institute of Technology, 2018) *and collection of other industry sources*

Item	Hinkley Point C-UK	Sizewell C UK	Vogtle- 3 & 4 US	Flamanville 3 France	Olkiluoto 3 Finland
Number of Units	2	2	2	1	1
Electrical Output	3260 MW~~e~~	3260 MWe	2200 MW~~e~~	1600 MW~~e~~	1600 MWe
Overall project cost (estimated or final)	$61bn (2024 estimate)	$49.92bn estimate	$36.8bn (2024)	$19.1 bn (2022)	$11bn
Overall project duration (final or estimated) months	264	144	216	252	216
Construction Duration	13 years estimated	9-12 years estimated	14 years	17 years	18 years
Reactor Technology	UKEPR	UKEPR	AP1000	EPR	EPR
Estimated Budget at Project Start	$21.4bn	$36.8bn	$14.0bn	$3.83bn	$3.0 bn
$/ kW	$18,700	$15,300	$16,700	$11,900	$6,900
	L-K Poland	Dukuvany II Czechia	Akkuyu Turkey	El Dabaa Egypt	Barakah UAE
Number of Units	3	2	4	4	4
Electrical Output	3300 MW	2000 MW	4500 MW	4500 MW	5600 MW
Overall project cost (estimated or final)	$49bn	$19bn	$25bn	$28bn	$32bn
Overall project duration (final or estimated) months	Unknown	144	120	120	144
Construction Duration	8-10 years estimated	n/a	10 years (planned)	8 years	6 years
Reactor Technology	AP1000	APR1400	VVER1200	VVER1200	APR1400
Estimated Budget at Project Start	Not finalised	$19bn	$20bn	$28bn	$25bn
$/ kW	$14,800	$9,500	$5,600	$6,200	$5,700
For clarity costs highlighted here are actual or estimated real time costs within public domain where dates indicating date of the estimate (estimate date) shown.					

5.10 SMR Overnight Construction Costs)

Studies of future US reactor costs provide FOAK cost estimates for LWR SMRs of $5,108/kW and $6,974/kW[8].

There are many independent reports and papers (see reference list) in the public domain that offer predictions on initiating costs for SMRs with modelled predictions on how these may evolve in the next 10 to 25 years. There is a wide range of costs within these reports with an inconsistent view on the

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[8] Used in evaluation

approach required to improve cost performance as they evolve from FOAK to FOAC status and continue to reach NOAK. It highlights common risks associated with cost and schedule with GW new builds. It also references potential pathways for opportunities to aid in reducing predicted costs.

The IEA produced an analysis in 2024 which referenced a range of SMR build scenarios: the STEPS (Stated Policies Scenario), APS (Announced Pledges Scenario) and NZE (Net Zero Emissions Scenario). These predict the rate of deployment of SMRs between 2030 and 2050 but there is a wide variance from 40 GW to 200 GW electrical output and the forecast number of SMRs ranges from 330 to 1,500 units.

The prediction for future costs, however, is highly uncertain as the FOAK projects are still in their early stages as discussed in Chapter 2. The analysis assumes that the FOAK SMR projects have construction costs (per unit of capacity) that are double those of large-scale reactors which are completed on time and on budget, yielding a cost of around $10,000/ kW in advanced economies and less than $6,000/kW in China and India. We believe this is reasonable, to account for factors such as building new infrastructure and skills.

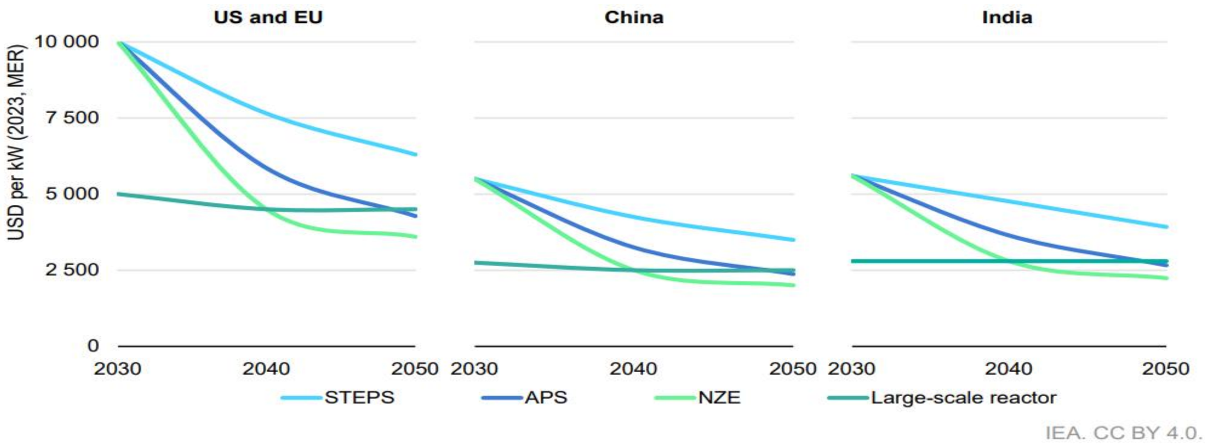
Key to reducing deployment costs is achieving high NOAK criteria. This may be more challenging than expected as NOAK requires essentially the same design, constructed and built by the same workforce and supply chain repeatably, as seen in factories. The inevitable differences in environmental, regulatory, codes and standards, site conditions, supply chain and operator will in reality drive a deployment back to FOAC or even FOAK in the worst case. This presents a degree of risk to early deployers.

A key claim associated with SMR deployment is the ability to reduce financing cost as discussed in Section 5.11 by bringing generation, and therefore revenue, online sooner with reduced construction times suggested.

The assessment suggests costs will reduce as deployment increases and experience in manufacturing and construction performance improves. We would expect a greater portion of each nuclear project will be modularised and built off-site, potentially offering significant efficiency gains.

In the IEA's APS, SMR costs are predicted to fall significantly in the 2030s and reach parity with large-scale reactors in the 2040s, at under $5,000/kW. Costs fall even faster in the NZE Scenario, which is due to faster deployment. The lower deployment rate as assumed in the STEPS scenario, leads to less development and limited cost reductions. In summary, the costs predicted for SMRs in Europe and USA (in the APS and NZE scenarios) in 2050 are less than half of the FOAK project (International Energy Agency (IEA), 2025).

It should be noted that these predictions are still well above the targets being quoted by SMR developers. For example, Westinghouse is targeting $3,400/kW for AP300 and GE Vernova $2,250/kW for BWRX-300 (Utility Dive, 2023; GE Hitachi, 2021).



Notes: MER = market exchange rate; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; SMR = small modular reactor. The cost of large-scale reactors is projected to be same in all three scenarios.

Figure 5.5: IEA SMR build scenarios, cost per KW (International Energy Agency (IEA), 2025)

In addition to the projected cost ranges for SMRs stated in the report there is published data on the cost of the Darlington project currently under construction (McClearn, 2025), this is shown as a comparison to published data from NuScale (Institute for Energy Economics & Financial Analysis, 2023).

In all cases, there have been significant cost increases for deployment projects from those originally put forward along with funding challenges. Many other countries are assessing SMRs for deployment.

Table 5.5: Summary of Published Data for SMRs (Institute for Energy Economics & Financial Analysis, 2023; McClearn, 2025)

Item	NuScale SMR	Darlington (BWRX-300)
Number of Units	4	1+3
Output	462 MWe	300 MWe to 1.2GWe
Overall real time cost (Estimated)	$9.3bn (2023)	$5.5 bn (2025) for first unit reported to become $21bn when complete (2024)
Overall project duration (Estimated) months	276	228
Construction Duration (Estimated)	n/a	5 years
$/ kW	$20,000 / kWe	$18,000/ kWe
For clarity costs highlighted here are actual or estimated real time costs within public domain where dates indicating date of the estimate (estimate date) shown.		

Countries assessing the potential deployment of SMRs include Sweden, Poland, Czechia, Romania, Slovenia and Bulgaria. All are said to be racing to deploy, while the USA, UK, Russia, South Korea, China and Canada are all developing SMR technologies. The challenges faced are common and include FOAK risks, Construction Risks, Market Risks, Regulatory Risks and Financing Risks. Comparatively, GW power plants have been through more deployments and are now more quantifiable.

5.11 Financing

Unless power plant funding is provided by sovereign arrangements (i.e. fully national government funded by operator and or vendor country), financing is inevitable and key. It is worthy of note that all new power plant development programmes have significant sovereign backing through various means. Finance cost is also a significant contributor to overall programme costs. Typically, new power plant projects are established by using a Special Purpose Vehicle (SPV) with investor equity and debt-based financing. To facilitate accessing debt there are usually significant security arrangements required through various guarantees, committed power take off agreement (PTO) or similar vehicles with a strong business case and good investment returns. Furthermore, financing is not normally available until certain conditions have been achieved. The cost of financing is significant, as discussed in Section 5.5 and illustrated in Chapter 2, Figure 2.11 (repeated below in Figure 5.6) and will likely be determined by several factors:

- Levels of programme risk (operator, vendor and supply chain).
- Level of debt, term and cover ratios.
- Security structures and associated credit capacities and ratings.
- Power take-off arrangements (affected by government policy).
- Foreign currency exchange.
- Competition for investment.
- Other forms of governmental support packages, including export credit, tax credits, lender of last resort.

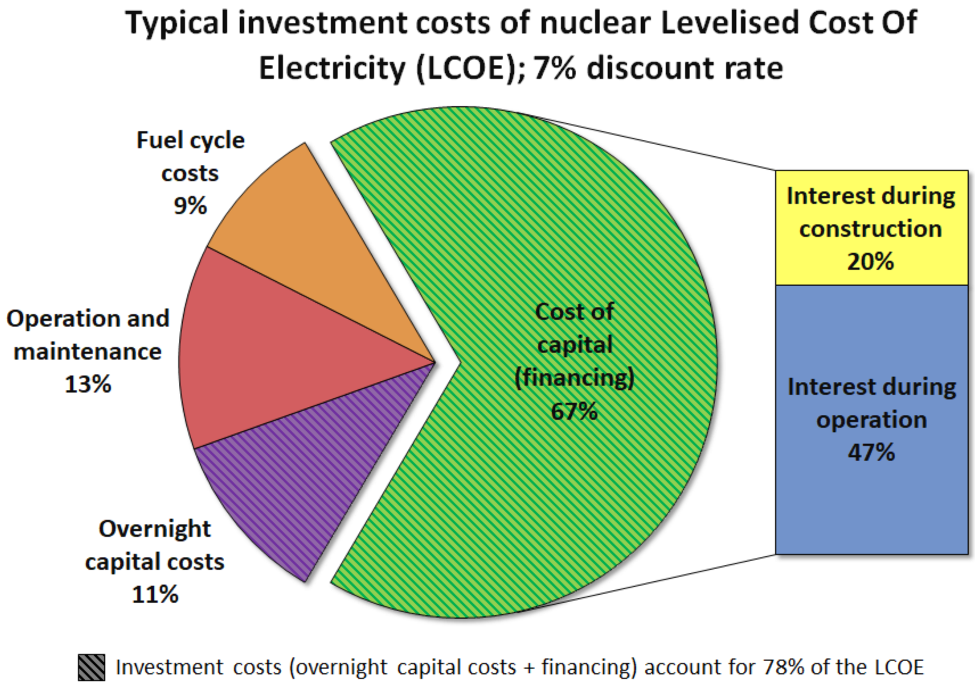


Figure 5.6: Typical investment costs of nuclear levelized cost of electricity (LCOE) 7% discount rate (Bodel, 2022)

Public funding alone is unlikely to be sufficient to fund the emerging demand, so private financing will be extensively required to scale up investments. SMRs are anticipated to cut the investment cost of individual projects when FOAK projects become more established with proven technology, stable design, effective modularisation, design and licensing, creation of a modularisation supply chain and reduction in construction risk. The report predicts that cash flow break-even could be as much as 10 years shorter than GW projects (International Energy Agency (IEA), 2025) on an equivalent basis. It is our judgement that this is probably overly optimistic and will need to be modelled appropriately.

