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Nuclear Decommissioning Profile Sweden

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1 Introduction

In the 1940s and 50s, Sweden experienced a continuous increase in the demand for electricity. It soon became clear that hydropower alone would not be able to meet the increasing demand. Thus, Sweden turned to nuclear power as a source of electricity (Kåberger 2007). However, before having a commercial interest in nuclear energy, Sweden, or the Swedish National Defense Research Institute (FOA, founded in 1945 to coordinate research in the field of military technology) pursued research in nuclear weapons. These research plans were not discussed openly until the mid-1950s. In 1968, Sweden joined the Treaty on the Non-Proliferation of Nuclear Weapons (NPT); by signing the treaty, Sweden agreed not to develop nuclear weapons (Jonter 2010).

A central reason Sweden developed its nuclear power industry was to be self-sufficient. It developed its own "Swedish Line." The Swedish Line concept foresaw that Sweden would extract its own uranium and use heavy-water reactor technology so that they could be loaded with natural rather than enriched uranium (Fjaestad and Jonter 2008; Jonter 2010). AB Atomenergi was founded in 1947 to hold responsibility over the civilian nuclear technology development (Jonter 2010). However, in the beginning of the 1960s, the light water reactor technology was introduced on the international market. This development put a damper on the Swedish Line because the light water reactors were economically more favorable and also more reliable. In 1965, Sweden placed its first order for a commercial power reactor station based on light water technology. General Swedish Electrical Limited Company (ASEA) manufactured the first light water reactor at the planned nuclear power plant (NPP) in Oskarshamn owned by the private consortium "Oskarshamnsverkens Kraftgrupp AB". The light water technology effectively terminated the plans for the Swedish Line (Jonter 2010). Table 1 shows the Swedish commercial nuclear power reactors in detail.

In 2020, the nuclear power reactors in Sweden provided around 29.8% (47.4 TWh) of its electricity (Schneider et al. 2021). Other main energy sources include hydro (around 45%), wind (more than 17%), and biomass power (around 8%) (Swedish Institute 2021). In general, the Swedish electricity market is characterized by high amounts of renewables. Based on the latest data, around 54% of electricity production stems from renewable energy (Swedish Energy Agency 2021). The power sector is supposed to constitute of 100% renewables by 2040 and Sweden is on its way to fulfill this target.

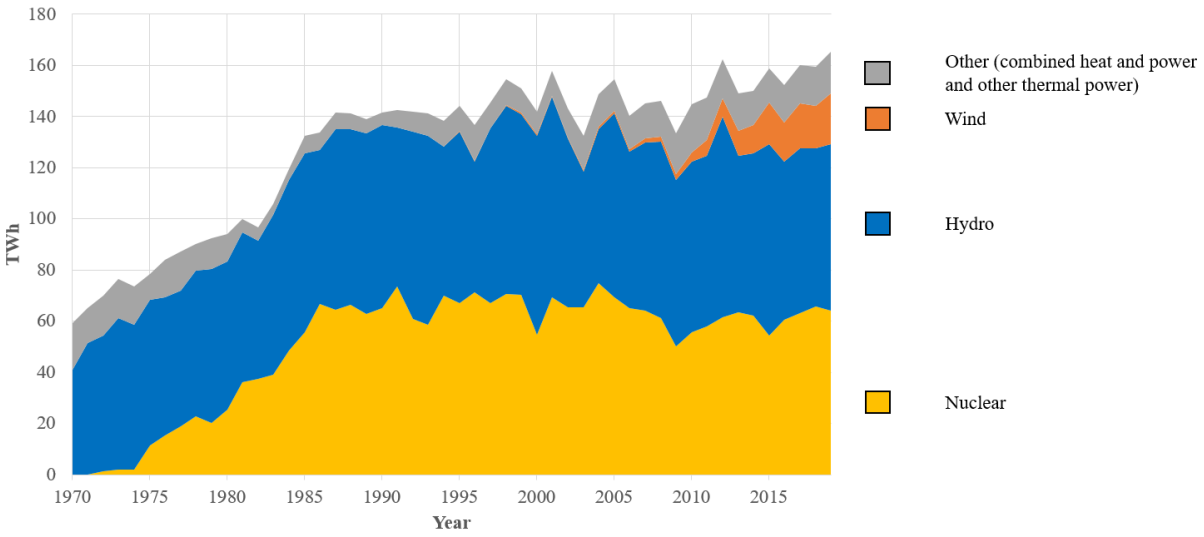
Figure 1 shows the development of the shares of different electricity sources over time. It can be seen that the share of wind power in the electricity mix has been increasing in the last couple of years, whereas the shares of nuclear and hydropower remain relatively constant since the 1980s. However, in recent years, Sweden experienced a large drop in the share of nuclear energy. This is mainly due to the shutdown of large nuclear power stations such as Ringhals-2 in 2019. It is to be expected that the share of nuclear energy decreases further as another power station, Ringhals-1, was shut down in 2021.

Table 1: Nuclear power reactors in Sweden

Nuclear Power Reactor	Grid connection	Type[1]	Net Capacity (in MW(e))	Status
Ågesta	1964-1974	PHWR	10	Permanent Shutdown
Barsebäck-1	1975-1999	BWR	600	Permanent Shutdown
Barsebäck-2	1977-2005	BWR	600	Permanent Shutdown
Forsmark-1	1980	BWR	990	Operational
Forsmark-2	1981	BWR	1121	Operational
Forsmark-3	1985	BWR	1172	Operational
Oskarshamn-1	1972-2017	BWR	473	Permanent Shutdown
Oskarshamn-2	1974-2013	BWR	638	Permanent Shutdown
Oskarshamn-3	1985	BWR	1400	Operational
Ringhals-1	1974-2020	BWR	881	Permanent Shutdown
Ringhals-2	1974-2019	PWR	852	Permanent Shutdown
Ringhals-3	1980	PWR	1072	Operational
Ringhals-4	1982	PWR	1130	Operational

[1] There are three types of nuclear reactors in Sweden: Pressurized water reactors (PWR), boiling water reactors (BWR) and one pressurized heavy water reactor (PHWR). Source: IAEA (2022).

Figure 1: Swedish electricity generation by source (1970-2019)



Source: Own depiction based on data from Swedish Energy Agency (2021).

During the last couple of years, operating NPPs in Sweden was unprofitable, as the costs of operating an NPP were higher than the prices received for electricity by the operators. The decline in nuclear electricity prices in Sweden can partly be attributed to subsidies for renewable energies reducing market prices in the Nordic Electricity Market, i.e. the merit-order effect (Plumer 2016). Further, favorable weather conditions led to an increase in the supply of hydro and wind energy (Kåberger and Zissler 2020).These low electricity prices are responsible for a reduction in supply of nuclear energy. The current electricity market conditions in Sweden are not favorable to nuclear energy. There is increasing uncertainty concerning the Swedish nuclear energy sector mainly caused by policies focusing on renewable energy. Over half of Sweden's nuclear reactors were permanently shut down by the end of 2020. In numbers, it means that 7 commercial reactors are currently undergoing decommissioning (Gillin 2020). Barsebäck-1 was shut down in 1999 and Barsebäck-2 in 2005 due to political reasons. Further, Oskarshamn-1 (off grid since 2013) was shut down in 2017 and Oskarshamn-2 in 2016 (Schneider et al. 2019). Ringhals 1 and 2 were taken out of service in 2020 and 2019, respectively (SKB 2019b; Vattenfall 2021a). Both, the reactors at Oskarshamn and Ringhals were shut down ahead of the originally planned shutdown date (IAEA 2022a).

