Delivery options for new nuclear Power in Sweden

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Executive summary

This study by Baringa for the Confederation of Swedish Enterprise (Svenskt Näringsliv) highlights the strategic choices regarding the delivery of new nuclear power and improves the knowledge base in the political debate. It provides guidance on which delivery models are most likely to be successful in the Swedish context. It considers how risks can be shared and mitigated between the private sector and the State in various delivery models and what lessons can be drawn from existing and planned nuclear programmes internationally.

The Confederation of Swedish Enterprise has effectively kick-started the debate in Sweden on how new nuclear power plants (NPPs) can contribute made possible, and now wants to drive it forward with a particular focus on measures the State needs to take to enable nuclear new build.

Historically, Sweden has benefited from an abundance of low carbon electricity, primarily due to its investments in hydroelectric power and nuclear energy, which have provided a stable and sustainable energy base. However, Sweden's electricity consumption is projected to increase significantly to meet its net zero targets, driven by the electrification of transport, industry, and heating systems. This will require significant expansion of power generation across different technologies. Nuclear energy can play a significant role in meeting Sweden's net zero transition challenges and building new nuclear should be considered as an important option for Sweden to achieve its net zero target.

After decades of limited levels of new build, the world is seeing a return to nuclear since ~2010 with many countries seeing nuclear energy as a reliable and safe form of low-carbon energy. The majority of the new construction projects are taking place in Asia, but Europe is seeing a strong increase too.

Various Generation III+ reactor designs have been approved by regulators internationally. With its focus on enhanced safety features, increased efficiency, and reduced construction costs it is now the default choice for new Large Scale Reactors (LSRs). Small Modular Rectors (SMRs) are a promising development for mid-term new build ambitions. They have not reached the same level of maturity as LSRs but once successful, cost-effective serialization has been achieved, they could provide an interesting option either to provide energy to industrial clusters or as building blocks for LSRs.

Nuclear new build programmes are capital-intensive projects with long development and construction times as well as long operational timeframes. The high capital costs, long construction times, and resulting financial risks make market-led projects financed solely by the private sector not feasible in Europe. Sweden has demonstrated an ambivalent attitude towards nuclear power, contributing to an unclear policy situation. Consequently, it should therefore implement project de-risking measures as well as risk-sharing mechanisms for residuals risks. The nature and implementation of these will depend to some extent on the selected delivery model but will typically at least include:

- Proportionate and predictable regulation
- Ensuring a mature design at the start of construction
- Effective project management

- Sharing of construction costs risk and market price risk.

Three potential delivery models appear to be viable for Sweden and should therefore be the focus of the Swedish Government:

- **Utility-led project with state backing** – Vattenfall's and Fortum's presence in the Swedish market and their engagement in feasibility studies for nuclear new build makes this an attractive option, both for a limited number of new nuclear power plants (NPPs) or as part of a larger programme (see next).
- **State-led programme with multiple NPPs from a single vendor** – The attractiveness of this model, which is pursued in Poland, France and the Netherlands, is largely contingent on the size of Sweden's nuclear ambition and society's support for strong government involvement can offer considerable benefits over (serialized) projects that are developed independently.
- **International SMR programme** – SMR vendors expect to deliver SMRs across Europe from a select number of strategically located "factories". An international state-led programme could contribute to successful outcomes for Sweden via shared design and approval processes severely de-risk projects and lower per-unit costs resulting from larger production series.

These delivery options, individually or when combining a utility-led or state-led programme delivering multiple LSRs in the 2030s is combined with an international SMR-programme can lead to a successful delivery of the Swedish ambition in the late 2030s/early 2040s.

The impacts of Europe's return to nuclear on Sweden's nuclear ambitions can be both positive and negative: learning effects and economies of scale through international collaboration can reduce risks and cost, but also increase demand for scarce knowledge and resources. Lagging somewhat compared to countries like the UK, France, Poland and the Netherlands, Sweden should now clearly state its nuclear ambitions, provide a clear policy trajectory and guiding principles around deployment to ensure vendors and manufacturers can start to plan for participating in its nuclear newbuild plans as well as build up a right-skilled, right-sized workforce to become an attractive partner for nuclear newbuild projects in what could become a seller's market.

1 Introduction

The Confederation of Swedish Enterprise is Sweden's leading employers' organization for the private business sector, bringing together 60,000 companies and 48 industry and employer organisations. It produces concrete proposals for measures and reforms that improve the business climate in Sweden. Specifically, it has effectively kick-started the debate in Sweden on how new nuclear power plants (NPPs) can be made possible, and now wants to drive it forward with a particular focus on measures the State needs to take to enable nuclear new build.

The aim of this study by Baringa is to highlight the strategic choices regarding the delivery of new nuclear power and improve the knowledge base in the political debate. The study provides guidance on which delivery models are most likely to be successful in the Swedish context and consequently which models are not.

The study considers how risks can be shared and mitigated between the private sector and the State in various delivery models and what lessons can be drawn from existing and planned nuclear programmes internationally.

Chapter 2 provides an overview of the Swedish power system and the role of nuclear in the future transformation of the electricity sector to provide a shared perspective that can act as a foundation for the outcomes and recommendations of this study. It provides background on the Swedish power system today, the Government's energy and decarbonisation policy, the expected impact on the electricity sector and the role of nuclear in meeting the challenges facing Sweden's journey towards its 2045 net zero target.

Nuclear technologies and their relevance for Sweden are discussed in Chapter 3. It provides an overview of relevant nuclear technologies, their maturity and role in the energy system. Different generations of large-scale reactors (LSRs) are introduced as well as a cross section of small modular reactors (SMRs). Key differences between LSRs and SMRs are highlighted to help inform the technology choice for Sweden's nuclear programme.

Chapter 4 forms the heart of this report. A high-level overview of investment costs for nuclear power plants is presented before discussing delivery models that implement different forms of risk-sharing (e.g. government investment or revenue support) and de-risking options (e.g. through legislative and regulatory support). Their importance in five archetypical nuclear delivery models is discussed and illustrated with recent examples, as well as their relevance and applicability to Sweden.

Sweden is not the only country in Europe considering building new nuclear power plants. At least eight countries have active programmes or are in the process of starting them, including UK, Poland and the Netherlands. The impacts of this return to nuclear on Sweden's nuclear ambitions can be both positive and negative and this is analysed in Chapter 5.

In the final chapter of this report the insights of the various analyses are combined to deliver a set of clear recommendations for Sweden and its Government to ensure its nuclear fleet can be extended in a timely, robust and financially sound way.

2 The Swedish energy system, power market and the role of nuclear power

2.1 Introduction

This chapter provides an overview of the Swedish power system and the role of nuclear in the future transformation of the electricity sector to provide a shared perspective that can act as a foundation for the outcomes and recommendations of this study.

Sweden has one of the lowest carbon-emitting electricity sectors in Europe today, thanks to the large shares of hydro, nuclear, biomass and, more recently, onshore wind power in its generation mix. Historically it has enjoyed a surplus of power and been a net exporter of electricity to neighbouring countries. However, the country could face many challenges, including generation inadequacy, in its quest to become a net zero economy by 2045. Delivering the nation's ambitious decarbonisation target will lead to a significant increase in electricity demand, requiring historic levels of investment in low-carbon generation (along with other infrastructure assets) that is also secure and affordable. Nuclear can play a key role in the transformation of the Swedish electricity sector.

The following sections provide further background on the Swedish power system today, Government's energy and decarbonisation policy, the expected impact on the electricity sector and the role of nuclear in meeting the challenges facing Sweden journey towards a net zero economy.

2.2 Overview of the Swedish power system

Part of the Nord Pool energy market, Sweden operates a zonal, energy-only electricity market (EOM). This market design has enabled efficient cross-border trade and cost-effective dispatch of power historically. Generators in Sweden primarily earn revenue through electricity sales in the Nord Pool market and through support mechanisms for renewables, such as certificate systems[1] and subsidies, encouraging the development and integration of renewable resources into the grid. The absence of a capacity market (CM), however, has influenced the types of technologies that have been invested in over the last 20 years.

The landscape of Sweden's power market is significantly shaped by the presence of major utilities such as Vattenfall, Fortum, and Uniper. By power generation volumes, Vattenfall is the largest in Sweden, with its portfolio consisting of hydro, nuclear, wind, solar and biomass. Fortum, a Finnish majority state-owned company, ranks 2nd largest with its nuclear, hydro and wind plants. Uniper, a German multinational power company, ranks the 3rd with its nuclear, hydro, and open-cycle gas turbine plants. Collectively they own and operate 22 GW of installed capacity with annual generation

[1] The certificates scheme is being phased out. Only renewable generators that have been commissioned before the end of 2021 are eligible to partake in it until 2035 with more recently commissioned generators being excluded.

of 101 TWh, representing 61 % of the total generation in Sweden in 2022. In addition to power generation, these companies are also active (to different degrees) in electricity distribution, trading, and retail. Due to their size and market position, they have significant market power and great influence in shaping policy development and energy transition in Sweden.

A highly industrialised country, Sweden has one of the highest per capital electricity consumption in Europe. It hosts several energy-intensive industries such as steelmaking, mining, forestry and paper, refining and chemicals. Together, industrial demand accounted for 36% of total electricity consumption, which was around 131 TWh in 2023.

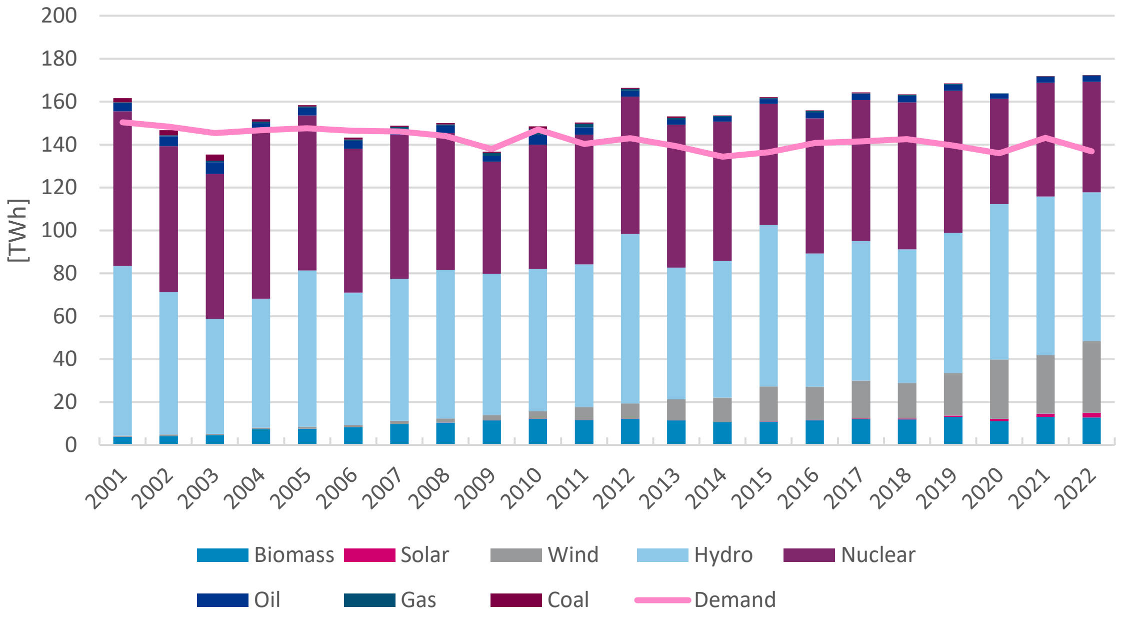

Figure 1 – Historical Swedish energy generation and consumption with the generation split by technologies.

Plant	Capacity [MWe]	First Grid Connection	Ownership
Forsmark 1	1,040	June 1980	Vattenfall
Forsmark 2	1,121	January 1981	Vattenfall
Forsmark 3	1,172	March 1985	Vattenfall
Oskarshamn 3	1,400	March 1985	Uniper (54.5%) & Fortum (45.5%)
Ringhals 3	1,081	September 1972	Vattenfall (70%) & Uniper (30%)
Ringhals 4	1,130	November 1973	Vattenfall (70%) & Uniper (30%)

Table 1 – Sweden's operational nuclear fleet and its owners.

A mix of low-carbon generation technologies meets the consumption. Figure 1 shows Hydro power is the biggest source of electricity production currently, representing around 40% of the generation mix, followed by nuclear (28%, see Table 1 for details), wind power (22%, with most of it being onshore wind) and biomass (7%).

The total generation amounted to around 160 TWh in 2023. Power generation and consumption are highly imbalanced between the north and the south. The internal high voltage transmission network has been developed to bring abundant hydro (and lately onshore wind) resource from the north to the south where most of the population and industries are located.

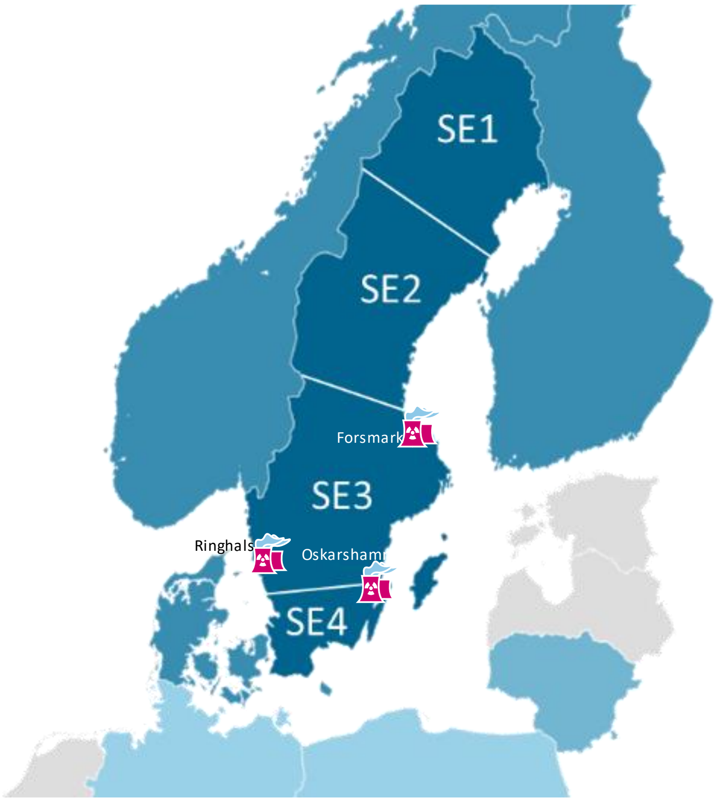

Figure 2 – Geographical overview of Swedish power market zones SE1 to SE4 and the locations of its operational nuclear power plants. Sweden has limited interconnector capacities internally between its zones as well as externally with all the highlighted Nordic, Baltic and Northern European countries.

Sweden is one of the best-connected European countries in terms of transmission capacities with its neighbours via interconnectors, including 4.1 GW with Norway, 2.8 GW with Finland, 2.44 GW with Denmark, 630 MW with Germany, 600 MW with Poland and 700 MW with Lithuania.[2] A net exporter of electricity on an annual basis, Sweden does rely on import during the coldest winter periods to meet its peak electricity demand. Interconnectors therefore play an important role for the Swedish power system in enabling export of surplus during periods of excess and ensuring security of supply during periods of shortfall.

The potential decommissioning of nuclear power plants in Sweden, primarily located in the southern zones near demand centres (SE3, see Figure 2), intensifies the previously described existing geographical mismatch in electricity supply and demand, as the bulk of hydroelectric and wind generation is in the north (SE1 and SE2). This situation challenges the current internal transmission infrastructure's ability to transport adequate electricity from north to south, particularly during peak demand. Although Sweden has made investments in both internal and external interconnectors,

[2] The figures given are the maximum capacities that the network owners have offered on Nord Pool since January 2018.

these may not suffice to bridge the gap that would be left by nuclear decommissioning without further enhancements or new projects. Consequently, southern Sweden could become more dependent on electricity imports during shortages, risking exposure to increased price volatility and higher costs in the European electricity market during peak times. As southern Sweden already has a weak power balance compared to other European zones, this further exposure to price volatility and supply security risks underscores the need for strategic planning in energy infrastructure and market operations to ensure reliable and stable electricity supply.

2.3 Swedish decarbonisation targets and implications for the electricity sector

Sweden has committed to zero net emissions of greenhouse gases by 2045 with the aim to achieve negative emissions thereafter. This ambition is encapsulated within a comprehensive climate policy framework introduced in 2017, which includes the Climate Act mandating annual climate reports and a four-yearly climate policy action plan from the Government. Key policies to reach these goals focus on energy efficiency, renewable energy, electric transport, and carbon capture technologies. Through these initiatives, Sweden seeks to meet its national targets and contribute significantly to global climate goals, demonstrating a strong commitment to sustainable development and environmental protection.[3] Amidst these efforts, Swedish policy makers must therefore navigate the energy policy trilemma of striving to balance the affordability of energy for consumers and industry, ensuring a sustainable transition towards renewable resources, and maintaining a secure and reliable energy supply to support these ambitious climate objectives.

Electrification is pivotal in realizing Sweden's climate aspirations. While projections from industry stakeholders vary, they share a view that there will be a substantial rise in electricity demand.

