DIW BERLIN

104

Data Documentation

Deutsches Institut für Wirtschaftsforschung 2023

# Decommissioning of Nuclear Power Plants: Regulation, Financing, and Production

Alexander Wimmers, Rebekka Bärenbold, Muhammad Maladoh Bah, Rebecca Lordan-Perret, Björn Steigerwald, Christian von Hirschhausen, Hannes Weigt und Ben Wealer

IMPRESSUM
DIW Berlin, 2023
DIW Berlin
Deutsches Institut für Wirtschaftsforschung
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ISSN 1861-1532

# Data Documentation 104

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# Decommissioning of Nuclear Power Plants: Regulation, Financing, and Production

Berlin and Basel, January 2023

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[5] This data documentation is part of the joint research project of University Basel and TU Berlin *"Best Practices for Decommissioning of Nuclear Power Plants: How to ensure efficient plant decommissioning under different regulatory schemes"*. Details on the project and further reports are provided on the project webpage. The research project was jointly financially supported by the Swiss National Science Foundation (SNSF) and the Deutsche Forschungsgemeinschaft (DFG), grant number 100018L 185154.

# Introductory Remarks

Alexander Wimmers, Björn Steigerwald, Christian von Hirschhausen

Over the last decades, the average age of nuclear reactor fleets world-wide has been steadily increasing as nuclear new build is advancing only slowly outside of China (Schneider et al. 2022; World Nuclear Association 2022). While some countries, such as France and the United States, are trying to prolong operational lifetimes of their respective fleets by extending licenses from 40 to 50 or even 60 years, old reactors are becoming increasingly costly to operate and susceptible to unforeseen closure from economically unviable maintenance or component replacement due to ageing material (ASN 2021; Lordan-Perret, Sloan, and Rosner 2021; Schneider et al. 2022). Resulting from this is a gradual shift of industry focus towards the nuclear back-end, comprising of nuclear waste management and nuclear decommissioning (Wealer and Hirschhausen 2020). While the former has been receiving more and more attention, especially in respect to recent developments in the German site selection process, nuclear decommissioning remains a niche field of research when compared to, e.g., nuclear new build in carbon-neutral energy systems.

However, decommissioning is an essential part of the nuclear system good that must not be overlooked when talking about economical, ecological, and social impacts of nuclear power (Irrek 2019; Wealer, Seidel, and von Hirschhausen 2019). Experience in decommissioning nuclear power plants is limited in the industry as so far, only about a dozen reactors, most of which small research and prototype reactors, have been successfully decommissioned in three countries, i.e., Germany, Japan, and the United States. In some cases, decommissioning works lasted longer than the reactor was online (Schneider et al. 2022). Nuclear decommissioning is a highly complex process that requires extensive regulatory oversight and highly asset specific knowledge as nuclear power plants can significantly differ from one another in design and conducted operation, and therefore radiological contamination (Kessides 2012; Irrek 2019; OECD/NEA 2016; Suh, Hornibrook, and Yim 2018). Further, the long-term nature of decommissioning projects requires substantial financial obligations for which in some cases liability issues remain unresolved or have been taken over by the state (Foster et al. 2021; Lordan-Perret, Sloan, and Rosner 2021).

We therefore present this data documentation to shed light onto a so far seldom regarded part of the nuclear system good. Our research focuses on six countries (France, Germany, Sweden, Switzerland, United Kingdom and United States), each with an, at least historically, strong reliance on nuclear power for electricity generation. Currently, these countries are following diverging paths in respect to their nuclear power policies, and the same goes for nuclear decommissioning.

This data documentation is structured as follows: We first provide an overview of the research results and highlight gaps that should be addressed in future research. Here, the technical complexity of nuclear decommissioning is introduced, also.

The subsequent chapters consist of the detailed country reports in alphabetical order: France, Germany, Sweden, Switzerland, the United Kingdom, and the United States. Each of these reports follows a standardized approach: After introducing the historical development and current situation of domestic nuclear power, we provide a general overview of nuclear regulation in the respective countries. Then, the focus shifts to nuclear decommissioning regulation and financing thereof. Where available, information is provided on developments on the production side, i.e., the actual progress of decommissioning domestic nuclear power plants. Each section closes with final remarks on country-specific developments that might give rise to further research questions.

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# List Of Acronyms

| Acronym | Meaning |
|---|---|
| AGR | Advanced Gas Cooled Reactor |
| ASN | French Nuclear Safety Authority |
| BASE | German Federal Office for the Safety of Nuclear Waste Management |
| BfE | Swiss Federal Office of Energy |
| BMUV | German Federal Ministry for Environment, Nature Conservation, and Nuclear Safety |
| DETEC | Swiss Federal Department of the Environment, Transport, Energy and Communications |
| DTF | Decommissioning Trust Fund |
| EDF | Électricité de France |
| ENSI | Swiss Federal Nuclear Safety Inspectorate |
| EW | Exempt Waste |
| EWN | Entsorgungswerk für Nuklearanlagen GmbH |
| FBR | Fast Breeder Reactor |
| GCR | Gas Cooled Reactor |
| GDR | German Democratic Republic |
| HLW | High-Level Waste |
| HTGR | High Temperature Gas Cooled Reactor |
| HWGCR | Heavy Water Gas Cooled Reactor |
| IAEA | International Atomic Energy Agency |
| ILW | Intermediate Level-Waste |
| LLC | Limited Liability Corporation |
| LLW | Low-Level Waste |
| LTE | Long Term Enclosure |
| NDA | Nuclear Decommissioning Authority (U.K.) |
| NLF | Nuclear Liabilities Fund |
| NPP | Nuclear Power Plant |
| NRC | Nuclear Regulatory Commission |
| NWF | Nuclear Waste Fund |
| PHWR | Pressurized Heavy Water Reactor |
| PWR | Pressurized Water Reactor |
| SGHWR | Sodium Gas Cooled Heavy Water Reactor |
| SGR | Sodium Graphite Reactor |
| SNF | Spent Nuclear Fuel |
| SSM | Swedish Radiation Safety Authority |

| | |
|---|---|
| STENFO | Swiss Decommissioning and Disposal Fund |
| U.K. | United Kingdom |
| U.S. | United States of America |
| VLLW | Very Low-Level Waste |
| VSLW | Very Short-Lived Waste |

# 1 Cross-Country Survey on the Decommissioning of Commercial Nuclear Reactors: Status, Insights and Knowledge Gaps

Rebecca Lordan-Perret, Rebekka Bärenbold, Muhammad Maladoh Bah, Alexander Wimmers, Björn Steigerwald, Hannes Weigt, Christian von Hirschhausen, Ben Wealer,

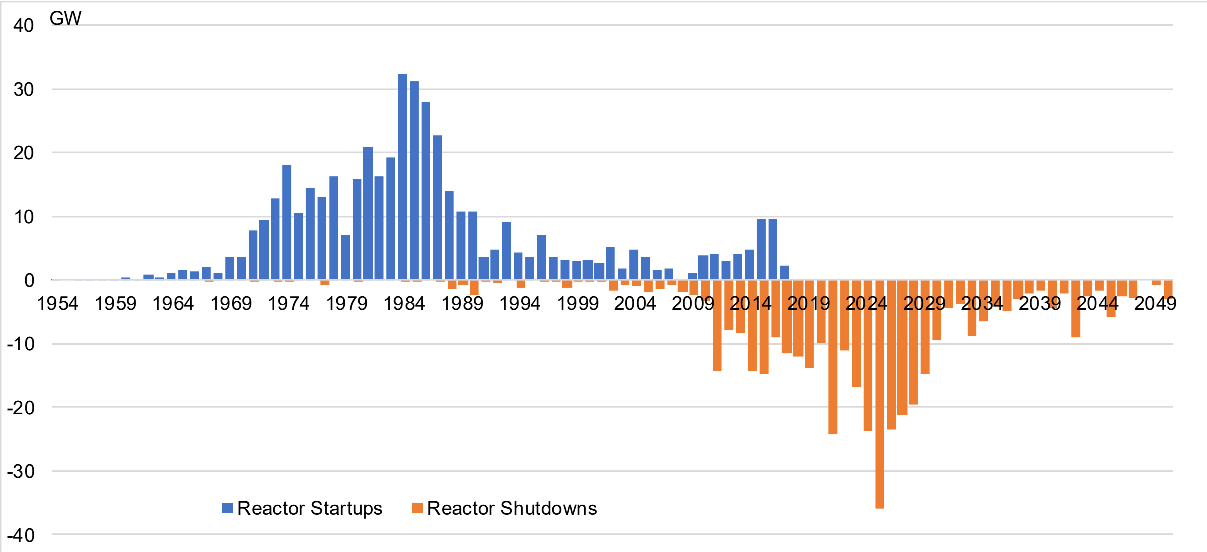
## 1.1 Introduction

In the coming two decades, approximately 200 of the 411 operating commercial nuclear power plants (NPPs) worldwide are coming to the end of their operational and economic lifetimes and will need to be decommissioned (Schneider et al. 2022; World Nuclear Association 2022c). Decommissioning is an expensive and lengthy process. It requires the removal of all fuel elements; decontamination of components and structures with radioactive contamination; dismantling and disposal of building materials; and–depending on the national policy in place–remediation of the site for alternative purposes.[1] Figure 1-1 shows the wave of newly built plants, mainly in the 1970s/80s and the corresponding inverse wave of anticipated plant shutdowns in the 2020s and beyond. Bloomberg estimates that the global decommissioning market up until 2027 will be worth approximately 9.5 billion USD (Bloomberg 2022).

It is of the utmost importance that licensees decommission their NPPs in a timely and conscientious manner, for unmanaged sites could present serious risks (Laraia 2018; Foster et al. 2021; Hirose and McCauley 2022). First and foremost, decommissioning is necessary and should be done in a safe and secure manner because nuclear materials pose safety risks to human health and the environment when stored, disposed of, or handled in ways that might lead to a release or an accident (Strahlenschutzgesetz 2017; Hirose and McCauley 2022). Decommissioning also reduces security risks related to the theft or intentional targeting of nuclear materials by removing nuclear materials from the site. These risks can have far reaching consequences, for example, in the case of releases into the air or ground water (e.g., Hanford Site in the U.S. (Gusterson 2017)). Secondary motivations to decommission relate to financial and regulatory factors. Once decommissioned, owners and operators are released from legal liability and may sell or reuse facilities buildings or the reclaimed land (NRC 2017).

[1] The IAEA Safety Glossary defines decommissioning as "*Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility*"… "*Decommissioning actions are taken at the end of the operating lifetime of a facility to retire it from service with due regard for the health and safety of workers and members of the public and the protection of the environment*"… "*Subject to national legal and regulatory requirements, a facility*"… "*may also be considered decommissioned if it is incorporated into a new or existing facility, or even if the site on which it is located is still under regulatory control or institutional control*" (IAEA 2007b, 48).

**Figure 1-1: Distribution of global nuclear reactor startups and shutdowns**




Note: Assuming a 40-year reactor lifetime. Based on data from Wealer et al. (2018).

Yet, the global decommissioning industry is still developing and remains largely untested. Around the world, only about a dozen *commercial* nuclear reactors have been decommissioned, some still pending release from regulatory controls (Schneider et al. 2022). Historically, licensees viewed decommissioning as a distant obligation and focused on constructing and operating NPPs rather than decommissioning them (Laraia 2012). The combination of inexperience and insufficient planning has led to some undesirable outcomes, such as cost and schedule overruns; as a result, countries are improving practices, planning, and implementation to avoid such outcomes in the future (McIntyre 2012; Invernizzi, Locatelli, and Brookes 2017). Even with appropriate guidance and regulations more readily available, the technical and financial capacity to decommission nuclear facilities varies greatly among countries.

Stakeholders in many countries with commercial NPP fleets are concerned about the nuclear industry's ability to decommission in a timely and safe fashion (Invernizzi, Locatelli, and Brookes 2017). First, stakeholders are concerned about how the government is regulating the industry, particularly regarding financial liability. For example, if licensees are unable to pay for decommissioning, the liability and remaining financial responsibility may ultimately fall on the taxpayer (Lordan-Perret, Sloan, and Rosner 2021). In France, there are 56 de-facto state-owned operational reactors that reportedly will face substantial shortfall in the funding set aside (Assemblée Nationale 2017). Another concern of stakeholders is whether the supply chain for decommissioning can meet the steeply rising demand, for example, specialized personnel, specialized materials and supplies (e.g., casks), and access to waste disposal (low- and high-level waste) (Scherwath, Wealer, and Mendelevitch 2019).

Decommissioning markets, regulations, and practices are not developing in a vacuum. Rather, they are occurring against the backdrop of an industry largely in decline in developed countries (e.g., most

European countries, the U.S., and Canada) and on the rise in some developing countries (e.g., China and India). The decline of the nuclear industry in developed countries can be attributed to nuclear accidents– most notably Fukushima Dai'ichi in 2011–the deregulation of electricity markets, the rise of competitive renewable technologies (Harribin 2017; Lazard 2021), rising construction and operation costs (Lovins 2022; Rothwell 2022), and a lack of political will (Pearce 2017). In some countries, operators facing strong market competition from other energy resources are shutting down plants before the end of licensed operating lifetimes.[2] However, the rise in interest in nuclear in the Middle East, Africa, and Asia can–in part–be attributed to a dramatic increase in energy demand for development (World Nuclear Association 2017). Some concerns have been raised as to whether the regulation in these countries is adequate, particularly considering the changing nature of the nuclear industry (Islam, Faisal, and Khan 2021). With old Western fleets subsequentially going offline and new plants coming online, expected to operate for up to 60 years, nuclear decommissioning will remain an important issue for the foreseeable future (Schneider et al. 2022). Thus, identifying best practices for decommissioning is crucial not only for the aging Western fleet but also to ensure that nuclear newcomers are able to decommission their plants at the end of their lifetime in a safe and cost-efficient manner.

In this survey paper, we explore the current situations in six countries to understand the following research question: What are the existing institutional, regulatory and legal, financial, and technical (production of decommissioning work) regimes for decommissioning?[3] These four main pillars—institutional; regulatory and legal; financial; and decommissioning production—provide the structure for this survey in which we describe the results of our deep research into France, Germany, Sweden, Switzerland, the United Kingdom (U.K.), and the United States of America (U.S.) (our individual country profile reports form the basis for this survey paper). Taken together, we identify insights from comparing these countries' approaches in order to identify research gaps that guide our current research into the best practices for commercial nuclear power plant decommissioning.

## 1.2 Background

### 1.2.1 What is nuclear decommissioning?

NPP decommissioning is an expensive, complex, and protracted effort to return the site to a state suitable to be used for other purposes. While most people think of what is called 'greenfield' decommissioning, in which the licensee returns the site to its original state and it is released for unrestricted use, there are decommissioning 'goals' in which the site can be released for restricted use (OECD/NEA 2016). Complete NPP decommissioning is composed of two main parts: radiological decommissioning and

[2] Some power plants were granted license extensions (e.g., Vermont Yankee in the United States), but were then subsequently shutdown during the extended license period – we still consider this "early" shutdown.