The NEA report on Financing Nuclear New Builds (Nuclear Energy Agency, 2024) has summarised the weighted average cost of capital (WACC) shown in Figure 5.7 below

Table *5.6* also shows a summary taken from the same NEA report of the financing arrangements supporting major GW development programmes.

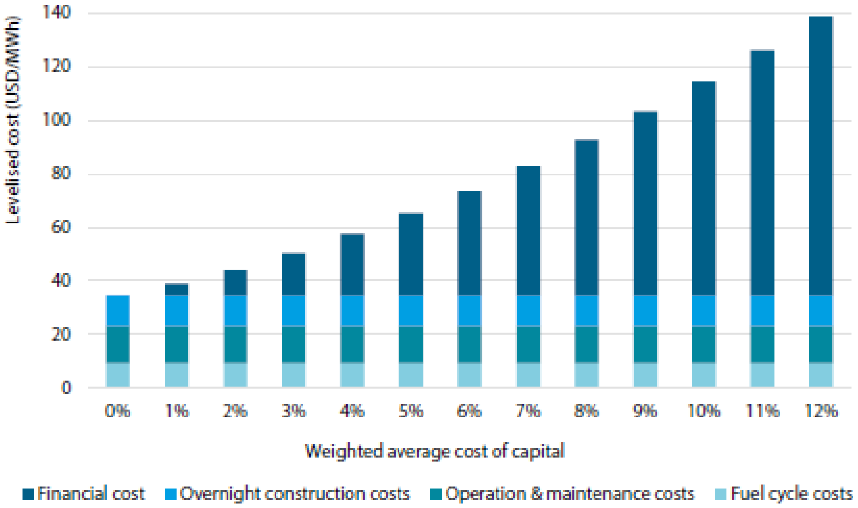


Figure 5.7: Weighted Average Cost of Capital (Nuclear Energy Agency, 2024)

Currently, public equity and commercial debt would appear to be the main sources of finance. Public finance in the form of equity plays a major role in financing nuclear projects, accounting for around 25% of total financing in USA, Europe and China, 60% in Russia and 40% in other emerging market and developing economies (EMDE). There is a lot of use of sovereign banks to provide commercial debt-based funding. Export credits are becoming widely used as well. There are also Government support packages in terms of lender of last resort. Refinancing is also common as the development programme proceeds, and construction risks are overcome. Investment in operating power plants is relatively easy and is observed in many regions, including use of green bonds.

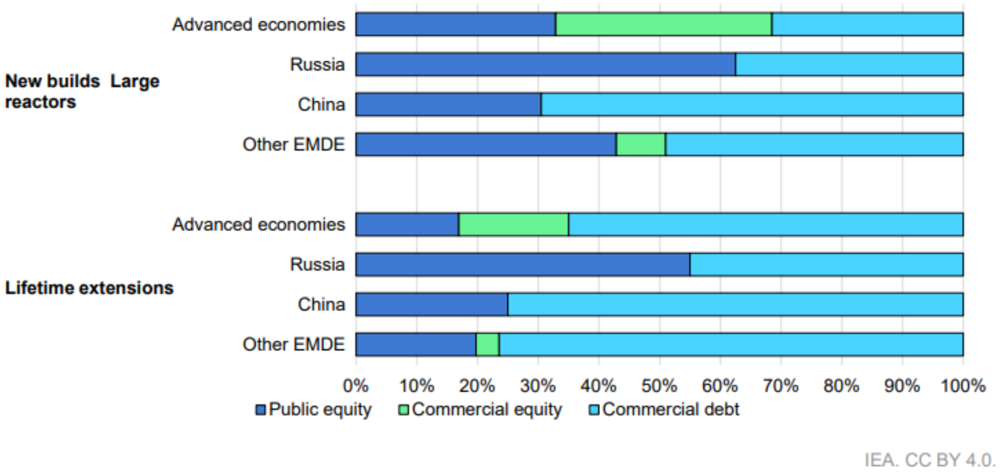
Governments often directly invest in these enterprises or provide support through guarantees to them to access low-cost loans, enabling State Owned Enterprises to secure large amounts of capital at low interest rates. Governments also frequently provide direct funding, subsidies, or tax incentives to cover early-stage nuclear development costs, such as research and development, feasibility studies, and initial infrastructure development.

There are also mechanisms to enable construction to be funded from receipts of existing power generation, thus reducing the level of debt required. In the UK this includes the Regulated Asset Base (RAB) model, although this does not allow for recovery of pre-FID investment. Similar models have been used in the USA.

Table 5.6: Summary of Financing Arrangements (Nuclear Energy Agency, 2024)

	Olkiluoto 3	Vogtle 3 & 4	Barakah	Akkuyu	Hinkley Point C	Sizewell C	Paks II	Dukovany
Status	Operational	Operational	Operational	Under Construction	Under Construction	Under Construction	Construction Licence issued	Preferred Bidder Selected
Nuclear Construction start year	2005	2013	2012	2018	2016	2025	2026	2025
Reactor Technology	EPR	AP1000	APR1400	VVER1200	UKEPR	UKEPR	VVER1200	APR1000
Capacity	1.6GWe	2.2GWe	5.6GWe	4.8GWe	3.2GWe	3.2GWe	2.4GWe	2.2GWe
Units	1	2	4	4	2	2	2	2
Owner	TVO	Georgia Power	ENEC	Rosatom	NNB Generation Company (HPC): EDF Group, CGN	Sizewell C: UKG/ EDF Group / Centrica / La Caisse / Amber Infrastructure	HG	CEZ
Financing Model	Manikala Principle	Construction cost recovery loan agreement	PPA govern-ment loan and guarantee	PPA inter-govern-mental agree-ment	Contract for Difference (CfD)	Regulated Asset Base (RAB)	Inter-govern-mental agree-ment	PPA government loan
Debt to Equity Ratio	75:25	0:100	80:20	n/a	0:100	TBD £5.5Bn debt over 13 banks	80:20	98:2

Commercial equity accounts for a significant share of total financing only in the advanced economies. Figure 5.8 summarises the sources of investment in new build large scale reactors.



Note: Finance from state-owned banks is categorised as commercial.

Figure 5.8: Financial Investment Sources (Nuclear Energy Agency, 2024)

Changes in the mixture of equity and debt will have a significant impact on the cost of financing nuclear projects in the coming decades. In the Announced Pledges Scenario (APS), the financing of nuclear power generation changes significantly, with equity financing rising faster than debt over the period 2024-2037. That is reflected in the fact that several countries have launched their nuclear programmes, requiring a larger part of the financing to come from equity to cover for the high risk and long lead times of initial projects. This could push up the overall cost of capital, as equity is more expensive than debt. Debt also rises, as government-backed projects are viewed positively by commercial banks. As the level of investment in nuclear starts to fall back by the middle of the 2030s, the capital structure of nuclear investment worldwide moves back towards that seen over the last 15 years.

Achieving low interest rates is essential to the feasibility of any power plant programme. We have observed rates between 5% and 10% [9] and have used these in the analysis undertaken assuming a 30/70 equity to debt ratio.

5.12 Build times

Build times generally comprise two phases:

- Development phase: That includes programme initiation and feasibility, where outcomes are defined, conceptual approaches developed and feasibility examined, and where the programme is developed sufficiently to enable financial investment (i.e. FID) leading to first nuclear construction.
- Construction phase: where the power plant is constructed and put into operation leading to Commercial Operations Date (COD).

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[9] Used in evaluation

The duration of the development phase varies considerably and is usually quite unique. It can take six to 10 years for GW power plants. It is critical to be ready for construction. From our assessment we cannot see any reason why SMRs would be significantly different.

For emerging countries, country readiness and capacity building will also need to be addressed during the development phase. Operational organisations will also need to be developed in parallel with plant construction to enable nuclear operations to commence including commissioning. Section 5.24 explores this further.

Construction phase time and costs for GW plants vary widely across countries and regions. More recent projects in Europe and the United States have seen significant cost and schedule overruns and delays. This is illustrated in Figure 5.9. Observations indicate construction timescales to be between five to 10 years[10] with a build gap of between 12 to 18 months.

Recent projects in Europe and the United States have been impacted by long construction times and extensive cost overruns. In Korea, there was a legacy of their nuclear reactors taking between four to six years to construct. The last three reactors, however, have taken in the region of ten years each to complete.

Japan's projects were also driving record timescales, already achieving near to 40-month construction timescales (3.5 years), and were targeting even further improvements to 37 months, integrated modularisation, 6D construction planning and simplification were some of the techniques being utilised.

China has brought large nuclear reactors into operation more quickly, both at home and in other countries; these have averaged just seven years per project between 2017 and 2023. Some have been FOAK designs, with several projects completed in just five years. This may be attributable to several factors:

- Access to major capital investment at government level.
- A different approach to planning for strategic projects.
- Standardised deployment models.
- Stable designs developed through integration of Western technology transfer and the indigenous development with limited changes.
- Investment in development of a much larger and cheaper labour force.
- Delivery focussed regulation.
- Both strong domestic R&D and manufacturing infrastructure, and continuous improvement metrics derived from a larger number of nuclear new build projects.

The size of both the nuclear and non-nuclear workforce in China also allows for multiple projects to progress in parallel, with particular investment in skills like inspection.

Whilst one of the Chinese designs, the Hualong-1, has gone through pre-licensing in the UK, no designs have yet been licensed and constructed in Western countries.

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[10] Used in evaluation

On a unit-by-unit basis, construction times for SMRs are expected to be shorter than those of GW power plants due to higher levels of modularisation, factory manufacturing, larger production numbers, and improved learning during the move to fleet and NOAK deployment. We would expect the level of modularisation to increase as FOAK status progresses to NOAK. This is seen frequently in ship and submarine building.

On an equivalent power output site with multiple SMR deployments, construction timescales will likely be longer and require a larger footprint to accommodate, but this is nevertheless expected to help financing solutions.

5.13 GW and SMR comparison and trends

SMRs and GW reactors exhibit distinct economic characteristics through design and deployment differences. SMRs generally are predicted to entail lower initial capital costs owing to their modular design, facilitating cost savings through standardized components and factory fabrication. However, this is conditioned by predicted higher costs at the FOAK stage with the predicted costs reducing in the NOAK stage.

The construction time for SMRs is shorter thanks to concurrent manufacturing and onsite assembly. In terms of financing and investment, SMRs may attract more private funding due to their manageable scale and potentially quicker returns. Their operational flexibility allows for scalability and phased deployment, aligning with varying energy demands. Large reactors involve higher upfront capital costs, longer construction times, and require substantial funding from government entities or major utility companies. While large reactors lack the flexibility of SMRs, they play a role in meeting specific capacity needs.