- Despite the slight decline over the last 20 years, industrial demand is anticipated to grow significantly over the coming decades[4], driven by electrification of traditionally carbon-intensive processes (e.g. fossil-free green steel), production of e-fuels, building of battery manufacturing facilities, deployment of data centres and other electrification activities.
- While efficiency gains are likely to put a downward pressure on consumption in the household and service sectors, electrification of the transport and mobility sector (through further adoption of electric vehicles) as well as heating (with heat pumps and electric boilers replacing ageing combined heat and power (CHP) plants) represent further growth nodes.

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[3] https://www.government.se/articles/2021/03/swedens-climate-policy-framework/

[4] RISE Research Institutes of Sweden 2024, 'How Sweden can meet increasing electricity demand', *RISE Research Institutes of Sweden website*, accessed 23 April 2024, <https://www.ri.se/en/our-stories/how-sweden-can-meet-increasing-electricity-demand>

These sources put overall Swedish electricity consumption in the range of 200 to 365 TWh per annum by 2050, representing an up to more than two-fold increase from today's level depending on the scenario and expected rate of electrification[5, 6].

Significant expansion of the electricity generation infrastructure is therefore required to ensure continued supply of clean, affordable and secure energy to Swedish customers. Several options have been identified; their merits are briefly discussed below:

- **Further exploitation of hydro resources**: Most hydro plants are in northern Sweden located around two river systems, Lule älv (or Lule River) and Ume älv (or Ume River). Most of the hydro resources not under strict environmental protection have already been exploited, leaving limited opportunities for expansion going forward. Moreover, stringent environmental regulations impose additional costs and risks on brownfield hydro projects and the cross-party agreed national plan for the reconsideration of hydropower features a target of a 1.5 TWh decrease of hydropower.
- **Expansion of the use of biomass** – Biomass benefited from the Elcert subsidy scheme and saw significant expansion in the late 2000s and early 2010s. There is limited scope for further expansion of biomass-based power production.
- **Lifetime extension of existing nuclear fleet** – Sweden built its current fleet of nuclear power plants between the 1960s and 1980s, with only six reactors (Forsmark unit 1-3, Oskarshamn unit 3 and Ringhals unit 3-4) remaining active today. Currently most of the reactors have a licence to operate until the end of their 60-year design life. Lifetime extension by a further 10 years, with decommissioning in the 2040s, would leave a gap of about 46 TWh to be filled by new generation by 2050 although it should be noted that Vattenfall's ambition is to extend the lifetime up to 80 years.
- **Continued deployment of onshore wind** – Onshore wind has been the main source of capacity expansion in recent years and likely to remain so in the future. However, intermittency of wind generation creates additional need for system flexibility and security during stress events (i.e. peak demand coinciding with low wind and solar output). Most of the development pipeline in Sweden is situated in the north, requiring significant transmission reinforcement to bring the energy down south.
- **Developing solar PV** – Solar is a relatively nascent sector in Sweden. Historically poor load factor and relative competitiveness of onshore wind have restricted the development of solar PV. Still, the continued decline in technology costs has made it economically viable to develop projects in southern Sweden, where load factors are comparable to those in the UK, a market with significant solar deployment. However, the value of the solar market in Sweden is relatively lower than in the UK, as more generation hours are concentrated within a shorter summer period. Also, land constraint and permitting issues might restrict the size and speed of solar deployment going forward. Like wind, solar also

[5] Håkansson, A 2023, 'Sweden's future power and energy production scenarios', Uppsala University, accessed 08 February 2024, <https://www3.uu.se/digitalAssets/1062/c_1062422-l_3-k_anita-a1-rapport-1.pdf>

[6] Svenska Kraftnat Long Term Market Analysis (LMA), 2024

brings intermittency challenges requiring significant investment in flexibility to counter the effects.

- **Exploitation of offshore wind** – Offshore wind projects are currently developed on a subsidy-free basis in Sweden. While project pipeline is large and diverse along the Swedish coast, project economics and uncertainty regarding grid connection arrangements are key hurdles to final investment decision (FID). The first offshore wind farm is unlikely to materialise until the early 2030s at the earliest. Questions remain over the pace and volume of deployment in the long run.
- **Further interconnection with neighbouring countries** – While a net exporter, Sweden does rely on import to meet its peak demand during the coldest winter peak periods. Further interconnection enables better sharing of resources and potentially provides diversification benefits when two countries have different generation mixes, including security of supply. However, the extent of diversification benefits depends on the future evolution of the power system in the respective countries:

As most of the growth in generation capacity in neighbouring countries is likely to come from wind and solar, the benefits might become eroded.

It should be noted that there is a significant risk regarding the consistency of wind patterns affecting the viability of wind power plants as a stable power source. Across all of northern Europe the covariation in wind pattern is considerably high, mitigating or exacerbating the viability in wind power generation, making it a key concern for energy production and grid operations.

The economic feasibility of wind power plants, therefore, depends not only on the average wind speeds at their locations but also on how wind speeds correlate across sites and over time. Effective grid management, including the integration of energy storage systems and the development of responsive demand-side management programmes, will be required to help mitigate the effects of covariation.

In summary, the existing hydro, biomass and nuclear fleet, while capable of providing firm power, is likely to play a declining role in the future. Onshore wind, offshore wind and solar are likely to play an increasing role going forward to meet Sweden's growing electricity demand, but intermittency of these renewable technologies means a greater need for system flexibility, which is underdeveloped today and will need to be exponentially expanded to address the challenges of intermittency.

Moreover, technology costs and supply chain risks present real challenges and uncertainty to the realisation of the required volumes of wind and solar capacity. As can be inferred from the waterfall chart in Figure 3, assuming an additional 5.45 TWh of onshore wind and solar deployment per year starting 2024 and another 2.63 TWh of offshore wind starting 2033, based on the highest historical deployment rate in Sweden, there would still be a demand gap of around 46 TWh in 2050.

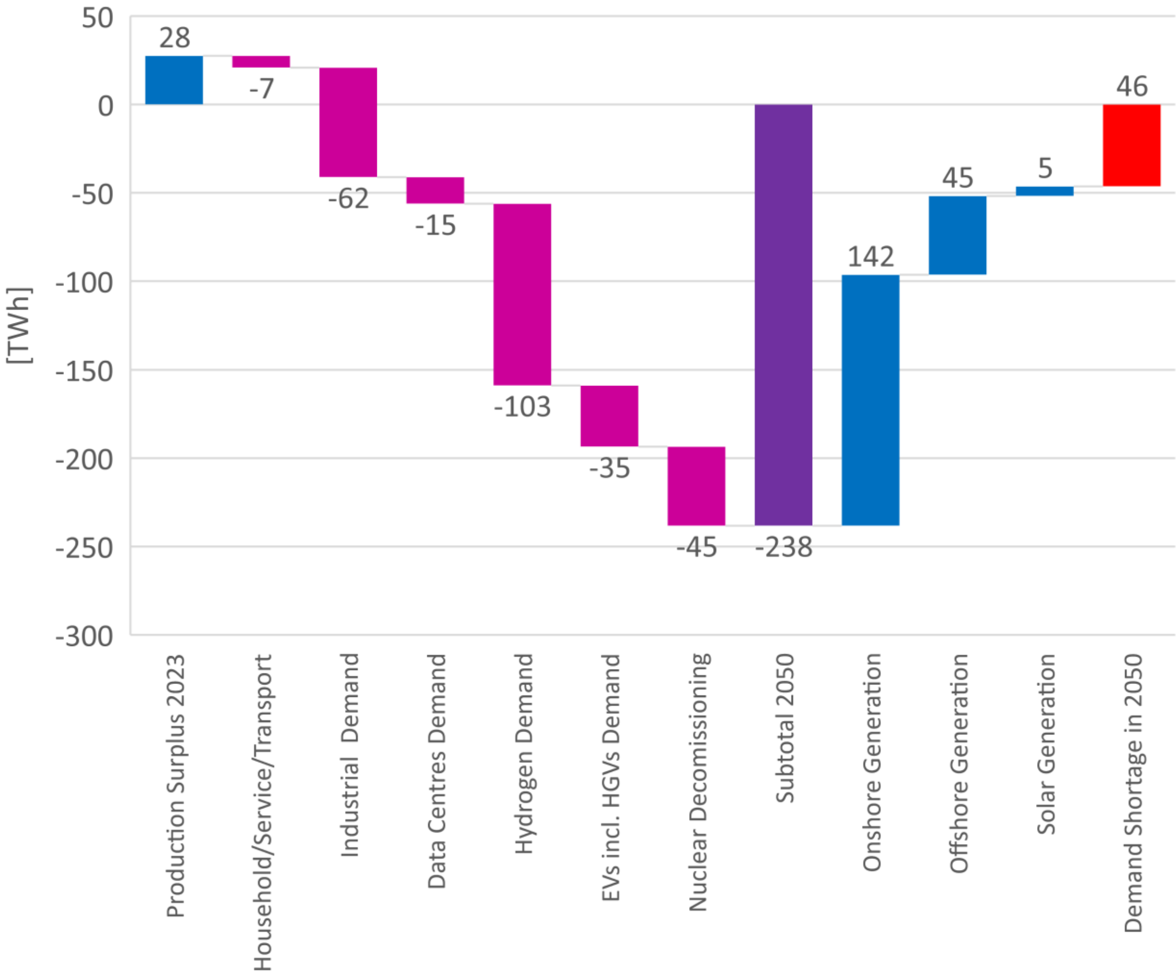

Figure 3 – Estimated changes to the net energy balance in Sweden from 2023 to 2050 due to demand increases and renewable energy rollout[7]. The decommissioning of nuclear power plants could lead to an overall demand excess that would have to be covered. Note that the data centre demand increase could be considered as conservative if computing workloads increase substantially due to the nascent AI boom.

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[7] Demand increases based on Svenska kraftnät Long Term Market Analysis (LMA) 2024; supply increase due to assumed yearly buildout of 2 GW additional onshore wind capacity at 30% load factor and 200 MW additional solar capacities at 12% load factor starting 2024, 750 MW additional yearly offshore wind capacity at 40% load factor starting 2033, assumptions based on historical trends and projected 2050 capacities. These projections can vary based on the underlying assumptions.

2.4 The role of nuclear in Sweden's future electricity system

Developing new nuclear plants is a critical option that must be included in the debate around future generation mix in Sweden. The benefits that nuclear new build bring include:

- **Source of large-scale low-carbon power production** – Nuclear reactors are typically 100s of MW in installed capacity with a capacity factor of 80-of 80-85%[8]. They can meet future demand increase at scale.
- **Firmness of power** – Nuclear typically operates on a baseload basis with some flexibility and controllability around the generation level. Unlike wind and solar, nuclear power is not weather dependent and is considered dispatchable power.
- **Diversification and security of supply** – In a system increasingly dominated by intermittent renewables, nuclear provides the necessary diversification benefit and reduces the risk of coincidental reduction in generation capacity during a e.g. low-wind, dark winter evening. It enhances security of supply by ensuring availability of supply during system stress events.
- **Locational diversification and proximity to demand** – While most wind development pipeline is located in northern Sweden, nuclear does not have such locational restrictions due to availability of resource. Nuclear plants therefore can be located in the south (e.g. on existing sites or new sites), closer to large industrial clusters, without as much reliance on the upgrade of the north-south transmission backbone. Additionally, large planned offshore wind projects in the south could necessitate balancing measures with hydropower from the north. This could lead to a scenario where new nuclear capacity might be required in the north to free up the more flexible hydro capacity for these renewable sources, ensuring a stable and diversified energy supply that meets regional demands efficiently.
- **Wider economic benefits** – Building new nuclear plants is not only beneficial to the power system and energy users in Sweden. Access to relatively cheap and secure base load power allows for better long term financial planning, enabling large industry investments that can benefit the country's economic health long term. It also conveys wider economic benefits such as supporting the local economy through employment opportunities, ensuring a viable nuclear supply chain and maintaining the knowledge and competence base around nuclear power.

It is possible for Sweden to achieve its net zero targets without building new nuclear plants, but several factors would need to materialise, including:

- Wind and solar would need to be further expanded, at annual deployment rates above historical levels, while ensuring community support and addressing public resistance that can delay or block renewable energy projects. Additionally, the (subsidy-free) economic

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[8] World Nuclear Performance Report 2023, World Nuclear Association, 2023

viability is a necessary requirement to ensure the long-term feasibility of wind and solar power plants.

- Further transmission expansion would be needed to bring wind-based generation in the north to demand in the south.
- System flexibility, through storage technologies, demand side response, interconnection with neighbouring countries, would need to increase substantially to counter the intermittency of renewables-based generation.

The realisation of some of these factors requires unprecedented levels of technology deployment (E.g. building onshore wind at a rate materially above 2 GW per year) and the maturation of unproven technologies (e.g. demand side response provided by vehicle-to-grid). If any of the factors would not materialise, Sweden could be at risk of failing to meet its net zero targets. Nuclear new build is therefore a sound option from a risk-mitigation perspective.

2.5 Conclusions

- **Historically, Sweden has benefited from an abundance of low carbon electricity**, primarily due to its investments in hydroelectric power and nuclear energy, which have provided a stable and sustainable energy base. This strategy has positioned Sweden as a leader in clean energy production, significantly reducing its carbon footprint compared to countries reliant on fossil fuels for electricity generation.
- **Sweden's electricity consumption is projected to increase significantly** to meet its net zero targets, driven by the electrification of transport, industry, and heating systems. As the country moves towards electrifying sectors traditionally dominated by fossil fuels, the demand for electricity is expected to rise, necessitating a corresponding increase in clean energy production to maintain Sweden's commitment to its environmental goals.
- **This will require significant expansion of power generation across different technologies** including onshore wind, offshore wind, solar, nuclear and potentially other emerging technologies. The diversification of Sweden’s energy portfolio will be crucial in ensuring a reliable and resilient energy system capable of meeting future demands while adhering to strict carbon emissions and environmental standards.
- **Nuclear energy can play a significant role in meeting Sweden’s net zero transition challenges**, offering a reliable and firm source of low carbon energy that can complement intermittent renewable sources like wind and solar. Nuclear energy’s capacity for continuous baseload power generation already is a pillar of Sweden’s energy generation today and could continue making it a key asset in stabilizing the grid and ensuring the availability of electricity regardless of weather conditions or time of day.
- **For Sweden to achieve its net zero target, building new nuclear should be considered as an important option**, alongside the expansion of renewable energy sources. Modern nuclear reactors, either Large Scale Reactors (LSRs) or as small modular reactors (SMRs), offer the potential for safe, flexible, and cost-effective nuclear power generation and provide a substantial contribution to Sweden's clean energy mix.

3 Nuclear technologies and their relevance for Sweden

3.1 Introduction

This chapter provides an overview of relevant nuclear technologies, their maturity and role in the energy system. Historically, nuclear power has been provided by nuclear power plants consisting of one or more nuclear reactors. The reactor types used in these plants have evolved considerably since the first commercial reactors came online in the late 1950s/early 1960. More recently, small modular reactors (SMRs) have emerged as an alternative to traditional large-scale reactors (LSRs).

LSRs plants and SMRs can fulfil different roles in the energy system, have different demonstrated maturity levels and carry different capital requirements and delivery risks. It is important to understand these differences since:

a) They impact their ability to contribute to Sweden's stated energy and climate goals.
b) They require different types and levels of state support.
c) They impact the feasibility and attractiveness of available financing options.

In the following sections the different generations of LSRs are introduced as well as a cross section of SMRs and key differences between the two. These differences are important to help assess the attractiveness and risks of the various common delivery models that are discussed in Chapter 4.

3.2 Four generations of nuclear power plants

Nuclear reactor designs are usually categorized by 'generation'; that is, Generation I, II, III, III+, and IV. This nomenclature for reactor designs was proposed by the US Department of Energy when it introduced the concept of generation IV reactors, and although widely accepted, it is not an exact science and certain (implementations of) reactor designs might occasionally be labelled differently. Every next generation is more advanced in terms of safety, development, deployment, reflected in increased levels of standardization. The impact of this on potential project costs (and by extension financeability) and duration is both positive and negative and should therefore be understood when considering technologies for new nuclear power plants.

Key differences between the reactor generations are presented here, illustrated where relevant with examples of their applications in utility-scale nuclear power plants.

3.2.1 The early years – Generation I

Generation I nuclear reactors were effectively prototype reactors, delivering on the promise of producing clean electricity for civilian use of nuclear power. These reactors were developed in the 1950s and constructed through the early 1960s, with the latest coming online in the early 1970s, and laid the foundation for subsequent generations. These early reactors primarily used natural uranium as fuel and graphite as a moderator.

The key reactor types within Generation I included gas-cooled reactors and early pressurized heavy water reactors. Gas-cooled reactors, like the Magnox reactors in the UK and the UNGG reactors in France, used carbon dioxide as a coolant. The era also saw the first Pressurized Water Reactors (PWRs), a light-water reactor design that uses ordinary water as both coolant and neutron moderator and is the reactor concept used by the majority of the world's nuclear power plants in operation today, as well as Pressurised Heavy Water Reactors (PHWRs), exemplified by Canada's CANDU (CANada Deuterium Uranium) reactors, employing heavy water as both a moderator and a coolant.