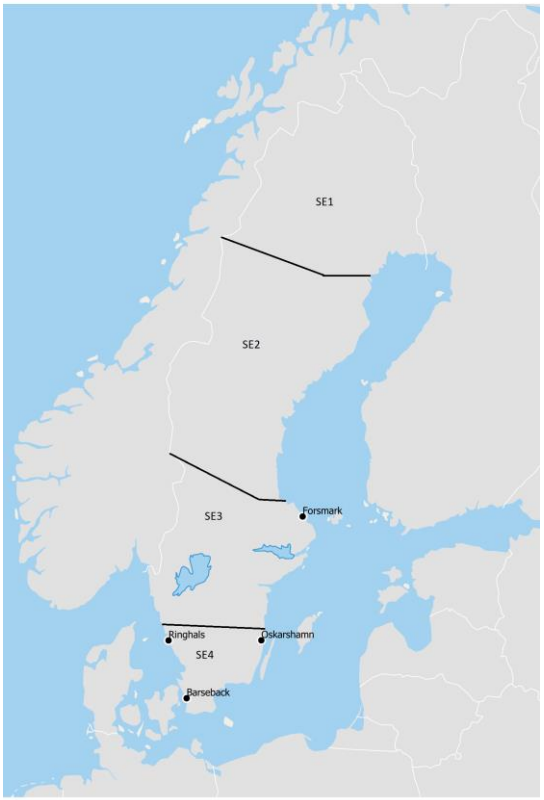
More information on the current decommissioning stages of the individual plants will be given in Section 5.2. In 2022, six nuclear power reactors are still operating in Sweden distributed among 3 power plants. For these six reactors, the expected operating planning time is 60 years (SKB 2019). The two youngest nuclear reactors, Forsmark-3 and Oskarshamn-3, are thus expected to keep operating until 2040 (Stralsakerhetsmyndigheten 2020b; IAEA 2022a).

The electricity market in Sweden was liberalized in 1996. The liberalization occurred both on the retail market and on the wholesale market. At the retail market level, this means that Swedish consumers themselves can decide from where they want to purchase their electricity. The market liberalization of the wholesale electricity market in Sweden has led to more acquisitions and mergers with an increasing dominance of big electricity companies. These big electricity companies all have a significant share of nuclear capacity. In addition to the increasing dominance of big electricity companies, there are more and more foreign acquisitions (head office outside of Sweden) of Swedish electric companies (Wang 2006). However, the largest Swedish electricity company, Vattenfall AB, remains 100% state-owned (Vattenfall 2021b).

Electricity transmission via the national electric grid is managed by Svenska Kraftnät, which is a governmental institution. A major task of Svenska Kraftnät is keeping the balance between the electricity produced and consumed in the electricity system (Svenska Kraftnät 2021b). Around the same time as liberalizing the electricity market, Sweden integrated its electricity market, together with other Nordic countries, into the common Nordic market (Nordpoolgroup 2020). Today, this market comprises 7 countries: Norway, Sweden, Denmark, Finland, Lithuania, Latvia and Estonia. Electricity is sold and bought at the Nordic power exchange, "Nord Pool", which is jointly owned by Svenska Kraftnät and its respective Nordic and Baltic counterparts. The annual electricity demand of these 7 countries is around

420 TWh. This demand volume is lower than that of Germany or France but higher than that of Spain, Italy or the UK. Therefore, it is considered to be one of the most important electricity markets in Europe (AleaSoft Energy Forecasting 2019). In the Nordic power market, the price of electricity is determined per bidding area. In total, there are 15 bidding areas divided by their geographical location (Svenska Kraftnät 2021a). As of 2011, Sweden has been divided into four bidding zones (THEMA Consulting Group 2019). Eight of the ten largest Swedish cities can be found in SE3 (Svenska Kraftnät 2017). Sweden's NPPs are located in SE3 and SE4 (Figure 2).

Figure 2: Bidding zones and nuclear facilities of Sweden



Source: Own figure.

In each bidding zone, the price of electricity is determined by supply and demand of electricity and the capacity of transmission between the bidding zones (Svenska Kraftnät 2021a). There are some price differences between the bidding zones which mainly reflect grid constraints and loss of production capacity (THEMA Consulting Group 2019). The zonal price divergence can cause some problems. A crucial problem is the lack of interconnection between the northern wind based SE1 and SE2 price zones to southern consumption locations in SE3 and SE4. It means that renewable energy produced from wind is often trapped in the northern part of the country. This has led to an unusually wide price spread between the four bidding zones in 2020 with southern areas delivering at a strong premium. The recent

shutdown of Ringhals-1 and Ringhals-2 reduced generation capacity in SE4 drastically (Energiforsk 2022).

This report provides an in-depth overview of the nuclear decommissioning landscape in Sweden. This report will cover the nuclear legal framework, decommissioning regulation, financial regulation and current decommissioning status.

2 Legal and Regulatory Framework

2.1 Governmental and regulatory framework

The main guiding laws in Sweden are the Swedish's Radiation Protection Act and the Act on Nuclear Activities (Box 1). On an international level, Sweden is a member of the IAEA, OECD/ NEA and the International Energy Agency (IEA) (IAEA 2022a). Furthermore, Sweden respects the conditions of the Euratom treaty signed by all the member states of the EU. The Euratom treaty was signed in 1957 and its main objectives are to promote and facilitate research in the nuclear field and to ensure civil nuclear materials are not diverted to other uses, particularly military uses (European Parliament 2021). In addition to treaties on a European level, Sweden is also a part of other international agreements, recommendations, treaties and conventions such as the Convention on Nuclear Safety or the Treaty on the Non-Proliferation of Nuclear Weapons (Stralsakerhetsmyndigheten 2020b; 2021b).

According to current national laws, old nuclear reactors that were shut down can be replaced with new ones at the same location (IVA 2016). Figure 3 shows all the important regulatory and governmental bodies and their respective influence on Swedish NPPs.

The Swedish legislative (the **Riksdag**) and executive (the **Government**) construct the legal framework for the nuclear industry. The Riksdag approves the laws proposed and specified by the Government (Swedish Institute 2020). The Government is also involved in the licensing process of nuclear facilities. Thereby, it grants and approves licenses for the operation and construction of NPPs as well as for the repository of spent nuclear fuel (IAEA 2022a).

Box 1: Legal Framework of the Swedish Nuclear Industry

The Act on Nuclear Activities, SFS 1984:3: contains the basic requirements for nuclear safety and postulates the licensing and general obligations of the licensee.