The economic dynamics of SMRs and GWs are influenced by factors such as reactor design, regulatory environments, and technological advancements, with each serving distinct niches in the energy landscape. It is important to note that SMRs have a shorter construction time (measured as the time it takes from the first laying of concrete to the date that commercial operation starts), and for this reason, they incur less interest costs during construction. Modularisation and standardisation, approaches that have successfully reduced construction times and costs in industries such as shipbuilding and oil and gas, offer significant potential for the nuclear power sector. GW reactors have also started on the modularisation process notably the AP1000 and ABWR. Given this, the financing needed would be less, which would decrease the interest burden.

A report published in July 24 by Idaho National Laboratory -Meta Analysis of Advanced Nuclear Reactor Cost Estimates- showed a predicted range of Overnight Capital Costs (OCC) between SMR and larger GW reactors.

	Small Modular Reactor 2030	Small Modular Reactor 2040	Small Modular Reactor 2050	Large Reactor 2030	Large Reactor 2040	Large Reactor 2050
Q1	$10,000	$8,000	$6,250	$7,750	$7,500	$6,000
Q2	$8,000	$5,250	$4,000	$5,750	$4,750	$3,750
Q3	$5,500	$2,500	$2,000	$5,250	$3,000	$2,250

Figure 5.9: OCC Range for SMRs and Large Reactors (Larson, et al., 2024)

This figure has been compiled from independent data sets. They are agnostic to technology related to findings from references in the report to (Abou-Jaoude 2023). It assumes that the SMR produces 300 MWe and the GW produces 1000 MWe. The ranges are governed by the following assumptions:

- Q1 Upper Quartile is a pessimistic estimate related to lack of learning, poor execution, lack of standardisation technology and supply chain issues
- Q2 Middle Quartile some experience and benefits are being realised
- Q3 This represents the optimistic estimate where the frequency of building improves delivery and efficiencies.

5.14 Risks and Uncertainties in Developing Power Plants

All development of nuclear power programmes faces significant risk that must be managed from programme inception. This is typically undertaken through a life-cycle approach with governance check points included throughout. Such a lifecycle model is illustrated in Figure 5.10.

This is further translated into a strategic level programme illustrated in Figure 5.11 that lays out the major activities typically required to develop and construct a nuclear power plant illustrating timescales and critical links.

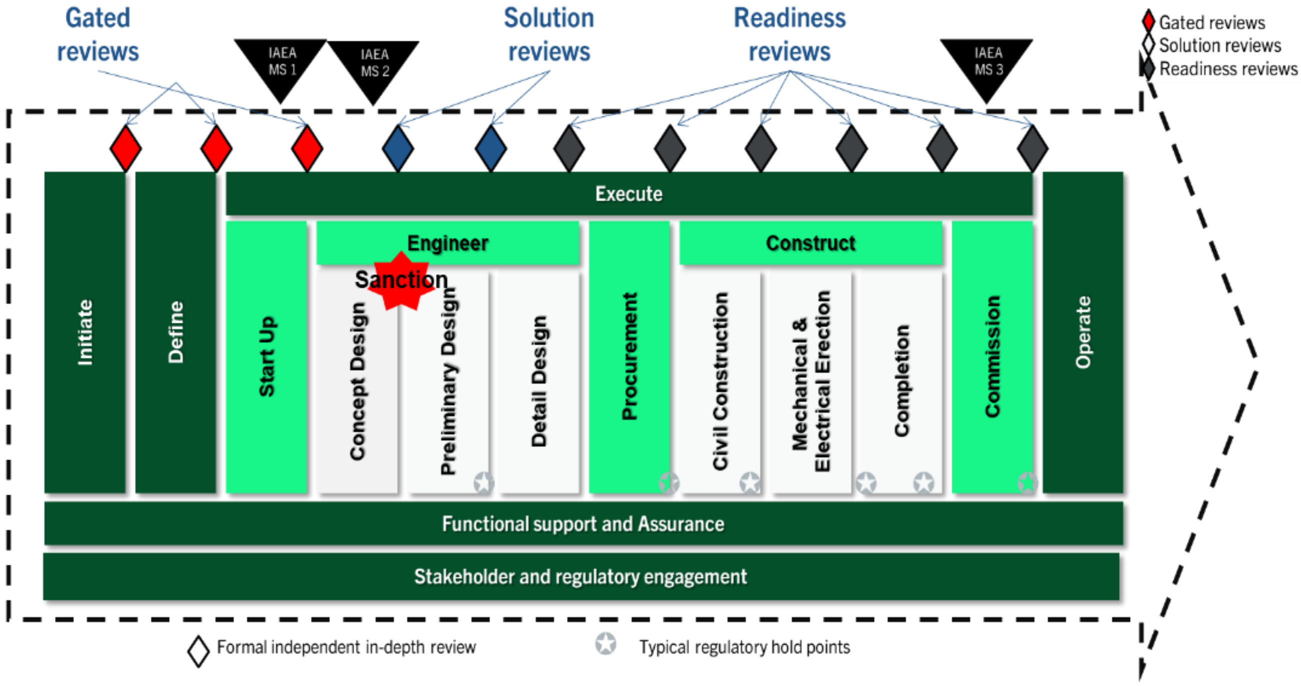


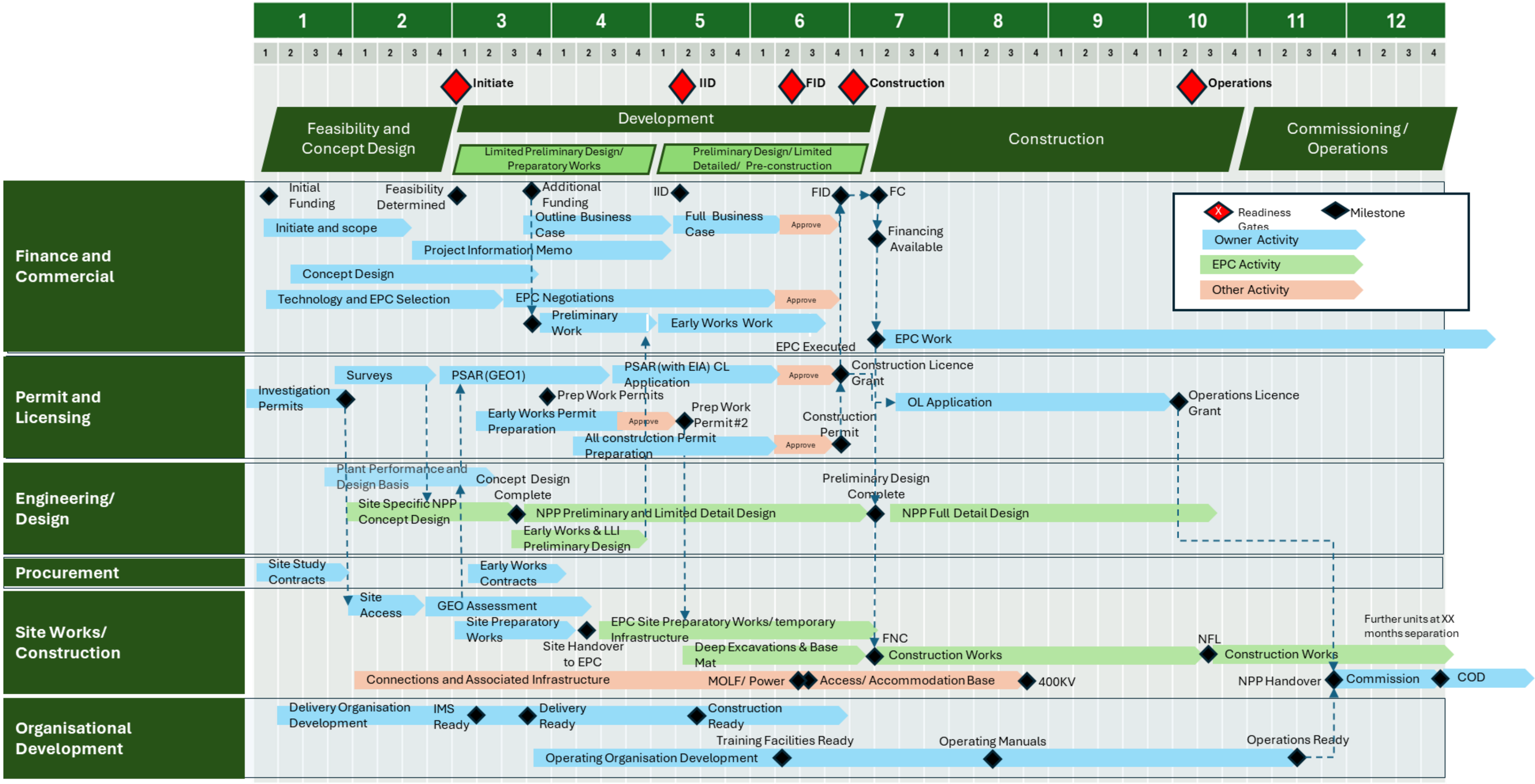
Figure 5.10: Lifecycle model for risk reduction

What is critical is the identification of all significant risks, them being characterised with mitigation strategies and managed through a risk management process. The risks we generally consider, and address are wide ranging typically as shown in Table 5.7.

Table 5.7: Typical Risk Areas in developing and constructing nuclear power plants

Political	Environment	Technical	Construction
• Political events • Changes to government and government support • Changes in law and regulation • Restructuring • Union actions • Public opinion/ consultation • Compliance with international instruments • Availability of waste disposal processes and facilities • Provisioning for decommissioning • Capability and capacity of regulators • Stability of country • Influence of other nations • Appointment of lead organisation (in some cases) • Export licence delays • Government to Government agreements • Governmental role in setting financial instruments, energy market etc	• Existing site issues • Force majeure events e.g. pandemic • Safety and hazards to population • Security and protection of nuclear facilities • Impacts and risks to environment • Design licences • Obtaining licences and permits for first nuclear construction • Obtaining licences and permits for further construction • Obtaining licences and permits for operation • Addressing climate change	• Unproven / novel technology and design • Licensing and or construction proceeding ahead of design maturity • Robustness of design processes • Poor quality (services, design, equipment and construction) • Robustness of design baseline including seismic and flooding • Robustness of safety case • Licensing requirements not harmonised or not understood • Safety classifications, design for safety, security and safeguards • Technical interfaces • Capable resource availability • Failures in testing and commissioning • Robustness & maturity of designs on handovers • Inadequacy of procurement specifications • Scope of vendor design	• Lack of intelligent customer • Construction readiness • Capable resource availability • Designs have not considered constructability adequately or design for construction safety • Inadequate construction planning • Site arrangements, layout and responsibilities • On site productivity • Off-site and on-site logistics • Defective materials and or components • Construction planning • Construction interfaces • Measurements and control of construction • Availability of on-site equipment • Availability of construction infrastructure • Adverse weather • Access to specialist equipment e.g. heavy lifting equipment, temporary equipment
Financial	Programme/ Project	Contractual/ Supply Chain	Operational
• Raising finance for capital expenditure • Business case not sufficient or robust • Uncertainty of capital costs • Uncertainty of operational costs • Uncertainty of maintenance costs • Uncertainty of decommissioning costs • Changes in tax treatments including carbon • Equity participation • Investing bodies • Foreign exchange exposures • Power demand and market pricing • Operational period • Control of pre-FID expenditure	• Ability and capabilities of lead organisation • Securing sanctioning of the programme • Site selection and suitability • Inadequate planning and control • Organisational structures • Delays to programme • Stakeholder engagement • Delivery, safety and quality culture • Adequacy of programme/ project governance • Regulatory review points • Site acquisitions • Robustness of cost base • Management of interfaces • Information integrity and management	• Lack of intelligent customer capability • Procurement process • Unreliable contractors • Contractual breaches • Addressing guarantees and warranties • Cost overruns and contractual delays • Failures in the supply chain, including quality • National capabilities and capacities • Capacity of national resources with capabilities • Security and robustness of supply chain • Capable resource availability • Supply chain capabilities • Ability to attract international supply chain • Other demands on the vendor and supply chain • Integration of supply chain	• Addressing operations in design • Operational readiness for different phases of project, ahead of and including operation • Availability of operation resources • Sourcing of spares and equipment availability • Improper operation and poor maintenance • Abilities to respond to emergencies • Shut down planning • Disposing and storage of waste • Timely fuel supply • Latent defects

Figure 5.11: Phase approach to nuclear power plant development (Generic Strategic Level Programme for GW Plant)



5.15 Observed causes of cost growth and delay

Table 5.8 provides a range of causes of cost increases and delays observed that can be summed up as the ability to access major capital investment at Government level, approach to planning strategic programmes through financing demands, poor deployment models, low stability in designs and low investment in the development of workforces.