Generation I reactors were derived from military applications and faced many challenges, including limited fuel efficiency, complex and costly construction, and limited safety features. Their generation capacity was low compared to today's standards, with most Generation I reactors hovering around or well below a few hundred MWe.

The US, UK and France featured the largest installed base of nuclear power plants powered by Generation I reactors. The last commercially operated Generation I reactors were decommissioned in the 2010s in the UK.

3.2.2 The golden age of nuclear power – Generation II

Generation II nuclear reactors emerged as a progression from the initial Generation I designs to address safety concerns, improve efficiency, and standardize reactor configurations. This second generation saw active development from the 1960s through the 1990s, marking a crucial phase in the establishment of nuclear power as a viable and widely adopted energy source. Unlike the diverse and experimental nature of Generation I, Generation II reactors displayed a more standardized approach, incorporating Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) as dominant designs. Both types are light water reactors that use enriched uranium as fuel and water as a coolant and moderator.

The 1973/74 oil crisis illustrated the importance of energy independence and is thought to be at least in part responsible for the NPPs construction peak in the 1980s.

Westinghouse, Framatome (now part of EDF), and General Electric were among the major vendors of the era, each offering distinctive reactor designs, while Russia (then the USSR) built a fleet of reactors based on its own VVER (Vodo-Vodyanoi Energetichesky Reactors) and RMBK designs, and Canada offered improved CANDU reactors.

Generation II reactors were originally designed for a life span of 30-40 years, but this has often been extended to 50-60 years, combined with (partial) upgrades, resulting in many Generation II reactors still being in operation today. This is the case in Sweden too, where its operational reactors are all of Generation II and came online in the 1980s. They have all seen multiple substantial upgrades since they first started delivering power to the grid, to both improve safety and to extend their lifespan. The reactors at Ringhals and Forsmark are expected to deliver power until the 2040s, while for the reactor at Oskarshamn the conditions have been created for it to remain operational into the 2060s, which would give it an 80-year lifespan[9,10].

3.2.3 Focus on passive safety and standard designs – Generations III and III+

Generation III/III+ nuclear reactors, developed from the late 20th century onward, represent an evolution from earlier designs and emerged in response to the need for enhanced safety and efficiency in nuclear power generation.

The key innovation in Generation III reactors is the incorporation of passive safety features, prompted by incidents such as the Chernobyl disaster and the Three Mile Island accident. Passive safety systems rely on natural processes like gravity, natural convection, and other physical phenomena to ensure a safe shutdown of the reactor in case of emergencies. This is a departure from relying solely on active safety measures, significantly enhancing the overall safety profile of Generation III/III+ reactors.

Prominent examples of Generation III reactors include the Westinghouse AP1000, KEPCO's APR-1400, CANDU's Monark-1000 and the European Pressurized Reactor (EPR). These reactors showcase standardized designs, simplifying regulatory approval and streamlining the construction process.

Building upon the advancements of Generation III, Generation III+ reactors continue the trend of improved safety and efficiency. These reactors further refine passive safety measures and include additional enhancements for increased resilience.

The gradual decommissioning of Generation II reactors combined with a steady (and since 2015 accelerated) coming online of Generation III/III+ reactors has resulted in ~35% of the world's reactor capacity being of this advanced type, as can be inferred from Figure 4.

Virtually all reactors being planned, constructed or under commissioning are using Generation III/III+ designs, including the UK's Hinkley Point C, making it currently the default technology for nuclear new builds.

Operational examples of Generation III/III+ reactors include the Olkiluoto 3 reactor (OL3) in Finland, an EPR, the Barakah APR-1400 reactors in the UAE and the Vogtle 3 reactor in the USA, an AP1000. These reactors contribute significantly to the global nuclear power capacity, offering reliable, low-carbon energy sources.

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9 https://world-nuclear.org/information-library/country-profiles/countries-o-s/sweden.aspx, accessed on February 19, 2024

10 https://www.uniper.energy/sweden/about-uniper-sweden/nuclear-power-sweden, accessed on February 19, 2024

3.2.4 Exploring new designs and fuels – Generation IV

Generation IV lacks a formal definition but broadly refers to reactor designs that have been under development since the start of the 21st century. It includes new reactor designs like the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very high-temperature reactor (VHTR). This generation aims to further improve the safety and cost-effectiveness of nuclear energy and explores the use of alternative fuels such as thorium, aiming for improved fuel cycles and reduced environmental impact.

Both established companies like Westinghouse, Hitachi and GE, as well as new players, like TerraPower in the US and Elysium Industries in France are developing Generation IV designs. TerraPower is actively involved in the development of traveling wave reactors, and Elysium Industries focuses on molten salt reactor technology.

Reactor designs are still being refined and tested, with only a limited number of reactors being planned or under construction. Some examples of Generation IV reactors include Russia's BN-1200 sodium-cooled fast reactor and China's CFR-600.

Generation IV designs are also being considered for Small Modular Reactors (SMRs – see Section 3.3), by companies like Thorizon in the Netherlands and Copenhagen Atomics in Denmark. As is the case for LSRs, Generation IV SMRs are largely still at the design or prototype stage, although it should be noted that the only operational Generation IV reactor, China's Shidao Bay Nuclear Power Plant, is in fact a high-temperature gas-cooled reactor (HTGR) SMR. In the UK, five UK organisations received funding across 6 projects to test the feasibility of HGTR technology. The aim of the programme is to demonstrate the feasibility of the technology in the early 2030s.

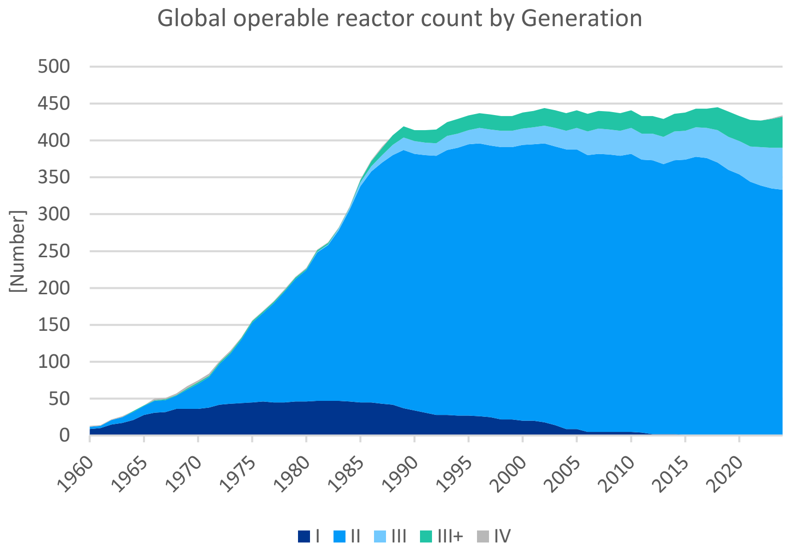
In its 2020 update[11], the World Nuclear Association deemed it likely for some of the Generation IV designs to be ready commercial operation before 2030. However, non-technological challenges facing the widespread deployment of Generation IV reactors include regulatory frameworks, public acceptance, economic viability, and securing a reliable supply chain for advanced materials and fuels.

As of this report's publication date, no Generation IV design is licensed in any European country.

3.2.5 The evolution of the world's nuclear fleet

The evolution of the world's nuclear fleet is illustrated in Figure 4 and Figure 5 that show the size of the fleet and the additions and removals from the pool of operable reactors, respectively. After a gradual increase from 1970 onwards, the size reactor fleet all but plateaued in the late 1980s. The fleet's capacity continued to slowly increase as lower capacity Generation II reactors were replaced with higher capacity Generation III/III+ ones.

[11] https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx, accessed on February 26, 2024



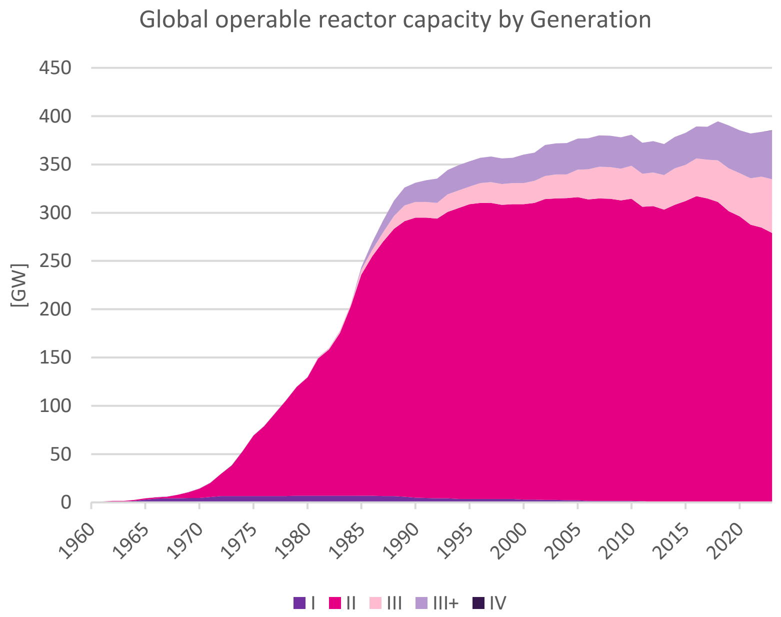
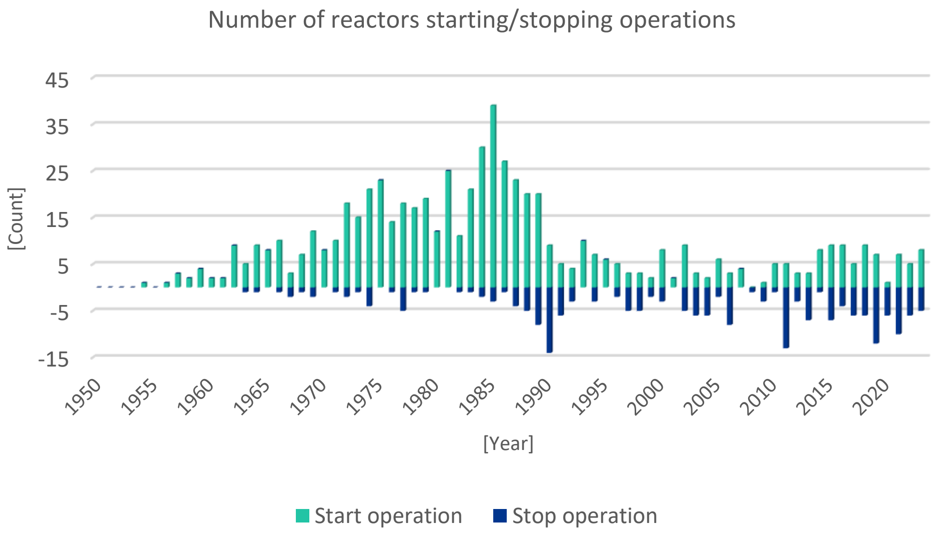


Figure 4 – The size of the world's nuclear fleet in terms of number of operable reactors (top panel) and operable capacity (bottom panel). Note that Generation II reactors still constitute the majority of the fleet, indicative of the long life span of nuclear power plants. Modern Generation III/III+ reactors are currently accounting for ~25% of the operable capacity.

Note that although Generation I at its peak in the early 1960s represented up to 70% of the fleet in terms of number of operable reactors, it never played a substantial role from a capacity perspective.

Gen II has always been, and continues to be to this day, the workhorse of the world's nuclear fleet. From 2015 on more and more Generation II reactors are being shut down, after having been in service for 40+ years, with Generation III/III+ coming online in increasing numbers. In 2023 the first modern Gen IV reactor came online in China (a High-temperature gas-cooled SMR at the Shidaowan plant) indicating that, like Generation III+ SMRs, this type of reactor is still very much a novelty.



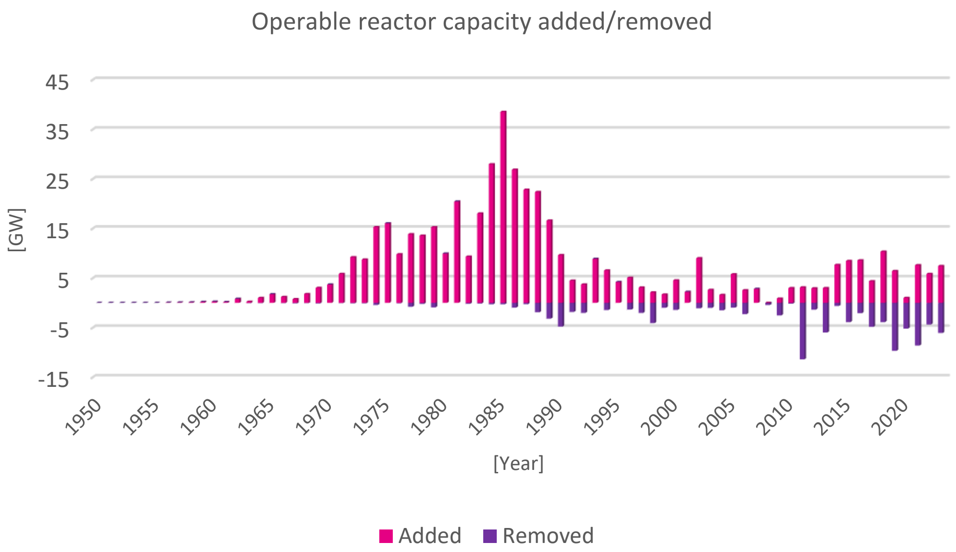


Figure 5 – The number of reactors starting and stopping each year from 1950 until today. After a net decline for decades, more capacity is now coming online than is removed, signalling a return to nuclear.

Based on publicly available data, the upward trend seen in recent years in reactor count and operable capacity is expected to continue, with 60 reactors being under construction in 17 countries, representing ~65 GWe of new capacity.[12] A further 110 reactors with a total gross capacity of about 110 GWe are planned, and over 300 more are proposed. Additionally, SMRs (see next section) could add significantly to the installed base from the mid to late 2030s when the first designs can be produced at scale.

3.3 Small Modular Reactors – Revolutionizing nuclear power?

Small Modular Reactors (SMRs) are a transformative approach to nuclear power that deviates from the traditional LSRs. SMRs are characterized by their smaller size, typically ranging from a few megawatts to a few hundred megawatts. The inherent size difference and modular design and construction is expected to yield several advantages:

- SMRs can be manufactured in a factory setting, allowing for modular construction and reduced on-site assembly time.
- The modular approach streamlines the manufacturing process, increases quality control, and consequently improves safety, and lowers overall construction costs, assuming sufficient modules are produced to achieve the required economies of scale.
- Gradual deployment of multiple SMRs at a single site can better follow the energy market needs, spread investment needs, and bring forward revenue streams compared to a traditional NPP of comparable size.
- SMR's modular designs can facilitate upgrading and replacement of components, contributing to lower maintenance and dismantling costs.
- Their smaller size enables a more versatile range of applications, such as remote power generation, dedicated power for industrial clusters and integration in multi-commodity energy hubs where they can provide power, heat or hydrogen depending on (local) energy market needs.
- Their reduced physical footprint and supporting infrastructure needs also means that they can be more easily placed close to demand centres, potentially reducing costs for power transmission and distribution costs at a system level.
- SMRs are seen as candidate for in-situ replacement for decommissioned coal-fired power plants, whose units are often comparable in capacity to larger SMRs. As such, SMRs could play a key role in decarbonizing the power sector.

3.3.1 Diverse classes and technologies of SMRs

SMRs can be categorized based on size and technology. From a size perspective, they are typically classified into three main categories: microreactors (1-10 MWe), small reactors (10-300 MWe), and

[12] https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx, accessed on February 19, 2024

medium size reactors (300-700 MWe) [13]. Each class caters to specific energy requirements and applications. Microreactors are suitable for remote locations or niche applications, while small and medium reactors are designed for broader energy needs.

From a technology perspective, the SMR space is a very dynamic one, with a wide range of designs based on Generation III+ and Generation IV reactors being pursued. Over 70 SMR projects exist globally (see Figure 6), ran by companies ranging from start-ups like Thorizon working on a Thorium-based design, to established industrial players like Rolls Royce developing SMRs with capacities over 400 MWe based on existing Light-Water Reactor (LWR) technology. Table 2 below provides a non-exhaustive overview of reactor technologies used in the SMR-space, typical capacities and vendors, to illustrate the diversity currently characterising the SMR development.

Vendor	Technology	Unit capacity	Status
Copenhagen Atomics	Gen IV Thorium MSR	50 MWe / 100 MWth	Building prototype, expects to have an operational 1 MWth demo reactor ready by 2025[14]
GE/Hitachi **(BWRX300)**	Gen III+ BWR	300 MWe / 870 MWth	Pre-licensing stage in USA and Canada, construction of first reactor to be complete late 2028[15]
Last Energy	Gen III+ PWR	20 MWe / 80 MWth	Conceptual design, expects to have first reactor operational in 2025 in Poland, 2026 in the UK
MoltenFlex	Gen IV MSR	24 MWe / 40 MWth	Basic design, expects to have first reactor operational by 2029
NuScale Power	Gen III+ PWR	77 MWe / 160 MWth	Design approved in the USA; pre-licensing activities in Canada, Poland, first commercial construction project in USA cancelled
EDF **(NuWard)**	Gen III+ PWR	2 x 170 MWe / 2 x 540 MWth	Completing conceptual design and pre-licensing, targets the

[13] The definitions used by the IEA, IAEA, US Nuclear Energy Institute and World Nuclear Association differ slightly, specifically towards the lower end of the scale.