[3] We will limit our analysis to six countries for reasons of practicality and feasibility.

conventional decommissioning (i.e., dismantling and demolition). Radiological decommissioning is the primary goal and requirement when decommissioning NPPs. Here, licensees remove and dispose of all radioactive materials, decontaminate all contaminated locations on site, and ensure that the entire site meets a strict standard for on-site radioactivity levels so that the regulators may release the licensee from radiological regulations (e.g., OECD and Nuclear Energy Agency 2006).

Once radiological decommissioning is complete, the site is said to be 'brownfield' and may be released from its radiological license for restricted uses. Some structures may remain on site to be used for other purposes. For example, if the licensee intends to use the site for another power plant, switching stations or office buildings may remain (Suh, Hornibrook, and Yim 2018). Some countries include intermediate decommissioning goals between brownfield and greenfield; the specifics of the land remediation and structure removal can vary from country to country, although our case study countries all mandate brownfield (Table 1-1). Once the site is brownfield, the decommissioning project becomes a regular industrial demolition and site restoration project, requiring less specialized personnel and equipment.

**Table 1-1: Mandated decommissioning goals by country**

| Country | Mandated Decommissioning Goals |
|---|---|
| **France** | Brownfield |
| **Germany** | Brownfield |
| **Sweden** | Brownfield |
| **Switzerland** | Brownfield |
| **United Kingdom** | Brownfield |
| **United States** | Brownfield by federal regulation,<br>but state-by-state remediation standards change |

Licensees may take different approaches to achieve their decommissioning goals, termed "decommissioning strategies," though all licensees not entombing their plant must complete radiological decommissioning within a country-dictated timeframe. This timeframe is sometimes dictated as a certain number of years (e.g., 60 years in the U.S.), and sometimes more vaguely defined (e.g., "as fast as possible" in France) (ASN 2021; NRC 2022). There are four main decommissioning strategies: immediate decommissioning (aka DECON and immediate dismantling), delayed decommissioning (aka deferred dismantling), long-term enclosure (aka SAFESTOR), and entombment (aka ENTOMB) (Foster et al. 2021; NRC 2017). The technical process of decommissioning usually follows the same pattern worldwide, regardless of the strategy chosen. In a first step, if all necessary licenses have been granted, the "warm-up stage" begins (see also Figure 1-3). During warm-up, some preparatory tasks are completed (e.g., defueling) and actual decommissioning begins (e.g., first components are removed). In the subsequent "hot-zone stage," highly contaminated parts, such as the reactor pressure vessel or the biological shield, are dismantled. The operations done during the hot-zone stage are the most complex and pose the most risks during the whole decommissioning process. Finally, in the "ease-off stage", buildings and remaining components are decontaminated and, depending on a brownfield or greenfield approach, dismantled or demolished, respectively. The landscape is also remediated during this phase (Schneider et al. 2018).

Licensees following an immediate decommissioning strategy begin radiological decommissioning as soon as possible after the post-operational phase. There are advantages and disadvantages to immediate decommissioning. The advantages include, first, that the personnel who operated the facility are still available, so operational knowledge of the NPP is not lost (IAEA 2005). Second, the NPP is still structurally sound, which reduces risks to decommissioning staff. Third, the site can be more quickly used for other purposes rather than standing idle. Fourth, the licensee can swiftly eliminate the radiological hazard of a contaminated site, thus reducing risk of radioactivity spreading into the environment (OECD/NEA 2006). A major disadvantage is that the short-lived radioactive isotopes, which pose the greatest health hazard to workers decontaminating on site, do not have time to decay (e.g., Cesium isotopes). Therefore, workers are potentially exposed to higher radiation doses. Furthermore, the quantity of waste that must be disposed of with stringent controls is also greater than if the short-lived isotopes are given time to decay. Finally, adequate funds to decommission following shutdown must be readily available, as there is no delay to allow fund investment returns to accumulate. Nevertheless, immediate decommissioning appears to be the least costly approach (Park et al. 2022; Suh, Hornibrook, and Yim 2018; Short et al. 2011; OECD and Nuclear Energy Agency 2006), though we still lack enough data to statistically verify this claim (Irrek 2019).

Licensees following a delayed or deferred decommissioning strategy put the NPP (or a reactor) in a storage status (long-term enclosure, LTE) for some number of years (delayed is typically 10 years, while deferred decommissioning can be 30-100 years (OECD and Nuclear Energy Agency 2006)), allowing short-lived isotopes to decay and additional funds to accumulate. Licensees might choose this approach on a multi-reactor site in which reactor shutdowns have been staggered (e.g., San Onofre Unit 1 (Electric Power Research Institute 2008)), so that they can decommission the entire site at the same time. These strategies reduce the expected dose for decommissioning workers and the amount of low-level radioactive waste that must be disposed of with more expensive and stringent controls. Disadvantages of this strategy include losing institutional knowledge, working in buildings that have had no maintenance in decades (a potential risk for structural damage), increased decommissioning costs[4], and the delayed ability to sell or use the site for other purposes (the properties for NPPs tend to be prime real estate) (OECD and Nuclear Energy Agency 2006; Suh, Hornibrook, and Yim 2018).

Finally, licensees—under certain circumstances—may follow an entombment strategy. Typically, entombment is an appropriate strategy when the plant has had an accident, making it impossible for workers to remediate the site safely and effectively. The U.S. Department of Energy has used the method with some research reactors (i.e., Hallam, Piqua, BONUS) (Laraia 2012). With entombment, the licensee

[4] According to the site-specific cost estimates of the nuclear power plants in the United States, a SAFESTOR approach is more costly than DECON or delayed DECON (Table 3.5, Short et al. 2011).

seals the NPP, including the reactor building, pressure vessel, etc., in place (Laraia 2012; NRC 2022). Another example of the entombment strategy is the Chernobyl plant that has a concrete sarcophagus enclosing the damaged reactor unit 4 (The New York Times 2016).

In Table 1-2, we compile the decommissioning strategies that we observed in our decommissioning case study countries. In our selected countries, most operators are opting for an immediate decommissioning strategy.

**Table 1-2: The decommissioning strategies allowed in our decommissioning case study countries**

| Country | Strategy | Historical Strategies |
|---|---|---|
| **France** | Immediate dismantling and “complete clean-out” | entombment & deferred dismantling used in past |
| **Germany** | Since 2017, only “immediate dismantling”, but LTE in certain cases if necessary | entombment & deferred dismantling used in past |
| **Sweden** | Immediate dismantling and deferred dismantling allowed | n.a. |
| **Switzerland** | Immediate dismantling and “safe enclosure” (=deferred dismantling) allowed | n.a. |
| **United Kingdom** | Initially for all Magnox: deferred dismantling (85 years), but now individual approaches, some with direct dismantling, others deferred | Strategy change. 8 in LTE (deferred dismantling) |
| **United States** | DECON = Immediate dismantling<br>SAFSTOR = Deferred Dismantling<br>ENTOMB = *in situ* disposal | Majority of licensees using DECON; approx. 10 in SAFESTOR; ENTOMB not seen as option for commercial reactors |

### 1.2.2 Current status and outlook of nuclear decommissioning

The international NPP decommissioning industry is still nascent. Worldwide, eleven commercial nuclear power reactors over 100 MW have been completely radiologically decommissioned (Schneider et al. 2022).[5] The plants that have been decommissioned (or are in the process) were built during a period where the idea of decommissioning was neither fully conceptualized nor planned (MacKerron 1989). Thus, the entire supply chain for NPP decommissioning—from the efficacy of existing regulations to how to dispose of the reactor pressure vessel—is learning-by-doing. This learning is accumulating slowly because decommissioning is a lengthy process and the industry is just beginning the decommissioning phase. However, in the coming decades the pace at which NPPs come offline and are decommissioned is expected to increase (OECD and Nuclear Energy Agency 2006), as a majority of the plants that were built in the 1970s are reaching the end of their operational lifetime (Figure 1-1). We display this trend in plant retirements in our case study countries; Table 1-3 shows the progress of

[5] Many more research and prototype reactors and other nuclear facilities have been decommissioned. Some of the experience gathered from these decommissioning projects is applicable to large commercial reactors; however, the scale and complexity of these projects as well as the institutions undertaking the projects (e.g., military or research institutions) result in important differences that affect the approach undertaken, the costs, and the project duration.

decommissioning commercial NPPs[6] by country. The majority of all the plants are in the early stages of decommissioning, not yet dismantling the reactor building and its internals (hot-zone).

**Table 1-3: Decommissioning progress as of June 2022**

| Country | Closed reactors (total) | Warm-Up | Hot-Zone | Ease-Off | LTE | Radiologically Decommissioned (of which are Greenfield) |
|---|---|---|---|---|---|---|
| **France** | 14 | 4 | 2 | 0 | 8 | 0 (0) |
| **Germany** | 30 | 9 | 8 | 9 | 1 | 4 (3) |
| **Sweden** | 7 | 3 | 4 | 0 | 0 | 0 (0) |
| **Switzerland** | 1 | 1 | 0 | 0 | 0 | 0 (0) |
| **United Kingdom** | 34 | 13 | 9 | 0 | 8 | 0 (0) |
| **United States** | 41 | 7 | 3 | 1 | 13 | 17 (6) |

The experience that has accumulated (mainly occurring in our case-study countries) has uncovered industry weaknesses. First, regulators need to update financial regulations from the old cost models—and the resulting estimations—that have proven inaccurate (e.g., in the U.S. (Short et al. 2011)). Faced with the current funding schemes, decommissioning stakeholders are understandably concerned that unfinanced decommissioning liabilities will become taxpayers' burden (Lordan-Perret, Sloan, and Rosner 2021; Schlissel et al. 2002; Thomas 2006). Second, there are also key logistical issues that must be addressed. These include potential supply chain bottlenecks and developing procurement strategies, potential decommissioning strategy innovations, and access to waste disposal facilities. For example, very few countries have been able to establish and maintain a plan for disposing of used fuel; and as a result, facilities continue to store waste on-site preventing a fully-decommissioned status (Rosner and Lordan 2014). Third, experiences from former or ongoing decommissioning projects show the potential for market distortions and inefficiencies (e.g., market concentration leading to market power, corruption in tendering processes, principal-agent issues in contracting).

The decommissioning experience to date has also shown an evolving industry with new innovative decommissioning services and financial products. As the industry anticipates more demand, many more decommissioning service providers are emerging. While licensees previously faced the age-old decision of "make or buy" for different stages of the decommissioning process, now licensees increasingly have the option of outsourcing the entire decommissioning process. Third-party decommissioning specialists are particularly gaining prominence in the U.S. where they have successfully decommissioned two sites (i.e., Zion and La Crosse). These specialists stand to capture more market share as they develop vertically integrated supply chains with specialized staff that can more efficiently complete

[6] Refer to Figure 1-7 in the appendix of this chapter for the classification of a commercial nuclear reactor.

decommissioning projects than licensees can (Stenger, Roma, and Desai 2019). This evolution needs to be closely monitored to ensure it produces desirable market outcomes.

## 1.3 Case studies

For our research, we selected six countries with mature nuclear industries: France, Germany, Sweden, Switzerland, U.K., and the U.S. We chose these countries because they encompass a range of decommissioning approaches in varying social, economic, and institutional settings. On one end of the spectrum, we have the U.K., which has, for the decommissioning of its so-called legacy fleet, recently reassumed full, state control, and it plans to do the same for the Advanced Gas Cooled Reactor (AGR) fleet currently operated by EDF Energy (NDA 2021a; House of Commons 2022). On the other end of the spectrum, we include the U.S.—with the largest fleet of light water reactors—which is using almost exclusively a market-based approach to decommissioning. This market-based approach includes some interesting developments including license transfers to third parties and innovative dismantling strategies. The U.S. also has the most experience in decommissioning commercial reactors: Including research reactors and NPPs with less than 100 MW capacity, 17 have been completely decommissioned and 11 are in the process of being decommissioned (Schneider et al. 2022; NRC 2021). In the following subsection, we provide a brief description of the context of the nuclear industry in each country. In subsections 2.3.1 - 2.3.5, we discuss the differences and similarities of these countries' ownership/regulatory structures, decommissioning financing, production of the decommissioning work, and access to nuclear waste disposal options.

### 1.3.1 Country Context

***France***

France currently operates 56 NPPs, corresponding to over 61 GW of installed capacity and recently around 2/3 of the country's electricity share (Table 1-4). *Électricité de France* (EDF), a majority state-owned utility, owns and operates all French commercial nuclear power reactors. EDF is also involved in the U.K.'s nuclear industry through its subsidiary, EDF Energy, which also has several projects in other European countries (EDF 2022). French energy policy has been closely linked to nuclear power since the declaration of the Messmer Plan in 1974. This plan envisioned the construction of more than 200 reactors by the year 2000 and has shaped the positive, domestic perception of nuclear power (Hecht 2009). In 2022, President Macron announced a commitment to nuclear energy with the construction of several new reactors in addition to Flamanville 3, a site currently under construction (Nussbaum and De Beaupuy 2022). This commitment comes despite the fact that Flamanville 3 has been delayed by several years and is substantially over budget (Rothwell 2022).

France has not yet decommissioned any reactors. While its operating fleet of PWRs is relatively standardized—a fact that EDF hopes will result in economies of scale during decommissioning—the fleet of shutdown reactors is technologically more diverse, and a disposal pathway for some of the specialized waste streams is still lacking (Schneider et al. 2022). EDF's assumptions that high degrees of standardization will increase decommissioning efficiencies are openly challenged by regulators and in research literature (Assemblée Nationale 2017; Dorfman 2017; Wealer, Seidel, and von Hirschhausen 2019). In 2016, EDF lengthened its former decommissioning schedule to reflect changes in their decommissioning approach. Previously, EDF had planned to dismantle its gas-cooled reactor (GCR) fleet under water. Now, it plans to dismantle these reactors in air. Work will begin at GCR Chinon A2 by 2033. The regulatory agency ASN opposes this change in decommissioning approach. However, EDF made this change because the utility encountered technical difficulties concerning limited available space in the flooded reactor cores and projected issues with the disposal of contaminated water (ASN 2021; EDF 2022). For a complete overview, see the French report in Chapter 2.