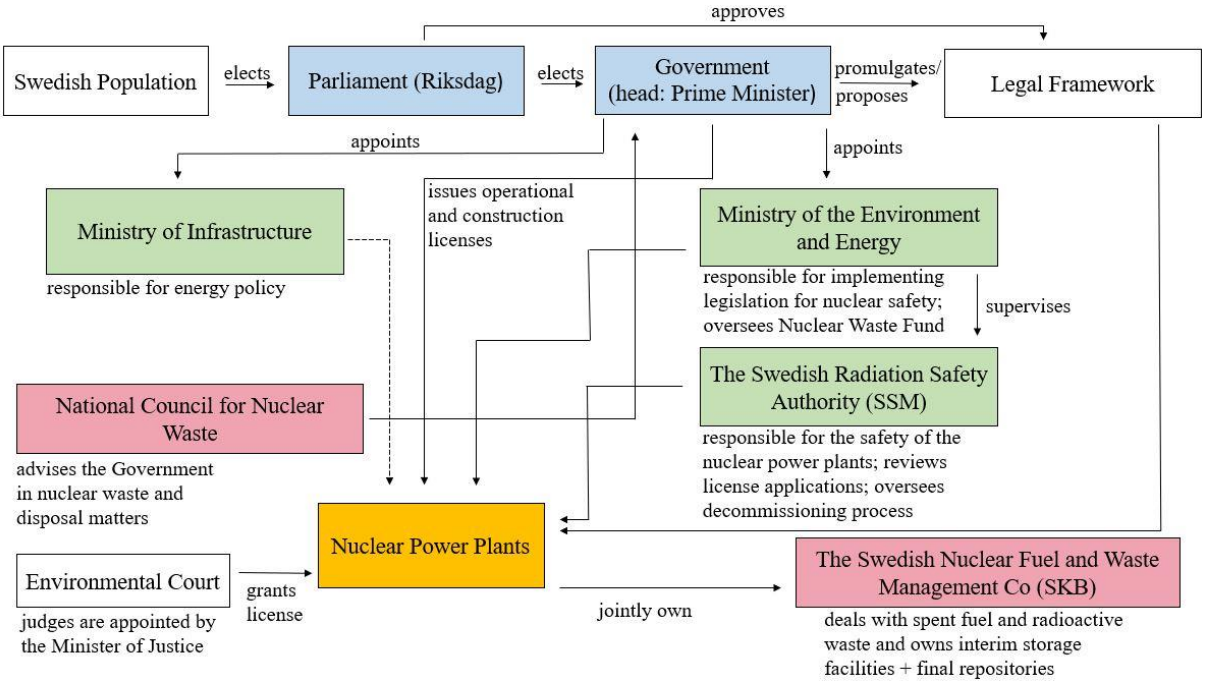
The Radiation Protection Act, SFS 1988:220: states the obligations for licensees concerning the radiological protection of the people and environment. It also holds the basic provisions on protection against ionizing radiation.

The Environmental Code, SFS 1998:808: The objective of the Code is to promote sustainable development and ensure a healthy environment for current and future generations. It includes general provisions on environmental protection.

The Financing Act, SFS 2006:647: Regulates provisions concerning the future costs of spent nuclear fuel disposal, decommissioning of NPPs and research in the field of nuclear waste.

The Nuclear Liability Act, SFS 1968:45: Implements the obligations of Sweden according to the 1960 Paris Convention on Third Party liability in the field of nuclear energy and the 1963 Brussels Convention Supplementary to the Paris Convention.

Figure 3: Governmental and regulatory actors and their connection to Swedish NPPs



Overarching governmental bodies are marked blue; agencies and departments green; bodies related to waste red; standard arrows reflect a direct influence by the actor on Swedish NPPs; dashed arrows reflect a possible or indirect influence. Source: Own figure.

The **Ministry of Infrastructure** is responsible for all matters with regards to energy, infrastructure, digital policy and post issues. It shapes energy policy and therefore, the promotion of nuclear energy falls under its purview (Government Offices of Sweden 2021a).

The **Ministry for the Environment** is responsible for the environmental policy of the Government. It tackles issues in relation to climate policy, biological diversity, radiation safety etc. and implements legislation for nuclear safety including security and radiation protection as well as legislation on nuclear liability (Government Offices of Sweden 2021b; OECD/NEA 2012). The **Swedish Radiation Safety Authority (SSM)** is subordinate to the Ministry for the Environment (Government Offices of Sweden 2021b). The Swedish Government decides on the assignments and budget of the SSM but decisions of the SSM are deemed to be independent on individual matters (Stralsakerhetsmyndigheten 2021a).

The SSM is tasked with the radiation protection of the people and the environment. Ensuring the safety of nuclear facilities is its primary goal. It holds a supervisory role and carries out inspections. Further, it makes sure that the NPPs fulfill the security mandates set by the law. It also holds an advisory role to the Government in matters of license renewals/ applications (Stralsakerhetsmyndigheten 2021c). Lastly, the SSM gives feedback on the cost calculations for decommissioning and waste disposal and determines the level of contributions by the nuclear licensees to the Nuclear Waste Fund (NWF) (OECD/NEA 2012).

The **Swedish Nuclear Fuel and Waste Management Co (SKB)** and the **National Council for Nuclear Waste** regulate nuclear waste management and is explained in detail in Subsection 2.6.