[14] https://www.copenhagenatomics.com/potential/, accessed on February 19, 2024

[15] https://www.gevernova.com/nuclear/carbon-free-power/bwrx-300-small-modular-reactor, accessed on February 19, 2024

			construction of a reference plant in France in 2030[16]
Rolls Royce	Gen III+ PWR	470 MWe / 1358 MWth	Currently detailed design completion and moving towards regulatory approval in the UK. First unit expected to be operational by early 2030s
Thorizon	Gen IV MSR	100 MWe / 250 MWth	Basic design; expects to build the FOAK reactor in 10 years
Westinghouse (APR300)	Gen III+ PWR	300 MWe / 900MWth	Detailed design, based on licensed AP1000 reactor. First operating unit is expected to be available in the early 2030s

Table 2 – Cross section of SMR vendors, technologies, and their applications to illustrate the breadth of initiatives and their maturity. Note that Generation IV design are more efficient, generally yielding a better MWe to MWth ratio.

3.3.2 Market maturity of SMRs

Despite lots of active players in the field and SMRs receiving a lot of attention in discussions around nuclear new build, the reality is that most designs are still at the pre-commercialisation stage. Table 2 shows that for most designs, their vendors expect to have a FOAK reactor operation in the early 2030s, suggesting that SMRs still have some way to go before delivering on their promise of cost-effective off-the-shelf carbon-free energy.

Few designs have received regulatory approval and there are only a few under construction or operational, as can be seen in Figure 6. Many designs are still at the conceptual or basic level while a completed detailed design is a prerequisite for completing a project on time and within budget.

The SMR industry recently suffered a setback when one of its lighthouse projects, the Carbon Free Power Project in Utah, powered by NuScale's SMR, was cancelled after municipal utilities withdrew from the project due to worsening economics,[17] further indicating that although SMR is a very promising nuclear technology, its market maturity might not be where it needs to be for Sweden to confidently embrace it as part of a strategy to increase its nuclear generation capacity in the mid-2030s.

[16] https://www.edf.fr/en/the-edf-group/producing-a-climate-friendly-energy/nuclear-energy/shaping-the-future-of-nuclear/the-nuwardtm-smr-solution/development-roadmap, accessed on February 19, 2024

[17] https://www.reuters.com/business/energy/nuscale-power-uamps-agree-terminate-nuclear-project-2023-11-08/, accessed on February 19, 2024

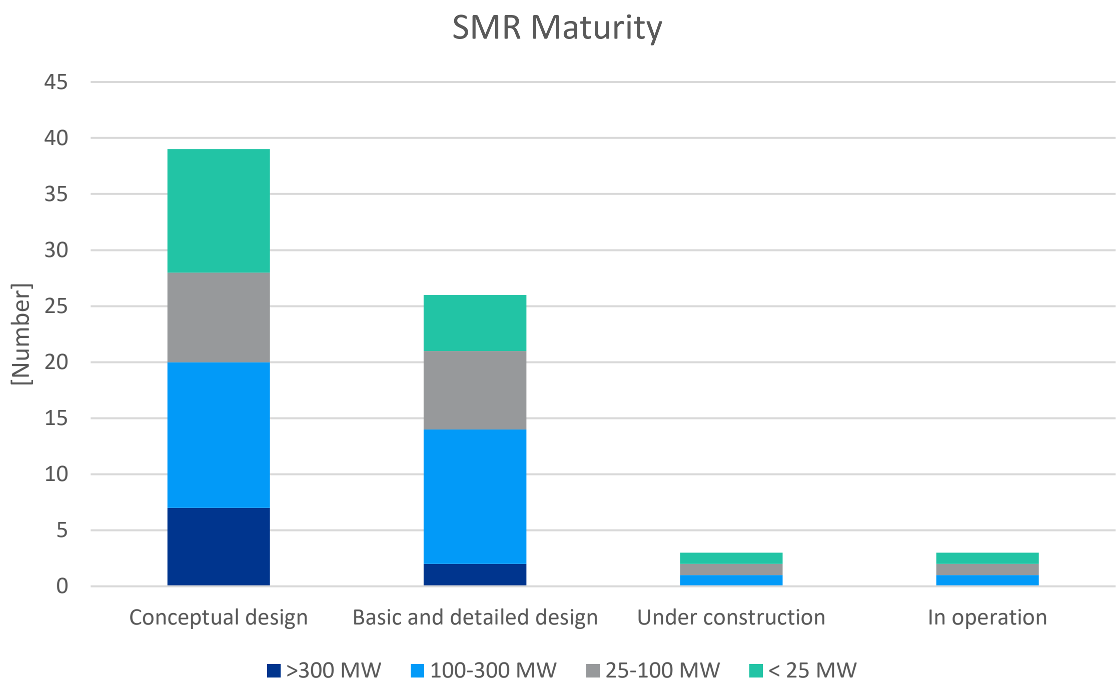


Figure 6 – Number of SMRs at various stages of maturity for different SMR capacity classes. The chart clearly illustrates that SMR as a technology is only now finding its way to the market, with only three SMRs in operation as of mid-2022.

3.3.3 Key differences between LSRs and SMRs

To facilitate the understanding of the key differences between traditional LSRs and SMRs, they have been summarized in Table 3. This data highlights both the potential (versatility, short construction periods, reduced siting requirements) as well as the challenges (limited approved designs, only FOAK reactors) that SMRs are facing. For both LSRs like EPC and leading Gen III+ designs like those of Rolls Royce and GE/Hitachi the design lifetime is 60 years but given the lifetime extensions observed for Gen II LSRs it is reasonable to assume there will be extensions for Gen III+ LSR and SMR too, resulting in an expected lifetime of 80-100 years for both.

Characteristic	LSR	SMR
Typical output	1.2-1.6 GWe	20-500 MWe
Maturity	Sizeable installed base of Generation III/III+ reactors; multiple licensed designs from various vendors	Few FOAK reactors operational; most designs unlicensed and scheduled for FOAK projects in the next 10 years.
Space requirements	3.4 km^2 per 1 GWe[18]	0.1-0.6 km^2 per GWe[19]
Power Infrastructure requirements	Requires HV-connection to transmission network	Connects to transmission grid or off-grid (power) infrastructure of local demand centre
Versatility	Historically used for power generation only	Many multi-commodity designs suited to generate power, heat or hydrogen
NOAK Construction time	6-8 years	2-3 years

Table 3 – Key differences between LSRs and SMRs. Note that all quoted numbers are 'typicals' based on averages from various data sources.

3.4 Conclusions

- **The world appears to be on the cusp of a return to nuclear** – After decades of limited levels of new build (see Figure 4 and Figure 5) the world is seeing a return to nuclear since ~2010. The majority of the new construction projects are taking place in Asia, but Europe is seeing a strong increase too, with Olkiluoto 3 coming online in Finland in 2022, new projects under way in the UK (Hinkley Point C and Sizewell C) and France (Flamanville 3) and projects being prepared in Poland and the Netherlands. This creates both potential benefits (e.g. in terms of international collaboration and learning effects) and challenges (e.g. in terms of limited vendor capacity) that will be discussed in more detail in Chapters 4 and 5.
- **Long lifetimes of reactors require long-term commitment** – The majority of the world's nuclear fleet is comprised of Generation II designs and were built in the 1970s and 80s. These reactors were designed for a 30-40 year lifetime but this has been extended to 60 years in some cases and 80 years seems feasible and is being pursued. It is therefore safe to assume a lifetime of at least 80 years for newly built LSRs, plus another 20-30 years for

[18] https://www.nei.org/news/2022/nuclear-brings-more-electricity-with-less-land, accessed on February 19, 2024

[19] Small Modular Reactors 2023, NRG, and references therein

decommissioning, signalling that the decision to build LSRs requires a long-term commitment from private and public sector parties in such a project. It also illustrates why 'whole lifetime' revenue support models, such as the Regulated Asset Base (RAB, see Section 4.4.3 for details) model that the UK Government is using for Sizewell C, can be suitable for new large scale reactors as these provide appropriate returns throughout the asset lifetime, rather than amortising CAPEX over a fixed period and then allowing investors to potentially earn supernormal returns if the asset life is much longer than originally anticipated.

- **Generation III+ is the default choice for new reactors** – The majority of the new Gigawatt-scale nuclear capacity that is being developed is based on Gen III+ reactor designs that focus on enhanced safety features, increased efficiency, and reduced construction costs. Various Generation III+ reactor designs have been approved by regulators internationally and are now exiting FOAK and can be considered NOAK. Generation IV is still very much at the early stages of development and progress has been uneven across the different designs. The lack of licensed Generation IV designs and examples of successful commercial deployment strongly suggest that Generation IV reactors should not be considered by Sweden as the expected time to the reactor's commercial operation date (COD) would be too long to meet its power generation challenges and the risk profile of a FOAK project would be disproportionately high (See also Section 4.3.
- **SMRs are a promising development for mid-term new build ambitions** – For SMRs, Generation III+ designs are closest to market maturity with Generation IV designs being pursued by various vendors. SMRs have not reached the same level of maturity as LSRs and any SMR project should therefore be considered FOAK. Given the challenges that come with FOAK projects these should not be put on the critical path for Sweden to address its power generation challenges. Once successful cost-effective serialization of SMRs has been achieved, they could provide an interesting option either to provide energy to industrial clusters, integrated in multi-commodity energy hubs where they can provide power, heat or hydrogen depending on (local) energy market needs, or as building blocks for LSRs.

4 Delivery models for new nuclear power

4.1 Introduction

Nuclear new build programmes are capital-intensive projects with long development and construction times as well as long operational timeframes. They therefore require solid, long-term commitments from all shareholders and stakeholders to be successful.

These long timeframes come with inherent uncertainties which represent significant risks to all involved pfrisk arties, probably more so today than in the first Golden Age of nuclear power as the energy transition is likely to continue to drive significant technological, market and societal change.

This raises the question of how financial risks should be shared between vendors/manufacturers of nuclear power plants, the State (taxpayers), and energy consumers. What are available and appropriate delivery models to implement risk-sharing for the two main risk categories: construction cost risks and revenue risks? The answer to this question will differ from country to country, and between project/programme types, and is heavily impacted by society's views on the respective roles of the public and private sector in developing large (infrastructure) projects, and its attitude towards nuclear power.

Risk that is removed does not need to be shared, and de-risking options are therefore an important element for successfully financing new nuclear power plants too.

Non-financial de-risking options can contribute significantly to a positive project or programme outcome. They include ensuring long-term policy continuity, providing a stable and predictable regulatory framework and harmonised licensing and permitting processes.

In this chapter, a high-level overview of investment costs for nuclear power plants is presented before discussing delivery models that implement different forms of risk-sharing (e.g. government investment or revenue support) and de-risking options (e.g. through legislative and regulatory support). Their importance in five archetypical nuclear delivery models is discussed and illustrated with recent examples, as well as their relevance and applicability to Sweden.

In the analysis, use is made of a simple role model that is presented in Table 4 below. The use of this role model facilitates understanding the key differences between the delivery modes and how this impacts risk.

Key roles	
Project Sponsor	Entity that initiates, champions, and provides strategic direction and support for a project, typically holding ultimate accountability for its success
Project Developer	Entity or organization responsible for conceptualizing, planning, financing, and executing a project
Vendor	Company that supplies the necessary nuclear technological solutions, equipment, and expertise.
Operator	Company that is responsible for the day-to-day management, operation, and maintenance of the plant post construction.
Other significant roles	
Legislator	Governing institution responsible for creating, amending, and enacting laws and regulations, which for nuclear power plants include safety standards, licensing requirements, and environmental regulations.
Regulator(s)	Agenc(y)(ies) tasked with overseeing and enforcing regulations, standards, and safety protocols related to the operation, construction, and decommissioning of nuclear facilities to ensure public and environmental safety.
Offtaker(s)	Utility company(y)(ies) or other energy purchaser(s), that enter(s) into a contract to buy the electricity generated by the plant, providing revenue for the project developers or owners.

Table 4 – Simplified, non-exhaustive role model for NPP newbuild projects. Depending on the delivery model, key roles will be fulfilled by different (combinations of) entities.

The model is not intended to be exhaustive but instead focuses on the roles that have the largest impact on de-risking options and risk-sharing mechanisms in the analysed delivery models.

4.2 Understanding investment costs for NPPs

To understand the importance of risk-sharing and de-risking measures for a financially sound nuclear new build project/programme what investment costs for nuclear power plants look like and how they are influenced by aspects like the cost of capital, construction times, which in turn are impacted by aspects like design maturity and regulatory stability. This section provides an overview of where costs occur in a plant's life cycle, what these costs are and how they change as a design moves from FOAK to NOAK.

4.2.1 Cost distribution over the life cycle of a LSR NPP

Where costs are incurred during the lifecycle of a power plant is very different for nuclear power plants compared to large fossil fuel-based generators. Unlike for example gas-fired power plants, LSR NPPs incur relatively low OPEX during their long lifetimes, but the upfront CAPEX is significant. The table below illustrates this for LSRs with data compiled from various sources[20,21,22]. It should be noted that these data are indicative and not reflective a particular project.

	Development	Construction	Commissioning	Operations	Decommissioning
Duration [Years]	6-8	7-10	1-2	60-80	20-30
Share of costs [%]	~10	~50	~2-3	~35-40	~1-5
Key activities	▶ Design ▶ Tendering ▶ Permitting	▶ Materials ▶ Labour ▶ Civil works	▶ Non-nuclear tests ▶ Fuel loading ▶ Nuclear tests	▶ Fuel ▶ Operations ▶ Maintenance ▶ Waste management	▶ Reactor shutdown ▶ Removal nuclear material ▶ Plant demolition

Table 5 – Indicative duration and costs of various stages in the life of a nuclear power plant in OECD countries[23].

The bulk of the costs (~60%) over the lifetime of an NPP are incurred during the development and construction phase, when no revenues exist yet. The estimated overnight construction costs for a LSR are of the order of 4 billion Euros per GWe[22]. Including the interest payments on borrowed funds (see next section) a new build requires the project partners to finance ~6 billion Euros before revenues from the sale of electricity start. For FOAK projects this number can be substantially higher (see also the next section) with outliers like the UK's Hinkley Point C now projecting a project cost

[20] https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx, accessed on February 19, 2024

[21] https://www.oecd-nea.org/upload/docs/application/pdf/2020-07/7530-reducing-cost-nuclear-construction.pdf, accessed on February 19, 2024

[22] Projected Costs of Generating Electricity, IEA & NEA, 2020 Edition

[23] Costs in the rest of the world are found to be significantly lower, with lower labour and commodity costs being a key contributor, but also less well understood due to lower data availability.

between 36 and 40 billion Euros in 2015 values before commissioning is complete[24]. The size of the required investment illustrates the importance of risk-sharing between the public and private sector and de-risking measures that help reduce financing costs and construction time overruns. Risk sharing and de-risking options are discussed in more detail in Section 4.4.

Due to the SMR market still being nascent there is insufficient data to provide a comparably documented view, but early academic work and expert views suggest that although the overall development and construction times will be lower, the relative share of their costs over in the lifecycle will be comparable[25,26,27].

4.2.2 Breakdown of investment costs

As is demonstrated above, NPPs require substantial investment. The required investment can be broken down into two different components:

- The Overnight Constructions Costs (OCC), which denote the costs of the project if no interest was incurred during construction, as if the project was completed "overnight".
- The Interest During Construction (IDC), the interest on borrowed funds during the construction period. Since no revenues are being generated yet, the interest is "capitalized", i.e. added to the loan.

Figure 7 below provides a breakdown of the investment costs for LSRs in OECD countries, assuming a Weighted Average Cost of Capital (WACC)[28] of 7% and a construction time of 7 years, showing that IDC make up a substantial amount of the total investment costs.

Nuclear production costs are therefore especially exposed to the cost of delays in two ways:

1. There is an impact on financing, since the longer the construction period, the higher the interests accumulated and therefore the greater the capital required.

[24] https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/hinkley-point-c-update-1, accessed on February 19, 2024

[25] The economics of very small modular reactors in the north, M. Moore, 4th International Technical Meeting on Small Reactors (ITMSR-4), 2016

[26] Economics and finance of Small Modular Reactors: A systematic review and research agenda, B. Mignacca & G. Locatelli, Renewable and Sustainable Energy Reviews, 2020

[27] State-of-the-Art Review of Small Modular Reactors, Carlo L. Vinoya et al., MPDI Energies, 2023

[28] The Weighted Average Cost of Capital (WACC) is a financial metric that calculates the average cost a company faces for its capital, considering both debt and equity. It's important because it helps a company evaluate the profitability of potential investments by showing the minimum return, they need to generate to satisfy their investors. WACC considers the cost of borrowing money (interest on debt) and the cost of obtaining funds from investors (return expected by shareholders).