Table 5.8: Factors contributing to programme delays and cost escalation

- Stop/ start conditions during development
- Covid
- Ground Conditions
- Design stability and changes
- Challenges to regulators
- Management challenges
- Rebooting the nuclear Industry
- Challenges to reach FID and lack of focus
- Financing challenges including security mechanisms
- New and developing supply chain
- Not adapting to codes and standards quick enough
- Development organisation (skills, staff and processes)
- Constrained supply chains
- Insolvency of reactor vendor
- Project suspension/ cancellations
- Engagement of new supply chain and constructer
- Poor performance
- Quality issues (suspect items)
- Efficiency in progressing M&E
- Contracting model
- Skills and capability rebuild
- Slow decision-making processes
- Sweeteners to local government to achieve permitting
- Extensive regulatory processes
- Extensive planning processes

In reflection the above, Table 5.8 provides specific information on the key GW programmes that have commenced in the past 15 years and their status. As shown, almost all new power plants programmes, largely GW at this time, suffer cost escalation and delays. The best performing programme is Barakah in the UAE, constructed in an emerging nuclear nation deploying technology that had not been build outside its home country. The reasons for why such delays occurred are well documented, echo the above summed up to be:

- The re-emergence of the nuclear industry building knowhow, capacities and capabilities within the supply chains and re-skilling the workforce.
- Design readiness including adaption to different regulations, codes and standards and, site conditions.
- Challenges to get funding and financing to programmes with economic downturns.
- External events such as Fukushima.
- Poor application of programme management.
- Stakeholder implications and public opinions.

What is clear in all the programmes gaining the financing is a significant challenge and is a significant cause in programmes progressing into the construction phase. There have been numerous shock events that have impacted nuclear power programmes during the recent times, the Fukushima event had a profound impact adding further new resilience measures and delays or even cancellations. Such events are difficult to reflect in risk management models due to the potential catastrophe impacts.

All nuclear power programmes need good programme management practices applied as the challenges tend to be of an organisational nature rather than technical challenge. Linking directly into Financing processes would also prove advantageous.

Table 5.9: Summary overrun and delay and cancellation experiences

Vogtle AP1000 Units 3/ 4 USA	Operational	The first new nuclear project in the United States in approximately 30 years – had experienced extensive delays and cost overruns. The initial capital cost estimate of about $5,600 / kWe (gross capacity) rose to $ 10,800/ kWe with the timeline extending significantly beyond initial projection of 4 years to around 10 years. Delays have been attributed to a variety of factors, including workforce management and a change in the engineering, procurement and construction contractors after construction had started and further exacerbated by insolvency issues with the technology contractor.
Virgil C Summer AP1000 Units 2/ 3 USA	Postponed	The Virgil C Summer project was sanctioned in 2008 to provide 2 AP1000 reactors for an original estimate of $9.8bn. The concept was to extensively modularise the construction. Work on the site commenced in 2013. The project was beset with delays between 2014 and 2017 mainly caused by manufacturing errors and construction inefficiencies. In 2017 the forecast cost was in the region of $25 Bn. Consequently, Westinghouse applied for bankruptcy and the project was terminated. Restart of this project is now being considered (De Chant, 2025).
Olkiluoto 3 EPR Finland	Operational	European projects have also seen large delays. The Olkiluoto 3 EPR project in Finland was initially planned to be operational by 2009 but was not connected to the grid until 2022. The original budget was about, $3,300/ kW, but costs escalated to $ 6,700/ kW due to design modifications, regulatory hurdles and supply chain disruptions (Bass, 2023).
Flamanville 3 EPR France	Operational	The Flamanville 3 EPR project in France experienced a significant cost escalation, with initial estimates of $ 3,200/ kW rising to, $11,600/ kW by the time it became operational in 2024, following a delay of 12 years. In all three European projects (UK, France and Finland), the use of an evolving new generation of reactors, namely the EPR, was a common factor. Design was still evolving when construction started, they were not built in series which would assist in generating cost reducing efficiencies, but were individually influenced by local operator choices, geography, geology and diverse associated infrastructure, as well as regulation.
Hinkley Point C EPR UK	In construction	Hinkley Point C EPR project has been beset with escalating costs and timelines. Initially estimated at about $8,700/ kW, the budget has risen to $18,700/ kW, with the completion date being pushed back several times from 2025 initially to 2029-2031, with around 1.5 years of the delay attributed to the Covid pandemic. The metrics for this project are still provisional as the project is still being constructed.
Sizewell C EPR UK	In construction	Sizewell C project is the sister project to Hinkley Point C utilising EPR technology and commenced in 2009. The arrangements around the financing of the project with the introduction of RAB and are significantly different with the UKG being a significant investor with EDF, Centrica and La Caisse and Amber Infrastructure. The delivery model is different as well but heavily reliant on Hinkley Point C. The project achieved FID in June 2025 with estimated build costs of £36.8bn and expected to take 9 to 12 years to complete. There have been considerable delays to gaining FID developing a suit ownership and financing structure.
Wylfa EPR/ AP1000/ ABWR UK	Cancelled	The Wylfa project was established in 2009 and went through 2 phases. Originally set up by German companies EON and RWE as a joint venture it made considerable progress. Fukushima caused Germany to pull out of nuclear power including this project. Hitachi bought the project in 2012 for ~£700m and furthered the project to now build 3 ABWR reactors and commenced the licencing process and developed the project significantly including setting up an EPC company with Bechtel. Operations where targeted for mid 2020s.They also engaged Exelon to support development of the operating model. However, following various discussions with the UKG that resulted in them assuming a 1/3 equity stake, providing debt funding and a CfD of £75/MWh for 35 years this was not sufficient for Hitachi to proceed. The project was cancelled. Site now being reconsidered for SMR construction with RR SMR technology.

Moorside AP1000 UK	Cancelled	The project owned by Nugen (in the third iteration of the business owned by Toshiba, in turn the owner of Westinghouse at that time) was to build 3 AP1000 power plant near Sellafield in UK. It was anticipated to be operational in 2024. The project faced many challenges including the Chapter 11 bankruptcy of Westinghouse in 2017. Following a review, KEPCO was selected as preferred bidder and wanted to use their own APR1400 technology that had not gone through the licencing process. Toshiba, in 2018, decided to wind up Nugen with the project being cancelled and handing the site back to the UK's Nuclear Decommissioning Authority.
Sinop Atmea Turkey	Cancelled	The Sinop project in Turkey was anticipated to be a shared project with Japan and was initially established in 2013.The project was to be a joint venture between MHI and Itochu utilising the Atmea technology MHI shared with Areva. The project included 4 units and was projected to cost $25bn with the first targeted to be operational by 2023. The project eventually grew to more than $46bn attributed to post Fukushima safety improvements, and the fall in value of the Turkish lira. Itochu pulled out in 2018 with other partners continuing for a while with the Japanese consortium abandoning the project later that year having failed to reach agreement on financing terms.
Hanhikivi VVER 1200 Finland	Cancelled	The Hanhikivi project was to construct a Rosatom VVER1200. It was based on the Mankala financing model involving 67 companies leading to Fennovoima being established in 2007. Rosatom where expected to have a 49% share. The site at Pyhäjoki was selected with significant site preparation undertaken and the licencing was progressing prior to its termination May 2022 citing significant delays and Rosatom's "inability to deliver the project. Terminated due to geopolitics.

5.16 Future GW and SMR costs assessment and opportunities to reduce costs

Cost predictions for GW and SMR power plants are expected to stabilise and be more predictable as new reactors begin to be built and learning is accomplished. Chapter 2 highlights the many projects planned or proposed or at even earlier stages in the European Union. We would be expected these to be well progressed by 2040. Gaining cost and schedule stability will provide the basis to improve it being a significant step forward for the industry.

Recognising this, Norway should in time be able to gain firmer and more realistic costs from both vendors and publicly available data should a decision to introduce a policy to prepare for nuclear power be made. We would advocate there be a 'deferment to expertise' recognising the uniqueness of nuclear infrastructure programmes and a national capacity plan be developed to transfer knowledge and capability to Norway. This should look to develop:

- A detailed country road map should be prepared communicating ambition and critical success factors.
- To engage the IAEA Nuclear in following the Energy Series No NG-T-3.2 Evaluation of National Nuclear Infrastructure Development 2008 19 criteria and encouraging INIR assistance support.
- A nuclear deployment programme schedule, strategies and plan.
- Sites should be identified and characterised to establish a design basis including environmental assessments.
- A plant performance requirements document should be developed establishing requirements.
- A regulatory environment including codes, standards and permitting requirements should be established.
- An oversight, developer and operator model that contains competent nuclear resources should be developed.
- A delivery model options explored and selected (e.g. EPC or other).
- Financing options and approaches.
- A technology selection process defined and ready to deploy including gaining costs and timescales.
- A procurement process ready to deploy.
- A cost firming process with selected Technology Vender needed to allow for progress pricing leading to FID and account for developing nature of the programme.
- A stakeholder and public engagement process and plan.

Chapter 2 has already explored a potential process for securing improved cost estimates from reactor vendors through the Bid Invitation Specification process. This journey will lead to more confidence in cost estimates providing a firm basis to build from.

Opportunities to reduce costs might include:

- Get the requirement capture and scope matured before costing. Ensuring that the design being costed that can be built in the jurisdiction is sufficiently detailed and risks and mitigations well understood, with probabilistic approaches to schedule and contingency management.
- Examining most efficient approach to financing the programme. Government support packages can secure lowest rates. The role of export credit can be extremely beneficial and could be explored.
- Multiple deployments of same technologies to gain leverage and NOAK benefits.
- Avoid FOAK but recognise and plan for FOAC deployments.
- Build relationships with Technology nation's regulators and accepted their approvals.
- Recognise supply chain risks and actively mitigate, including exploring more collaborative approaches to risk ownership, and clear risk appetites.
- A considered liability regime.
- Harmonise codes and standards as much as possible.
- Grow and develop momentum to avoid costly programme pauses.
- Have responsive decision making and governance structures.
- A clear licensing strategy, exploring minimal viable operator regime aligned to technical decision-making needs and meeting regulatory requirements
- Drive to digitisation.
- Consider and cost benefits of localisation (if minimised costs will be lower).
- Driving in commercial models that are highly incentivised.