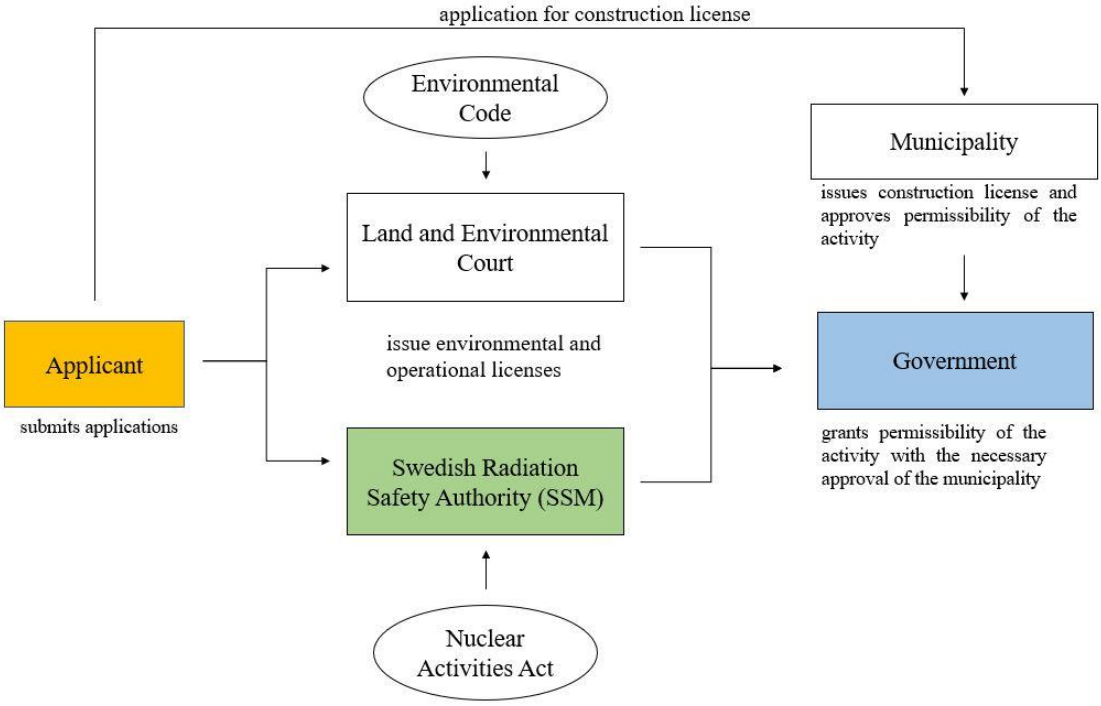
2.2 License provision and extension

The main legal framework of the licensing process consists of the Environmental Code (1998:808), the Nuclear Activities Act (1984:3) and the Radiation Protection Act (1988:220) (Kärnavfallsradet 2013). The licensing process shown in Figure 4 involves several different actors. As a first step, the applicant prepares and submits the license application, which has to fulfill the criteria according to the Environmental Code and the Nuclear Activities Act. The matter then moves on to the Land and Environmental Court and the SSM who examine the application according to the Environmental Code and the Nuclear Activities Act, respectively. The Court and the SSM coordinate and release a statement of opinion. Based on these statements of opinion, the Government issues the permissibility according to the Environmental Code and the license according to the Nuclear Activities Act. At this stage, the municipality can intervene and state their approval or disapproval of the activity. The Government can only approve of the activity if the Municipal Council does so as well (Kärnavfallsradet 2013; OECD/NEA 2012). However, there is the possibility of overruling the veto of the Municipal Council if the activity is "of the utmost importance for the national interest" (Kärnavfallsradet 2013). If the Government grants permissibility according to the Environmental Code, the matter goes back to the Environmental Court who then issues the license and its conditions under the Environmental Code (Kärnavfallsradet 2013; IAEA 2022a).

Through a separate channel, the licensee also has to apply for and obtain a permit in order to construct the facility according to the Planning and Building Act from the municipality. The SSM is not involved in this permit (OECD/ NEA 2012).

There is no time limit on the operational license of a nuclear facility in Sweden (IAEA 2022a). Thus, as long as the licensee meets the requirements of the nuclear laws and ordinances as well as the conditions set in the initial license, the operation of the NPP is allowed (Stralsakerhetsmyndigheten 2020c). However, these requirements might change at any point during a plant's lifetime if the government demands it. Plant operators must comply with the newly issued requirements in order to continue operation (IAEA 2022a).

Figure 4: Licensing process



Source: Own figure.

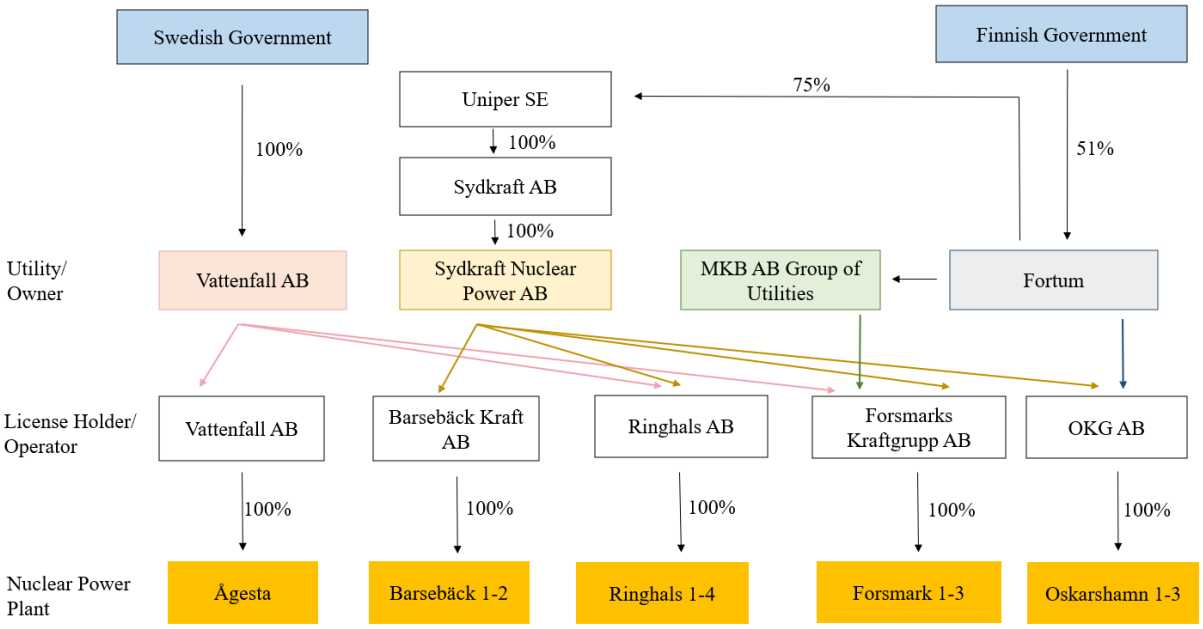
2.3 Oversight

The Government holds the main oversight with regards to the licensing process of nuclear facilities. Further, it specifies requirements in laws which have to be fulfilled by the licensees of nuclear facilities (OECD/NEA 2012). SSM is the responsible authority in the matters of nuclear safety and radiation protection. Hereby, it holds a supervisory role and carries out inspections (Stralsakerhetsmyndigheten 2021c). It is also responsible for the technical safety reviews of licenses and makes sure that the licensee complies with all necessary safety requirements (OECD/NEA 2012; Ministry of the Environment 2019). Concerning waste management, SKB is the main regulatory body. It is owned by the nuclear power companies and its tasks include ensuring the safe transport of radioactive waste from NPPs to interim and final storage facilities (SKB 2021a). Furthermore, it is also involved in the decommissioning process as it manages the disposal of waste arising from the dismantling of NPPs (IAEA 2022a).

2.4 Ownership

The ownership of NPPs in Sweden consists of private and public ownership (World Nuclear Association 2020). Figure 5 shows the ownership structure of the Swedish NPPs. All active NPPs are partially owned by several utilities, which implies a high level of cross-ownership of Swedish NPPs. Further, several NPPs are partial owned by international firms, that is, Fortum and Uniper.

Figure 5: Swedish NPPs and their owners and operators



Source: Own figure.

In the following, the utilities depicted in Figure 5 will be explained in more detail.

- **Vattenfall AB** is 100% owned by the Swedish state. It is a multinational company as it owns and produces power from hydro, nuclear, solar, wind, biomass, natural gas, waste and coal in the following countries: Denmark, Finland, France, Germany, Netherlands, Poland, Sweden and the UK (Vattenfall 2021b). For example, Vattenfall holds shares of three German NPPs: Brunsbüttel and Krümmel which were never restarted after Fukushima and Brokdorf, which is scheduled for closure in 2021 (Schneider et al. 2019).
- **Sydkraft Nuclear Power AB** is a subsidiary of Uniper for its operations in Sweden (Uniper 2022).
- **Fortum** is a big multinational power company with its main share-holder being the Government of Finland (Simply Wall St 2020). Fortum is the 3rd largest power generator in the Nordic countries and one of the leading heat producers globally (Fortum 2021d). It owns 140 hydro power plants located in Sweden and Finland and is co-owner of several other hydro power plants (Fortum 2021b). Further, it owns two NPPs in Finland and co-owns three other nuclear power plants: one in Finland and two in Sweden (Fortum 2021c). Concerning wind power, Fortum operates three wind farms in Norway, one in Sweden, one in Finland and four in Russia (Fortum 2021f). Fortum also owns and co-owns several solar power plants in Russia (Fortum 2021e) as well as CHP and condensing power plants in Denmark, Finland, Latvia, Estonia, Lithuania, Norway, Poland, Russia and Sweden (Fortum 2021a).