2. There is a direct impact on construction costs, as delays means more labour and equipment costs, and potentially higher materials costs through external factors such as inflation and global supply chain disruptions.

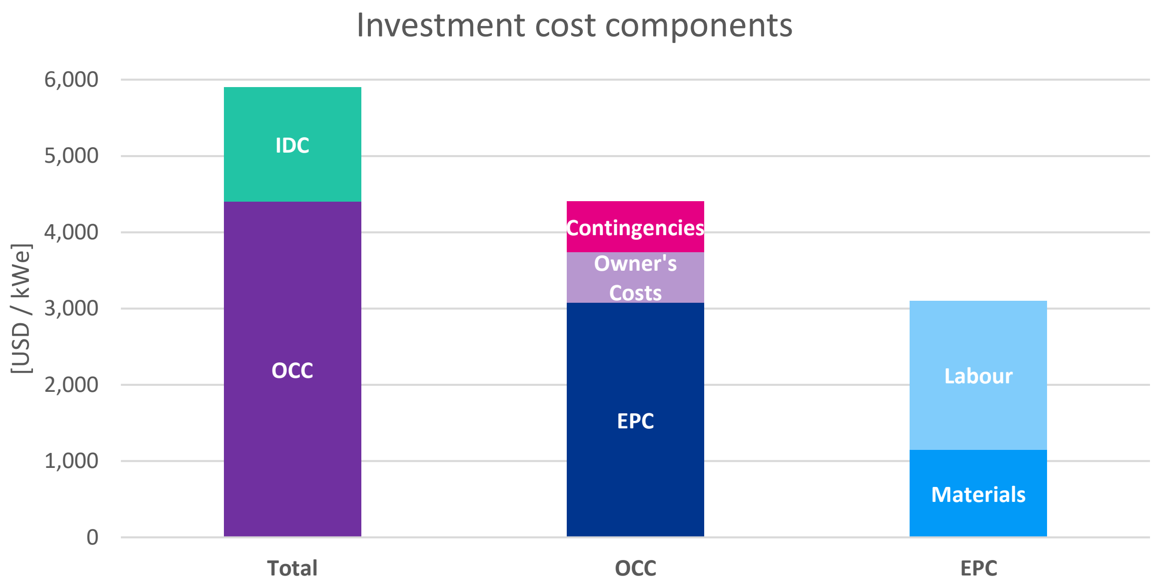


Figure 7 – Breakdown of average investment needs per kWe in OECD countries. IDC based on a cost of capital of 7% and construction time of 7 years[21] .

Table 6 shows the impact of increasing WACC and construction times on the share of IDC in the total investment costs. Both have a strong impact on the overall investment needed, illustrating the importance of reducing financing costs. This can be achieved by getting access to capital under better conditions, for example with higher government involvement in the financing scheme. The benefits of lower costs of capital become more pronounced as the construction time increases.

	Construction period		
Cost of capital	**3 years**	**5 years**	**10 years**
3%	5.8%	8.6%	15.3%
5%	12.8%	18.7%	32.4%
10%	17.6%	25.5%	43.0%

Table 6 – Share of cost of capital (IDC) of total investment costs per kWe as a function of WACC and construction time, assuming an OCC of 4500 USD/kWe. Reproduced from[21].

This again illustrates the importance of structuring a nuclear new build project or programme in such a way, through de-risking and risk-sharing measures, that low-cost capital can be attracted and the construction process can be confidently managed.

4.2.3 The FOAK premium and the potential for construction cost reductions

A First of a kind (FOAK) project is the first project to construct a reactor of a type in a specific market, as opposed to Nth of a kind (NOAK) projects, a term used to describe that several reactors of the same type have already been constructed in that market. FOAK projects have shown to be typically substantially more expensive and prone to delays than NOAK projects.

For Europe, effectively only three suppliers for Generation III/III+ LSRs exist[29] and as of early 2024, only one Generation III/III+ is in operation in Europe. This NPP, the Olkiluoto 3 reactor in Finland, started delivering power to the grid in 2023 and was not exempt from paying the FOAK premium.

Note that FOAK does not apply to the technology only: if design changes are required of a design that was previously licensed and built in an advanced market economy, it effectively moves from NOAK to FOAK status again and can occur very substantial costs with no added (safety) benefits.

Also note that for SMRs, FOAK and NOAK should be interpreted slightly different: successfully delivering a single SMR does not elevate an SMR-type from FOAK to NOAK, as it does not demonstrate that the promise of SMRs – cost-effective standardized multiples – has been successfully delivered. FOAK and NOAK for SMRs should therefore be considered to apply to a *series of reactors*, not individual reactors.

Although FOAK and NOAK often-used industry-standard concepts, the reality of a nuclear new build project is often more complex with every large-scale project having elements that are FOAK, at least because of site-specific geology. The extent to which the success factors listed below can be lined up will make a difference in outturn cost.

Given the impact of FOAK elements on a project’s costs and duration, it is important to understand the causes of this FOAK premium, and how these can be mitigated.

Key factors that contribute to higher costs for FOAK include[22, 30]:

- **Design maturity** – An incomplete detailed design at the start of construction can result in unforeseen costs to meet safety standards, complex engineering requirements, and supply chain challenges.
- **Effective project management** – Lack of strong project management with experience in all key aspects of the project can lead to poor execution planning at the time of the construction start.
- **Regulation stability and predictability** – Changing the rules during the game, or lack of clarity on what the rules will be, lead to delays as compliance is ensured at each stage of construction and drives up costs through forced design changes and risk premiums.

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[29] EDF with its EPR reactor, KEPCO with its APR1400 reactor and Westinghouse with its AP1000 reactor. All three are Pressurized Water Reactors (PWR).

[30] The World Nuclear Supply Chain – An Overview, Greg Kaser, NEA International WPNE Workshop Paris, 11 March 2014

- **Multi-unit and series effects** – FOAK projects contain both a risk premium reflecting the contingency element built into component and plant prices as well as a profit element that takes account that there may not be any follow-up projects. Both are typically absent from a project/programme comprising multiple units.

The size of the FOAK premium can be gauged from Table 7 where the budget overruns of recent Generation III/III+ FOAK projects is expressed as a ratio of the initial budget.

Reactor type	Country	Construction start	Power [Mwe]	Initial budget [USD/kWe]	Actual cost [USD/kWe]	Ratio
AP1000	China	2009	2x 1,000	2,044	3,154	1.54
	US	2013	2x 1,117	4,300	8,600	2.00
APR1400	Korea	2008	2x 1,340	1,828	2,410	1.32
EPR	Finland	2006	1x 1,630	2,020	7,362	3.64
	France	2007	1x 1,600	1,886	8,620	4.57
	China	2009	2x 1,660	1,960	3,222	1.64
	UK *)	2018	2x 1,600	8,063	12,500	1.55

Table 7 – Construction costs of recently completed and under construction (*) FOAK Generation III/III+ projects. Data sourced from [22, 24, 31].

The costs reductions that can be achieved from a mature detailed design in an established, stable regulatory context leveraging a built-up supply chain can be substantial. Historic data[32] for LSRs shows that costs can drop to ~60% for the 4th reactor at the same site, and to ~75% for the 4th reactor in a single unit per site programme.

Provided that the scale and timing of Sweden's nuclear ambitions allow for it, a programmatic approach aiming for serial deployment of multiple identical reactors should be considered as this has been shown to provide substantial cost advantages over multiple units of different types.

[31] The World Nuclear Industry Status Report 2019, Mycle Schneider et al., 2019

[32] Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, NEA & OECD, 2020

4.3 Trends in delivery models for NPPs

In a 2022 report for the Dutch Ministry of Economic Affairs & Climate[33], Baringa developed six case studies on current and planned nuclear power plant new build projects. As part of these case studies, Baringa analysed the delivery models applied, with a focus on their indicative risk profile and the level of government support. Figure 8 represents an updated summary of those case studies.

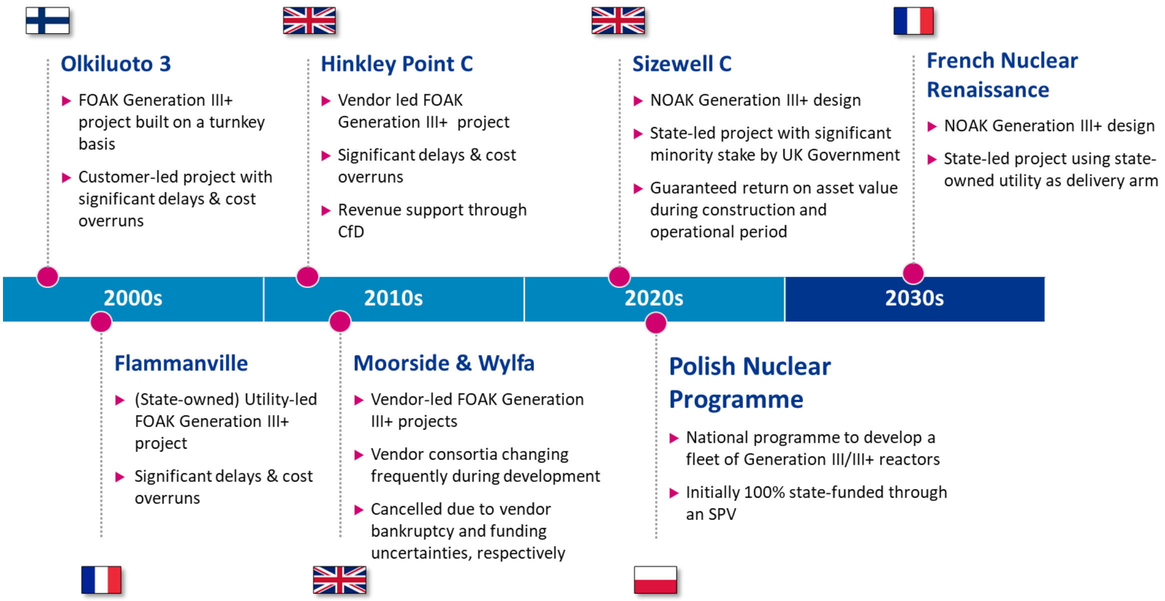

Figure 8 – Summary of recent and current nuclear newbuild initiatives in Europe.

From Figure 8 two trends become apparent:

1. FOAK projects carry a demonstrably high risk of delays and cost overruns.
2. The challenges with vendor-led projects in the UK signal the need for strong (financial involvement) of the State for new NPPs.

The high capital costs, long construction times, and resulting financial risks associated with nuclear power projects can make them challenging for utilities to include on their balance sheets without significantly impacting their financial health and credit ratings.

Consequently, governments with nuclear power ambitions need to trigger NPP new build projects with risk reducing incentive schemes like the UK Government did with the Contract for Difference (CfD) mechanism for Hinkley Point C and the Regulated Asset Base (RAB) model for Sizewell C. These models are explained in more detail in Section 4.4.3.

[33] Financing models for new nuclear power plants – European Nuclear Power Plant case studies, Baringa, 2022

The trend towards higher level of government shareholding appears to develop into emergence of nuclear new build programmes rather than projects, initiated and (largely) funded by the State. It is therefore safe to conclude that some level of (financial) government support will be required in Sweden for new LSRs too.

4.3.1 A note on SMRs

The emerging SMR market does not offer historic data to distil delivery trends from. Stakeholder interviews conducted for this study indicated that vendors have very different perspectives on how to successfully go to market with their product. Where some pursue fully privately financed SMR development leveraging PPAs and advocate (small scale) new nuclear to be treated similarly to other energy projects with no government support required, others see government balancing sheet funding as key for the first units and expect the State to form a development company to place contracts and drive early project development.

Low power prices and carbon prices, an energy only market, and regulatory processes tailored to multi-billion Euro Gigawatt-scale projects are seen as the key threats to (privately funded) SMRs.

4.4 Risk sharing and de-risking options

This section builds on the context described in this chapter to identify specific options to address the risks associated with new nuclear build, focussing on options to reduce societal risk first, and then consider the options for fairly sharing the residual risk between the stakeholders in nuclear programme or project.

4.4.1 De-risking options

What can be done to improve the expected economic return of new nuclear projects and to reduce the chance of society facing long-tail downside risks? We split these actions into two categories: those that drive down the lifetime costs of the project, and those that provide fair remuneration for the services provided by the project.

Risk in this context refers to an assessment of the probability of variation between the central expectation at the time a decision is made and the outcome of the decision. Risk in infrastructure projects generally is asymmetric: civil engineering costs, for example, can blow out in the face of unexpectedly bad ground conditions by far more than better-than-expected conditions can reduce costs. The common theme linking actions aimed at mitigating risk is therefore to reduce the likelihood of long-tail downside risk by bringing forward the certain knowledge of conditions.

Table 8 and Table 9 summarise suggested potential actions to mitigate risk areas across each of the phases of the project.

Project phase	Risk area	Action to mitigate risks	Actor
Pre-construction	Design approval	▶ International coordination ▶ Proportionate regulation ▶ Adequately staffed regulator	Regulator Legislator
	Development consent	▶ Streamline points of contact ▶ Balanced regulatory remit	Legislator
Construction	Design changes	Mature design at start of construction	Vendor
	Satisfying conditional approval	▶ Minimise local content requirements ▶ Minimise non-standard conditions	Legislator
	Supply chain	▶ Programme commitment ▶ Effective sequencing ▶ Incentive to partner to completion	Sponsor
Operation	Taxation	Track record of non-discrimination	Legislator
	Fuel supply	▶ International coordination ▶ End-to-end strategy	Operator
Decommissioning	Long-term plan	Waste final repository in operation	Legislator

Table 8 – Risk mitigating actions to drive down costs across project phases.

Risks can be addressed at every stage of the project from pre-construction through to decommissioning, as visible in the track record of large infrastructure in general is the realisation of worse-than-expected outcomes at any point. However, specifically for nuclear projects, the risks are strongly front-loaded in construction phase and the biggest gains can be made in this area.

In keeping with the theme of bringing forward certainty, starting with a mature design is the single most significant factor in predicting the success of a nuclear project. Minimising changes to designs that have already been constructed, by, for example, foregoing the temptation to impose local content requirements avoids the introduction of new sources of uncertainty.

Risk also refers to the expected income of the project. Knowing that the income will fully reflect the value of the project reduces the downside risk of poor economic outcome because of too-low remuneration.

However, these risks cannot be fully eliminated as the future social value of the project is unknowable: the value of low-carbon power in addressing climate change is itself a political decision subject to uncertainty. So, while these actions are helpful, from a social perspective, revenue risks can more effectively be dealt with through risk-sharing arrangements.

Project phase	Risk area	Action to mitigate risks	Actor
Operation	Climate policy	EU ETS / Social value of CO_2 abatement	Legislator
	Electricity market reform	▶ Capacity adequacy market ▶ Ancillary system services markets	Legislator

Table 9 – Risk mitigating actions to provide fair remuneration in the operational phase of a project.

The consensus view is that the magnitude and significance of the actions to drive down costs vastly exceeds the materiality of actions to provide fairer remuneration, reflecting the relative maturity and efficiency of wholesale electricity markets and European climate policy.

4.4.2 Risk sharing

Even with de-risking as set out in the previous section, new nuclear projects still face some significant risks that will lead to financing challenges. Key risks include:

- **Pre-construction risk** – It can take 5-10 years and cost hundreds of millions of pounds to secure required approvals, and during which time Government policy can change, or projects may prove to be unviable for economic or technical reasons (e.g. Hitachi are reported to have written off almost £2bn spent developing the proposed Wylfa Newydd project in the UK after failure to secure an agreement with the government that enable the project to take FID).
- **Construction risk** – The lengthy, complex, and bespoke construction period for large-scale NPPs means that fixed price, 'turnkey' construction contracts are not available, and projects can face long delays and significant cost overruns. For example, construction of Olkiluoto 3 took 12 years longer than anticipated and cost three times as much; Hinkley Point C is currently running at least 4 years behind schedule and costs have almost doubled[34].

[34] Both projects should be considered as FOAK projects.

- **Political risk** – NPPs can face significant political risk during their development, construction and operational periods, arising from changes in government policies or public opinion that can significantly affect the feasibility and profitability of nuclear power ventures. For example, a change of Government could lead to a change in policy on support for new nuclear power during the project development stage (such as when Theresa May became Prime Minister of UK and launched a review of the Hinkley Point C deal just a few hours before the intended signature of the contract), or in extremis require existing operational assets to shut down (as has been seen recently in Germany, and in Japan following the 2011 earthquake and resulting Fukushima incident).
- **Regulatory risk** – NPPs can face significant regulatory risk during their operational period from changes in safety standards, licensing requirements, or environmental regulations imposed by governmental authorities, leading to delays, increased costs, or even NPP shutdowns/suspended operation – e.g. to retrofit expensive safety features (as was seen following the Fukushima incident).
- **Market price risk –** NPPs are typically 'price takers' in the power market due to their low short-run marginal cost (SRMC), and the longest power purchase agreements that are typically available are around 15 years – meaning that operators would be exposed to market price risk for over 70% of the expected lifetime. Note that PPAs are typically signed no more than 3 years ahead of power generation, so in practice it is unlikely that NPPs will be able to sign binding, fixed price PPAs at the time of FID – and may therefore be exposed to market price risk for 100% of their lifetime (absent government support).