All points should be considered in the development of the road map mentioned above. Key will be deciding when to progress to gain benefit from the progress that will be made in the industry but be able to secure the slots required given the resource constraints that are likely to appear.

5.17 Main Cost Drivers for Operation and Maintenance costs

The main cost drivers and cost classes for operating and maintaining power plants are:

- Operational staff that includes Management, corporate, operations and maintenance staff that are typically around 700 to 1,000 for a GW plant and expected to be around 500/ plants for SMR based plants usually accounted for in O&M costs (See discussion below).
- Plant outage costs including loss of revenue accounted for in Financial Models.
- Plant design issues, latent errors, reliability and breakdowns (Unexpected shutdowns) leading to loss of revenue accounted for in Financial Models.
- Performance and safety upgrades sometimes driven by external events accounted for in O&M costs.

- Fuel Costs with typical 18 month fuelling Cycles (usually 1/3 loads) accounted for in fuel costs.
- Waste and Spent Nuclear Fuel management accounted for in waste costs.
- Decommissioning and dismantling costs accounted for in decommissioning costs.
- Impact of load following costs (explored in Chapter 3).
- Financing and depreciation costs.

At the moment, we have not seen any indication that operational staff numbers would be significantly lower for LW SMRs (IAEA, 2001). ‘IAEA TECDOC 1193 Staffing requirements for future small and medium reactors (SMRs) based on operating experience and projections January 2001’ supports this. A view could be the functional requirements remain like GW with similar administrative support. Modularisation could operational aspects in relation to spare holding and change outs. There may be benefit is where at scale exists (NOAKs) allowing to cover multiple power plants with limited specialists. More economies of scale in spare holding and service procurement. Inconclusion, the thoughts expressed here based on a /MW basis could be higher.

Outage times can vary significantly and depend on plant generation however, with plant and operational improvements outages do tend to improve for a period, Expected planned outages are as typically shown in Table 5.10. As shown in the technology assessment section in Chapter 2 , interrogating outage management strategies and plans as part of technical assessment will be beneficial

Table 5.10: Typical Outage Period for GW LWR reactors

Region / Fleet	Typical outage duration (days)	Notes
USA — 2023 average	~ 38 days	According to Commodity Insights data the average length of US nuclear refuelling outages in 2023 was 38 days.” (S&P Global, 2024)
USA — 2024 average (to July)	~ 34 days	As of July 31, U.S. nuclear plant refuelling outages this year have lasted an average of 34 days.” (U.S. Energy Information Administration, 2024)
Spain / Europe (example)	~ 30 days	The duration of the refuelling outage is on average 30 days.” (ForoNuclear, 2020)
Korea (APR1400 reference)	Target: 16 calendar days (basic refuel)	Paper reports for the yet to be built EU-APR “16 calendar days for refuelling and regular maintenance outage” target. (Korean Nuclear Society, 2016)

When considering GW power plants, plants tend to include facilities accommodating 10 years of operation for radioactive waste treatment and storage including spent nuclear fuel ponds, and sometimes dry fuel stores as discussed in Chapter 4. We are not clear as to what facilities are being made in SMR technologies.

Prior to operations commencing, waste strategies, plans and facilities will need to be considered at a national level addressing longer term storage that Governments are usually responsible for. This includes any offsite interim storage measures and final disposition facilities and management. Funds to fulfil this obligation are generated during operations and should cover the expected life costs. These need to be clarified prior to operation to establish levy levels to be accounted for in the financial model and power take off agreements.

The amount of radioactive waste is relatively small compared to other thermal electricity generation technologies. They are neither particularly hazardous nor hard to manage relative to other toxic industrial waste. Waste generated is classified into Low (LLW) ~90%, Intermediate (ILW) and High-Level Waste (HLW). Waste is either treated or conditioned with costs varying accordingly. There is also Very Low Level Waste (VLLW) containing radioactive materials at a level which is not considered harmful to people or the surrounding environment. This waste is disposed of through domestic refuse, however some countries such as France are currently developing specifically designed VLLW disposal facilities.

Radioactive waste volumes anticipate over the lifetime on power plant operation will need to be a key area to explore to right size future Interim and Disposition facilities. The amounts vary technology to technology.

Spent Nuclear Fuel (SNF) can be treated as a resource (i.e. reprocessed) or as waste as discussed in Chapter 4. Safe methods for final disposition of high-level radioactive waste have been technically proven. Again, cost of such disposal needs to be agreed.

5.18 Nuclear Fuel Costs

Typically, costs are \$6–\$10/MWh for GW plants[11]. This is a key advantage of nuclear fuel that it offers a very high energy density source of power. Costs include uranium procurement, enrichment, and fabrication, The fuel cycle is explained further in Chapter 4. Fuel contracts are typically let with the reactor vendor for the first few cycles to retain accountability for plant performance and then may be competed in a context of a strategy suitable for the nation and developer/ operator.

The World Nuclear Association published the Economics of Nuclear Power which contained a general analysis of the front-end fuel cycle cost of uranium (WNA, 2023) as shown in Table 5.11. Generally, uranium prices look to be increasing and are likely to continue with expected demand to increase. This will likely drive the market to reprocessing requiring additional facilities world-wide to accommodate.

To note however, unlike more conventional generation technologies, fuel is a less contributory factor to overall operational costs typically 9%.

Table 5.11: Typical Front End Fuel Cycle Costs of 1kg of Uranium as Finished UO_2 Fuel Assembly (WNA, 2023)

Process	Amount Required x price*	Cost	Proportion
Uranium	8.9 kg U_3O_8 x \$94.6/kg	\$842	51%
Conversion	7.5kg x \$16	\$120	7%
Enrichment	7.3 SWU x \$55	\$401	24%
Fuel Fabrication	Per kg	\$300	18%
Total		\$1663	

These prices are approximate at the end of September 2021. However, fuel costs are reducing in the USA fuel costs have declined by 23% between 2012 and 2019 according to the Nuclear Energy Institute.

Comparative analysis by Pannier and Skoda provides a detailed simulation-based assessment of fuel costs for Small Modular Reactors (SMRs) and Large Light Water Reactors (LWRs), offering valuable insights into the long-term economic implications of nuclear fuel cycle choices. Their study focuses on a specific type of LWR SMR, and integral pressurized water reactor (iPWR) SMR design and

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[11] Used in analysis

contrasts them with established large reactor technologies using 2014 market data for uranium, conversion, enrichment, and fabrication. More recent information is available through publications behind paywalls for approved organisations only.

The study confirms that SMRs, particularly LWR SMRs, are expected to incur higher fuel costs than GW LWRs. Simulated average fuel costs for GW LWRs were found to be approximately $3.86/MWh, while SMRs ranged from $3.95 to $7.47/MWh, with an average of $5.84/MWh. This represents a 15% to 70% increase[12]. The differential is primarily attributed to lower plant energy density and fuel burnup cycles in SMRs, which reduce the energy extracted per unit of fuel (Pannier & Skoda, 2014). Key reactor-specific findings include:

- The Westinghouse SMR (W-SMR) and Korean SMART reactor showed relatively lower fuel costs among SMRs, at $4.51/MWh and $4.88/MWh respectively (Pannier & Skoda, 2014).
- NuScale and mPower designs exhibited higher costs, at $5.76/MWh and $6.60/MWh (Pannier & Skoda, 2014).
- The Holtec HI-SMUR design, while innovative in safety and siting, has the highest cost at $7.47/MWh (Pannier & Skoda, 2014).

SMRs, have similar fuel cycles to GW of 18-24 months intervals, and co-generation capabilities (e.g., desalination), which can increase fuel costs. For example, higher enrichment levels to meet longer fuel cycles, while reducing outage frequency and cost, tend to raise the cost per MWh due to increased enrichment costs and fabrication complexity (for example larger number of unique fuel assembly types per core and reload).

Sensitivity analyses underscore the importance of burnup and thermal efficiency in determining fuel cost. Improvements in these parameters could significantly reduce SMR fuel costs over time, particularly as designs mature and operational experience accumulates. The study also notes that fabrication costs, assumed at $275/kgU, are a major contributor to overall fuel cost, especially for SMRs using non-standard fuel forms or multiple configurations.

In conclusion, while SMRs offer potential advantages in lower CAPEX per unit, modular deployment, safety, and siting, their OPEX fuel cost disadvantage relative to large reactors remains an important consideration. The main consideration is the cost of finance avoided through shorter time for the first reactor to generate electricity. Future cost reductions will likely depend on design standardisation, fuel cycle innovation, and operational optimisation. These findings reinforce the need for integrated techno-economic assessments when evaluating SMR deployment strategies, particularly in markets where fuel cost competitiveness is a key driver.

5.19 Operation and Maintenance (O&M) Costs

O&M OPEX costs for large GW reactors range are shown in the table below, from a report issued by MIT Energy Initiative. Staffing, maintenance, and regulatory compliance are key drivers. Fuel and operational capital costs are generally consistent across USA and Europe. O&M Costs are taken from this provides an overview of costs within different countries and these ranges for several countries are illustrated in *Table 5.12* below (Massachusetts Institute of Technology, 2018).

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[12] Used in analysis

Table 5.12: Country Specific Nuclear Operating Cost Ranges (Massachusetts Institute of Technology, 2018).

Country	Unit Size (MW)	Fixed O&M Cost($/MW-yr)	Variable O&M Cost($/MWh)	Fuel Cost ($/MMBtu)
USA	1000	$95,000	$6.89	$1.02
China	1000	$59,677	$4.33	$0.84
United Kingdom	1000	$180,759	$13.11	$1.02
France	1000	$115,123	$8.35	$1.02

The variations in O&M costs across countries could be related to differences in labour expenses, nuclear technology and regulatory regimes.

For LWR SMRs, whilst there will be some potential economies of scale across a fleet of SMRs, the systems are very similar in number and function, and therefore the labour costs for these plants are likely to be like GW, and higher per kW.

Initial spares excluding fuel provisioning typically adds 1–2% to capital costs, ensuring operational reliability during early years. Some projects have added to provision for replacement of some major components such as a reactor pressure vessel head.

5.20 Waste Management Costs

According to World Nuclear Association Web site most nuclear power plant operators are setting aside levies. This is 0.1¢/kWh in the USA and 0.14 ¢/kWh in France that is to provide funds to manage and disposal of waste. Consideration of policy alignment with international best practices (e.g., US, EU, IAEA, GAO) will be essential for cost benchmarking, assisting with regulatory frameworks and harmonization. Practices such as early design-stage for waste management and decommissioning should lead to improved costs for future reactors.

The U.S. has accumulated over 86,000 tons of spent nuclear fuel, growing by ~2,000 tons annually (Cranmer, 2024). With no permanent repository operational, interim storage at reactor sites is dominating current practice. Dry cask storage is widely used post-cooling, but long-term container degradation risks persist. The costs for storage and managing the waste is illustrated in Table 5.13.