**Table 1-4: Summary Statistics on French Commercial Nuclear Power Plants**

| Technology | Net Capacity Range [MW(e)] | Age Range [years] | Status |
|---|---|---|---|
| 60 PWR | 350 - 1630 | 23 - 44 | 56 operating<br>3 shutdown<br>1 under construction |
| 8 GCR | 39 – 540 | 9 – 24 | 8 decommissioning |
| 2 FBR | 130 – 1200 | 13- 36 | 2 shutdown |
| 1 HWGCR | 70 | 18 | 1 shutdown |

Note: PWR: Pressurized Water Reactor, GCR: Gas cooled reactor; FBR: fast breeder reactor; HWGCR: heavy water gas cooled reactor

***Germany***

In 2011, after the Fukushima disaster, Germany decided to end commercial operation of NPPs by the end of 2022. This led to the subsequent shutdown of Germany's NPPs, of which only three remain operational as of mid-2022, corresponding to 6% of electricity generation in 2021 (Table 5) (BP 2021). This political decision was widely accepted for the last ten years, until Europe's energy crisis of 2022 resulted in calls for some plants to continue operating. As of October 2022, three plants, Emsland, Isar-2 and Neckarwestheim-2, will remain operating until spring 2023 to ensure energy security during the cold winter months (BMUV 2022). German utilities have been decommissioning NPPs for several years (Table 1-5). Germany is one of the few countries worldwide to have decommissioned a large commercial nuclear plant—Würgassen—although the site is not yet fully released from regulatory control because nuclear waste is still stored there (Schneider et al. 2022). Germany's decommissioning market is composed of multiple decommissioning projects being carried out in parallel. The utilities plan to complete these tasks as quickly as possible. For them, decommissioning is pure liability without the profits from electricity generation (BMWI 2016; Deutscher Bundestag 2021). For a complete overview, see Chapter 3.

**Table 1-5: Summary Statistics on German Commercial Nuclear Power Plants**

| Technology | Net Capacity Range [MW(e)] | Age Range [years] | Status |
|---|---|---|---|
| 9 BWR | 183 – 1347 | 9 – 37 | 9 shutdown |
| 20 PWR | 62 – 1410 | 0.5 – 37 | 17 shutdown<br>3 operating |
| 2 HTGR | 13-296 | 3 – 21 | 2 shutdown |
| 1 FBR | 17 | 13 | 1 shutdown |
| 1 PHWR | 52 | 18 | 1 shutdown |

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor, HTGR: High temperature reactor; FBR: fast breeder reactor; PHWR: pressurized heavy water reactor

***Sweden***

Sweden has a fleet of 13 nuclear power reactors at five different NPP sites (Table 6). Currently, around 30% of Swedish electricity production stems from nuclear power (Schneider et al. 2021). The Swedish electricity market is characterized by a high amount of renewables (around 54% of total production) (Swedish Energy Agency 2021), consisting of the main energy sources hydropower, wind, and biomass. In recent years, Sweden experienced a large drop in the share of nuclear energy. This is mainly due to some large reactors shutting down recently, such as Ringhals-2 in 2019. Public support for nuclear power in Sweden is mixed, but has been increasing lately (World Nuclear News 2019). In addition, new policy developments are supportive of nuclear power: Sweden decided to abolish their nuclear energy capacity tax in 2017 with a phase-out over two years. Furthermore, in a policy reversal, the government will now allow the construction of up to ten new reactors at existing sites (World Nuclear Association 2022b). However, so far, there are no concrete plans for new NPPs. As of this writing, no Swedish commercial reactors have been fully decommissioned yet (Table 1-6). Compared to other countries, Sweden is quite far along in developing solutions for waste disposal and storage processes: Sweden has already selected a site for the permanent, geological storage of spent fuel (World Nuclear News 2020). For a complete overview, see Chapter 4.

**Table 1-6: Summary Statistics on Swedish Commercial Nuclear Power Plants**

| Technology | Net Capacity Range [MW(e)] | Age Range [years] | Status |
|---|---|---|---|
| 9 BWR | 473-1400 | 25-46 | 4 operating,<br>5 decommissioning |
| 3 PWR | 852-1130 | 40-45 | 2 operating<br>1 decommissioning |
| 1 PHWR | 10 | 10 | 1 decommissioning |

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor, PHWR: Pressurized Heavy Water Reactor

***Switzerland***

Switzerland has been operating commercial NPPs since 1969 when Beznau-1 first came online (swissinfo 2016). Currently, there are four NPPs operating in Switzerland and one commercial NPP undergoing decommissioning (Table 1-7). In fall 2022, Switzerland selected a site for its deep geological repository for nuclear waste (Nagra 2022a). Nuclear power contributes 32.9% to total domestic production, second only to hydroelectric power (BFE 2021). In 2017, Switzerland decided to exit nuclear power and forbid new NPPs from being built (UVEK 2020). Leibstadt will be the last NPP to come offline sometime in the 2040s (SRF 2019). In general, the society is mixed in its support for nuclear power. Recently, there is some discussion of reversing the 2017 decision to halt new builds (Hägler 2022). For more information on Switzerland, refer to Chapter 5.

**Table 1-7: Summary Statistics on Swiss Commercial Nuclear Power Plants**

| Plant | Technology | Net Capacity [MW(e)] | Age [years] | Status |
|---|---|---|---|---|
| Beznau-1 | PWR | 365 | 50 | operating |
| Beznau-2 | PWR | 365 | 48 | operating |
| Gösgen | PWR | 1010 | 41 | operating |
| Leibstadt | BWR | 1220 | 36 | operating |
| Mühleberg | BWR | 373 | 47 | decommissioning |

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor

***United Kingdom***

The U.K. was one of the first countries to generate electricity commercially from nuclear energy. In these early days, decommissioning was not adequately considered, resulting in today's significant challenge of decommissioning the so-called *legacy fleet*. This fleet consists of mostly old Magnox reactors with incomplete on-site documentation and complex nuclear waste streams. Inexperience and poor planning led operators to gather waste in so-called ponds that are filled with radioactive sludge that must now be carefully and arduously removed (MacKerron 2015; BEIS 2021; NDA 2022). As of today, nuclear still plays an important role in electricity generation with nine AGRs, approx. 5.9 GW, operated by EDF Energy (Table 1-8). In 2021, nuclear accounted for 15% of electricity generation in the U.K. (BP 2021). Following the recently published *Energy Security Strategy 2022,* the country is planning to increase nuclear capacity to 25 GW by 2050 (HM Government 2022). EDF began building a two-unit PWR at Hinkley Point C in 2018, which is already experiencing construction delays (EDF 2022). In terms of decommissioning, the Nuclear Decommissioning Authority (NDA) has reassumed control of shutdown reactor sites after an attempt to privatize nuclear decommissioning failed (House of Commons 2020; NDA 2021a). The legacy fleet and AGRs currently operated by EDF Energy will be decommissioned by the NDA and thus paid for in full by the British tax payer (NDA 2021b). The NDA plans to complete decommissioning for most of its fleet by 2125, except for the Scottish Dounreay site (NDA 2021a). For a complete overview, see Chapter 6.

**Table 1-8: Summary Statistics on British Commercial Nuclear Power Plants**

| Technology | Net Capacity Range [MW(e)] | Age Range [years] | Technology |
|---|---|---|---|
| 3 PWR | 1198 – 1630 | 28 | 1 operating<br>2 under construction |
| 41 GCR | 24 – 620 | 18 – 47 | 31 shutdown<br>10 operating |
| 2 FBR | 11 – 234 | 14-19 | 2 shutdown |
| 1 SGHWR | 92 | 23 | 1 shutdown |

Note: PWR: Pressurized Water Reactor, GCR: Gas cooled reactor; FBR: fast breeder reactor; SGWR: sodium gas cooled heavy water reactor

***United States***

The U.S. has the largest commercial nuclear power reactor fleet. At its peak in 1990, the industry was operating 112 reactors, mostly based on light-water technology (Table 1-9). The commercial nuclear industry began in the 1950s and grew with great momentum until the 1980s. Now, however, the reactor fleet is not only ageing (average age 40.7 years) but also facing stiff competition from other technologies, in particular new renewables and gas power plants when the price of gas was low. The 92 operating reactors currently account for 19% of total electricity generation. Support for nuclear power is mixed in the U.S., largely falling along partisan lines. However, both recent Democratic and Republican administrations supported a role for nuclear in any future energy mix. The Biden administration has already put forward two federal level support schemes[7] to secure the continued operations of all operating reactors over the coming years. The new policy development is part of the administration's effort to reduce emissions and achieve a clean electric grid (Schneider et al. 2021). However, the industry has only planned and built a few reactors, with only a single reactor (Watts Bar 2) coming online since the 1980s. Currently, Vogtle units 3 and 4 are the only new reactors under construction and are expected to begin commercial operations in 2023. On the decommissioning front, the U.S. has accumulated substantial decommissioning experience with 14 commercial reactor units fully decommissioned and 11 reactors currently undergoing active decommissioning. However, early evidence from completed decommissioning projects suggests cost and schedule overruns may be an important financial risk for this industry (Lordan-Perret, Sloan, and Rosner 2021). Nuclear licensees are increasingly pivoting towards specialist decommissioning companies to take over and complete the decommissioning project as elaborated earlier. As an example, the most recent units to complete decommissioning (Zion 1 and 2) were outsourced to Zion*Solutions*—a subsidiary company of Energy*Solutions*. For a complete overview, see the final Chapter 7.

[7] The Civil Nuclear Credit Program (CNC) and the zero-emission Nuclear Power Production Credit (NPPC).

**Table 1-9: Summary Statistics on US-American Commercial Nuclear Power Plants**

| Technology | Net Capacity Range [MW(e)] | Age Range [years] | Technology |
|---|---|---|---|
| 43 BWR | 22-1401 | 3-53 | 31 operating<br>7 decommissioning<br>5 decommissioned |
| 81 PWR | 60-1314 | 1-54 | 61 operating<br>12 decommissioning<br>8 decommissioned |
| 2 HTGR | 40-330 | 8-13 | 1 decommissioning<br>1 decommissioned |
| 1 FBR | 61 | 6 | 1 decommissioning |
| 1 SGR | 75 | 1 | 1 decommissioning |
| 2 AP-1000 | 1250 | n.a. | 2 under construction |

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor; HTGR: High Temperature Gas Reactor; FBR: fast breeder reactor; SGR: Sodium graphite reactor; AP: Advanced Pressurized Water Reactor

### 1.3.2 Organization

Each country allows different ownership structures. In Figure 1-2, we group them in two large categories to highlight similarities and dissimilarities that we have identified. The umbrella term ‘centralized’ refers to a single owner, which in the case of France, is a single publicly owned corporation. By ‘decentralized’, we try to capture the role of private industry, publicly owned entities, and cooperatives. The country-specific details of ownership structure vary based on country-specific laws. For example, in the U.S., corporate laws encourage licensees to create a series of limited liability corporations (LLC) that distance a parent company from its subsidiaries. We provide a brief description of each ownership structure below.

**Government**

Under a government structure, the state retains ownership of the NPPs. This means that there is no possibility for other actors or institutions to obtain shares, i.e., shares are not traded on the stock exchange. For example, the U.K.’s NDA is a non-departmental agency of the government that reassumed control (and ownership) of the British legacy fleet for decommissioning. Previously, multiple private actors owned these reactors. Thus, nuclear decommissioning has become a matter of the state, which can also be seen in the planned transfer of EDF Energy’s AGRs to NDA ownership for decommissioning.

**Publicly Owned**

The public ownership classification encapsulates ownership by utility companies and corporations that operate as commercial entities, but that are ultimately owned by public actors. This form of ownership structure is present in all our case-study countries as demonstrated in Figure 1-2. A clear example of public ownership is France where EDF fully owns and controls all 56 of France’s operating reactors and

11 out of its 14 shutdown reactors.[8] In the U.S., public ownership takes the form of state utility companies that own shares of nuclear reactors. For example, Nebraska Public Power District is a state-owned utility company that fully owns the Cooper 1 reactor. In Switzerland, nuclear reactors are largely owned by public entities such as the cantons[9] or cities (Kernkraftwerk Gösgen 2020). The NPP Beznau is fully owned by the North-East Swiss cantons (Axpo 2020). Similar to the Swiss case, the ownership structure in Sweden is characterized by a high involvement of publicly owned utilities. For example, Vattenfall, which is 100% owned by the Swedish state, is the majority shareholder of Ågesta and Forsmark (IAEA 2022). In Germany, the six legacy nuclear reactors at the Greifswald and Rheinsberg nuclear plants are owned by Entsorgungswerk für Nuklearanlagen (EWN) GmbH, a fully government owned corporation. Germany's domestic utility EnBW is responsible for four NPPs and is majority owned by the federal state of Baden-Württemberg and nine municipalities located therein (Deutscher Bundestag 2021).

**Investor Owned**

Under the investor-owned structure, large private corporations fully or partially own NPPs. In the U.S., for example, many utilities are large investor-owned companies that own the NPPs (e.g., Exelon, Entergy, Dominion). These companies typically act as parent companies, owning NPPs through their subsidiaries in the form of LLC. The LLC then fully or partially owns the nuclear reactor. In Germany, the fleet of reactors are majority owned by both large domestic utilities (E. ON and RWE) and the Swedish utility Vattenfall. Further examples of investor ownership are found in Switzerland and Sweden, respectively, where private companies may own shares of—rather than fully own—NPPs.

**Cooperative Owned**

Cooperatives are not-for-profit organizations that are owned by their members. In the U.S., cooperatives with nuclear ownership interests are large electric utilities that generate electricity from a broad portfolio of technologies and supply power to a coalition of electric distribution cooperative members. In turn, cooperative members distribute power to local end-users. For instance, the Georgia-based utility, Oglethorpe Power Cooperative, owns 30% of the Vogtle 1 & 2 reactor units and the Edwin Hatch 1 & 2 reactor units. Electricity generated from Oglethorpe is supplied to its 38 local cooperative members that distribute power to approximately 4.4 million end-users at reduced rates (OPC 2021). Cooperatives in the U.S. share ownership of nuclear reactors with other ownership structures as well, such as investor-owned companies and state-owned utilities.

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[8] In October 2022, the French government initiated a process to fully nationalize EDF at a cost of €937 billion (Mallet and Thomas 2022). When this nationalization is complete, nuclear plants would transition to The full governmental ownership.

[9] Cantons are the constituent states of Switzerland. Each canton has its own cantonal constitution and its own legislative, executive and judicial authorities.