- **MKB AB Group of utilities** is majority owned by Fortum (Largest Companies 2022).
- **Uniper** is an international energy company and operates hydro, coal, gas, and nuclear plants in Germany, UK, Sweden, Netherlands, Hungary and Russia (Uniper 2021a). Fortum owns around 75% of the shares of Uniper (Flauger 2020).

Barsebäck Kraft AB, Forsmark Kraftgrupp AB, OKG Aktiebolag and Ringhals AB are the operators of the NPPs. They also jointly own SKB and are therefore responsible for the safe management and storage of spent nuclear fuel and radioactive waste at their respective NPP sites as well as at the final and interim storage sites at Forsmark and Oskarshamn. Further, they are tasked with the decommissioning of their respective NPPs and the associated facilities (OECD/NEA 2012). Table 2 reports the distribution of shares of power plants in Sweden.

Table 2: Distribution of owner shares of Swedish NPPs in %

Nuclear Power Plant	Vattenfall AB	Sydkraft Nuclear Power AB	MKB AB Group of Utilities	Fortum
Ågesta	100			
Barsebäck 1-2		100		
Ringhals 1-4	70.4	29.6		
Forsmark 1-3	66	8.5	25.5	
Oskarshamn 1-3		54.5		45.5

Source: Own compilation based on data from IAEA (2022a); Vattenfall (2022).

2.5 Liability

According to SSM, the operators of the NPPs bear full responsibility for the safety of their facilities, their workers and the surrounding environment during power operation of the plant as well as during the process of decommissioning of the facility (Stralsakerhetsmyndigheten 2020b). They are liable to pay compensation for nuclear damages even if there has been no fault of negligence on their part but are not liable for damages cause by war events (Swedish Ministry of Justice 1982).

According to the Nuclear Liability Act (SFS 1968:45), the operator of a nuclear installation that causes a nuclear incident is strictly and exclusively liable to provide compensation to those who have been personally harmed or have suffered a damage to property or loss as a result of the incident. The amount of the operator's liability has been increased progressively since 1968 (from originally 50 million SEK in 1968 to 3,300 million SEK in 2001).[1] It is mandatory for the operators of Swedish nuclear facilities to have insurance that covers their liability. For that, an insurance pool was created in

[1] 50 million SEK correspond to 9.7 million USD in 1968; 3,300 million SEK correspond to 319.5 million USD in 2001.

1956 with the purpose to provide financial insurance to the Swedish nuclear industry. In 2002, the Swedish and the Finnish nuclear insurance pools merged and are now known as the Nordic Nuclear Insurers (NNI) (Nordic Nuclear Insurers 2021a). The NNI provides the following insurances: material damage insurance, business interruption insurance and the compulsory third party liability insurance (Nordic Nuclear Insurers 2021b). The operators must report their compulsory third party liability insurance to the National Debt Office for revision. Once revised, the Office transmits the declaration along with a statement of opinion to the Government for assessment if the insured amount is sufficient. According to the National Debt Office, a "sufficient amount" for a third party liability insurance of a facility owner with a nuclear power reactor is about 1,200 million € (Swedish National Debt Office 2022a).

If a liable operator cannot pay the full amount following a nuclear incident the state will compensate the victims from a maximum sum of SEK 6 billion (around 570 million €) per incident (OECD/NEA 2008).

2.6 Nuclear Waste Management

The Act on Nuclear Activities legally regulates the handling of radioactive waste (OECD/ NEA 2012). The primary responsible body with regards to nuclear waste management is **SKB**. SKB is jointly owned by the utilities that operate the Swedish NPPs[2]. SKB operates the final repository for short-lived radioactive waste (SFR) and the centralized interim storage facility for spent nuclear fuel, Clab (SKB 2020b). The main duties of SKB include the management and safe disposal of spent nuclear fuel and radioactive waste (SKB 2021a). Moreover, its competence also includes research and technical development concerning the safe disposal of radioactive waste and spent nuclear fuel (OECD/NEA 2012).

Another important body is the **National Council for Nuclear Waste** that is an independent advisory committee of scientific experts. It advises the Government in subjects of nuclear waste and the decommissioning of nuclear installations (Kärnavfallsradet 2021).

The interim storage facility for spent nuclear fuel "Clab" is located at Simpevarp, around 25 km north of the NPP Oskarshamn. Clab started operating in 1985. All spent nuclear fuel (SNF) from Swedish NPPs is kept at Clab while waiting for the final repository to begin operating. Initially, the spent fuel is kept at the respective NPP for about a year. After that, the spent fuel is moved to Clab. At Clab, it is stored in deep storage pools about 30 meters below ground. The water shields against radiation and the hot fuel are being cooled down in the pools. This process makes it easier to manage the SNF when the final repository is ready to operate (SKB 2019b; 2020a).

The final repository for low and intermediate levels of radioactive waste, SFR, is located at Forsmark and started operating in 1988. It was the first facility of its kind worldwide. It is for low and

[2] Distribution of ownership: 22% OKG Aktiebolag, 12% Sydkraft Nuclear Power AB, 36% Vattenfall AB and 30% Forsmark Kraftgrupp AB (SKB 2020b).

medium levels of waste (e.g., operational wastes like protective clothing, etc.) that do not need to be actively cooled (SKB 2021b). The waste is kept 60 meters below the bottom of the Baltic Sea. Most waste stems from the operations of the Swedish NPPs. Further radioactive waste comes from hospitals, veterinary medicine, research and industry. For the future, it is planned that the radioactive waste from the decommissioning of the Swedish NPPs will be disposed of at SFR. For that, SKB submitted an application at the end of 2014 to extend the SFR On December 22nd 2021, this application was approved by the Swedish government (SKB 2021b).

Sweden is far along in the process of having a permanent repository for high-level radioactive waste. The site of the disposal facility is Forsmark. Under the current timetable, SKB plans on starting construction of the used fuel repository and the encapsulation plant in mid-2020. The encapsulation plant will be built next to the interim storage facility at Oskarshamn, whereas the final repository will be built at Forsmark. Construction will take around ten years (World Nuclear News 2020b). Mandated by SKB, Sweco, a Swedish engineering consultancy company, will prepare the detailed design of the planned facility and of the planned extension of the existing final repository for low and intermediate-level radioactive waste (SFR) (World Nuclear News 2020a).