Table 5.13: US Waste Management Costs (Cranmer, 2024)

Interim Storage (100-year NPV):	Permanent Disposal	Cost per kWh
Centralized: $109,341–$211,393 per MTHM Reactor-site: $94,762–$318,651 per MTHM Total U.S. liability: $8–$27 billion (existing waste), growing $200–$600M/year	International range: $148,000–$1,041,000 per MTHM Yucca Mountain (GAO): $298,866–$488,391 per MTHM + $109,341 sunk costs DOE estimate: $50.2 billion unfunded liability (2023)	Long-term disposal: <$0.001 to ~$0.013/kWh[13] Mid-range: $0.0025–$0.006/kWh

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[13] Used in analysis

There are also reports from a Nordic country suggesting the upper range could be as high as 0.7 c/KW (Porelius, 2023). This value is added as worst case in Table 5.17 later in this chapter.

In relation to determining future strategies, centralized interim storage could offer cost efficiencies if co-sited with power station deployments, particularly for SMRs. Modular SMR designs constructed on multi-unit sites could reduce waste generation per unit of energy, especially if reprocessing becomes viable. By integrating Waste Costs into LCOE Models, it would ensure that full lifecycle costs, including interim and permanent storage, are reflected in techno-economic assessments (Porelius, 2023).

Integration of modular construction and digital engineering can reduce both capex and long-term waste handling costs.

5.21 Spent Nuclear Fuel

After about 10 years of power plant operation the plant Spent Nuclear Fuel (SNF) pools will be at capacity and therefore an SNF strategy needs to be developed along with any facilities for reprocessing (if applicable), interim storage if final disposition available. Depending on a national strategy and the use of reprocessing approaches, storage and disposition of Spent Nuclear Fuel (SNF) will become necessary. Many countries are looking to final disposition facilities and providing both dry and wet interim SNF facilities.

A typical cost for an interim storage facility would be $14m/ site with operating costs at $1m growing to $6m to $12m after shutting down (Cranmer, 2024). *Table 5.14:* provides indications of costs per metric tonne. Any facility will need to be correctly sized in a suitable secure area to accommodate the SNF volumes generated over the period where final disposition solutions are available. According to the SMR Cost Reduction Study, SMRs will influence waste management economics with some reports suggest that there is likely to be a larger volume of fuel coming from SMRs (EY, 2016).

Table 5.14: 50-Year Cost Estimates (USD per Metric Tonne)

Interim Storage Type	Capital Costs ($/MT)	Annual O&M ($/MT)	50 Year O&M Total	Total 50 year Costs
Wet Poll (On-site)	$50.0k (est)	$10.0k	$500k	$550K
Concrete Dry Cask	$84.5K	$17.5K	$875K	$959.5K
Metal Dry Cask	$299.4K	$17.5K	$875K	$1,174.4K
Dual Purpose Cask (DPC)	$376.7K	$17.5K	$875K	$1,252K

Final disposition facilities are being closely examined with many countries looking to deep geological facilities. Cost for this could be extensive and highly dependent on many factors including suitable geotechnical sites being available and the work required to make secure for many centuries. As by way of example, and according to IAEA report, Cost Estimate of Onkalo Disposal Facility for Spent Nuclear Fuel, the final disposition facility in Finland at Olkiluoto operated by Posiva covering both investment and the operating costs of the above and underground facilities, the decommissioning of the encapsulation plant and the closure costs of the repository are estimated to be ~$0.5bn and the total operating costs are ~$2bn. Other larger facilities are estimated to be ~2bn in just construction with much depending on the volumes to be stored etc (Kukkola, et al., 2005).

5.22 Decommissioning Costs

Decommissioning nuclear facilities is a complex, multi-phase process driven by national government policy and strategies with regulatory oversight. Whilst decommissioning plants will be some 60 to100 years in the future, consideration during the develop of new power plant programmes is key. To fund this most developers are required to establish decommissioning pools that generate through its operational life and are accounted for through levies included in any Power Take-off Agreement (PTA). Understanding the costs prior to FID is essential to ensure sufficient funds are generated and protected. This is implemented in any finance model for clarity on strategy, plan and costs. The UK operates the concept of the Funded Decommissioning Plan for example for new build power plants.

The costs for decommissioning can vary greatly based upon facility type size, complexity and strategic approach. Approaches typically are immediate or deferred dismantling. Larger GW reactor decommissioning costs can range between $0.5bn to $2bn and durations ranging from 5-30 years. Much depends on technologies and waste generated along with political desire. Some examples of international practices, cost structures, and benchmarking methodologies, with a focus on the International Structure for Decommissioning Costing (ISDC) drawing on several case studies are highlighted.

We provide here some decommissioning benchmarks illustrating there are different approaches taken by different countries. Determining factors include legislation and regulator. Case studies taken from the NEA Costs of Decommissioning Nuclear Power Plants are illustrated in Table 5.15 (Nuclear Energy Agency, 2024). Key drivers are Waste volumes, site remediation standards, disposal access.

Table 5.15: International Decommissioning Benchmarks (Nuclear Energy Agency, 2024)

Country	Strategy	Cost / Funding	Framework	Regulatory Bodies
Korea	Immediate decommissioning	$662m[14]/ unit RWA 2922	WBS for NPPs; ISDC for research reactors	NSSC, KINS
Switzerland	Immediate dismantling	$3.73 bn for decommissioning; $2.14bn for post-operational phase	Two state-controlled funds updated every 5 years	SFOE, ENSI, NSC
United Kingdom	Shift from safe enclosure to continuous decommissioning	$20.37bn for Magnox gas cooled reactor fleet (NDA)	Lifetime Plans mapped to ISDC	ONR, Environment Agency, NDA
United States*	Both immediate decommissioning (DECON) and deferred safe-storage (SAFSTOR) approaches are used	$340m-$470/ unit	Licensing and financial assurance overseen by Nuclear Regulatory Commission (NRC); licensees must report decommissioning fund status every 2 years.	NRC
France	Deferred dismantlement for major fleet	$300m/ GW capacity; ~ $23 billion national provision for 58 reactors	Standardised large fleet; multi-unit sites	ASN, IRSN

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[14] Used in evaluation for low case

Germany	Early phase-out; long-term deferred dismantling	$1bn/ [15]reactor (e.g. Rheinsberg)	Multi-unit sites; legacy systems	BfS, GRS
* Completed - Haddam Neck, Maine Yankee, Trojan, Rancho Seco All converted to $				

Furthermore, we have undertaken previous assessments utilising the NEA OECD Decommissioning Nuclear Power Plants Policies, Strategies and Cost report which is an extractive of material referring to PWR LW reactors (NEA OCED, 2003). With adjustments for economics, we anticipate decommissioning costs for a GW power plant between $600m to $1,000m [16] per reactor unit with its balance of plant.

For SMR on a comparative unit by unit basis we would anticipate significant less particularly as many of the designs will be incorporating features to support decommissioning. On a unit-by-unit basis the volumes would be less. However, on a power output comparative basis it is likely to be higher as more to decommission and equally greater volumes.

Table 5.16: Extract from NEA Decommissioning Nuclear Power Plants Policies, Strategies & Cost 2003 (NEA OCED, 2003)

Country	Name of Plant	Capacity (MWe gross)	Total Cost	
			MUSD	$/kWe
Immediate dismantling				
Belgium	Doel1-2 (Twin Unit)	412 x 2	280	340
Belgium	Tihange 1	1009	213	212
Germany	Germany PWR	1200	315	262
Italy	Trino	270	245	909
Slovenia	Krsko	707	332	470
South Africa	Koeberg	944x2	317	168
Spain	Spain ref. PWR	1000	166	166
Sweden	Ringhals 2	917	85	93
Switzerland	Beznau (2x380)	380x2	259	341
Switzerland	Gosgen	1020	238	234
United States	Haddam Neck	587	452	769
United States	Maine Yankee	900	379	421
United States	Trojan	1155	296	256
United States	Zion	1085x2	904	417
Deferred dismantling				
Brazil	Angra 1	657	198	301
Brazil	Angra 2	1350	240	178
France	Average_ref. PWR	1070 x 58	13973	225
Germany	Germany_ref. PWR	1200	331	276
Japan	Tsuruga 2	1160	470	405
Netherlands	Borssele	481	168	348
Slovenia	Krsko*	707	152	216
**Deferred by 80 years*				

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[15] Used in evaluation as worst case
[16] Used in evaluation

5.23 Global observations and comparisons/ drivers for change

There are many global trends to be observed in the development of nuclear power plants worldwide. Increases in energy requirements, low carbon production and energy security have played and are playing their part. More recently is the drive of technology companies (Hyperscalers) for large energy demand to power AI based data centres is becoming a clear factor and the engagement of the nuclear industry with new nuclear technologies looks to be commencing with significant activity in all areas covering all types of technologies. This is likely to:

- Require the nuclear industry to grow considerably pressuring existing talent and resources potentially causing cost increases due to demand and pressurising supply chains.
- Driving new approaches to regulation to enable deployment of technologies across boundaries enabling some fleet effects drive plant costs down through NOAK and even production lines.
- Modularisation exists in the current market but the drive to greater levels and factory thinking is becoming even more dominate driving costs down.
- Developing now are ranges of power bands of technology ranging for single digit MW reactors through to large GW reactors offering more tailored solutions with cost benefits.
- Approaches to operations to become centralised for fleets of power plants looking to reduce costs including shared maintenance support and spares pools.
- Digitisation of power plants supporting construction, operation, maintenance and decommissioning with remote monitoring allowing greater efficiencies and cost reductions.
- Factors such as regulatory changes, learning effects, project management, labour costs, standardisation and modularisation.

As the nuclear power market continues to develop and with SMR technologies being commercialised, there is an opportunity to develop new supply chains using modern supply chain approaches seen in other industries. This would introduce innovation and production-based techniques that should provide cost benefits. Currently these supply chains are only beginning to be established.

In respect of operational costs, the Nuclear Energy Institute reports that in 2021, the average total generating cost for U.S. nuclear plants was $29.37/MWh, down 35% from 2012 (Nuclear Energy Institute, 2021). Whilst these figures exclude spent fuel storage, attributable to spent nuclear fuel (SNF) being seen also as an asset for reprocessing, and decommissioning costs. There is a potential trend in driving greater performance from power plants where economies of scale can be obtained with multi-unit sites and operators with multiple plants who consistently report lower generating costs, suggesting potential efficiencies including centralised waste handling.

5.24 Cost premiums for emerging nuclear nation

An emerging nuclear nation will likely face a number of cost premiums in addition to being part of the European region where costs tend to show higher and delays are apparent. As with all emerging nuclear nations, Norway will likely need to build capacity in the following areas:

- **Regulation** – to develop regulations, adapt existing ones and build a competent regulatory organisation.

- **Nuclear competent workforce –** to develop a nuclear competent workforce that can support the full depth and breadth of the supply chain in services (technical, commercial, construction etc.) and manufacture.
- **Operator organisation –** to develop an operator organisation that can operate the plant once constructed.
- **Supply Chain –** to develop a competent supply chain to support a programme through the life cycle.
- **Nuclear-related knowledge –** to gain general nuclear related knowledge so as to become an Intelligent Customer.
- **Educational institutes –** to engage educational institutes to develop STEM graduates with interest in participating in nuclear programmes
- **Supportive public** - to develop a positive and supportive public. Make the case for adopting nuclear power solutions.
- **Engaging with the international nuclear community**.