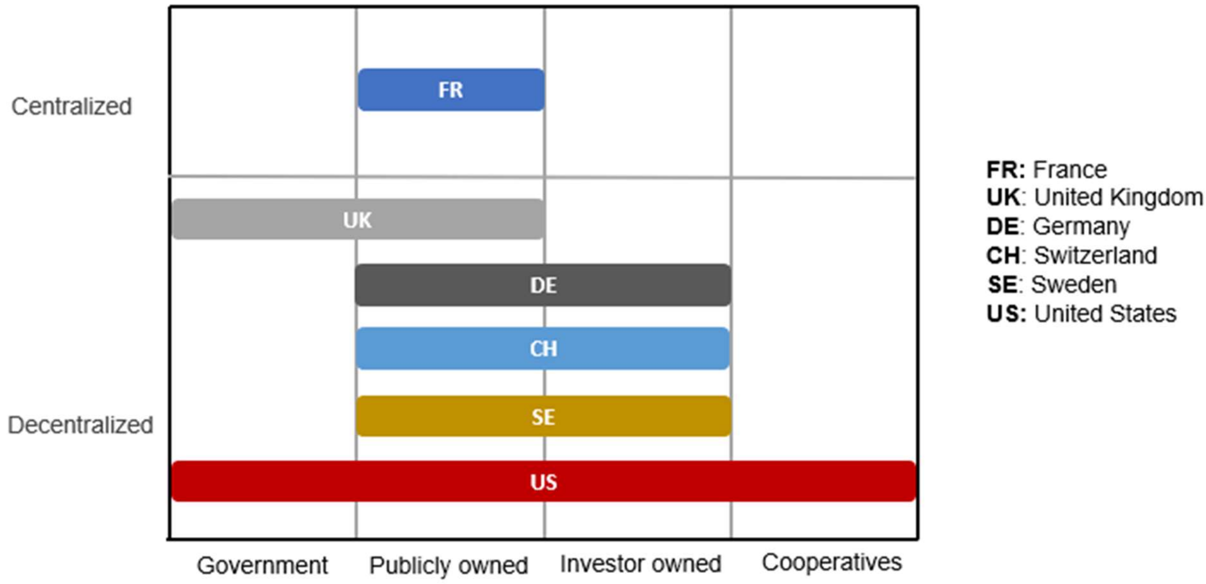
**Ownership Changes**

Ownership of nuclear plants in some countries is subject to change before or during the decommissioning process. In some countries, NPPs have changed ownership during operations. These ownership changes may affect decommissioning if the new owners decide to alter the existing decommissioning schedule (e.g., by pursuing a longer operating license or by shutting down early). These ownership changes may affect how owners finance or conduct decommissioning, although changes depend on the regulations in each country. In the countries we considered, the financial regulations for decommissioning remain the same in the cases of during-operation ownership changes. In countries like Sweden and Switzerland, the decommissioning funds remain in the hands of central bodies who manage and collect these funds from the licensees/owners (STENFO 2021a; Kärnavfallsfonden 2020). In the U.S., the decommissioning funds remain with the plants and remain segregated from the control of the new owners (Lordan-Perret, Sloan, and Rosner 2021).

Ownership may change during the decommissioning phase as well. If the licensee decides to undertake the decommissioning process itself (i.e., “make” or self-production), we find that ownership does not change because of decommissioning (see section 2.3.4). If the licensee decides to outsource the decommissioning project, however, ownership might change hands during the decommissioning process. For example, in the U.S., third-party specialists are engaging in different contracts to decommission NPPs. In a “license acquisition” decommissioning model, the decommissioning specialist (e.g., Holtec International) purchases the NPP, along with all other assets and liabilities (including waste), prior to decommissioning.[10] We hypothesize that these arrangements may have a larger influence on decommissioning financing and production. Another example of the transfer of ownership during the decommissioning process is the U.K. The NDA has reclaimed ownership over all shutdown reactors belonging to the old legacy fleet and thus, is in charge of their decommissioning (Holliday, HM Government, and Department for Business 2021). Further, EDF and the NDA reached an agreement in 2021 stating that ownership of all of EDF’s AGRs will also be transferred to the NDA once the reactors have been defueled (House of Commons 2022). PWR at Sizewell B will remain in EDF Energy’s ownership (EDF 2022). Thus, currently, all shutdown reactors in the U.K. belong to (or will belong to) the NDA (see Chapter 6).

[10] In a “license stewardship” decommissioning model, the decommissioning specialist (e.g., Energy*Solutions*) assumes the role of licensee the NPP during the decommissioning process. The ownership of the plant remains, however, with the original owner.

**Figure 1-2: Country comparison of nuclear power plant ownership**




Note: This Figure reflects the current ownership structure of the countries as of October 2022. Projected changes in ownership structure are not included, for example, French transition to full government ownership.

### 1.3.3 Regulation

In every country, the nuclear industry is highly regulated. In some countries, the regulators are centralized in one agency overseeing the entirety of the industry from granting licenses to environmental protection to safety inspections (e.g., France with ASN or the U.S. with the NRC). However, in other countries the regulators come from diverse bureaus within the government and government agencies. For example, in Switzerland, the government bureau for environment (DETEC) plays an important role in granting licenses, while a separate government agency ENSI is responsible for safety and security (Chapter 5 for more details).

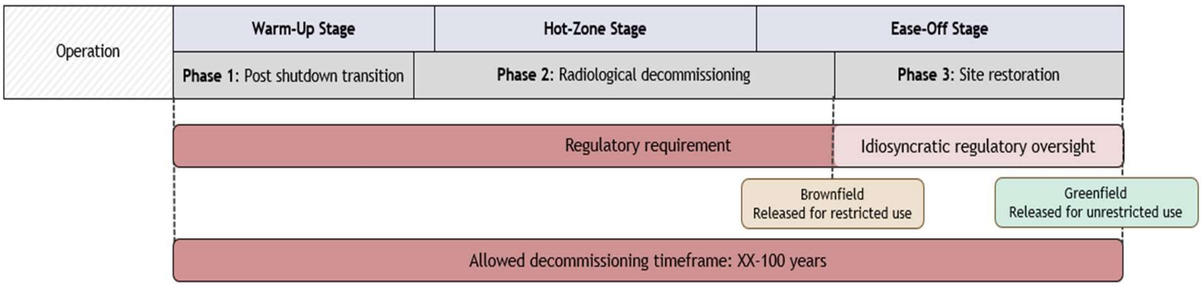
As the nuclear industry has developed, countries have moved to make their regulators entirely independent of the nuclear industry, recognizing that it is not good practice to have the same bodies promoting and regulating the industry. However, in an industry with highly specialized personnel with highly specialized skillsets, total independence is quite hard to achieve, and some industries have been accused of having a rotating door between industry and the regulatory bodies (von Hippel 2021).

Over the lifetime of a NPP, there are some important regulatory junctures. Figure 1-3 shows the regulatory steps that occur toward the end of a plant's lifetime. Prior to official shutdown of the nuclear reactor, licensees prepare detailed decommissioning plans and submit them to the appropriate regulatory bodies. While the contents of this plan vary across countries, it typically consists of the planned decommissioning activities, timelines for the planned activities, and in some cases, a decommissioning cost estimation.

Actual decommissioning proceeds with the phases described in Section 2.2.1. The important regulatory junctures follow the post operational phase when decommissioning officially begins; the end of the hot-zone phase when the site can be released from radiological regulation, although this sometimes occurs during the ease-off phase, when buildings have been fully decontaminated (brownfield); and following the ease-off phase, when the plant can be released as a 'greenfield' site (Figure 1-3).

Licensing requirements during the decommissioning process vary across the countries. Licensees in the U.S., Sweden, and the U.K. maintain the operational license throughout the decommissioning process, while licensees in Switzerland, Germany, and France are obligated to apply for a specific decommissioning license to proceed with the decommissioning project. In Switzerland and France, the licenses are issued by federal governmental authorities, and in Germany, by federal state government authorities. Turning to the role of agencies in the decommissioning process, we find that in five case study countries, a single governmental body maintains regulatory jurisdiction throughout the decommissioning process. Examples include ENSI in Switzerland and the NRC in the U.S. Germany is the exception, in that the BMUV and its subsidiary agencies BASE and BfS oversee the entire decommissioning process.

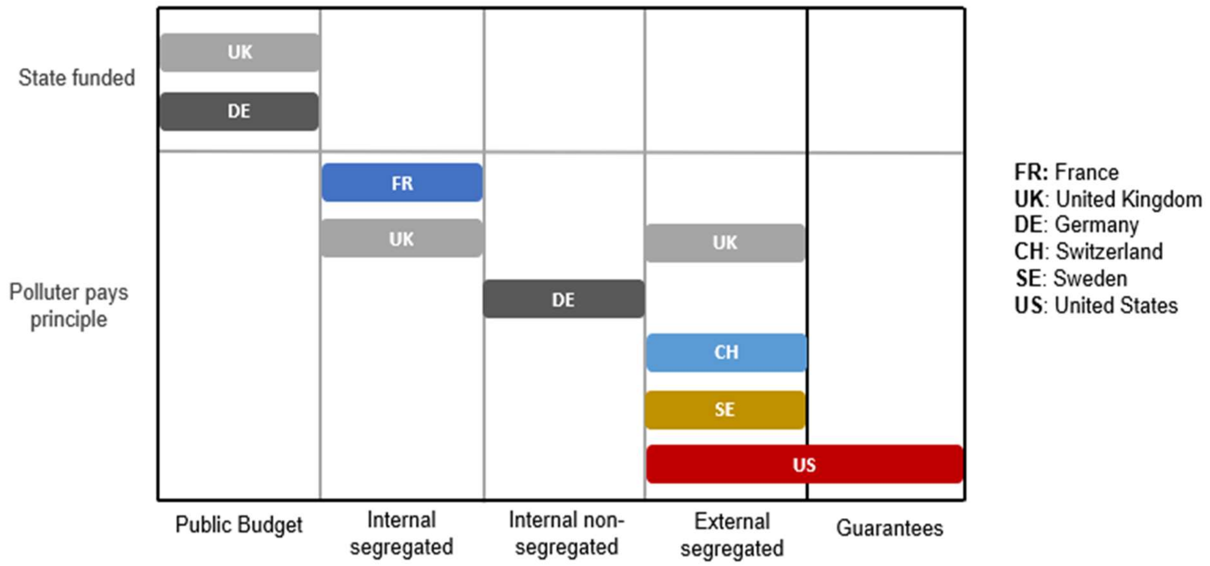
**Figure 1-3: A generalized depiction of the lifetime of a nuclear power plant and some important regulatory junctures**




### 1.3.4 Financing

In general, the "Polluter Pays Principle" is widely accepted among countries. It implies that the polluter, i.e., the nuclear power operator, is responsible for the costs of decommissioning and waste disposal (OECD/NEA 2006). In reality, however, this principle is implemented in varying degrees. In Sweden and Finland, for example, the principle is a legal requirement. In other countries, the state has taken over and is primarily responsible for the funding of decommissioning (Irrek, Kirchner, and Jarczynski 2007; Irrek 2019). In the case of the government paying, financing and fund accumulation are relatively straightforward: the licensees submit their decommissioning costs to the government that appropriates the needed funds accordingly. In contrast, under "polluter-pays", the licensees may accumulate, secure the liquidity of, and invest funds in three main ways: Internally segregated funds, internally non-segregated funds, and external segregated funds (Irrek, Kirchner, and Jarczynski 2007). In Figure 1-4, we show how the countries in our case studies organize their decommissioning financial provisions. Licensees financing their own decommissioning must set money aside in funds at regular intervals (typically yearly). To calculate appropriate payments, licensees usually prepare and submit decommissioning cost estimates along with assumptions about amortization, investment earnings, remaining operational lifetime, etc. Most regulators require licensees to revise their cost estimates regularly, particularly when nearing the decommissioning phase (OECD/NEA 2016). The regulators oversee and verify the adequacy of these funds. Still adequacy of funds is a concern in many countries, for example, the U.S. (Lordan-Perret, Sloan, and Rosner 2021). In particular, countries that require the licensees to fund decommissioning are concerned that the government will need to use public money to finance unfunded decommissioning liabilities. All monetary values inflation-adjusted to 2020. Where necessary, exchange rates to USD and EUR are provided.

**Figure 1-4: Decommissioning fund organization**




**Public Budget**

In some cases, funds for decommissioning come from the respective government's budget. The U.K.'s NDA recently assumed full responsibility for nuclear decommissioning of the legacy fleet and will work on dismantling EDF Energy's AGR fleet once these plants have been defueled (NDA 2021a; House of Commons 2022). As a non-departmental agency, the NDA is fully funded by the British government that has been making provisions for many years (NDA 2021b). In the former German Democratic Republic (GDR), the state owned and operated the NPPs. Consequently, decommissioning responsibilities stayed with the state after German reunification. State-owned company EWN has been working at former sites Greifswald and Rheinsberg for several decades and is fully funded by the

German federal state (Besnard et al. 2019; EWN 2021). Public budget financing can—in some cases—go against the "polluter-pays-principle," as demonstrated by the NDA's future responsibility of AGR decommissioning (which is supposed to be funded by the Nuclear Liabilities Fund, which has in turn received substantial cash injections by the British government, see below). Whatever the case may be, due to the long-term process of decommissioning, the government will use future taxpayers' money to clean-up nuclear legacies.

**Internal Segregated**

Under an internal segregated fund arrangement, licensees make payments to a fund, which is self-administered and managed. These funds are separated from other business interests the company/entity may be engaged in as well as other company/entity assets. In contrast to the internal non-segregated approach, licensees earmark the funds specifically for decommissioning purposes through the segregation process. This increases protection against insolvency and provides a greater degree of transparency. Furthermore, it also facilitates oversight over the funds (OECD/NEA 2016; Irrek 2019). France uses an internal segregated fund approach according to Article 20/II of the 2006 Waste Law (Schneider et al. 2018).

**Internal Non-Segregated**

With an internal non-segregated funding scheme, licensees self-administer and manage funds as with an internal segregated arrangement. However, non-segregated funds need not be managed or separated from other company/entity business interests or assets. The company holds the funds within its account in the form of reserves and discloses the accumulated provisions by year. Therefore, there is no requirement that a specific amount of funds is dedicated or earmarked for decommissioning purposes (Irrek 2019). This approach was used quite frequently within the OECD (OECD/NEA 2006) but has lost its popularity in recent years. Concerns have been raised especially with respect to liquidity and sufficiency of funds (OECD/NEA 2016). West German utilities use this approach for financial assurance (Schneider et al. 2018).

**External Segregated**

Under an external segregated fund arrangement, licensees make regular payments to a fund (or funds), which is (are) completely separate from their other assets. Once the licensees have deposited money into such a fund, they no longer have control over, or access to, the money (Schneider et al. 2018).

In some countries, a central body aggregates the funds and redistributes the money during each decommissioning project. For example, in Switzerland, the financial agency STENFO (National Decommissioning and Waste Disposal Fund Organization) is in charge of managing two separate funds for decommissioning and waste disposal. The operators of Swiss NPPs contribute to the funds annually.

The fees are calculated based on cost estimation studies which are carried out every five years (STENFO 2021b). The money in the two funds is intended to cover all decommissioning and dismantling costs as well as the disposal costs of the resulting decommissioning waste. According to Swiss law, STENFO may not reimburse decommissioned NPPs until all the plants are radiologically decommissioned–even if a fully decommissioned site has over paid (UVEK 2019). Sweden has a similar system in place. Decommissioning is financed by funds from the Nuclear Waste Fund (NWF). The NWF is a government authority and manages the fee payments, fund assets and keeps other governmental authorities informed (Kärnavfallsfonden 2020). In addition to paying fees to the NWF, Swedish NPP operators also have to provide collateral to cover future fees and unforeseen events (Swedish National Debt Office 2022; Stralsakerhetsmyndigheten 2015).