To enable projects to succeed, the host state will generally need to implement mechanisms to share or mitigate these risks. Table 10 below illustrates some of the mechanisms typically used to share specific risks.

Risk Category					
Risk-sharing mechanism	**Development**	**Construction**	**Political**	**Regulatory**	**Market price**
Grants for project development (e.g. FEED studies, licensing)	●				
State-owned or public-private development company	●	●		○	
Export credit guarantees from vendors		○			
Fixed price revenue support (e.g. CfD)					●
Risk-sharing revenue support (e.g. Regulated Asset Base model, CfD with pain / gain share)		●		○	●
Change in law / political risk protection		●	●		
Change in regulation protection		●		●	
Insurance provision for low-probability high impact events			○		
Loan guarantees		○			

Table 10 – Illustrative risk-sharing mechanisms used to support NPP financing. Bullets indicate which risks the mechanism primarily impacts; dark shading indicates significant risk-sharing, light bullets indicate moderate.

4.4.3 Revenue support schemes

Three often encountered revenue support schemes are described in some detail in this section to facilitate understanding the role they can play in increasing investability in nuclear new build.

4.4.3.1 Contract for Difference

A Contract for Difference (CfD) is a long-term contractual agreement between a low carbon electricity generator and a government-owned counterpart designed to provide the generator with price certainty over the lifetime of the contract. This type of revenue support is used in GB for renewables (intermittent and baseload) and nuclear with some differences in terms. The GB scheme is described in more detail below.

The contracts provide a difference payment that is calculated by comparing a reference price, which is a measure of the market price for electricity, and the generator's strike price, which varies from project to project. If the reference price is below the strike price, the generator is paid the difference for each unit of electricity that is generated, with the money coming from a levy placed on electricity retailers. When the strike price is below the reference price, the generator pays the difference and the money is channelled back to retailers. In GB, there is no volume cap in CfDs – generators can receive (or pay) the difference payments for all electricity they generate within the contract term.

A CfD is a private law contract between a generator and a government-owned counterpart under which the generator's income per unit of electricity is fixed. In GB, this role is fulfilled by the Low Carbon Contracts Company (LCCC). LCCC has an obligation to raise revenue by a levy on electricity retailers to pay difference payments, or to return difference payments received from generators to retailers.

CfDs contain a 'milestone delivery date' (typically 12-18 months after award) by when the generator must have made a material financial commitment to the project, and a final delivery window for development. Although CfDs provide price stability, they do leave projects exposed to volume risk and cost-base risk (including construction cost), as well as basis risk (i.e. the risk of achieving the reference price). CfDs typically do provide some protection from qualifying changes in law and regulation.

CfD allocation can be by competitive auction or bilateral negotiation, with signature after project pre-development conditions met – though for nuclear only bilateral negotiations have been tried. Hinkley Point C is a recent example where a CfD has been agreed as a revenue support scheme. Contract terms for renewables are typically 15 years and for nuclear 35 years, with assets expected to operate on a merchant basis after contract expiry.

Whilst CfDs have been successful in attracting investment at a low cost of capital to renewables projects, with the exception of Hinkley Point C they have not been successfully used for NPPs. A key reason is that the strike price is typically fixed at the time of award, which for nuclear projects can be 10-15 years before the plant is operational and when construction costs are highly uncertain. In addition, payments only commence once the plant is fully operational. This means investors face full cost and delay risk, which as described above can be non-trivial in the case of NPPs.

Furthermore, by providing a fixed electricity price for each unit of generation, CfDs can remove incentives on generators to respond to price signals in the market, which may increase the overall cost of the electricity system to consumers in the longer term. The UK Government is currently consulting on reforms to the electricity market, including the possibility of moving to 'deemed CfDs' that pay on the volume of potential generation rather than actual output.

4.4.3.2 Regulated Asset Base

A RAB model is a type of economic regulation historically used in the UK for monopoly infrastructure assets such as water, gas and electricity networks but now also being implemented for the Sizewell C

NPP. It is also being considered outside of the UK as revenue support scheme for nuclear, e.g. in the Netherlands.

The primary objective of adopting a nuclear RAB model is to attract investment from financial markets into new nuclear projects at a low cost of capital, thereby reducing the cost to consumers of nuclear power. It is seen as attractive by investors as it provides a robust revenue stream with relatively low risk for the economic lifetime of the asset. The RAB model allows investors to start recovering their costs before plant completion, thereby avoiding the build-up of interest on loans, which would ultimately lead to higher costs to consumers once the NPP is operational (see also Section 4.2).

In the UK, Government and private investors have co-funded pre-development of Sizewell C to designation (site selection, design approval, development consent), with government providing the majority of the funding from designation onwards to the final investment decision. The RAB licence lasts for the entire economic life of the power station. The licence determines the revenue stream due to investors based on agreed rate of return. Competitive allocation of RAB company shares minimises cost of capital.

The regulated return to investors is funded by a levy on electricity suppliers, based on the value of the RAB (the value of the NPP investment on which the return is made) and WACC with legitimate operating costs for e.g. maintenance being recouped on a pay-as-you-go basis. In the UK, the energy regulator (Ofgem) acts as the economic regulator for the RAB licence, making decisions on matters such as eligible expenditure, depreciation and indexation which ultimately drive allowed revenues. Under the RAB, investors share project risk and costs with consumers (i.e. there are pain / gain share provisions built into the RAB), and a Government Support Package protects investors from high impact / low probability risks (such as discontinuation of the project due to certain political risks, and insurance of last resort).

Whilst a RAB model addresses many of the downsides of CfDs for investors, it does so by transferring substantial cost, delay and performance risk to electricity consumers and / or taxpayers. This provides much less certainty over the eventual value for money of NPPs to the Government and may weaken incentives on developers to deliver to time and budget. RAB models also involve the Government (and / or the economic regulator) having to take a much more active role in project development, construction and operation, with consequential impacts on resource and budget requirements.

4.4.3.3 Power Purchase Agreements

Power Purchase Agreements (PPAs) are contracts between a power generator and a buyer, typically a utility or a large consumer of electricity, where the generator commits to supplying a certain amount of electricity at an agreed-upon price (or indexed to a reference price) over a specified period. PPAs can play a role in facilitating the financing, construction, and operation of power generation projects.

In enabling nuclear new build, PPAs can play a significant role in mitigating the substantial upfront capital costs. These agreements provide a level of certainty for investors and lenders by guaranteeing a revenue stream over the long lifespan of nuclear facilities, typically spanning decades. This assurance helps secure financing for construction, as lenders are more willing to invest in projects with assured revenue streams.

For buyers, nuclear PPAs offer stable, low-carbon electricity supply over the long term, which can help meet sustainability goals and hedge against volatility in fossil fuel prices and environmental regulations.

We do not currently see NPPs being financed purely on the basis of voluntary PPAs with offtakers, but regulated PPA models where utilities or retailers are obliged to purchase a certain proportion of their supply from certain generator types have been successfully used in several markets to finance construction of assets (particularly renewables) and could in principle be applied to NPPs. However, a key challenge is whether – particularly in a liberalised electricity retail market – it is feasible for utilities or retailers to offer contracts of sufficient tenor (e.g. 35 years), and whether these contracts would be sufficiently credit-worthy to support raising the level of capital required.

Voluntary PPAs may be more feasible in the context of SMRs, given the lower level of capital required, smaller output, opportunity for 'private wire' supply, and potentially faster delivery. This is the route being targeted by some developers such as Last Energy, who claim to have signed PPAs with over 35 offtakers for their 20MW SMR (although how bankable and binding these PPAs are is unclear).

4.4.4 A word on State Aid

Factors external to the utility will also affect the design of support mechanisms, most notably, State Aid rules put in place by the European Commission. State Aid rules ensure that support, including that provided by risk-sharing mechanisms, is targeted at objectives of common interest, is the minimum intervention necessary to achieve the objective, and does not significantly distort the wider market. These tests of necessity, appropriateness and proportionality can be passed, as shown by the Commission's decision approving United Kingdom aid for Hinkley Point C NPP in the UK. However, it must be noted that legal challenge to this decision was not concluded until September 2020, six years after the original decision and well into the construction of the NPP itself.

Given the long lead times for getting approval, it is important to start the process early with a pre-notification to the Commission as soon as the contours of the any form of government support become clear.

4.5 Common delivery models for nuclear new builds

This section describes five archetypes for nuclear newbuild projects with increasing levels of state involvement. For each archetype, recent or current examples are given, key de-risking and risk-sharing options are provided and its relevance and attractiveness for Sweden is discussed.

4.5.1 Entrepreneur-led project

4.5.1.1 Introduction

The first category is the entrepreneur-led project. This is conceptual rather than actual at this point in time, as there have not (yet) been any nuclear projects successfully commercialised purely by entrepreneurs. However, several companies are now actively pursuing this approach to developing SMRs, which – given their smaller size and (theoretically) lower construction cost risk – the proponents believe have the potential to be developed in a manner similar to other power generation projects. One of these companies is Last Energy, a US SMR developer that claims to have signed PPAs for 34 units of its 20MW PWR reactor with four industrial partners in the UK and Poland[35] (although it is likely that these PPAs are non-binding).

In an entrepreneur-led model, private sector project developers act as Project Sponsor, Project Developer, Vendor and Operator. They would acquire sites and permits, and develop projects without explicit government subsidy, likely based on forward power sales to Offtakers through PPAs or similar instruments.

It is highly unlikely that such a model could work for FOAK SMRs, but if early, government-supported projects are successful then it could prove to be a long-term route for enabling new nuclear projects to wean themselves off government subsidy/support and compete effectively in the market.

4.5.1.2 De-risking and risk sharing in an entrepreneur-led model

Proponents of this model claim that all that is required is for new nuclear projects to be treated on a "level playing field" so it can compete on an equal basis with other power generation projects. However, in practice this would likely require significant changes to the regulatory landscape, such as:

- Ensuring regulatory processes are tailored appropriately to the size of projects – which for 20MW SMRs would mean a dramatic reduction in the burden of regulation.
- Opening up a much greater choice of locations in which nuclear reactors can be sited and streamlining the permitting process.
- Reforming power markets so that they fully internalise the value of the services provided by different technologies (e.g. security of supply, ancillary services, etc.).
- Appropriate protection / compensation from nuclear-specific changes in law (e.g. political shutdown, retrospective changes in safety standards).
- Confirmation that nuclear power is considered 'sustainable' for the purposes of Environmental, Social & Governance investment and corporate greenhouse gas emissions reporting.

[35] https://www.lastenergy.com/news-press/last-energy-secures-ppas-for-34-smr-nuclear-power-plants-in-poland-and-the-uk

For this model to materialise, strong involvement from the Legislator and Regulator(s) would be required.

4.5.1.3 Attractiveness and relevance for Sweden

In theory, the entrepreneur-led model is highly attractive – it could enable widespread deployment of SMRs within a liberalised electricity market without placing a burden on public finances or requiring significant state involvement.

However, there is currently low confidence that this route would actually deliver any projects, since no SMRs have to date been deployed commercially under any model, and there are recent examples (e.g. NuScale's Carbon Free Power Project in Utah[36]) of projects being cancelled at relatively advanced stages. It would likely require significant effort and take time to make the required regulatory and market reforms, some of which may be unpopular if they are perceived as weakening nuclear safety standards, with no guarantee of success.

Sweden is also unlikely to be a target market for entrepreneur-led SMR development given its relatively lower power prices, thanks to the extensive hydropower and wind resources.

On balance this model is therefore not deemed viable at this point in time but could be considered in future as the commercial viability of SMRs becomes clearer.

4.5.2 Customer-led project

4.5.2.1 Introduction

The second archetype is the customer-led project. In this type of project, a group of utilities and industrial power users act as Project Sponsor and cooperatively initiate and finance a project to build an NPP through a joint venture, that acts as Project Developer and Operator. Each shareholder contributes a proportion of the costs of building and operating the plant, and acts as Offtaker, receiving electricity supplies for their own use (industrial power users) or to supply consumers (utilities) proportional to their share in the joint venture. Any access power is sold through the wholesale market.

The best-known model for a customer-led project is probably the Mankala model[37], which was developed in Finland after World War II. Its collaborative approach solved Finland's challenge of meeting a rapidly increasing need for electricity when individual companies were not able to carry out capital-intensive power plant projects. Since then, it has been used extensively in Finland for power and thermal energy production facilities. Around ~ 40% of electricity generation and ~ 66% of

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[36] https://www.nuscalepower.com/en/news/press-releases/2023/uamps-and-nuscale-power-agree-to-terminate-the-carbon-free-power-project

[37] The name originates from a decision from the Finnish Supreme Administrative Court (1963) confirming the legality of the model in relationship to one of the first projects to benefit from it, a hydropower project called 'Mankala'.

nuclear power capacity have been built using this model, and it underpins a significant share of hydro and wind farm investments. Since the 1970s, almost all Finnish NPP's have been financed by the private sector and through the Mankala model. The most recent project was Olkiluoto 3 which was completed in 2023.

4.5.2.2 The Mankala model

In the Mankala model, investors, often electro-intensive industrial and municipal power users act as Project Sponsor and establish a limited liability company (LLC) for the construction and operation of an NPP. The is financed through a combination of debt and equity financing and acts as Project Developer and Operator. The LLC contracts a Vendor to deliver the NPP.

The LLC owners are the Offtakers and have the right to get a share of the produced electricity corresponding to their share of ownership, which is sold to them at the cost of production. At the same time, they commit to cover also their pro-rata shares of the actual costs of the company. Therefore, the LLC is not exposed to market risks, as these are taken by the end users. The operating model is included in the companies' articles of association.

The lenders do not have recourse to the shareholders' balance sheet, although in case the LLC goes bankrupt the shareholders typically commit to take over the debt. The Mankala structure is therefore attractive for banks, as several creditworthy owners will ensure the long-term cash flow, and as a result the LLC can be heavily leveraged.

The Mankala model is illustrated in Figure 9 below.

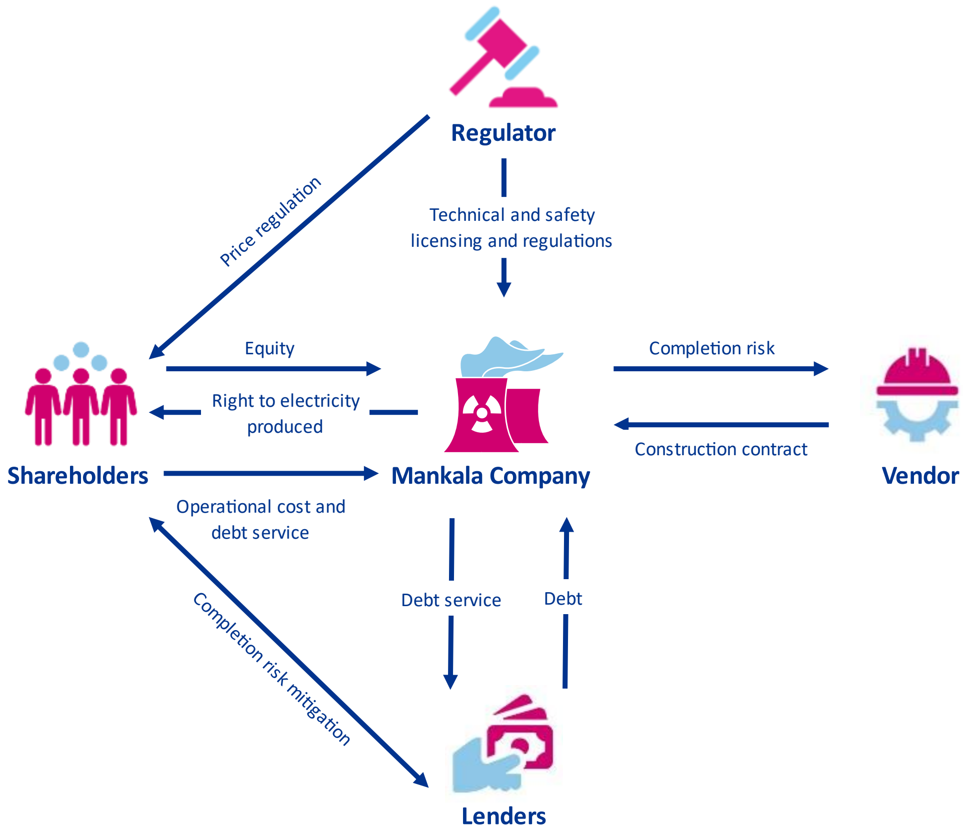


Figure 9 – Schematic representation of the Mankala model, reproduced from [33].

Although fully privately funded, a customer-led NPP project can be initiated by the government, as was the case for the Olkiluoto 3 project, in which case the government takes on the role of Project Sponsor.

4.5.2.3 De-risking and risk sharing in the customer-led model

De-risking and risk-sharing of a collaborative project is achieved through the following mechanisms:

- Active role of the State in supporting the project by promoting societal benefits and supporting stakeholder engagement.
- A stable long-term price, not subject to price volatility on the wholesale market, and with security of supply.
- Sharing of investment risk between several and diverse investors, which is of particular benefit to small shareholders.
- An enhanced valuation by rating agencies who take solidarity among shareholders into account, resulting in reduced cost of capital.