These are all areas that will need to be addressed to support any introduction of nuclear power. The cost associated with this will need to be properly explored and defined against a Capacity Development programme. The IAEA has provided useful publications (Reference IAEA Nuclear Energy Series No NG-T-3.2 Evaluation of National Nuclear Infrastructure Development) providing a three-stage approach over 19 areas as illustrated by Figure 5.12 and offers an Integrated Nuclear Infrastructure Review Service (INIR) to support emerging nuclear nations.

Figure 5.12: IAEA 19 nuclear infrastructure issues (IAEA, 2022)

Should Norway choose to adopt nuclear power, it will need to develop a clear road map with a milestone plan to ensure readiness, drive programme certainty, create a nuclear regulatory regime and increase capacities in nuclear skills and industries.

5.25 Analysis

Having considered the information found in this research and applying a judgement using the experiences collectively gained in our 50 years involved in multiple nuclear power plant developments, we summarize our cost expectations, as shown in Table 5.17. The basis of this table includes the following assumptions:

- All figures assume 2025 economic conditions unless otherwise stated.
- Northern Europe region norms are appropriate.
- An emerging nation needing to establish nuclear regulation and capacities.
- An emerging nuclear nation is likely to utilise proven technologies leading to FOAC deployment and a reference plant that is adapted to local regulations, codes and standards, and siting conditions – ideally regulations would consider a FOAK regulatory environment.
- Government related costs will need to address several factors including implementing nuclear related legislation, regulation and development to support a nuclear programme including capacity building in skill, supply chain capabilities and addressing public opinion and stakeholder engagement.
- Developer costs include land acquisition, a developer organisation with staffing levels typically 600 to 1,000 plus the development of the operator organisation of typically 400 to 500 per reactor, plus management and other scope allocated to the developer such as site evaluation and preparation, licencing, non-site infrastructure and temporary construction facilities, training facilities, and insurances.
- Assume the power plant delivery model will be akin to an Engineer, Procure, Construct (EPC) type contract approach with a competent organisation engaged to support a developer.
- GW power plants are normally built in pairs providing a ~ 2GW output power plant and costs include Nuclear Island, Conventional Island, Balance of Plant, Infrastructure and supporting facilities including security. The solution needs to ensure all licencing requirements are meet.
- SMR power plants are likely to be built in batches of three or more. In terms of development costs, we have assumed six SMRs to be comparable to a GW plant giving 2.1GW output power. Again, all the same elements of the GW are included.
- Construction and operational times align to norms as shown.
- Fuel and O&M costs are provided annually.
- Waste and SNF is facilitated within the power station for first 10 years utilising facilities provided.
- Once the capacity of power plant waste and SNF facilities is exhausted, additional facilities will be required on either an interim or final disposition basis. Estimates are used to determining levy arrangements to fund any conditioning or storage facilities.

- Following shut down and defueling, decommissioning estimates similarly help establish levy arrangements to fund decommissioning. Estimates for spent fuel storage and decommissioning are also indicated.
- FINEX estimate methodology is shown in the table and is a crude but reasonable approach.

The information in Table 5.17 should only be taken as a guideline based upon data that has been assimilated from the multiple sources within this report. The financial information is taken from multiple public reports issued between 2018 and 2022, which refer to cost information obtained around 2015. Consequentially, all cost elements, CAPEX, FINEX, OPEX and DISEX, are assumed to have reflected circa 2015 economic conditions. This assumption is a necessary judgment regarding the economic basis of the publicly available information used to provide meaning and further analysis.

To ensure the information is current and meaningful, we have updated the 2015 economics costs to reflect 2025 economic values. This has been accomplished by the application of a factor of 1.34 to 2015 economics costs to determine 2025 economics cost. This adjustment is based on an average escalation factor of 3.0% per annum, reflecting typical material and labour cost increases across Norway, Europe, the United States, and Japan, as represented by published CPI data. It also incorporates an allowance for exchange rate risk between the US dollar and the euro, which has fluctuated between $1.05 and $1.33 per euro during the period (a variation of approximately 21%).

When assessed, this indicates approximately 3% average escalation that has been used to determine the uplift factor as indicated above that is applied to 2015 economics costs.

In seeking further validation, we reviewed additional indices, such as GDP-IPD primarily sourced from the U.S. Bureau of Economic Analysis. CPI data broadly aligns with our conclusions, while other measures present a mixed picture that is difficult to reconcile consistently with the underlying cost drivers. These measures have therefore not been adopted in our assessment.

We recognise that alternative perspectives may exist regarding the methodology; however, we consider this approach to represent a rational and defensible basis for escalation.

We have also included estimated real time cost (CAPEX) to enable comparisons to be made to publicly available programme costs and add further validation that is illustrated in Table 5.17. This has been accomplished by projecting the sum of Owners Costs Pre FID and Post FID and, Power Plant Costs from 2015 to accountable for real programme timescales assuming start date of 2023 giving credit for some work already accomplished. The factor applied is 1.56 and established using the same approach discussed above projected to a 2/3 midpoint of a 12-year programme that develops and constructs to operation the power plants. i.e. 2030. This does not include FINEX as this will require more sophisticated modelling.

For a more accurate result, we would recommend undertaking a structured AACE class 5 or 4 estimate involving much greater detailed analysis supplemented by a much more detailed assessment and procurement competition that would overcome commercial sensitivities. On the timescales being considered, there is an opportunity to undertake commercially sensitive discussions about a range of technology types to better understand potential costs.

Also, the number of projects being completed over the next five to ten years, and particularly the transition to more fleet construction, provides an opportunity for further assessment of the business case.

Table 5.17: Modelling of Nuclear cost breakdown structure

Nuclear Cost Breakdown (All costs escalated to 2025 economic conditions unless indicated otherwise set)	Type of Cost	GW (2*1 GW = 2GW)		SMR (6*350 MW =2.1GW)		Comment
		Low	High	Low	High	
Government Costs for National Capacity and Infrastructure		TBD	TBD	TBD	TBD	Need to define scope and extent
Developer/ Owners Cost (Pre FID)	CAPEX $bns	**3.0**	**7.0**	**3.0**	**7.0**	bn $ Observations from various programmes and anticipate similar for SMR
Developer Costs/ Owners Cost (Post FID) (Additional to pre-FID)	CAPEX $bns	**5.0**	**9.0**	**5.0**	**9.0**	bn $ Observations from programmes and anticipate similar for SMR
Total Developer/Owners Costs	CAPEX $bns	**8.0**	**16.0**	**8.0**	**16.0**	Developer/Owners cost Pre FID + Post FID
Time to get to FID		5 years	10 years	5 years	10 years	
Power Plant Output		2GW	2GW	2.1GW	2.1GW	Twin GW @1GW/ 6 SMR @350MW to get site of 2.1GW
Power Plant Costs	CAPEX $ /kw CAPEX $ bns per unit CAPEX total $bns	6.5 6.5 **13.0**	8.5 8.5 **17.0**	6.9 2.4 **14.5**	9.4 3.3 **19.7**	Have assume 85% to reflect potential for increased learning for 6 SMR (FOAK to NOAK) recognising same site, same design, same workforce, same supply chain etc. If different sites this would be different. The cost assessments assume that no worst-case events or extreme delays occur.
Total Developer/Owners Costs & Power Plant costs - Overnight Cost	CAPEX $ k /kw CAPEX $bns	**10.5** **21.0**	**16.5** **33.0**	**10.7** **22.5**	**17.0** **35.7**	Developer/Owners cost Pre FID + Post FID + Power Plant costs
Total Developer/Owner Cost & Power Plant Costs - Real Time Estimate figures	CAPEX $bns	**24.3**	**38.4**	**26.1**	**41.5**	The sum of Developer/Owners Costs (Pre FID + Post FID), and Power Plant Costs (Overnight 2015 figures) factored by 1,56 to provide index-adjusted real time equivalent for comparative purposes. 3% escalation applied over 12-year programme
Construction Timescales (For first Unit)		6 years	12 years	6 years	12 years	Full power plant development
Construction Intervals (For subsequent units)		12 months	18 months	12 months	18 months	

Nuclear Cost Breakdown (All costs escalated to 2025 economic conditions unless indicated otherwise set)	Type of Cost	GW (2*1 GW = 2GW)		SMR (6*350 MW =2.1GW)		Comment
		Low	High	Low	High	
Financing Costs up to COD	FINEX $bns	**1.7**	**8.2**	**1.5**	**6.8**	Would expect timescales to be similar for GW and SMR however earlier revenue SMR could reduce – Assumes 30% Equity with low @ 5% high @10%
Financing Costs post COD	FINEX $bns	**6.6**	**22.4**	**7.1**	**23.7**	Assume a payback period of 30-years with low @ 5% and high @10%
Fixed O&M Costs	OPEX $k MW/y OPEX $ m/yr	155 309	242 484	Probably Higher	Probably Higher	SMR will be operating 6 units and therefore unless significantly different operating regimes likely to be significantly higher although potential digitization and multi-unit operations possible
Variable O&M Costs	OPEX $ MWh/y OPEX $ m/yr	11 86	18 132	Probably Higher	Probably Higher	Assumes 7.5K hours of operation / yr
Fuel Cost	OPEX $/MWh OPEX $m/yr	8 **81**	13 **134**	9 **99**	23 **245**	15% low 70% high increase for SMR caused by lower plant density and shorter burnup cycles - Assume 80% load factor and 85% availability
Waste and SNF (10 Yr Operation) Cost	OPEX	Nil	Nil	Nil	Nil	Assumed with power plant facility and operations
Operational Timescales		100 yr	60 yr	100 yr	60 yr	
Waste (post 10 Years Operation)	DISEX $cent/kWh	0.01	0.70	Probably Higher	Probably Higher	Facilities required need definition including Interim and Permanent disposition so using US data
Long term disposal Cost	DISEX Lifetime $m	**20**	**1400**			
Spent Fuel (post 10 Years Operation)	DISEX 50-year Interim $m	**65**	**600**	Probably Higher	Probably Higher	Final disposition excluded and addressed in the narrative – Assume similar for SMR
Decommissioning	DISEX Complete $bn	**1.20** for 2 units	**2.00** for 2 units	Probably Higher	Probably Higher	SMR likely on 6 unts to have increased volumes

Assumptions and explanations of the calculations in Table 5.17 are presented below:

- These figures are Amentum's observations across several programmes.
- 1st Fuel Load assumed in CAPEX
- Real Time Estimate 2025 figures of Owners and Power Plant Costs are calculated as follows:
    - (Developer/Owners Costs (Pre FID) Developers/Owners Costs (Post FID) + Power Plant Costs) * 1,56
- FINEX calculated as follows using 2015 data and then moderated to 2025 in the table above:
    - Calculated by years x debt level x year midpoint x interest rate i.e. 9.5*0.7 *4*5% =~$1.3bn up to COD and post COD assuming 30 years at 1/3 midpoint i.e. (9.5+1.3)*0.3 * 30 * 5% = ~$4.9bn - TOTAL = ~$6.2bn
    - Calculated by years x debt level x year midpoint x interest rate i.e. 12.5*0.7 *7*10% = ~$6.1bn up to COD and post COD assuming 30 years at 1/3 midpoint i.e. (12.5+6.1)*0.3 * 30 * 10% = ~$16.7bn - TOTAL =~$22.8bn
    - Calculated by years x debt level x year midpoint x interest rate i.e. 10.7*0.7 *3*5% =~$1.1bn up to COD and post COD assuming 30 years at 1/3 midpoint i.e. (10.7+1.1)*0.3 * 30 * 5% = ~$5.3bn - TOTAL = ~$6.4bn
    - Calculated by years x debt level x year midpoint x interest rate i.e. 14.6*0.7 *5*10% = ~$5.1bn up to COD and post COD assuming 30 years at 1/3 midpoint i.e. (14.6+5.1)*0.3 * 30 * 10% = ~$17.7bn - TOTAL = $22.8bn

5.26 Comparative Assessments

Table 5.4 and Table 5.5 include reported real-time costs of some known projects. As will be observed, there appear some significant differences in comparison to Table 5.17 figures factored by the actual power levels that merit explanation. These can be accounted for as follows:

- Information in Table 5.17 are set in the economics of 2025 and are overnight costs.
- Some of the projects are incomplete and therefore remain forecasts.
- There are no completed SMR programmes, so the information is speculative, particularly about NOAK builds.
- In some cases, it is likely that the full reactor development (generic design) costs may be attributed to the project projecting higher than normal costs.
- The exact scope included is unclear and may differ.
- Site and regulatory conditions have an impact on costs when understood (for example seismic, codes and standards)
- The economic periods of cost reports vary and project real time costs or costs incurred.
- We would assume much of the owner's costs for developing the programme and delivering it would be included.
- Inclusion of costs for developing the operator organisation are not treated consistently.
- Corporate aspects such as oversight, human resources, information, and procurement are not always included in the same way.
- Financing costs are not included.