In the U.S., licensees often use a segregated fund approach. Unlike in Switzerland or Sweden, the funds are not pooled or centrally managed, rather the money remains associated with individual reactors/power plants in a so-called Decommissioning Trust Fund (DTF). There are clear regulations on how licensees may invest these funds and how the licensee may spend the funds once decommissioning has begun (10 CFR 50.75). Approximately 70% of licensees accumulate funds over the lifetime of the facility, while the remaining 30% use other mandated methods (see Surety Methods/Guarantees below), alone or in combination (Moriarty 2021). The NRC mandates licensees to provide reports on their DTF balance on a biennial basis to ensure that adequate funds are set aside for decommissioning (10 CFR Part 50.75(f)(2)). Once a reactor enters the decommissioning stage, the NRC requires that licensees subsequently submit DTF fund balance reports annually.

In 1996, the Nuclear Liabilities Fund (NLF) was set-up to cover liabilities of British AGR decommissioning, then owned and operated by state-owned utility British Energy (Thomas 2006). The British government made payments to the NLF. Originally, the British government did not intend for British taxpayers to bear any financial decommissioning responsibilities; however, due to the unexpectedly low performance of the NLF on the market since its creation, the funds are estimated to be insufficient (Nuclear Liabilities Fund 2021). These insufficient funds resulted in the British government applying cash injections of an expected sum of approximately 10 billion GBP[11] into the NLF funds in 2020-2022 (House of Commons 2022).

**Surety Methods (aka Guarantees)**

In the U.S., licensees may use a variety of financial instruments (or a combination) to satisfy financial assurance requirements, including surety bonds; letters of credit; parent company guarantees (so-called surety methods); and prepayment and trust funds (see External Segregated Funds). While the laws and regulations on fund accumulation and adequacy remain the same, some licensees can obtain surety bonds/insurance and guarantees from third parties for their decommissioning liabilities. Third parties

[11] 1 GBP = 1.18 USD = 1.15 EURO 2022

must submit financial documents and pass a financial vetting by the NRC (10 CFR 50.75(e)(1)(iii)). Approximately 30% of licensees use guarantee methods, alone or in combination (Moriarty 2021).

### 1.3.5 Production

As mentioned above, nuclear decommissioning is a complex process, both from a regulatory and organizational perspective as well as a technical perspective. Given the complexity and specialized nature of much of the decommissioning work—and the necessary equipment and infrastructure—many licensees choose to outsource some or all of their decommissioning work. Outsourcing ranges from hiring a consulting firm to produce cost estimates to having a contracting firm dismantle the reactor pressure vessel to outsourcing the entire decommissioning project to a third party. Licensees must answer the age-old question: “Make or Buy”?

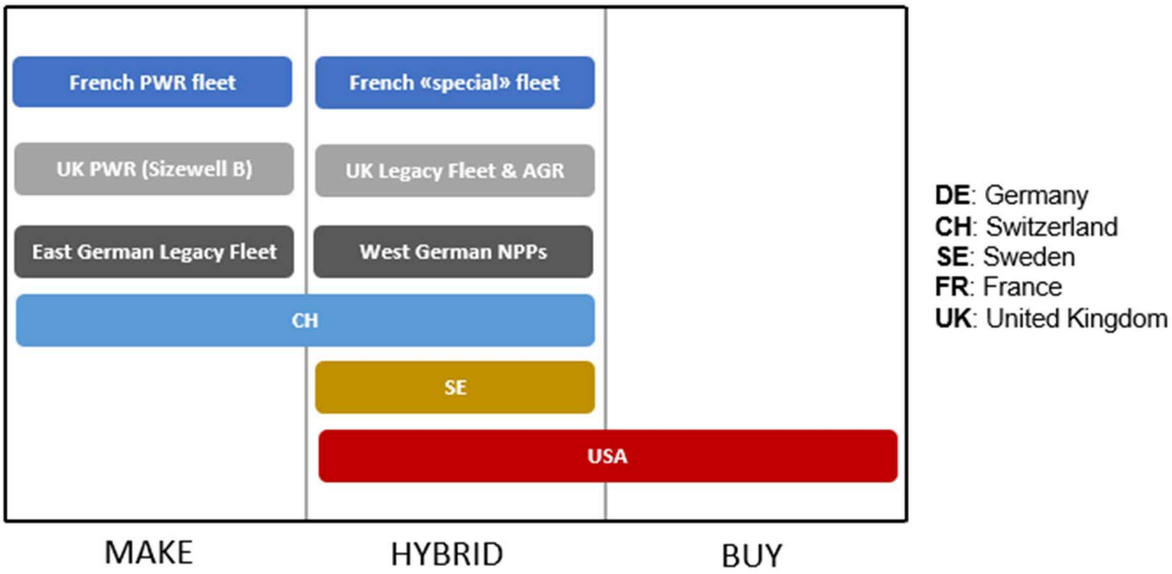
In the case of nuclear decommissioning, this question is particularly relevant for the most complex and risky tasks of decommissioning, which occur during the hot-zone phase. This phase is characterized by a high degree of asset specificity. Licensees/operators must ask themselves whether it will be more efficient to outsource tasks to specialized firms (“Buy”) or build up their own knowledge and specialized workforce to conduct these tasks themselves (“Make”).

Specialized firms undertake projects at different NPPs, thus they acquire a high-level of efficiency and competency. The experience of these firms is very valuable and can save scarce resources (relative to a “Make” decision), particularly in more complicated cases. However, there are risks related to contracting. For example, in the U.S., there were multiple documented cases where contractors did not perform their work adequately, resulting in delays and legal battles (Short et al. 2011). These sorts of contracting issues are commonplace in other industries as well: Another age-old issue, the principal-agent problem (Furubotn and Richter 2005). Licensees that choose to outsource an entire decommissioning project can mainly solve this principal-agent problem by aligning the specialized firm’s incentives with their own (expediency, cost efficiency, safety). For example, in the U.S., third-party decommissioning specialists like Holtec International and Energy*Solutions*, are completing entire decommissioning projects. There are different types of decommissioning contracts ranging from temporary responsibility and management of a facility during decommissioning (license stewardship) to purchasing shutdown NPPs to conduct decommissioning themselves (license acquisition) to management of an entire fleet of decommissioning reactors (fleet model) (Stenger, Roma, and Desai 2019).

Other licensees choose a “Make” model, often when they have more than one unit to decommission, or they intend to leverage earned experience in order to provide decommissioning services in the emerging industry (see EDF’s plans for its PWR fleet). Another option often mentioned in literature is a hybrid approach that involves some form of strategic cooperation between industry actors (Klein 2005).

In our analysis, we seldom found a single approach that was applicable to a whole country (Figure 1-5). In France, EDF plans to follow a Make approach for its PWR fleet by using knowledge from its subsidiary Cyclife, and thus achieve scale effects and cost savings. For its more diverse fleet of GCRs, old PWRs (e.g., Chooz-A) or FBRs (Super-Phénix), EDF has contracted decommissioning tasks to outside contractors such as Westinghouse or Orano.[12] In Germany, most utilities have outsourced decommissioning tasks to others (Buy), but for the East German NPPs, state-owned company EWN conducts decommissioning itself and is also involved in other projects. Utility-owned fuel cask manufacturing company, GNS, is also actively involved in German nuclear decommissioning projects. Swedish utility, Uniper, has tasked its own parent company Fortum with decommissioning, keeping production de-facto in-house, while Vattenfall has tasked Westinghouse for its shutdown reactors. The U.K. has shifted from a privatized so-called "parent-body-organization"-model[13] (Buy) to a hybrid strategy, as state-owned site license companies are officially tasked with decommissioning, but contract certain tasks to industrial actors, such as Cavendish Nuclear. Switzerland, for now, relies on the Make strategy. However, Switzerland collaborates closely with external experts especially for highly specialized tasks, e.g., the cutting up of large components such as the reactor pressure vessel (BKW 2020).

**Figure 1-5: Diagram of Make or Buy production decision that nuclear licensees undertake.**




[12] Just like EDF, Orano is also majority owned by the French state.
[13] Refer to the UK Report for further detail on the PBO scheme.

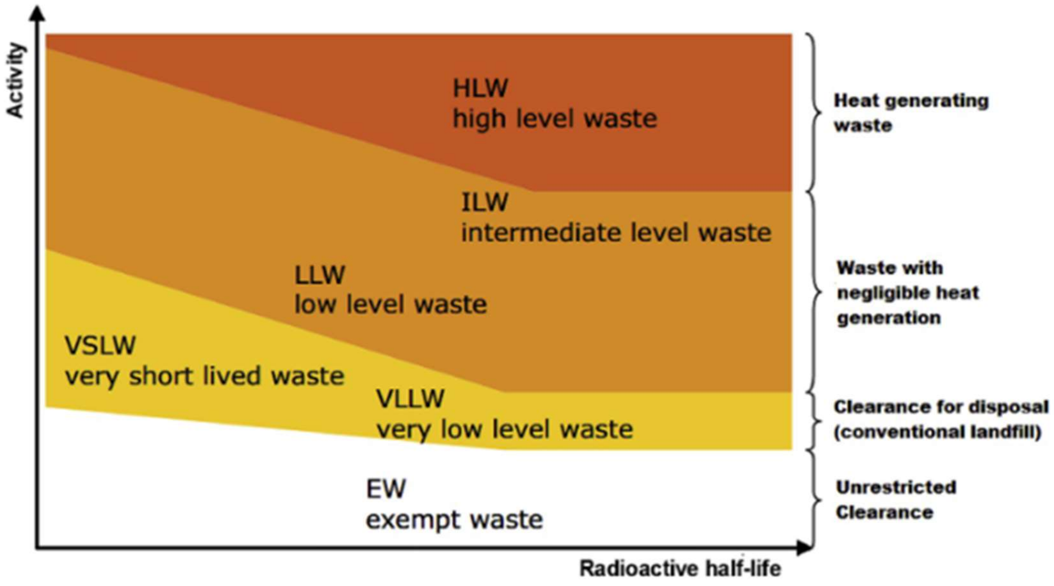
### 1.3.6 Nuclear waste management

When a licensee decommissions its NPP, there are multiple radioactive waste streams. These waste streams vary in terms of their radioactivity, thus they must be disposed of with different regulatory controls and technologies. While the details of waste disposal worldwide are both interesting and important, we will provide a simple treatment here in which we focus only on wastes and waste disposal to the extent that they are essential for decommissioning, that is, whether licensees have access to appropriate disposal routes for the most important waste streams.

Regulators around the world categorize radioactive wastes by their radioactivity and half-life (IAEA 2009). These and other indicators help regulators determine how licensees must package the waste, at what type of facility the waste must be disposed, and the length of time the wastes must be isolated from humans and the environment. According to the International Atomic Energy Agency (IAEA), there are six waste classifications: Exempt Waste (EW), Very Short-Lived Waste (VSLW), Very Low-Level Waste (VLLW), Low-Level Waste (LLW), Intermediate Level-Waste (ILW), and High-Level Waste (HLW). LLW, ILW, and HLW are the classes of waste that influence decommissioning because the licensees must have access to specialized disposal for these wastes before the site can be fully released from radiological regulations. We take for granted that licensees have access to normal industrial waste disposal for EW and VLLW.

LLW is waste that exceeds clearance levels with potentially both longer-lived (though in small amounts) and shorter-lived radioisotopes present and must be isolated for—on the order of—hundreds of years. ILW is characterized by the presence of more long-lived radioisotopes. It cannot be disposed of in near surface facilities. However, ILW does not need any heat dissipation measures (e.g., the reactor pressure vessel). HLW, on the other hand, generates a lot of heat and must be packaged and disposed of in ways that manage this heat. Further, HLW must be isolated for *thousands* of years. Geological repositories are the suitable disposal method for HLW; however, as a temporary solution, this waste can be stored in consolidated interim storage sites in special containers until a deep geological repository is operating. Spent nuclear fuel (SNF) falls into the category of HLW (Figure 1-6) (IAEA 2009) and is typically the waste that people think of associated with nuclear power.

**Figure 1-6: Conceptual figure of IAEA waste classification and proper disposal routes.**




Source: Thierfeldt and Schartmann (2009)

In Table 1-10, we indicate for each of our case study countries whether a disposal route for each LLW, ILW, and HLW is "unplanned," "planned or under construction," or "available."

**Table 1-10: Radioactive waste disposal options by country and waste level (IAEA 2016)**

| Country | LLW (near surface disposal) | ILW (intermediate depth disposal) | HLW/SNF (interim storage) | HLW/SNF (deep geological disposal) |
|---|---|---|---|---|
| **France** | - | Planned to be disposed of with HLW | - | Planned; site selected |
| **Germany** | Available | Planned to be disposed of with LLW; currently in interim storage | Available Dry Storage (on-site) Available Wet Storage Obrigheim NPP (Consolidated) | Unplanned |
| **Sweden** | Available | Available | Available Wet Storage at NPP (Consolidated) | Planned/ preparatory work underway |
| **Switzerland** | Planned | Planned to be disposed of with LLW; currently in interim storage | Available | Planned; site selected |
| **United Kingdom** | - | - | Available Dry Storage at NPP Available Wet Storage at NPP (Consolidated) | - |
| **United States** | Available | Available but only for military waste; commercial waste to be disposed of in a yet unplanned repository | Available (on-site) Planned (consolidated) | Unplanned |

Almost all countries with nuclear power struggle with the management of HLW and SNF. Worldwide there are only a few countries (i.e., Finland, France, Sweden, Switzerland) that have sited a location to build a geological repository. Finland is the only country currently building a geological repository, which should begin operating in the next few years (World Nuclear Association 2022a). Despite this, decommissioning is still possible. Without a solution for the final disposal of high-level waste, to decommission licensees can either construct an interim storage facility on-site, as many countries have, or seek consolidated storage (government or privately supplied). With an interim storage or a consolidated site, licensees can remove SNF and proceed with dismantling facilities with HLW by isolating and storing the HLW and SNF until a final disposal route becomes available. However, with final disposal facilities being available only in a few decades, challenges arise in terms of interim storage as storage facilities and interim nuclear waste containers such as the German CASTOR are often only licensed for a few decades, in the case of Germany, 40 years. This means that until a final disposal facility is operational, new licensees will have to be granted or waste will have to repackaged to ensure maximum safety (Endlagerkommission 2016).

A larger hurdle for some countries is access to low- and intermediate-level wastes. As LLW is the majority of the waste that results from decommissioning (IAEA 2007a; OECD/NEA 2016), we observe that access to LLW disposal may be a critical chokepoint for decommissioning.

Turning to our surveyed countries, all countries have dedicated nuclear waste regulations and acts that share similar requirements regarding safety and security. Concerning the oversight over nuclear waste, we find some variation in our countries especially about the involvement of the government. In Sweden and Switzerland, nuclear waste is not overseen by a dedicated governmental agency. Rather, two independent bodies, the Swedish Nuclear Fuel and Waste Management Company (SKB) and the Swiss National Cooperative for the Storage of Radioactive Waste (Nagra), are tasked with the management and designing of disposal facilities for of radioactive waste (SKB 2021; Nagra 2022b). Even though these bodies are deemed independent, the government is directly involved through, for example, granting approval of disposal sites or extension of disposal facilities. In our other countries, France, Germany, U.S. and the U.K., the government has a direct oversight over the management of nuclear waste not only through approval of sites but also in terms of operating and sometimes building of the required facilities. For example, in Germany, there is the so-called "national disposal program" that is subject to the supervision of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. The program defines that nuclear waste is of national responsibility (BMUV 2015). In the U.S., the NRC has full regulatory oversight over the disposal of LLW, ILW and HLW waste, spent fuel management and the transportation of nuclear waste.