4.5.2.4 Attractiveness and relevance for Sweden

Successful application of a collaborative model like the Mankala model depends on whether there are enough energy-intensive industries and (municipal) utilities willing and able to participate in a NPP project.

Although demonstrably successful in the past, the challenges faced in Finland's Olkiluoto 3 project have cast doubts on the viability of the Mankala model for new NPPs. A fully privately funded project with an EPC/vendor taking full responsibility for construction risks, does not fit the size, complexity and risks associated with today's LSR NPP projects. As there are no more vendors offering turnkey fixed price NPPs, more risk falls on Mankala-shareholders, pushing it into the same risk-realm as the utility-led model (see below) - if project costs end up at an outturn level comparable to Hinkley Point C / Olkiluoto 3 this would very unattractive commercially.

Some interest has been expressed by electro-intensive industries from Sweden and Norway in participating in a nuclear new build project in Sweden but at this stage it is unclear if this would result in co-investing or in providing revenue guarantees through a PPA. In any case, given the size and risk associated with a LSR NPP project, it does not appear to feasible to implement one without a public-private partnership. It is unlikely that the State would provide the required risk-reducing support while leaving all the benefits with the Mankala-shareholders and without having a steer in the project.

For SMRs, the feasibility for a collaborative-led project might be more appropriate as the expected project size and complexity should be significantly lower, once an SMR-vendor/reactor model has reached the NOAK stage.

4.5.3 Utility-led project

4.5.3.1 Introduction

In the utility-led model, a utility contracts with a Vendor while acting as Project Sponsor, Project Developer, Operator and Offtaker. The viability of this model strongly depends on the structure of the electricity supply industry which varies significantly by country and is changing through time.

At one extreme, a single utility can be responsible for the generation, transmission, distribution, and supply of power to households and businesses within its region. Through most of the twentieth century, this was the dominant model. In the US this traditional model still exists in some states, notably Georgia, where the Vogtle NPP has been built by the Georgia Power company. The regulatory model for investor-owned monopolies like Georgia Power allowed the cost of construction to be passed through in utility bills.

The introduction in the UK of retail competition, allowing rival suppliers to provide first large businesses and eventually households with power over a separately-owned distribution network, over the period 1990-1998, prompted other countries to follow, with Sweden among the first to adopt the model. In the European Single Market, the emphasis is on unbundling and the introduction of new forms of competition. European utilities now typically own generators competing in the wholesale market, and customer supply businesses competing in the retail market. Transmission and distribution networks are owned and operated by state-owned or regulated businesses independent of generation or supply interests.

Utilities competing in their regional wholesale market have not been observed to engage in nuclear new build. Partly this reflects the historical timing of the introduction of wholesale competition in the late 1980s coinciding with the hiatus in new nuclear starts following the accident at Chernobyl.

4.5.3.2 De-risking and risk sharing in the utility-led model

Apparent from this introductory context is the paramount need to consider risk sharing mechanisms in the utility-led model. In Europe, even for utilities with the largest values of fixed assets, such as Fortum, balance sheet strength is insufficient to support the risks of investment in a new nuclear power station. The period of return (40+ years from investment decision) and the variability of return are simply too large for a single project. The essence of the utility business model is diversification of project and technology risk across its portfolio, but the size of a new nuclear power station means construction and wholesale market risk makes this a ‘bet the business’ decision.

Nonetheless, if appropriate state-backed risk sharing mechanisms are put in place, the utility-led model is attractive. The right utility can bring:

- Project development expertise
- Access to sites
- Existing nuclear operations
- Supply chain relationships
- Power purchase / Offtake agreements

These attributes contribute to significantly de-risking the project, which, as we have shown, is key to making risk-sharing palatable.

What do appropriate mechanisms look like? The answer to this question will vary depending on the characteristics of the utility itself. Risks that look acceptable when added to one portfolio may appear unacceptable when added to another. The lack of precedent in Europe for this model means that the process of negotiating an appropriate mechanism will not be straightforward.

4.5.3.3 Attractiveness and relevance for Sweden

As described in Section 2.2, Vattenfall and Fortum are utilities with significant presence in the Swedish market. Both utilities, in response to the opening of the opportunity by the government to pursue nuclear newbuild, have launched feasibility studies.

Vattenfall has published its initial conclusions, assessing the next steps to achieve the conditions precedent to a positive final investment decision. No insuperable obstacles were identified, enabling the process to move forward.

This progress makes this an attractive option for Sweden that should be explored further, also as part of a broader state-led (international) programme (see also Section 4.5.5).

4.5.4 State-led project

4.5.4.1 Introduction

Many NPPs are developed as state-led projects, where a government takes a lead role in driving and financing (or underpinning) project development on a single project at a time (rather than committing to a programme of reactors). The degree of state involvement varies, but typically a state-led project would involve the government acting as Project Sponsor and Project Developer, determining the location of power plants, selecting the Vendor (who can but does not need to act as Operator), providing a substantial amount of funding, and offering revenue support in its capacity as Legislator and Regulator. Power is typically sold to Offtakers through the wholesale market.

4.5.4.2 UK new nuclear – Sizewell C

Although the UK's new nuclear programme started out in 2008 as market-led with an intention that power stations would be developed and financed solely by the private sector, only one project (Hinkley Point C) has ended up being developed by the market (i.e. EDF), with other projects proving to be unviable due to a deteriorating cost and market context. This was driven by a range of factors, including the significant cost overruns faced by other LSRs (such as Flammanville, Olkiluoto 3, VC Summer and Vogtle projects), tighter regulatory standards after the Fukushima disaster, faster than anticipated cost reductions in renewables and other low carbon technologies, and the low commodity price environment following the 2008 financial crisis.

As a result, the UK Government has stepped in to lead development of the next large-scale project, Sizewell C (the second EPR to be built in the UK, with EDF as the Vendor and Operator). This has involved the UK Government:

- Becoming a joint venture partner in the project development company and investing significant equity in project development
- Anticipating providing the majority of the equity and debt funding for project construction – and hence taking on overall responsibility for delivering the project
- Establishing RAB revenue support model (see Section 4.4.3), which will pay revenue during construction and ensure the financeability of the project by setting revenue according to 'allowable costs' (i.e. consumers will share construction cost and delay risk with investors). The risk profile is calibrated to attract 'strategic investment' from parties that have expertise to contribute to the project and ability and willingness to assess and manage the risks of nuclear development – the UK Government is not seeking to attract very low cost, low risk 'passive' capital during the construction period.
- Putting in place investor support packages to protect against low probability but high impact events, such as failure to complete construction, political risk, etc.

4.5.4.3 De-risking and risk sharing in a state-led project

De-risking and risk-sharing under a state-led project is achieved through the following mechanisms:

- The state leading and driving project development – for example, by selecting the site(s), technology, delivery partners and contractors.
- The government (or state-owned entities) providing a majority of the funding and hence being controlling shareholders for project development and construction. This gives government a strong incentive to put in place appropriate market and regulatory frameworks to enable the project to succeed, as taxpayers are directly exposed to cost overruns or delays that could result from political interference or regulatory changes.

Note that if projects are entirely financed by the state, they may not need the same level of revenue support as projects seeking private sector investment. However, in the case of Sizewell C, the UK Government is looking to attract strategic investment from the market alongside the Government's stake, which necessitates revenue support and investor protection mechanisms that de-risk the project for investors.

4.5.4.4 Attractiveness and relevance for Sweden

This could be an attractive model for Sweden if the Swedish Government only wishes to commit to one (or a small number of) large-scale NPPs in the first instance – for example, alongside developing a fleet of SMRs. It allows the Government to control and calibrate nuclear development, avoiding the need to provide very extensive de-risking to attract private sector capital or to take on liabilities for a fleet of projects.

However, the single project approach means that overall costs may be higher, as it is not possible to capture learning effects and economies of scale from a fleet approach (see below).

4.5.5 State-led programme

4.5.5.1 Introduction

Building on the state-led project archetype, for countries that have a nuclear ambition that exceeds a single new NPP, a state-led programme in which multiple reactors of the same type from the same vendor are constructed under the same support scheme can offer considerable benefits over (serialized) projects that are developed independently. Various forms of state-led programmes that seek to build out a fleet of reactors can be observed, and examples are introduced below.

4.5.5.2 French Nuclear Renaissance

In 2022, French Government announced a "renaissance" for the nuclear industry, expecting as many as 14 new reactors to be build. This marked a strong policy reversal for Macron, who promised in 2018 to close 12 nuclear reactors as part of a move away from nuclear. The new two-prong strategy, focussing on both renewables and nuclear, serves to strengthen energy independence, security of supply and from stable prices, close to electricity production costs, for a long period.

The French Nuclear Renaissance programme is a classic state-funded programme, with the French State acting as Project Sponsor and Project Developer, delivered through state-owned utility EDF, acting as Vendor and Operator. The State assumes responsibility for securing EDF's financial situation through public backed guarantees and its financing capacity in the short and medium-term, while making policy changes to provide income security to the utility company. The risk in development of the NPP is owned by EDF, but since EDF is fully state-owned the risk is effectively carried by the taxpayers.

4.5.5.3 Polish Nuclear Programme

Poland plans to build a fleet of 6-9 GWe of nuclear capacity based on large, proven PWRs. To this end, it is implementing a model where a Special Purpose Vehicle (SPV) is created, and initially fully owned by the State. The SPV acts as the Project Sponsor, Project Developer and Operator of the NPP. It facilitates the investment process, conducts site investigations as well as obtains all necessary licenses and permits required for the construction of the envisaged NPPs.

The Polish Government selected a single Vendor as strategic co-investor to help create low-cost project financing options for the NPP programme. The Vendor will contribute its experience to the construction and/or operation of NPPs and increase the credibility of the project, which will help attract export loans and other sources of capital.

While the SPV would be 100% state-owned to start with, the State will start to divest along different phases of the project, providing certainty to investors albeit at a premium as divestiture options are released closer to the plant's COD. Poland currently plans to retain a majority stake in the SPV, selling 49% of its shares to the strategic investor. Alternative scenarios are being considered as well though which assume the State will sell all SPV shares prior to COD to a mix of energy consumers and public shareholders. In this approach, the SPV evolves into something closely resembling the Mankala company discussed in Section 4.5.2.2.

The Polish model is one of the leading models being considered in the Netherlands for its nuclear new build ambitions[38].

4.5.5.4 De-risking and risk sharing in a state-led programme

A programmatic approach to build out a fleet of identical reactors in close succession offers both direct and indirect financing benefits, in addition to those identified for state-led projects that contribute to de-risking and risk sharing:

- A state-initiated and (partly) funded programme for multiple units provides a strong signal of commitment to the national industry, stimulate local supply chain build-up, and thus increase the share of local content of newly build NPPs.
- In the emerging SMR space, vendors expect to deliver SMRs across Europe from a select number of strategically located "factories". A strong programmatic approach might contribute to SMR-vendors opting to invest in local production capacity.
- The absence of risk premiums and profit elements associated with FOAK or single unit/site projects will reduce the financing costs.

[38] On March 5, 2024, Dutch parliament adopted a resolution calling for extending the nuclear newbuild programme from 2 to 4 LSRs, making a programmatic approach more likely.

- A single strategic co-investor linked to the technology provider will enable economies of scale and lower costs of construction and operation.

4.5.5.5 Attractiveness and relevance for Sweden

The attractiveness of a state-led programme as opposed to state-led projects for Sweden is largely contingent on the size of its nuclear ambition and society's support for strong government involvement.

Although Sweden's projected generation deficit in 2050 can be met by 4-6 modern LSRs, it is probably more prudent to assume that this deficit will be met by a mix of generation technologies. Add to this the fact that Sweden has indicated to pursue a technology-agnostic nuclear new build policy, leaving it to the market whether SMRs or LSRs should be built, and the a priori likelihood of a programmatic approach is low.

However, it is worth for Sweden to consider such a programmatic approach across borders and collaborate with other countries that consider either new LSRs or an SMR programme, with Finland being a prime candidate for this, but it should also look more widely at connecting with the UK, Dutch, French or Polish programmes. Although advantages from government support might not apply fully, or would need to be designed differently, many advantages linked to design maturity, licensing and supply chain would still exists, as well as removing some elements of resource competition (see also Sections 5.2 and 5.3).

4.6 Conclusions

Nuclear newbuild projects can be classified under five different archetypes, with different levels of government involvement, and consequently different approaches to project de-risking and risk sharing. Of these five archetypes, two are expected to be infeasible for Sweden at this point:

- **Entrepreneur-led** – This is conceptual rather than actual at this point in time, as there have not (yet) been any nuclear projects successfully commercialised purely by entrepreneurs. However, several companies are now actively pursuing this approach to developing SMRs. In theory, the entrepreneur-led model is highly attractive, but Sweden is unlikely to be a target market for market-led SMR development given its relatively lower power prices, thanks to the extensive hydropower and wind resources.
- **Customer-led** – In this type of project, a group of utilities and industrial power users chose to cooperatively finance a project to build a nuclear power plant through a joint venture. Although fully privately funded, a customer-led NPP project can be initiated by the government. Some interest has been expressed by electro-intensive industries from Sweden and Norway in participating in a nuclear new build project in Sweden but at this stage it is unclear if this would result in co-investing or in providing revenue guarantees through a PPA. In any case, given the size and risk associated with a LSR NPP project, it does not appear to feasible to implement one without a public-private partnership.

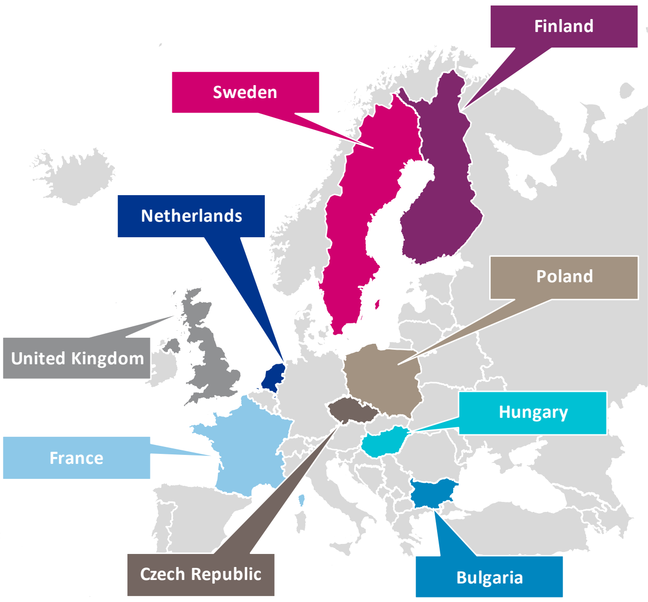
Three other archetypes are found to be attractive to Sweden, and could serve as a basis for Sweden's nuclear newbuild programme:

- **Utility-led** – Utilities competing in their regional wholesale market have not been observed to engage in nuclear new build. In Europe, even for utilities with the largest values of fixed assets, balance sheet strength is insufficient to support the risks of investment in a new nuclear power station but with appropriate state-backed risk sharing mechanisms the utility-led model is attractive. Vattenfall and Fortum are utilities with significant presence in the Swedish market. Both utilities have launched feasibility studies for nuclear newbuild. Vattenfall has published its initial conclusions, and identified no insuperable obstacles were identified, enabling the process to move forward.
- **State-led project** – Many NPPs are developed as state-led projects, where a government takes a lead role in driving and financing (or underpinning) project development on a single project at a time. The degree of involvement varies, but typically a state-led project would involve the government determining the location of power plants, selecting the technology, providing a substantial amount of funding, and offering revenue support. Note that if projects are entirely financed by the state, they may not need the same level of revenue support as projects seeking private sector investment. However, some level of strategic investment from the market is often sought to bring in specific expertise, obtain a credit rating and enforce delivery rigor. This could be an attractive model for Sweden if its Government only wishes to commit to one (or a small number) of large-scale NPPs in the first instance – for example, alongside developing a fleet of SMRs.
- **State-led programme** – Building on the State-led project archetype, for countries that have a nuclear ambition that exceeds a single new NPP, a state-led programme in which multiple reactors of the same type from the same vendor are constructed under the same support scheme can offer considerable benefits over (serialized) projects that are developed independently. France, Poland and the Netherlands are examples of European countries favouring this fleet-based approach. A programme for multiple units provides a strong signal of commitment to the national industry, stimulates local supply chain build-up, increases the share of local content of newly build NPP and enables economies of scale for both LSRs and SMRs. The attractiveness of a state-led programme as opposed to state-led projects for Sweden is largely contingent on the size of its nuclear ambition and society’s support for strong government involvement.

5 Impact of Europe's return to nuclear power for Sweden

5.1 Introduction

In a push to reduce its dependence on fossil fuels, the world appears to be embracing nuclear power at levels not seen since the 1980s. Many (European) countries are (re)starting nuclear newbuild programmes, including the UK, Poland and the Netherlands. The map in below shows European countries with active or recently completed LSR nuclear newbuild projects/ programmes.