3 Decommissioning Regulation

3.1 Decommissioning policy

In Sweden, the operators of the nuclear facilities bear full responsibility with regards to the safety of their plants, protection of their workers and the surrounding environment. This full responsibility also holds during the decommissioning process. Hereby, the SSM has the oversight and carries out regular checks to ensure that the operators meets their responsibility (Stralsakerhetsmyndigheten 2020a). Reactor operators apply for a renewed operational license from the SSM every 10 years. There is no maximum lifetime for Swedish NPPs, thus, as long as the reactors are deemed safe by the SSM Authority, they may renew their operating licenses indefinitely and continue to operate (Qvist and Brook 2015).

Possible decommissioning strategies include the direct and the deferred dismantling of the nuclear facility. "Direct dismantling" means that the NPP is dismantled right after its shutdown with a short period of post-service operation. In Sweden, this strategy has been chosen by Oskarshamn 3 and will be followed by all Swedish BWR in the future. "Deferred dismantling" indicates that the plant will not be immediately dismantled after its shutdown. The period of post-service operation lasts for several years and is followed by a period of reestablishment. During this time, the plant is being kept in a state of safe enclosure. Barsebäck was forced to implement deferred dismantling due to political decisions to close the plant and the non-availability of disposal facilities (Hansson and Jönsson 2009). For both strategies, decommissioning is finished when the former site is released from the Act on Nuclear Activities and the Radiation Protection Act (Stralsakerhetsmyndigheten 2020a). The site is either fully restored to its state before the construction of the NPP ("greenfield") or some facilities are left on site which pose no radioactive danger anymore ("brownfield"). The site of the former NPP Barsebäck will be a brownfield and is intended to be used for new power generation (Gillin 2020).

3.2 Regulatory and legal process

According to Sweden's Act on Nuclear Activities (SFS 1984:3) it is the responsibility of the nuclear power companies, i.e., the license holder, to show how their NPP can be safely decommissioned and dismantled when it is no longer in service. The Financing Act ("finansieringslagen") (SFS 2006:647) states that the owner of a reactor is obliged to calculate the estimated cost of decommissioning of the NPP (Larsson, Anunti, and Edelborg 2013). The Act also deals with the financial aspects in terms of the disposal of nuclear waste (OECD/ NEA 2012). The Radiation Protection Act (1988:220) contains provisions for decommissioning, ensuring the protection of the surrounding environment (OECD/ NEA 2012).

The operators of NPPs are required to have finalized a decommissioning plan before they shut the plant down. According to the Act on Nuclear Activities (SFS 1984:3), decommissioning work is

done under the operational license and thus, no additional license for decommissioning is required (Amft, Leisvik, and Carroll 2017).

3.3 Oversight

SSM oversees the shutdown and the decommissioning of nuclear facilities. It intensifies its regulatory control and inspections throughout the entire decommissioning process and makes sure it is done in a safe manner with respect to the radiation protection of the surrounding environment and people (Stralsakerhetsmyndigheten 2020a). SKB is responsible for the safe disposal of decommissioning waste.

4 Financial Regulation

4.1 The funding of decommissioning

The arrangement of the financing of decommissioning and waste disposal is regulated in the Financing Act (2006: 647) with the associated Ordinance (2017: 1179). It is stated that the means in the NWF have to ensure financing of all future decommissioning, management and disposal of spent fuel and nuclear waste, including the research needed for these activities (Ministry of the Environment 2019). The NWF is a government authority, overseen by a Board of Governors who are appointed by the Government (Kärnavfallsfonden 2021). The main tasks of the NWF include receiving fee payments from the fees levied on the NPPs, managing and disbursing the fund assets, and keeping the National Debt Office informed about the fund (Kärnavfallsfonden 2020a).

NPP operators pay an annual contribution to the fund. The fees are calculated individually for each licensee based on the electricity generated. This applies to all reactor owners with one or more operational nuclear power reactor, which are Forsmark Kraftgrupp AB, OKG Aktiebolag and Ringhals AB. As Barsebäck NPP has been shut down permanently, the operator, Barsebäck Kraft AB, pays a fixed annual amount (SKB 2019b).

The fee to the NWF covers the following costs and expenses (Kärnavfallsfonden 2020b) (Kärnavfallsfonden 2020b):

- the licensees' costs for safe management and disposal of waste products,
- the licensees' costs for safe decommissioning and dismantling of nuclear facilities,
- the licensees' costs for the research and development needed for safe management and final disposal of residual products as well as decommissioning and dismantling of facilities,
- the state's costs for management of the fund assets and review of questions concerning fees, disbursement of funds etc.
- the state's costs for supervision of the decommissioning and dismantling of nuclear facilities,
- the state's costs for review of questions concerning final disposal and monitoring and control of the final repository,
- the licensees', the state's and the municipalities' costs for information to the public in matters relating to management and disposal of spent nuclear fuel and nuclear waste, and
- costs for support to non-profit organizations for efforts in connection with questions concerning siting of facilities for management and disposal of spent nuclear fuel.

In addition to paying fees, the reactor owners also have to provide two types of guarantees. The first one is to cover the fees, which have not been paid yet. The basis for this guarantee is called the financing

amount and amounts to 103.1 billion SEK[3] according to the latest cost study by SKB (2019b). The second guarantee is a supplement to the financing amount and mainly covers unforeseen events. It is called the supplementary amount. In line with the new Financing Ordinance, the supplementary amount is not reported in the cost study anymore (SKB 2019b). Should a reactor owner not be able pay his annual fees or his funds in the NWF are deemed insufficient, the guarantees take over. For reactor operators, the guarantees are provided by the owners of the nuclear power companies (parent company guarantee) (Swedish National Debt Office 2022b). The current fees and guarantees have been determined by the Government based on recommendations from the National Debt Office and are intended to cover the individual reactor owner's future needs for decommissioning and waste disposal (Nuclear Waste Fund 2021; SKB 2019b).

4.2 Current balance in funds

As of 31.12.2021, the total capital of the fund stood at 80.8 billion SEK (2020 price level)[4] (Nuclear Waste Fund 2021). Table 2 shows the fee payments of all NPP operators to the NWF in 2021. In addition to the nuclear power operators in the table, other nuclear license holders also contribute to the fund (Swedish National Debt Office 2022b).

Table 3: Fees to the Nuclear Waste Fund and Current Balance as of 2021 (in 2020 SEK levels)

Operator	öre/ kWh	Energy delivered (TWh)	Fair value of the fund per licensee (SEK thousand)
Forsmark Kraftgrupp AB	2.9	25.5	24,240,635
OKG AB (Oskarshamn)	5.5	9.1	14,916,658
Ringhals AB	4.6	14.8	27,439,822
Barsebäck AB	0	0	13,100,822
Vattenfall (Ågesta)	0	0	285,335

Note: 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020). Source: Nuclear Waste Fund (2021); Swedish National Debt Office (2022b).