Seeking to provide some explanation for the differences we have developed a rough and crudely modelled real-time cost from our internal power plant development models adjusted to a 2GW model, baselined from $12bn and $8bn owner's cost as extracted from Table 5.17. The outcome would be around $32bn for the 2GW plant assuming a 3% escalation. Escalation modelled at this level would also have to account for exchange rate fluctuations and include commodity and material escalations along with labour cost escalation. It reflects a generic programme timescale of 10 to 12 years for the modelled 2GW power plant with construction of six years per unit. To be comparative this must be adjusted for actual plant power levels as shown in Table 5.18. Explanations of potential issues that could be causing difference are highlighted in Section 5.14. This should be used with caution and does not take into account regional impacts.

Table 5.18: Comparative Table Real Time Costs (Crude Assessment)

Project	Units	Total Electrical Power	Table 5.4/5 Reported Costs	Table 5.4/5 $/ kW	Table 5.17 factored by power level	Table 5.17 $/ kW
Hinkley Point C	2	3.2GW	$61bn	$18,700	~$51.0bn	$16,000
Vogtle 3 /4	2	2.2GW	$36.8bn	$10,800	~$35.2bn	$16,000
Flamanville 3	1	1.6GW	$14.8bn	$11,600	~$25.6bn	$16,000
Olkiluoto 3	1	1.6GW	$11bn	$6,700	~$25.6bn	$16,000
Poland L-K	3	3.3GW	$49bn	$14,800	~$52.8bn	$16,000
Elektrarna Dukovany II	2	2.0GW	$19bn*	$9,500	~$32.0bn	$16,000
Akkuyu	4	4.5GW	$25.0bn	$5,600	~$72.0bn	$16,000
El Dabaa	4	4.5GW	$28.8bn	$6,200	~$72.0bn	$16,000
Barakah	4	5.6GW	$32bn	$5,700	~$90.0bn	$16,000
Darlington	1 plus 3	300MW/ 1.2GW	$5.5bn/ $21bn	$18,000	~$4.8bn/ ~$19.2bn	$16,000
NuScale	4	462MW	$9.3bn	$20,000	~$7.4bn	$16,000

* Probably excludes owner's costs

Whilst quite generic, there are significant gaps which perhaps reflect the realisation of the risks. In all cases the FOAK challenge suggesting that the strategy to be adopted needs to consider these matters.

5.27 Summary Cost

From this document you will observe that there is much activity developing in the nuclear power sector with the:

- Deployment of GWs ongoing with 107 in planning and a further 310 being considered.
- Beginning of SMR deployments looking to achieve volume and lower costs through factory construction and modularisation.
- AMR technologies being progressing for later deployment.

Key dominators in the market are Russia and China; however, the USA is beginning to wake up as a result of the demand for energy associated with AI-based data centres. Hyperscalers have access to huge amounts of capital and will begin to drive the market globally. As the market heats we would anticipate costs in deploying both GW and SMR technologies to become more predictable with a view of significant reductions as technologies move from FOAK to NOAKs at bulk. This applies to both GW and SMR technologies. SMRs are expected to benefit more however, because of the quantity of deployments and drive to factory-based modularisation.

Other than plant acquisition, costs and timescales can be heavily impacted by adaptation of technology to regulatory (codes and standards included), site conditions, country readiness, developer capabilities and infrastructure needed to enable construction and operation. Norway would need to establish capacity to support the deployment of any technology.

In compiling this report, we explored considerable amounts of publicly available information. We have presented those that we believe are credible and will help inform opinions. We have undertaken an analysis of the information and provide a summary in

Table 5.6. This addresses all key aspects.

However, there are several areas to highlight in relation to CAPEX that includes:

- The available information on recent GW projects is limited, consisting mainly of summaries that compare planned versus actual completion dates and related cost performance. These summaries cover recent programmes but exclude those in India and China.
- Information associated with SMR projects is published by a wide variety of sources, including government agencies, private industry and supply chains. It is very variable and speculative with sources providing higher costs than that being offered by the technology providers. It is forecast that the initial SMR FOAK projects will have a higher cost than GW reactors. However, it is expected that the process of improvement through NOAK will achieve longer-term savings. There are several differing estimates as to the NOAK number and scale that would be needed to realise cost savings.
- Much of the data does not take a realistic account of the project variables that impact cost such as location, geology and ground conditions, associated infrastructure as well as changes driven by national regulations or localisation of the supply chain. Nor is there much published data around developer costs, which can be extensive together with operator development costs. These are all crucial to understand programme costs on which a business case can be built.
- Any programme delivery certainty will require significant amounts of work and should be considered in a structured way, addressing the full scope of the programme, financing needs and achieving financial investment decision (FID).
- Traditional project financing costs, if attainable, can be one of the largest elements of cost influenced by influenced by factors such as programme duration, the amount and quality of work delivered, and the extent of supporting guarantees. Alternatives could be considered and should be explored.
- To attain realistic costs there is a significant amount of work to be concluded to inform the basis including conducting studies, undertaking technology selection processes and having a cost development process that links to key activities. It will be crucial to engage with the technology providers through possible market engagement processes leading into procurement.
- Costs to achieve a Financial Investment Decision (FID) will be extensive, with the risk that a programme may not be financeable. It is anticipated that this will be the same for FOAK SMRs until they achieve NOAK status.

In relationship to OPEX,

- Operational and maintenance costs represent another variable, primarily influenced by the local cost of labour. Fuel costs, by contrast, tend to be globally consistent and relatively stable, accounting for only around 10% of total whole-life costs.
- Waste, spent fuel and decommissioning costs are other areas that vary widely, influenced by technology, labour costs and national legislation. National governments usually assume

responsibility for these and is paid for from funds built up through the operational lifetime of the power plant. These will need to be established and built into any financial model to determine levies needed to generate decommissioning funds.

6 Summary and Conclusions

Following an open tender by the Royal Norwegian Ministry of Energy on behalf of the Norwegian Nuclear Commission, Multiconsult and Amentum was asked to produce a detailed, technical data report providing an updated overview and mapping of the status of various reactor technologies and power plant designs. It has provided an overview of GW, SMR and AMR reactor technological maturity, and looked at estimated timelines for implementation and commercial availability. It has reviewed the technology status of the global nuclear market of medium to large nuclear power plants and their major components. The report also looked into the ability for nuclear to support flexible operation and give and idea of associated impact and cost. The report gives an overview of the lifetime costs of nuclear power plants. Research was based upon publicly accessible information and avoided direct engagement with vendors to remain independent. And of course it was conducted outside of any procurement process. The report was not tasked with making recommendations but with providing a digest of information. It focuses on providing summaries of information that provide a balanced view of the status of the market, risks and opportunities, in order to inform future phases of work by the Commission.

Appendix A: Definition of Technology and Manufacturing Readiness Levels

The concept of Technology Readiness Levels (TRLs) is one that is widely used to give an indication of how close to commercial deployment a technology is in its real environment. Initially developed by NASA in the USA for Space application development, this has been adopted globally by Governments, Research organisations and commercial organisations alike, including in the nuclear sector.

The below details the NASA definitions of Technology Readiness Levels (NASA, 2014):

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

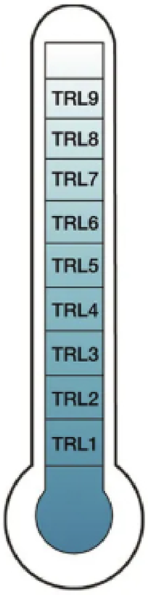
TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place

We have included a second example of how this TRL system has been adopted by nuclear organisations from a UK Government reference developed by the UK Nuclear Decommissioning

Authority (NDA). The key difference is that a nuclear system needs to be subject to irradiation in a relevant radiological environment before it can be deemed exposed to a representative environment. This is important as some technologies are proposing to go from the drawing point to construction and operation without conventional irradiation qualification processes such as irradiation in a Materials Test Reactor.



Technology Readiness Levels (TRL)

- TRL9 Operations
- TRL8 Active Commissioning
- TRL7 Inactive Commissioning
- TRL6 Large Scale
- TRL5 Pilot Scale
- TRL4 Bench Scale Research
- TRL3 Proof of Concept
- TRL2 Invention and Research
- TRL1 Basic Principles

Figure A.1: Example Nuclear TRLs (Gov UK, 2014).

TRL assessments can be made as a whole product, collection of system, individual system, individual component in a system. This means that they can be highly subjective, often over assessed or assigned a higher TRL than is realistic. Clearly the assignment of TRLs can be very influential in determining financial investment or determining residual risk, or even determining whether an investment can be assigned as a research and development activity. They must be viewed with caution. It is very difficult to assess TRLs without access to the design, safety case and other forms of engineering substantiation.

The **Manufacturing Readiness Levels** system is a structured scale used to assess how ready a technology is for manufacturing at the required quality, cost and production rate. It compliments TRL by focusing on the industrial capability rather than the technical performance. It is very useful at measuring and managing manufacturing risk ensuring that processes, supply chains, tooling and quality systems are mature enough before full scale production begins. Even if a technology is at a high TRL, it may not yet be manufacturable at scale.

The 10 level definitions can be briefly described as follows (US Department of Defence):

Research Phases

MRL 1: Basic manufacturing implications identified

MRL2: Manufacturing concepts identified

MRL3: Manufacturing proof of concept developed

MRL4: Capability to produce the technology in a laboratory environment

Development Phases

MRL5: Capability to produce prototype components in a production relevant environment

MRL6: Capability to produce a prototype system or subsystem in a production relevant environment

MRL7: Capability to produce systems/subsystems in a production representative environment

MRL8: Pilot line capability; ready to begin low rate initial production

Production Deployment

MRL9: Low rate production; capability in place to begin full rate production

MRL10: Full rate production and lean production practices in place

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