## 1.4 Insights from case studies

Based on our analysis of these case study countries, we have identified common themes and insights. From these themes and insights, we derive a suite of research opportunities. We have organized this by topic.

### 1.4.1 Insights from organization/regulation

***Interlinkage between ownership and nuclear decommissioning***

Based on our findings and the recent developments in the nuclear decommissioning industry, the link between nuclear decommissioning and ownership is one potentially highly relevant research topic. Ownership influences decommissioning directly and indirectly. It directly affects decommissioning via financing and scheduling, production of decommissioning work, and eventual liability for any unfunded decommissioning work. For example, regulators may not require government owners to set liquid funds aside because the government can guarantee the liquidity of its funding by the simple fact that it is has access to government funds. Government owners are not necessarily incentivized to the same extent as investor owners to decommission sites rapidly with shareholders closely watching the balance sheets. If the NPP is owned by corporate investors, however, incentives might present themselves differently. Corporate investors have an incentive to sell their power plants once they stop producing energy to eliminate the liability from their balance sheets (Stenger, Roma, and Desai 2019). If the facility is purchased by a decommissioning company, as in the case of the U.S., (e.g., Holtec), decommissioning production will largely be undertaken by the owners who have in-house expertise and resources.

***Influence of regulatory framework on nuclear decommissioning***

The decommissioning process is heavily bound to country-specific laws and regulations, and the regulations differ substantially across countries. Sometimes, decommissioning oversight is consolidated under the jurisdiction of a single governmental body. From the vantage point of large-scale project management, having a single regulatory body has the advantage of unified coordination and oversight. Concerns have also been raised about the impact of having multiple regulatory bodies on the nuclear decommissioning process. More importantly, the degree of regulatory stringency has a significant bearing on the decommissioning process. As regulations become more stringent, decommissioning compliance costs rise (Invernizzi et al. 2019). For example, changes to asbestos regulation in the U.K. in the late 1990s reduced the number of landfill sites that could accept asbestos waste from nuclear sites, resulting in an increase in waste disposal costs (Downey and Timmons 2005).

Across the globe, particularly in Asia and the Middle East, nuclear newcomer countries are slowly emerging. These countries are faced with the significant challenge of developing the entire nuclear regulatory infrastructure from the ground-up, as in the UAE, or systematically overhaul outdated legislation to meet international best practices such as in Bangladesh, Pakistan and Turkey (IAEA 2021;

AlKaabi 2022). Inevitably, newcomer countries will tend to conform to regulations of vendor countries when formulating their domestic regulations (IAEA 2021). The key challenge then is to harmonize 'foreign' regulations with domestic legislation and capacity. Moreover, another challenge for newcomer countries is keeping nuclear regulations abreast with the continuous development of the nuclear industry. In this dimension, regulations covering the back-end of the nuclear spectrum (i.e., decommissioning and nuclear waste) may potentially lag behind. In Bangladesh, for example, despite the ongoing construction of two reactors at the Rooppur NPP, concerns have been raised about the deficiencies in nuclear waste regulations (Islam, Faisal, and Khan 2021).

### 1.4.2 Insights from financing decommissioning

Across the board, financing emerges as one of the most contentious and complex issues for decommissioning stakeholders. As relatively few commercial nuclear power reactors have been decommissioned, there is not a lot of data on how much decommissioning actually costs. Furthermore, the decommissioning industry is nascent and supply chains are just beginning to develop, and arguably not yet to scale. As a result, costs for decommissioning goods and services are neither stable nor entirely predictable. Some major themes that are common across our studies countries include how the decommissioning market will develop, cost estimations, estimations of contingency for cost and schedule overruns, the adequacy of funding (both in terms of contributions and returns on investments), how funds are monitored, security of funds, and liability for unfunded decommissioning work.

***Improving of cost and contingency estimations***

Cost estimations across the countries vary significantly. Based on the experience (mainly from the U.S.) accumulated up until now, cost estimations have proved inaccurate and could be improved to reflect the knowledge derived from completed projects (Short et al. 2011; Assemblée Nationale 2017). Importantly, these cost models do not uniformly underestimate decommissioning: some important aspects (e.g., LLW disposal) of the cost of radiological decommissioning are underestimated, while other aspects are overestimated (Short et al. 2011).

As is often the case for complex, long-duration megaprojects, calculating contingency for cost and schedule overruns is challenging. Cost and schedule overruns typically arise from a variety of sources, including unrealistic cost assumptions (e.g., Ahiaga-Dagbui and Smith 2014); poor management of tradeoffs and risks (Ahiaga-Dagbui and Smith 2014; Ökmen and Öztaş 2010); overly optimistic planning or more intentional corruption and strategic misrepresentation of costs (e.g., Flyvbjerg, Skamris Holm, and Buhl 2004). The nuclear industry is notorious for cost and schedule overruns during construction (Sovacool, Gilbert, and Nugent 2014; Rothwell 2022), and the experience to date has indicated that the decommissioning industry may also experience cost and schedule overruns. The financial incentives of the party decommissioning the plant are likely to influence the incidence of cost overruns. In particular, government-owned facilities may invest less into accurately estimating contingencies with the knowledge that the state will finance the unfunded liabilities.

***Decommissioning fund adequacy and transparency***

Both the difficulty in estimating costs and relatedly, contingencies, makes evaluating the adequacy of funds very difficult. Numerous stakeholders have an interest in verifying the adequacy of decommissioning funds. However, for most stakeholders this process is opaque because it requires deep subject-matter knowledge and careful consideration of all financial assumptions (e.g., inflation, discounting, etc.). Developing a more transparent and accurate method to assess fund adequacy emerges as a top priority for us.

***Determining financial liability***

Additionally, we see across all countries that fund monitoring and ultimate liability are important issues. Stakeholders are concerned about who will end up being responsible for any possible unfunded decommissioning liabilities, and monitoring the accumulation and evolution of these funds is one measure against shortfalls. We have already established how liability for unfunded decommissioning costs would be handled in the American legal system (Lordan-Perret, Sloan, and Rosner 2021). This research gives rise to our interest in how other countries handle these liability issues.

***External influences on decommissioning funds***

Furthermore, in many countries, market developments affect decommissioning funds. In particular, across our case study countries, licensees often accumulate decommissioning funding over the course of the plant's operational lifetime and invest these funds. Thus, decommissioning funds are both affected by shifts and developments in competitive electricity markets (e.g., including increasing renewable capacity), shifting natural gas prices (e.g., shale gas boom and the Russian invasion of Ukraine, and out-of-market support schemes) and developments in financial investment markets.

### 1.4.3 Insights from production

***The make or buy decommissioning production decision***

Nuclear decommissioning comprises a heterogeneous system of complex tasks for which an industry is slowly developing in the light of increasing reactor closures in the coming decades. In this regard, the question of vertical integration, mainly during the hot-zone phase, is of interest. Decommissioning nuclear reactors is characterized by high asset specificity. Therefore, only a limited number of firms are active. Nevertheless, we find that no case-study country chooses only one approach ("make", "buy", or "hybrid"). Therefore, there must be external or internal conditions that influence nuclear operators' choices in terms of this vertical integration of decommissioning tasks and, consequentially, knowledge.

***The role and influence of specialized firms***

It appears that highly specialized actors are emerging in the nuclear industry to assert themselves on the still nascent nuclear decommissioning market. Experience gained in early decommissioning projects can be used to later dominate the industry, when more and more NPPs come offline in the decades to come. These specialists have begun to take over whole to-be-decommissioned plants (in the U.S.) or are involved in the decommissioning of full reactor fleets (for some West German utilities). Furthermore, these specialists stand to not only increase efficiency of decommissioning from a project-management perspective, but they are also inventing new methods with new proprietary technologies that may change the cost structure of decommissioning and waste disposal. Thus, there are a myriad of ways in which these specialists could influence the decommissioning market, the future nuclear industry, and waste management. Taken together, we believe there most certainly will be new market tensions (e.g., access to resources) and new business cases that must be carefully scrutinized.

***Developing the decommissioning supply chain***

The anticipated concentration of NPPs reaching the end of their respective lifetimes in the decades to come raises concerns about the ability of the decommissioning industry to meet demand for materials and services. Particularly, nuclear decommissioning requires skilled human capital and specialized materials and infrastructure (e.g., storage casks, cranes, etc.). In all of our case study countries, access to complete, readily available, and competitive supply chains appears to be a challenge. Furthermore, we have identified risks for market power and various supply chain bottlenecks that may negatively influence decommissioning.

***Inspecting claims of efficiency***

Countries and industry players that plan on conducting multiple and/or decommissioning projects in parallel are also suggesting substantial gains in efficiency. However, external stakeholders are still unable to transparently understand the assumptions on economies of scale and potential synergies. In the past, especially for the construction of NPPs, the nuclear industry has failed to deliver on such promises (Koomey and Hultman 2007; Grubler 2010).

### 1.4.4 Insights from nuclear waste management

***Access to waste disposal facilities***

While we had intended to avoid nuclear waste issues to the extent possible in this study in order to focus exclusively on decommissioning, nuclear waste storage and final disposal emerged repeatedly across all the case study countries. Perhaps the most essential issue that emerged during our survey of the countries was access to waste disposal.

Whether licensees have access to low-, intermediate-, and high-level waste storage and disposal influences decommissioning across financing, organization, regulation, and production. Firstly, whether a plant has access to waste disposal appreciably changes the costs and schedule of decommissioning. For example, if LLW disposal is scarce, the costs will be higher, negatively influencing the overall cost to decommission the plant. Secondly, limited access to final waste disposal facilities and on-site interim storage facilities can also delay decommissioning progress and efforts. Without an interim storage location, plants are forced either to delay decommissioning or build their own (again, additional costs). Finally, we can also see signs of access to waste disposal having feedback effects on the nuclear industry (for example, regarding new builds and current operation).

## 1.5 Conclusion

In this survey paper, we bring together the insights from six country case studies on decommissioning commercial NPPs. The six countries we selected for our research have commercial nuclear industries that span a wide spectrum in terms of organization, regulation, financial provisions, and production of decommissioning services. The resources these countries have at hand, their decommissioning experience, the energy markets in which their industries operate, the public sentiment, and the history of commercial nuclear power generation often differ, yet similarities arise.

Ultimately, our purpose is to find best practices that span some of these differences but that also remain best practices when implemented in different settings. Across all the aspects of decommissioning that we consider—organization and regulation; financing; production; and waste disposal—we want to be able to evaluate practices. The decommissioning industry is one in which projects are long-duration and the results of many of these practices will not be realized during perhaps even our lifetimes. Therefore, an overarching research gap arises for us: What indicators should we use to evaluate decommissioning outcomes over the short run in order to forecast the efficacy of these practices over the long run? In using these measures, what are the best practices—and practices to avoid—that our research has identified?

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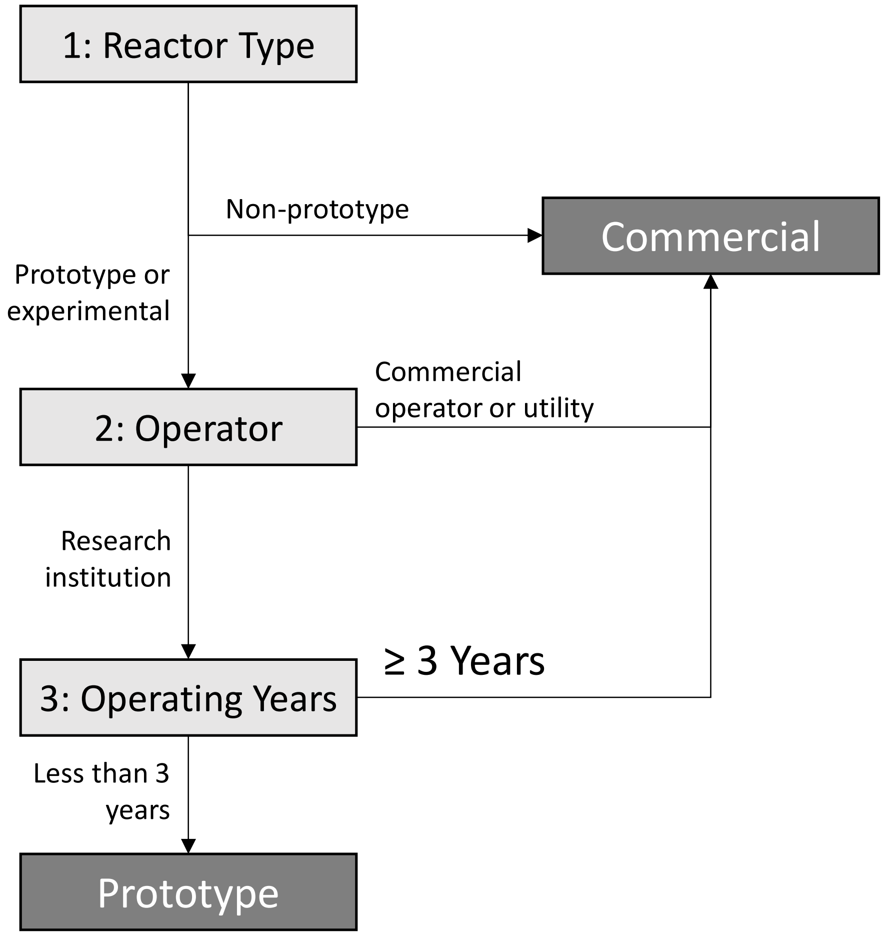
# Appendix

## Appendix A: Reactor classification

**Figure 1-7: Commercial nuclear reactor classification**



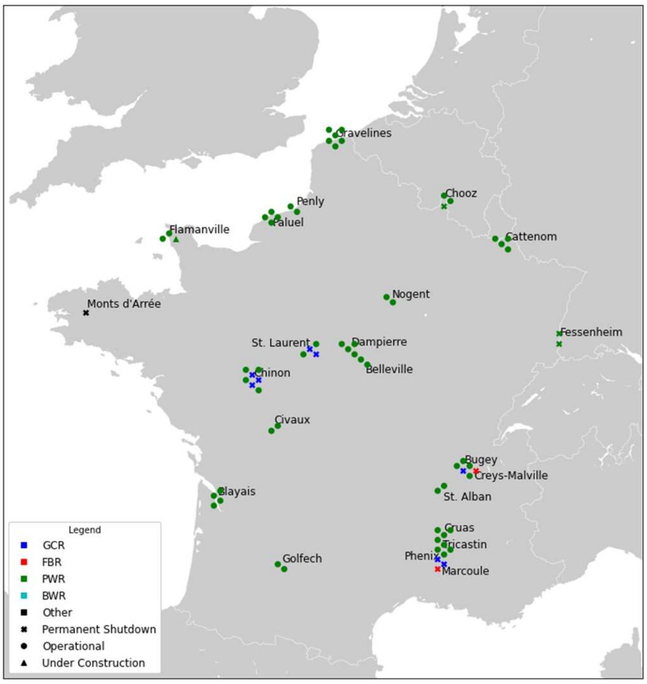
# 2 France

Alexander Wimmers, Christian von Hirschhausen, Björn Steigerwald

## 2.1 Introduction

With a fleet of 56 nuclear power plants (NPPs) still in operation, corresponding to a total capacity of over 61 GW, France has the second-largest operational NPP fleet worldwide and half of the operational reactors of the EU27. Currently, 14 NPPs with a combined capacity of 5.5 GW have been permanently shut down. They consist of various reactor types, such as a heavy water reactor (HWR) at Brennilis, numerous graphite-cooled gas reactors (GCR) at Bugey, Avoine, Marcoule and Saint-Laurent des Eaux, fast breeder reactors (FBR) in Creys (Phenix) and Marcoule as well as several pressurized water reactors (PWR) at Chooz and Fessenheim. An overview is provided in Figure 2-1 below and in Table 2-8 in the appendix of this chapter (IAEA 2022a).