4.3 Cost assessments

By law, each reactor owner is obliged to prepare a calculation of the costs for all measures concerning the disposal and management of nuclear waste as well as all costs arising from decommissioning and

[3] Corresponds to 103.6 billion SEK in 2020 price levels; 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020).
[4] 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020).

dismantling of the NPPs. SKB is tasked with this calculation of cost estimates of all future costs, which is carried out periodically every three years. The cost estimates are calculated for the whole Swedish nuclear fleet. This means that individual cost estimates for individual NPPs are not available (SKB 2019b). The future cost calculations are based on the reactor owners' current planning assumptions with respect to expected operating times and expected volumes of radioactive waste and spent nuclear fuel. The two designs reported in the latest cost study of 2019 are called the reference design and the financing design. The reference design reflects the nuclear power companies' current plans, which include assumed operating time and expected volumes of radioactive waste and spent nuclear fuel. The financing design differs from the reference scenario in terms of expected waste volumes (difference in calculation) and assumed operating time of the NPPs (fixed at 50 years). The fees and guarantees are calculated based on the financing scenario (SKB 2019b). The current estimate of all future costs for waste management and decommissioning for all the reactors and waste is 110.5 billion SEK. [5] Once SKB has calculated the costs and the appropriate fees and guarantees, they are formally submitted the National Debt Office. The Office reviews them and makes recommendations to the government about the appropriate fees required (Swedish National Debt Office 2022b; SKB 2019b).

4.4 Cost experience and accuracy of assessments

Information about cost experience and accuracy of cost assessments is scarcely available for Sweden. As described above, Sweden has an elaborated financing scheme in place that requires the provision of two types of guarantees. The adequacy of the proposed guarantees are assessed by the Swedish National Debt Office (Swedish National Debt Office 2022b). The Ordinance on the Financing of the Residual Products of Nuclear Power specifies that the guarantees have to be unlimited in time and cannot be a property on which nuclear activities are carried out (Swedish Government 2017). According to the Financing Act (2006:647), fund resources that are not used will be returned to the individual fee payer. However, any surplus (accrued interests on fund resources) will go to the state (Swedish Government 2006). So far, there have been no concerns raised that the money in the NWF will not be enough or that cost assessments of the decommissioning of Swedish NPPs might not be accurate.

4.5 Funding Liability

If a reactor owner cannot pay and the assets in the NWF and guarantees are insufficient, the state (i.e., the tax payers) must jump in as a last resort. However, the special financing system of the NWF should prevent this from happening. The money of other fund contributors may not be used to cover each other's costs (Kärnavfallsfonden 2020c).

[5] 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020).

5 Production

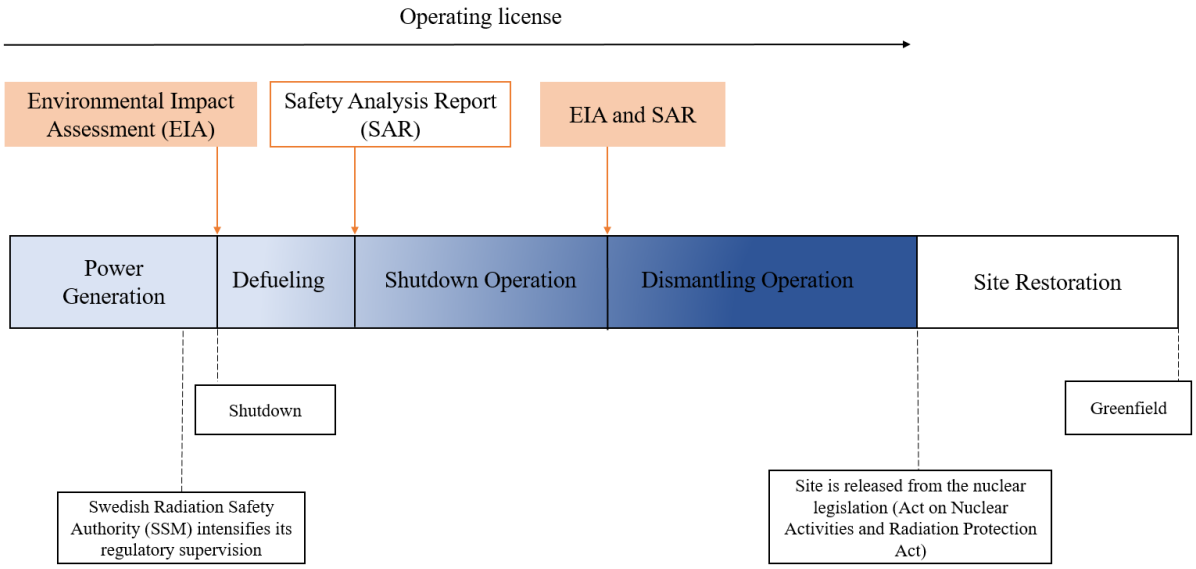
5.1 Overview

Sweden has very limited experience in the decommissioning of nuclear reactors overall and no experience in the decommissioning of commercial nuclear reactors. The only completed decommissioning work is the decommissioning of the research reactor R1 at the Royal Institute of Technology in Stockholm. Even though this decommissioning work is not directly comparable to the decommissioning of a commercial reactor, it still provides valuable information and knowledge (SKB 2005).

5.2 Progress

Figure 6 shows an overview over the decommissioning process. The preferred decommissioning strategy is to directly dismantle the reactor. Once the reactor has reached the end of its lifetime, SSM intensifies its supervision and regulatory controls. This is done as, according to SSM, there is a risk that adherence to safety guidelines might decline when shutdown is near (Stralsakerhetsmyndigheten 2020a). In Sweden, decommissioning is carried out under the operating license. Thus, there is no need for a specific license to decommission the power plant. However, there are certain regulatory documents that have to be obtained when moving from one stage of decommissioning to another. Firstly, an Environmental Impact Assessment (EIA) must be approved by the environmental court to start the defueling of the reactor. During the defueling, the reactor is emptied of all spent nuclear fuel. When defueling is finished, there is an incentive for the operator to get a new Safety Analysis Report (SAR) approved by SSM as some restrictions can be lifted, once no spent fuel is left on site. However, the SAR is not necessary to advance to the next phase in the decommissioning process. Throughout shutdown operation, the plant is being prepared for its future dismantling and first dismantling work is carried out where possible. A second EIA and a second SAR must be approved by the environmental court and SSM respectively, to move to the dismantling stage (Rannemalm, Eriksson, and Bergh 2016). During dismantling, the workers, among other things, check where radioactive substances are present. The end of the dismantling stage is reached when there is no radioactive contamination left on site. Following that, the site is released from all nuclear legislation by SSM and can be used for other industry purposes (“brownfield”) (Stralsakerhetsmyndigheten 2020a). If the decommissioning goal “greenfield” is specified, then conventional dismantling of all building structures follows the nuclear dismantling of the power plant.

Figure 6: Overview over the decommissioning process



Source: Own figure.

In the following, the decommissioning progress of all shutdown reactors in Sweden is reported.

Ågesta

Ågesta was a pressurized heavy water reactor that provided heat and electricity to the suburb of Farsta in Stockholm (Vattenfall 2020). It was the first Swedish commercial nuclear reactor connected to the electric grid. The reactor was shut down on June 2, 1974. After its shutdown, the plant was emptied of nuclear fuel and heavy water. Currently, the site is being used as a training location for Stockholm's fire services. The dismantling of the plant began in 2020 and Vattenfall as the operator and owner of Ågesta will be responsible for the safe decommissioning of the plant (Vattenfall 2020). Westinghouse, a US nuclear manufacturing company, has signed a contract with Vattenfall and will undertake the dismantling work. Westinghouse will plan, design and manufacture the tools for the segmentation of the NPP as well as perform the work on site. The company has extensive experience in the decommissioning of BWRs, PWRs, research reactors, sodium-cooled reactors, fuel fabrication plants and gas-cooled reactors (Westinghouse Electric Company LLC 2020).