Country	Under construction	Planned
Bulgaria	0	2 (2.3 GWe)
Czech Republic	0	1 (1.2 GWe)
Finland*)	0	0
France	1 (1,650 MWe)	14 (~25 GWe)
Hungary	0	2 (2.4 GWe)
Netherlands	0	2-4 (3-6 GWe)
Poland	0	6 (6-9 GWe)
United Kingdom	2 (3,200 MWe)	10 (~15 GWe)
Sweden	0	10 (~15 GWe)

*) Finland recently completed the OL3 reactor, the first newly build reactor in Europe in over a decade.

Figure 10 – European countries with active or recently completed LSR newbuild projects /programmes and their sizes.

The impacts of this return to nuclear on Sweden's nuclear ambitions can be both positive and negative: learning effects and international collaboration creating cost reductions, but also increased demand for scarce knowledge and resources.

This chapter explores these effects and analyses their relevance for, and impact on, a future Swedish nuclear programme.

5.2 Economies of scale and potential for international collaboration

Europe's return to nuclear offers two distinct benefits for Swedish nuclear newbuild efforts. Firstly, for both LSRs and SMRs holds that a large number of new build projects removes the risks resulting in the FOAK premium (see also Section 4.2) observed in recent and current European newbuild projects, provided these projects leverage the same mature, standardized design. Secondly, the ability to develop true NOAK NPPs increases if (neighbouring) countries can combine their nuclear power ambitions into a joint programme aimed at developing a fleet of identical reactors. International collaboration to achieve these economies of scale should at a minimum result in joint licensing but ideally extend to include more de-risking and risk-sharing options such as joint planning of consecutive construction projects, joint supply chain development and aligned construction risk and revenue support mechanisms matching the participating countries power market structures.

5.2.1 What this means for Sweden

Sweden's nuclear ambition might not scale to the point where a new fleet of LSRs will be constructed, and international collaboration might be a way still achieve NOAK benefits. For SMRs, the time scales for achieving a fleet size that delivers true NOAK benefits could be significantly shortened if through international collaboration licensing can be streamlined, investor confidence bolstered, and deployment accelerated.

It therefore stands to reason that Sweden explores a joint programme with for example Finland, a country that like Sweden, depends for a substantial share of its power supply on nuclear energy. SMRs appear a particularly interesting technology to collaborate on, given Finland's interest in them as they start phasing out coal for power generation and district heating, and could help position Sweden and Finland as an SMR production hub, bring further benefits in terms of knowledge building and job creation (see also Section 5.4).

5.3 Limited number of vendors with limited capacity

Over the past decades a consolidation trend has resulted in there now only being three LSR vendors to choose from: France's EDF, a fully nationalised utility, Canada's private equity-controlled Westinghouse and Korea's state-controlled KEPCO. Given the complexities of LSR technology and projects it is highly unlikely for new vendors to enter this market anytime soon. Although only EDF has live construction projects (Hinkley Point C in the UK and Flamanville in France) all three are contracted or preparing to enter tenders for LSRs in various European countries.

- EDF is preparing to start the construction of Sizewell C in the UK, conducting a technical feasibility study for a two-reactor NPP in the Netherlands and preparing the start of what is scheduled to be the first of many EPR reactors in its home country France.
- Westinghouse, with Bechtel as EPC, has been selected by Poland as the technology vendor for its nuclear programme, with the first NPP scheduled for COD in 2033, and is also conducting a technical feasibility study for a two-reactor NPP in the Netherlands.

- KEPCO is the third vendor conducting a technical feasibility study for a two-reactor NPP in the Netherlands and is in the advanced stages of signing a contract with Poland's state-run power company PGE and Polish private power company Zespol Elektrowni Patnow-Adamow-Konin SA to build a nuclear power plant that consists of two or four reactors with a 1.4 GWe each.

Because these countries are all ahead of Sweden in terms of their nuclear new build programmes, there is a real opportunity that some or all of these vendors will be contracted to capacity before a project or programme in Sweden is in a position to tender for LSRs. This could result in starkly reduced options and increased costs if Sweden finds itself in a 'sellers' market'.

For SMRs the situation is different in the sense that there are many more vendors/developers are active in that space, but the number of designs/technologies that is sufficiently mature to approach market-readiness is limited. Couple this with a substantial number of (European) countries that are interested in deploying SMRs as part of their decarbonization and energy security strategies and a situation not dissimilar to that for LSRs emerges, where demand could exceed supply in the short to medium term.

5.3.1 What this means for Sweden

In addition to the looming generation deficit, discussed in Chapter 2, the vendor capacity situation provides another strong argument for the Swedish Government to take a more active role in developing a nuclear programme, in line with international trends (see also Section 4.3). Failing to do so, and leaving the development of NPP, be they LSRs or SMRs, predominantly to market parties, could result in vendors preferring countries where stronger Government involvement has led to better signposting of long-term plans and clearer supporting frameworks.

The aforementioned situation also means that from a de-risking a risk sharing perspective the Swedish State needs to create conditions that, as a package, are on par with what is available/considered in other countries.

5.4 Workforce challenges and opportunities

The nuclear power sector faces significant workforce challenges as it seeks to expand with both large-scale reactors and Small Modular Reactors (SMRs). Building and operating nuclear power plants require a substantial and highly skilled workforce, spanning various disciplines including engineering, construction, operations, maintenance, safety, and regulatory compliance, and a return to nuclear for European countries means building out that workforce. For the UK, its current 77,000-strong nuclear workforce would need to more than treble in the next decade to deliver 24 GWe of nuclear by 2050[39].

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[39] Press release "Record growth in nuclear workforce from new build projects", Nuclear Industry Association, September 12, 2023

Drawing on data from an OECD report from 2018[40], Table 11 provides an overview of the size of the average workforce size for a single unit 1,000 MWe advanced light water reactor during the various stages of its lifecycle.

Phase	Workforce size	Duration	Labour years
Construction	1,200	10-12	12,000-14,400
Operations	600	60-80	36,000-48,000
Decommissioning	150	20-30	3,000-5,000

Table 11 – Indicative average direct workforce size during various lifecycle stages of an NPP[40].

Several factors contribute to the challenges in meeting the workforce demand in the nuclear sector. One significant factor is the aging workforce. The bulk of the world's current NPPs were constructed in the 1970s and 1980s (see Section 3.2) with very little growth in the industry for the next two decades. Consequently, many experienced professionals are now approaching retirement age. In a recent report by the French nuclear industry association GIFEN[41], an industry growth of 25% was forecasted in the volume of work by 2033, and the need for 60,000 full-time new recruitments to achieve this scope (half to compensate for retirements, half for business growth).

Additionally, there is a shortage of new talent entering the nuclear industry partly due to a lack of specialized education and training programmes tailored to nuclear technology. Furthermore, despite nuclear energy being a carbon-free source of energy, and young being motivated by social issues such as climate change, careers in science, technology, engineering and mathematics (STEM) are struggling to attract talent at the rate of other areas such as IT, media or business and for those with an affinity to STEM, the nuclear sector might not be an obvious career choice when comparing against e.g. the wind and solar industry.

Across Europe, various countries are taking steps to build out a workforce befitting its nuclear programmes. In the Netherland various parties in the Dutch nuclear and education sectors recently signed a declaration of intent aimed at boosting vocational education in nuclear technology[42]. The UK is promoting a model of employer-funded education via its Destination Nuclear[43] initiative.

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40 Measuring Employment Generated by the Nuclear Power Sector, OECD, 2018

41 https://www.euronuclear.org/news/projects-innovations-workforce-and-talents-how-will-the-nuclear-of-the-future-cope-with-them/, accessed on February 29, 2024

42 https://www.world-nuclear-news.org/Articles/Dutch-initiative-to-boost-nuclear-workforce, accessed on February 28, 2024.

43 https://www.destinationnuclear.com/, accessed on March 4, 2024

5.4.1 What this means for Sweden

Addressing these workforce challenges requires concerted efforts from industry stakeholders, governments, and educational institutions to attract and retain talent, develop robust training programmes, and foster innovation in the nuclear workforce ecosystem. This need for competence building has also been identified by Svenskt Näringsliv as critical to realizing Sweden's nuclear ambition[44].

By proactively addressing these challenges in collaboration with the Swedish Government and education sector, Sweden's nuclear industry can build a sustainable and skilled workforce to support its growth and development in the coming years.

Investing in workforce development signals Sweden's ambition and commitment to nuclear vendors and EPCs and makes it a more attractive partner for nuclear newbuild projects.

This in turn brings economic growth and increases the local content of nuclear newbuild projects, as well as positioning it as a potential export hub for nuclear expertise and technology.

5.5 Conclusions

- Europe's return to nuclear offers great potential for learning effects and lowering risks for cost and project overruns associated with recent and current FOAK projects.
- A programmatic approach is better suited for achieving these benefits than multiple individual projects. International collaboration to achieve economies of scale should be considered if/when Sweden's nuclear ambitions don't suit a programmatic approach, or when accelerated delivery is a key consideration, e.g. with respect to SMRs.
- The industry's expected growth, in combination with an impending retirement wave, requires the industry to recruit at scale. Failing to do so can result in a demand for NPPs that exceeds the industry's delivery capabilities. Coming somewhat late to the party compared to countries like the UK, France, Poland and the Netherlands, Sweden should now clearly state its nuclear ambitions to ensure vendors and manufacturers can start to plan for participating in its nuclear newbuild plans.
- A successful nuclear newbuild programme requires a right-skilled, right-sized workforce. Swedish Government should work with the education sector and the nuclear sector to build curricula and attract talent to the sector, to become an attractive partner for nuclear newbuild projects in what could become a seller's market.

[44] Startprogram för ny kärnkraft, Svenskt Näringsliv, September 2022

6 Recommendations

Europe appears to be at the dawn of a second golden age for nuclear, with at least 8 countries engaged in or preparing nuclear new build programmes that could add as much as 50 GWe new nuclear capacity, clearly signalling a renewed interest in this safe, reliable and carbon-free form of energy, not withstanding some challenges observed with recent nuclear new build projects.

With SMRs still being at the early stages of maturity and with a limited number of vendors for LSRs being active in the market, demand for NPPs could start to exceed supply. To ensure its nuclear fleet can be extended in a timely, robust and financially sound way, Sweden should consider the following:

- First and foremost, Sweden should clearly articulate its vision for nuclear energy. This includes providing a clear policy trajectory, and guiding principles around deployment (including any red lines that might exist) to provide clarity and signal its commitment to the market.
- Lessons learned from recent/ongoing newbuild projects for LSRs have shown that market-led projects financed solely by the private sector are not feasible in Europe and that some form of government support is needed. Sweden should therefore implement project de-risking measures as well as risk-sharing mechanisms for residuals risks. The nature and implementation of these will depend to some extent on the selected delivery model but will typically at least include:
  - Proportionate and predictable regulation
  - Ensuring a mature design at the start of construction
  - Effective project management
  - Sharing of construction costs risk and market price risk.

  The process for State Aid approval by the European Commission should be started early on, if applicable.
- Three potential delivery models appear to be viable for Sweden:
  - **Utility-led project with state backing** – Vattenfall and Fortum are utilities with significant presence in the Swedish market. Both utilities, in response to the opening of the opportunity by the Government to pursue nuclear newbuild, have launched feasibility studies. Vattenfall has published its initial conclusions, assessing the next steps to achieve the conditions precedent to a positive final investment decision. No insuperable obstacles were identified, enabling the process to move forward. This progress makes this an attractive option, both for a limited number of new NPPs or as part of a larger programme (see below).
  - **State-led programme** – A state-led programme in which multiple reactors of the same type from the same vendor that are constructed under the same support scheme can offer considerable benefits over (serialized) projects that are developed independently. The attractiveness of this model, which is pursued in Poland, France

and the Netherlands, is largely contingent on the size of Sweden's nuclear ambition and society's support for strong Government involvement.

- **International SMR programme** – In the emerging SMR space, vendors expect to deliver SMRs across Europe from a select number of strategically located "factories". An international state-led programme could contribute to successful outcomes for Sweden via shared design and approval processes severely de-risk projects and lower per-unit costs resulting from larger production series. It might also entice SMR-vendors to invest in local production capacity. Collaborating with Finland on such a programme would stand to reason, but Sweden should also look more widely at connecting with the UK, Dutch, and Central European initiatives.

- These delivery options are not mutually exclusive. A combination of a utility-led NPP or state-led programme delivering multiple LSRs in 2030 could very well be combined with an international SMR-programme delivering part of the Swedish ambition in the late 2030s/early 2040s.
- Sweden should decide early on its delivery model, as this drives many key topics around de-risking, revenue support and State Aid.
- Delivery happens through people, and selecting a delivery model alone is not sufficient. To create a right-sized right-skilled workforce for delivering Sweden's nuclear newbuild programme, the Government should support educational institutions and industry to develop and implement curricula across a wide range of levels and topics.
- Finally: the risk-reduction potential of reforming Sweden's energy-only market to provide (nuclear) power providers to additional revenue streams is considered minimal, and therefore not considered critical path.

Appendix A Glossary of terms

Term	Description
BWR	Boiling Water Reactor, a type of light-water nuclear reactor.
CANDU	Canada Deuterium Uranium – Canadian Pressurized Heavy Water Reactor (PHWR) design
CAPEX	Capital expenditures – Costs an organization spends to buy, maintain, or improve its fixed assets. In the case of power plants this includes a.o. buildings, generation equipment and supporting infrastructure.
CfD	Contract for Difference – Long-term contractual agreement between a low carbon electricity generator and public sector counterpart, designed to provide the generator with price certainty over the lifetime of the contract.
CM	Capacity Market – Market that provides compensation for the mere readiness, or capacity, for power production.
COD	Commercial Operation Date – The date on which a project is substantially complete and commercially operable.
EOM	Energy Only Market – Market where power generators only sell electricity to buyers.
EPC	Engineering, Procurement and Construction.
EPR	European Pressurized Reactor, a third-generation pressurised water reactor design.
FEED	Front End Engineering Design) means Basic Engineering which is conducted after completion of conceptual design or feasibility study.
FOAK	First Of A Kind: a FOAK project is the first project to construct a reactor of a type in a specific market.
GWe/MWe	Giga/Megawatts electrical – the electrical power output of a reactor.
GWth/MWth	Giga/Megawatts thermal – the thermal output of a reactor.
HTGR	High-temperature gas-cooled reactor – reactor type that uses uranium fuel and graphite moderation to produce very high reactor core output temperatures that enable applications such as process heat or hydrogen production.

IAEA	International Atomic Energy Agency – intergovernmental organisation that for cooperation in the nuclear field, promoting the safe, secure and peaceful use of nuclear technology.
IDC	Interest During Construction.
IEA	International Energy Agency – intergovernmental organisation that provides policy recommendations, analysis and data on the global energy sector.
LSR	Large Scale Reactor – Traditional Gigawatt-scale nuclear reactors.
LWR	Light Water Reactor, a type of thermal-neutron reactor that uses normal water, as opposed to heavy water, as both its coolant and neutron moderator.
NEA	Intergovernmental agency that is organized under the OESO to further the environmentally friendly and economical use of nuclear energy for peaceful purposes.
NOAK	N-th Of A Kind, used to indicate that several reactors of the same type have already been constructed.
NPP	Nuclear Power Plant.
OCC	Overnight Construction Costs – the cost of a project if no interest was incurred during construction, as if the project was completed "overnight".
OECD	Organisation for Economic Co-operation and Development – Intergovernmental organisation with 38 member countries from predominantly Europe, the Americas, Australia and Japan.
OPEX	Ongoing cost for running a product, business, or system. In the case of power plants this includes a.o. costs for fuel and maintenance.
PHWR	Pressurized Heavy Water Reactor, a type of heavy-water nuclear reactor.
PPA	Power Purchase Agreement – Long-term contract between an electricity generator and a customer such as a utility, government or company.
PWR	Pressurized Water Reactor, a type of light-water nuclear reactor.
RAB	Regulated Asset Base – Model that allows investors to receive a guaranteed return on investment for the lifetime of the asset.
RMBK	Reaktor Bolshoy Moshchnosty Kanalny – A water cooled, graphite moderated reactor design of Soviet origin.

SMR	Small Modular Reactor, a class of reactors designed to be built in a factory before being shipped to operational sites for installation.
SPV	Special Purpose Vehicle – Legal entity created to fulfil narrow, specific or temporary objectives. SPVs are typically used by organisations including governments to isolate financial risk.
VVER	Vodo-Vodjanoi Energetitsjeski Reactor (Water-Water Energy Reactor) – A type of Pressurized Water Reactor (PWR)
WACC	Weighted Average Cost of Capital – a company's average after-tax cost of capital, weighing debt and equity financing.

Appendix B Stakeholder interviews

For this report, the following stakeholders kindly provided their views on the development in the nuclear sector and opportunities and challenges for Sweden, specifically.

Name	Role	Organisation
James Widdicks	Head of policy for Sizewell C	DESNZ, UK Government
Jesper Marklund	Manager New Nuclear Development, Sweden	Fortum
Michael Crabb	SVP, Commercial	Last Energy
Carl Berglöf	National Nuclear New Build Coordinator	Ministry of Climate and Enterprise, Sweden
Alastair Evans	Director of Corporate Affairs	Rolls Royce SMR
Robert Bergqvist	BD Lead, Sweden	Rolls Royce SMR