**Figure 2-1: Location of French NPPs by status and type**




Source: Own depiction with data taken from IAEA's Operating Experience (2022b)

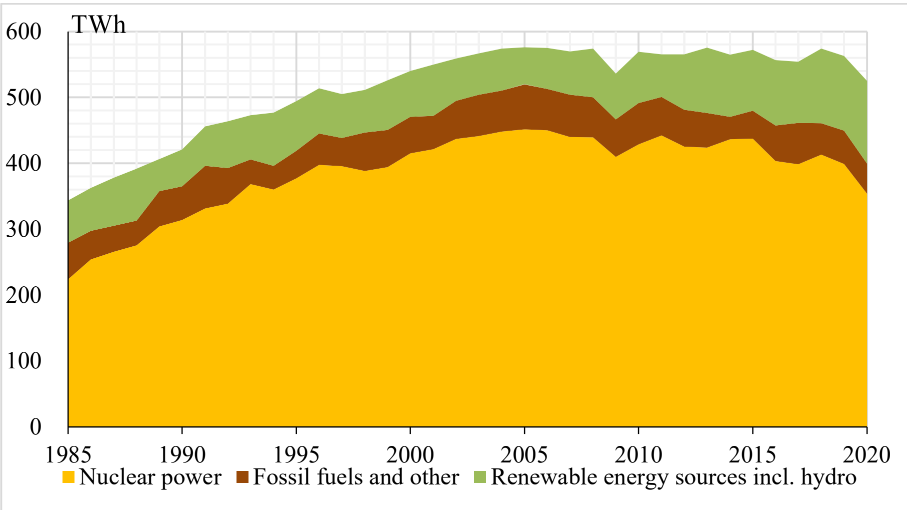
After World War II, the French electricity sector was nationalized by regrouping private utilities to one single state-owned utility, Électricité de France (EDF), in April 1946 (EDF 2022). Around the same time, Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) was founded and entrusted with the development of nuclear technology in France, for which initial enthusiasm was fuelled by the achievement of a chain reaction at France's first experimental nuclear reactor Zoé in 1948. EDF and CEA quickly joined forces in nuclear technology development and by the 1950s, UNGG[14]

[14] In French: *Uranium Naturel Graphite Gaz*

technology deployed at the first gas-graphite reactors (GCRs) G-1 and G-2 at Marcoule and Chinon A1 had become known as the "French system". EDF's main goal was to produce electricity, not plutonium, and so, other technologies, such as light water reactors (LWR) were also explored (Hecht 2009). The first French pressurized water reactor (PWR) at Chooz-A became operational in 1967(IAEA 2022a). EDF's initial plans in the late 1960s had been to purchase a "modest" four LWRs built by Framatome under an American Westinghouse licence (Hecht 2009), but during the oil crisis in 1974, Prime Minister Messmer announced an ambitious plan to build 80 reactors until 1985 and 170 by 2000 (Topçu 2007). The plan however resulted in the launch of only 13 reactors within two years, followed by a further 23 by the end of the decade. By 1984, the Westinghouse contract had expired, as Framatome had successfully "frenchified" the LWR design (Hecht 2009). Until 1991, construction began at 19 additional large PWRs. 26 years later, in 2007, EDF began construction of a European Pressurized Reactor (EPR) at the Flamanville-3 site (IAEA 2022b). The large share of nuclear energy in the French electricity mix, which peaked at 78.3% in 2005 and has been declining since, to 67.4% in 2020, is shown in Figure 2-2 (BP 2021).

Up until 1999, when the French electricity market was opened to other producers and distributors, state-owned EDF had held a monopoly in electricity distribution. It became a "société anonyme" (public limited company, PLC) in 2004 (EDF 2022). In 2022, the French state still held around 85% of the shares when plans were announced to fully renationalize the company (Rose and Hummel 2022). The ARENH scheme, introduced in 2011, keeps consumer electricity prices artificially low, as EDF is forced to sell a predetermined amount of electricity from nuclear generation to other utilities, as explained in Section 2.2.1. This is one reasons for the increasing debt of EDF and reduction of credit ratings, see Section 2.6 (Dorfman 2017).

**Figure 2-2: Electricity mix in France from 1985 to 2020 in TWh**




Source: Own depiction compiled from BP (2021)

In 2015, the *Act on Energy Transition and Green Growth* aimed at reducing France's greenhouse gas emissions by 40% compared to 1990 levels by 2030 while also reducing the share of nuclear in the electricity mix to 50% by 2025, instead of around three quarters in 2015 (Gouvernement Francais 2014). This was to push the development of renewable energies in France. However, in 2018, the nuclear share reduction goal was postponed to 2035 (Louet, White, and Evans 2018; Felix 2019). In 2021, France's Autorité de Sûreté Nucléaire (ASN - Nuclear Safety Authority) announced the extension of operation licenses for the French 900 MW nuclear fleet at Chinon, Blayais, Bugey, Gravelines, Cruas, St. Laurent des Eaux and Tricastin (NEI 2021). Lifetime extensions beyond 40 years at other plants (the mean age of the French fleet is 36.5 years as of June 2022 (IAEA 2022b)) will likely require substantial upgrades (Schneider et al. 2022). Additionally, a new reactor at Flamanville is being built, but the completion date has been postponed from 2012 to, as of writing, mid-2023 with cost vastly exceeding the initial budget (Diekmann 2022; Rothwell 2022). During the 2022 presidential election campaign, President Macron announced the new build of up to 14 new reactors (~25 GW) as of 2028 (Nussbaum and De Beaupuy 2022). Some of these reactors could be of an optimized design of the EPR, the EPR2 (EDF Undated). However, in Europe, all three EPR projects (EDF: Flamanville-3 and Hinkley Point-C, UK; Orano: Olkliuoto-3, Finland) have faced significant cost increases and delays, while only one project has been connected to the grid for test production (EDF 2022; WNN 2022b). In 2020, the two oldest large commercial PWRs at Fessenheim, operational since 1978, where the first non-research and non-prototype reactors to be shut down since 1994. France's first PWR at Chooz-A had been closed in 1991. Decommissioning has been underway since. Initial decommissioning plans for the early GCRs had to be revised due to technical issues (EDF 2022; ASN 2021). With France's limitation of the nuclear share to 50% by 2035 and announced extensive nuclear new build, as well as ongoing technical issues at the ageing fleet (e.g., critical corrosion at Chinon) and outages due to cooling water issues from low water levels in rivers, an increasing amount of planned, but also unexpected, shutdowns of nuclear reactors might occur (Alderman 2022). With France's large nuclear fleet, standardized only to some extent, this might pose significant challenges in terms of decommissioning, as will be explored in Section 2.5.

## 2.2 Legal Framework

### 2.2.1 Governmental and regulatory framework

The legal framework on decommissioning of NPPs in France is based on four legal codes, or laws, that determine responsibilities during the process of decommissioning: the Public Health Code (Code de la santé publique), the Environment Code (Code de l'environnement), the Energy Code (Code de l'énergie) and the more recent Energy Transition for Green Growth Act (Loi de transition énergétique pour la croissance verte). Governmental policies are enforced through acts that are then included into these codes.

In articles L1333-1 to L1333-32, the Public Health Code sets basic rules and regulations regarding so-called nuclear activities, i.e., activities linked to the use of substances and devices of natural or artificial sources that contain radionuclides or are radioactive themselves. This includes the nuclear energy industry as well as the medical sector. These rules follow three principles, defined in Article L1333-2: The justification principle defines that before activities that might cause exposure to radiation can be conducted, advantages thereof must be weighed against radiation exposure risks. The optimization principle limits the exposure of persons to radiation and the risk of accidents to levels as low as state-of-art technology allows. The limitation principle states that persons conducting any nuclear activities may only be exposed to certain radiation levels unless for specially regulated research or clinical reasons (Légifrance 2016b).

ASN, the French nuclear safety authority, defines five more principles that also include liability issues (ASN 2021).

The Environment Code defines regulations in terms of information and transparency and sets liabilities and necessary provisions in terms of operation of NPPs and waste management (Légifrance 2016a). The most important acts amending the Environmental Code concerning the nuclear industry shall be described below.

**Box 3-1: Legal Framework of the Nuclear Industry in France**

**Public Health Code**: Defines three principles - justification, optimization and limitation - for nuclear activities to follow and sets further regulations to limit radiation exposure.

**Environment Code**: Defines liability, transparency, safety and decommissioning regulations. The Code was amended in various acts. Most notable were Act No. 2006-686 on Transparency and Security that created the ASN and Act No. 2006-739 (Waste Act) that entrusted CEA and CNE with nuclear waste management and long-term enclosure research. The Waste Act also introduces the polluter-pays-principle.

**Energy Transition for Green Growth Bill:** This act sets the target of nuclear electricity generation share reduction to 50% by 2035 and commands the decommissioning process of any given NPP to be conducted as fast as possible. It also defines the necessary licensing procedure for decommissioning to commence.

**Energy Act**: The ARENH scheme is designed to limit the impact of high wholesale electricity prices on final consumers. Each year, EDF must sell pre-defined electricity volumes (120 TWh in 2022) for a fixed price.

The first is the Act on Transparency and Security in the Nuclear Field (No. 2006-686), which was introduced in June 2006. It represented a profound overhaul of the legal framework to nuclear activities and the supervision thereof. The act includes a defined plan for decommissioning and termination procedures. Nuclear safety is regulated with technical provisions and organizational measures. These nuclear safety regulations are defined and enforced by the French state, to some extent through ASN. For example, the State Council can order the definitive shutdown and decommissioning of NPPs and determine the necessary implementation procedures by decree. It also ensures that the public is informed about the risks and effects on health, safety, and the environment. People engaged in nuclear activities must also remain informed about risks and effects on personal health and safety, and those responsible for these activities bear the costs of preventive measures. The act also instated the French nuclear safety authority ASN (Autorité de Sûreté Nucléaire) with the responsibility for monitoring nuclear safety and radiation protection as well as providing information to the public. Decrees issued by ASN can authorize all license applications for so-called basic nuclear installations (BNI), except for major decisions such as new build, shutdown, or decommissioning. For this, the ministers tasked with nuclear safety and radiation protection have the final say and approve the rules of procedure of ASN. The same ministers decide on the general rules on transparency and security in the nuclear industry by adopting or approving ASN's regulatory decisions. ASN further regulates technical issues (ASN 2006b; 2021).

As mentioned above, facilities that are subject to ASN oversight are called BNI. BNI are those facilities that are under construction (provided they require a so-called Creation Authorisation Decree, see Section 2.2.3*)*, in operation, shut down or undergoing decommissioning, until having been delicensed by ASN. Most civil nuclear activities and installations are listed in ASN's annual report. This list of BNI includes, amongst others, all nuclear reactors and large installations for preparation, enrichment and other treatment of nuclear fuels and waste. As of December 2020, the list held 124 BNIs. (ASN 2021)

The second act, on Sustainable Management of Radioactive Material and Waste (No. 2006-739), known as Waste Act, was also introduced in June 2006. It dictates the preparation of a national plan for the management of radioactive materials and waste, which is to be updated every three years. An inventory of radioactive materials and waste present in France is also to be drawn up every three years. Furthermore, it sets the new schedule for research on high-level and long-lived intermediate-level waste, and it prohibits the permanent storage of foreign waste on French soil. In the past, France was active in treating foreign spent fuel and waste. The return of nuclear waste resulting from these activities to originating countries is also regulated in this act (ANDRA 2022). It further states that disposal in deep geological formations is the solution for the management of high-level and long-lived radioactive waste. It regulates the organization and financing of the sustainable management of radioactive materials and waste and provides for economic support measures. Operators must assess the cost of dismantling their facilities and the cost of managing their spent fuel and radioactive waste. Initially, a report had to be submitted to ASN every three years. Furthermore, the polluter-pays-principle is introduced, meaning that NPP operators are responsible for long-term provisions for radioactive waste management and decommissioning (ASN 2006a; 2009; 2021).

Following the introduction of the waste act, the Commissariat à l'Énérgie Atomique et aux Énergies Alternatives (CEA) was entrusted with the research and development concerning high-level and long-lived intermediate-level radioactive waste management, partitioning and transmutation (CEA 2015b).

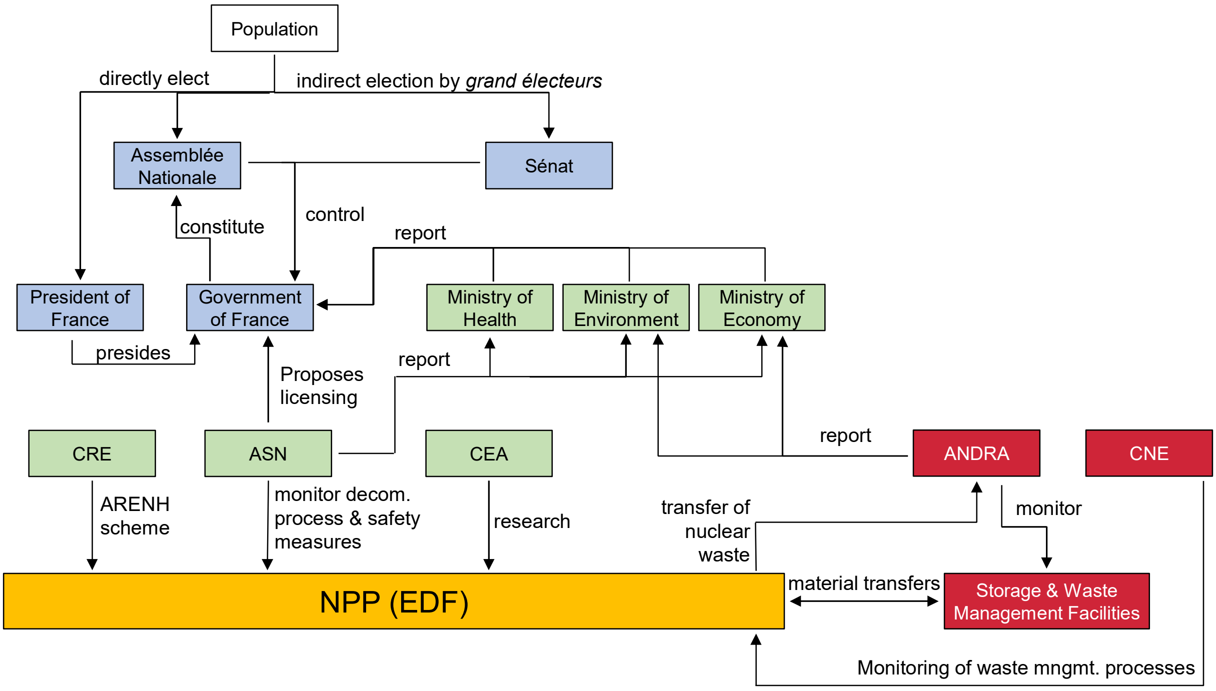
The waste act also instructed the Commission National d'Évaluation (CNE2) with the evaluation of various programs concerning waste management. The abbreviation CNE2 is used to distinguish the current commission from the first commission of the same name that was originally introduced in 1991. CNE2 consists of 12 expert members, nominated by Parliament and the French Academies for Science and Political Science (CNE2 2021).