Barsebäck 1 and 2

The units at Barsebäck were shut down for political reasons in 1999 and 2005, respectively. After shutdown, all spent fuel was transported to the centralized interim storage facility, Clab, in Oskarshamn. Major decontamination work has also been done early on. However, some radiological decontamination work had to wait due to a lack of storage or disposal facilities for decommissioning waste. As decommissioning work at Barsebäck had been put on hold the site became a training ground for staff

from other sites. In 2016, an on-site disposal facility for low and intermediate nuclear waste was built. The operation of the new disposal facility allowed for additional preparations for dismantling and demolition. The work done so far includes the segmentation of the reactor pressure vessels and the drainage of the pools above and adjacent to the reactors. Dismantling in radiological areas started in 2020 and will be finished in 2028. At the end of the decommissioning work, Barsebäck will become a brownfield site and is intended to be used for other power generation. Uniper, the owner of Barsebäck, is responsible for the decommissioning work (Gillin 2020). Contracts have been awarded to the Finnish company Fortum who will be in charge of dismantling the turbine auxiliary systems, water supply systems and moisture separator heaters (Energynews 2022). Further, the Spanish multinational GD Energy Services (GDES) has been awarded a contract to work on the dismantling of Barsebäck and Oskarshamn NPPs (Foro Nuclear 2022).

Oskarshamn 1 and 2

Oskarshamn 1 and 2 were taken out of service in 2017 and 2013 for economic reasons. Uniper is the majority owner of the NPP Oskarshamn and is responsible for the decommissioning work (Uniper 2021b). Oskarshamn-3 is considerably younger than the other two reactors and is expected to operate until 2045. Both shut down reactors have been emptied of all nuclear fuel, which has been transported to the adjacent interim storage facility Clab. Additionally, segmentation of internal components in both reactor pressure vessels has been completed. Preparations have begun to expand on-site disposal facilities for low and intermediate nuclear waste from decommissioning work around Sweden. Large-scale dismantling work of both reactors started in 2020 and will be completed by 2028. The buildings will remain in place after the removal of the radiological inventory as they might be used for other purposes later on. The radiological dismantling and demolition work of Barsebäck and the two reactors at Oskarshamn will be undertaken as one big common project to create logistical and economic benefits (Gillin 2020). A part of that decommissioning project will be managed by the Fortum, i.e., dismantling the turbine auxiliary systems (Energynews 2022).

Ringhals 1 and 2

Ringhals 1 and 2 were shut down in 2020 and 2019, respectively. In both cases, the shut-downs happened because of economic reasons. Ringhals-2 is Sweden's oldest PWR. As Vattenfall is the main shareholder of Ringhals it will be responsible for the decommissioning work. Vattenfall is currently undertaking detailed studies and preparations for the decommissioning work. Furthermore, Vattenfall has also started a study concerning the future use of the site. The head of Vattenfall's Nuclear Decommissioning business unit, Sven Ordéus, states: "After the release from regulatory control, any buildings for which there is a future use will not be demolished. Which those buildings are will depend on the results of the ongoing study" (Gillin 2020). The extensive dismantling of Ringhals-1 and Ringhals-2 is scheduled to

begin in early 2023. According to Vattenfall, the entire demolition is expected to take around 8-10 years (dpa, Berlin 2020).

5.3 Actors involved in the decommissioning process

There are several actors involved in the decommissioning process. The main responsibility of the safe decommissioning and disposal lies with the license holder of the specific plant (Amft, Leisvik, and Carroll 2017). Further, SKB who is the owner of the interim storage facility, Clab, is responsible for the safe transport and storage of nuclear waste arising from decommissioning (SKB 2021a). From a legal perspective, the Environmental Court and SSM approve permissions, which are necessary for the decommissioning process to commence. SSM also holds the main oversight over the entire decommissioning process by regularly carrying out inspections (Stralsakerhetsmyndigheten 2020a). There are also external contractors involved in the decommissioning process. Some tasks are entirely outsourced and taken over by specialized and experienced companies such as Westinghouse or GDES.

6 Country specific nuclear and decommissioning developments

Sweden has shut down over half of its nuclear reactor fleet. This puts pressure on alternative electricity sources, mainly on renewables, which are expected to resume the role of nuclear energy. According to forecasts, the Swedish energy market for renewables will continue to grow within the next couple of years. Contributing to the growth in the renewable electricity market are various government initiatives to reduce CO2 emissions and the 100% renewable electricity target by 2040 (IRENA 2020). This target, however, should not be taken as a fixed stop year for nuclear energy (Swedish Energy Agency 2018). Concerning the status of the renewable electricity sources in Sweden, hydropower is at its limits of expansion. This implies that other renewable sources have to grow in order to fulfill the renewable target and to fill the gap that the shut-down of nuclear reactor leaves (Qvist and Brook 2015). Wind energy has experienced a strong growth in the last decade and will likely play a big role in Sweden's electricity future (IEA Bioenergy 2021). Geographically, Sweden has technical potential for land-based wind power as it is a very long stretched country with long coastlines and sparsely populated areas. Furthermore, there is also substantial potential for off-shore wind power. Theoretically, there is potential for photovoltaic power in Sweden as well, though the potential is limited due to changing sunlight hours; solar energy would only be available from March-October. In the current electricity mix the share of PV is almost negligible. Thus, solar power cannot be used as an electricity source during the high demand winter months and this might strain then the power balance (IVA 2016). A further issue that Sweden faces is the fact that the envisioned expansion of wind power will primarily take place in the sparsely populated North, whereas most electricity is consumed in the South. Bottlenecks might therefore occur (IVA 2016). Ongoing research focuses on regional grid companies and how they might be of help in overcoming this bottleneck in the national transmission grid (Engman 2021).

The future of nuclear power in Sweden is not straightforward. On the one hand, there are structural problems in the sector such as the reduced profitability of Swedish NPPs which may cause more reactors to shut down in the future (IVA 2016). On the other hand, recent policy developments have been strengthening the position of nuclear power. One of those is the abolishment of the nuclear energy capacity tax. The capacity tax on nuclear energy was in place since the late 1990s. By increasing operating costs for NPPs the tax was potentially harming the nuclear industry. In 2017, the Swedish government decided to phase-out of the tax over two years. A second policy development in favor of nuclear power is the allowance to expand nuclear capacity at existing sites. In order to make up for the 1200 MWe lost due to the closure of Barsebäck 1 and 2, the government permitted to increase capacity at other existing reactors. In total, 1619 MWe has been added to operating reactors. Thirdly, the government also allowed for the construction of up to ten new reactors at existing sites (World Nuclear Association 2022). In 2022, Fortum announced that it would carry out feasibility studies for the

construction of new reactors at their sites in Finland and Sweden (Forsmark and Oskarshamn) (World Nuclear News 2022).

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