Furthermore, the waste act tasked governmental agency Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA) with governing sustainable nuclear waste management procedures. This includes the identification of a site for a nuclear waste disposal facility for high-level and long-lived intermediate waste (Cigéo project) as well as a site for long-lived low- level waste. Additionally, ANDRA monitors the Manche Disposal Facility (now sealed) and the two existing surface disposal facilities (CSA and Cires (both located at Morvilliers, in the Aube district)) (ANDRA 2019).

The third major act, the Act on Energy Transition for a Green Growth*,* was introduced in August 2015. It defines France's decommissioning strategy to conduct "dismantling as rapidly as possible" (ASN 2021, 30). The act's main objective is to reduce greenhouse gas emissions in France by 40% until 2030, as mentioned in Section 2.1. Further included in this act was regulation on the process of decommissioning, that will be described in detail in Section 2.3.2 (ASN 2018).

Finally, regulation unique to French market is defined in Articles L336-1 to L336-10 of the Energy Act that implement the ARENH (Accès Régulé à l'Énérgie Nucléaire Historique) scheme. This scheme grants access to nuclear power production volumes to independent utilities following French market liberalization, as all commercial NPPs are owned and operated by EDF, the majority-state-owned utility. The ARENH scheme allows so-called alternative electricity suppliers to purchase electricity (nuclear and hydroelectric) from EDF, for a fixed price to supply final customers. The amount of electricity covered by the ARENH scheme is determined by the Energy Act and is fixed by the French government. The current maximum is 150 TWh per year. The fixed price, currently set at 42 EUR/MWh for the first 100 TWh of 2022 and 46.2 EUR/MWh for another 20 TWh, is determined by CRE (Commission de Regulation de l'Énérgie) (CRE 2022). The goal of the ARENH scheme is to limit the impact of high wholesale electricity prices on consumer prices (EDF 2022). An overview of the interrelations between involved governmental bodies and agencies is provided in Figure 2-3.

**Figure 2-3: Legal framework and regulations for French NPPs**




Source: Own depiction.

### 2.2.2 Ownership

Currently, 56 nuclear reactors on 18 sites are in operation in France with a mean age of just over 36 years. To date, 14 reactors on 9 sites have been permanently shut down. At 10 reactors, EDF is owner and operator. EDF also owns Chooz-A, but this reactor, an early PWR that was closed in 1991, is operated by Société d'Énérgie Nucléaire Franco-Belge des Ardennes (SENA), a collaborative LLC owned by EDF and Belgian utilities (Sfen 2017). CEA owns the shutdown research and prototype reactor Phénix (FBR) as well as G-2 and G-3 (GCRs) in Marcoule. G-2 is also partly owned by EDF (20%). Table 2-8 in the annex provides an overview of the shutdown of nuclear reactors in France (IAEA 2022a).

Other nuclear facilities in France, e.g., fuel production facility Malvési or fuel rod conditioning plant La Hague, are owned and operated by Orano SA. As of December 2021, the French state owned 79.99% of Orano’s shares. Apart from operating NPPs, Orano is involved in the complete nuclear cycle, from uranium mining over fuel processing to waste management, conditioning and packaging (Orano 2022).

#### 2.2.3 License provision and extension

Final decisions on licensing, de-licensing, lifetime extensions etc. of NPPs are made by the French government. Beforehand, ASN reviews individual authorization applications for all nuclear facilities. For small-scale nuclear facilities, e.g., in the medical field, ASN issues licences itself, but for authorizations for BNIs (see Section 2.2.1), such as new construction or decommissioning of nuclear power plants, it can only give recommendations. The transport of radioactive substances must also be authorized by ASN (ASN 2021).

#### 2.2.4 Oversight

In France, ASN is tasked with overseeing nuclear installations and practices. Every year, a detailed report on nuclear safety is published. The last report covered the year 2020 and was published mid-2021. In this report, ASN provides detailed insight on its assessment of operating practices, safety, environmental protection etc. at NPPs in operation, mainly owned and operated by EDF. ASN also assesses the facilities operated by Orano, CEA and ANDRA. Assessments on smaller licensees in the medical sector, industrial and research sector and those involved in the transport of radioactive substances are also included in the report. (ASN 2021)

ASN itself is overseen by elected officials. This is ensured on the one hand through the above mentioned yearly report that is presented to the government, parliament and many other administrative authorities and elected officials, and by about ten hearings before Parliament each year. (ASN 2021)

ANDRA also reports directly to the ministers of Energy, Research and the Environment. Further scrutiny of ANDRA's activities is conducted by CNE2 that publishes an annual report to Parliament (ANDRA 2019; CNE2 2021).

### 2.3 Decommissioning Regulation

#### 2.3.1 Decommissioning policy

Since 2009, ASN has been imposing a decommissioning strategy that aims at rapid dismantling and clean-up of BNIs. It was put into legislation in 2015 with Act 2015-992 (Energy Transition for Green Growth). The strategy is based on two basic principles: "immediate dismantling" and "complete clean-out" (ASN 2021).

The goal of immediate dismantling is to decommission the site as fast as possible. This is to be implemented with 4 steps. First, decommissioning must be taken into account in the design stage of a BNI. Second, licensees must anticipate when decommissioning work will become necessary and apply for a decommissioning licence before shutdown. Third, licensees must make sufficient provisions for decommissioning and account for unforeseeable events. And finally, the decommissioning process must be completed in the shortest possible timeframe. This however can vary strongly (years or decades) depending on the BNI. (ASN 2021)

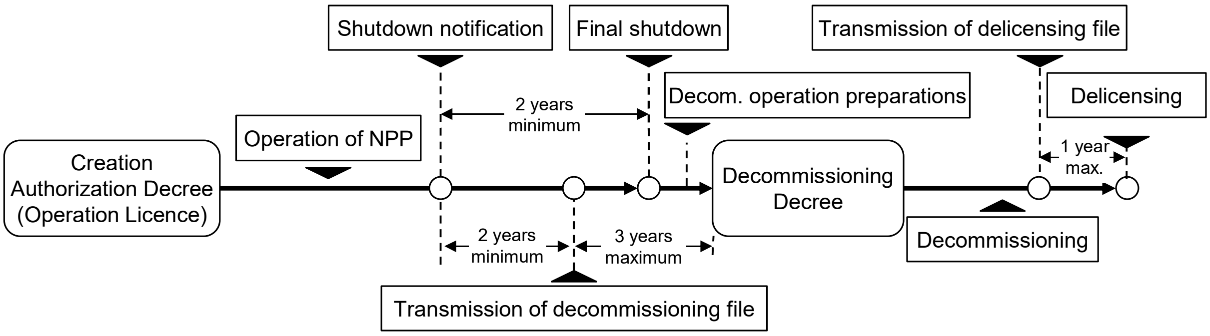
The principle of complete clean-out aims at the complete removal of any hazardous, mainly radioactive, substances from buildings, structures, or soil – in essence the goal of radiological decommissioning world-wide. To achieve this, licensees must utilize economically viable state-of-the-art techniques and procedures. In certain cases, in which the elimination of all contamination would lead to unreasonable cost increases and delays, ASN allows for a clean-out to "go as far as reasonably possible" (ASN 2021, 341). The licensee must justify the reasons in detail and ASN judges on a case-by-case basis. Whether a site has completed full clean-out is also determined by ASN for each individual site. Guidelines on procedures for different types of nuclear sites (NPPs, fuel treatment facilities, etc.) have been published. (ASN 2021)

EDF states that it is following the strategy of immediate dismantling, but aims at restoring sites to their "original condition [and make them] reusable for industrial facilities" (EDF 2022, 403). There is no clear regulation on whether BNIs are to be returned to a greenfield status for unrestricted use, as shown by ASN's lax definition of the complete clean-out principle. Further, EDF's statements are contradictory. Their goal to make sites reusable for industrial facilities can be interpreted as a brownfield status. This means that decontaminated and non-radioactive buildings on-site can be used for nuclear or other industrial purposes. While the aim for original condition could well be seen as attempt for greenfield decommissioning (Schneider et al. 2018; ASN 2021; EDF 2022).

### 2.3.2 Regulatory and legal process

In France, a BNI must acquire a Creation Authorization Decree that can be defined as an operation licence. As this decree only includes regulation for the operation of the BNI, a new licence, the Decommissioning Decree, must be applied for before the decommissioning process can commence. This decree must be transferred to ASN at least two years after shutdown notification was given, but no more than three years before decommissioning actually begins. The shutdown notification must be handed to ASN at least two years before the actual final shutdown occurs. The decommissioning file must contain a detailed plan of the decommissioning procedure, from the moment of shutdown to the planned final state of the site, and it must show how the licensee plans to conduct the process as fast as possible. Each part of the process must be described in full detail in terms of risks, involved stakeholders and, if applicable, contractors as well as management intent. Certain steps might be under additional scrutiny by ASN and require individual approval. The whole file is analysed in a public manner. (ASN 2021)

**Figure 2-4: Decommissioning process**




Source: Own depiction based on ASN (2021)

### 2.3.3 Oversight

ASN is fully responsible for decommissioning production oversight. One of the tasks is to ensure that resources are allocated to the decommissioning of the sites with the highest radiation risk. Furthermore, ASN evaluates whether decommissioning operations are on schedule and are conducted as described in the provided decommissioning files. Safety precautions and defences against unforeseeable events are also under scrutiny. ASN defines the guidelines of the French National Radioactive Materials and Waste Management Plan (PNGMDR), which is updated and published every five years. It also ensures that operators implement PNGMDR rules. (ASN 2021).

In terms of financial oversight, nuclear licensees must publish reports on their current balance of provisions for decommissioning and waste management to the General Directorate of the Treasury (DGT) and the General Directorate for Climate and Energy (DGEC) that are responsible for this oversight and are authorized to prescribe measures if funds are deemed inappropriate (ASN 2021).

### 2.3.4 Liability

In France, the polluter-pays-principle transfers liability for decommissioning and waste management (excluding long-term storage) to the operator of the nuclear facility. Thus, EDF is responsible for the decommissioning of French commercial NPPs. Decommissioning of research facilities and other nuclear facilities such as uranium enrichment plants is the responsibility of the respective operators, CEA, Orano, or ANDRA (ASN 2021). However, as EDF is majority owned by the French State (by law, the share must not fall below 70%), final liability, in the possible case that EDF fails to meet its obligations, lies with the French taxpayer (Dorfman 2017; EDF 2022).

## 2.4 Financial Regulation

### 2.4.1 The funding of decommissioning

As mentioned above, the polluter-pays-principle is a central part of French decommissioning legislation. This principle is mostly applied to the financing of the necessary decommissioning work on French nuclear facilities. Following this, nuclear licensees, i.e., the operators, must provide funds that cover all current and future costs of decommissioning. These costs are structured into five categories. The first category covers decommissioning costs. Categories 2 and 3 cover spent fuel management costs and legacy waste retrieval and conditioning costs, respectively. Long-term management of radioactive waste is covered by the fourth category. Finally, category five funds must also provide financial security for the long-term monitoring of waste disposal facilities. (ASN 2021)

Nuclear licensees are required to submit detailed reports on their current balance in funds every three years and provide annual updates to the French government. The General Directorate of the Treasury (DGT) and the General Directorate for Climate and Energy (DGEC) are responsible for this oversight and are authorized to prescribe measures if funds are deemed insufficient (ASN 2021).

Provisions for decommissioning and nuclear waste management are held in separate funds depending on the operator. EDF and Orano both make provisions for their respective nuclear facilities according to above mentioned regulation. EDF's provisions are made mostly for its NPP fleet, while Orano is responsible for waste management and fuel treatment facilities at, e.g., La Hague. ANDRA currently collects funds from nuclear operators through fees for long-term waste storage research and will begin collecting funds for the construction of the Cigéo project in 2025. And finally, CEA also makes provisions for its research facilities (European Commission 2013; Wealer, Seidel, and von Hirschhausen 2019; EDF 2022).

As is common practice in accounting for long-term provisions, funds accumulated today are discounted to future values. Each operator has a different approach in terms of inflation rates and other measures, but the maximum discount rate value is mandated by the French state. From 2024 onwards, the value may not exceed the real long-term rate published by the European Insurance and Occupational Pensions Authority (EIOPA). For 2021, the maximum real discount rate was set to 2.8% (Dorfman 2017; EDF 2022).

### 2.4.2 Current balance in funds

***Électricité de France (EDF)***

EDF is the operator of the 56 currently operational PWR reactors and several shutdown reactors of different types, including Fessenheim-1 and -2, Chinon or Super-Phénix at Creys-Malville. Furthermore, EDF is responsible for the construction of the new NPP at Flamanville. Thus, the provisions made by EDF are substantial, as is shown in Table 2-1. As of end-December 2021, provisions are discounted with a real discount rate of 2% (discount rate of 3.7% with inflation of 1.7%). EDF also makes provisions for so-called last cores. These funds shall cover cost from scrapping fuel from only partially burnt fuel rods in a shutdown reactor (EDF 2022).

***Orano***

Orano, formally Areva, operates nuclear fuel treatment facilities at Aude and Tricastin. It also operates fuel recycling and packaging facilities La Hague and Melox. Orano must therefore make provisions for these facilities. In 2021, these provisions were discounted with a discount rate of 3.56% and an inflation rate of 1.6%. An overview of Orano's provisions is provided in Table 2-2. (ASN 2021; Orano 2022)

**Table 2-1: Provisions made by EDF for its nuclear operations (in million EUR$_{2020}$[15])**

| Provision | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|
| **Spent fuel management (incl. waste removal & conditioning)** | 13,115.69 | 11,171.72 | 11,133.31 | 10,853.12 | 11,652.06 | 11,322.00 | 11,520.62 |
| **Long-term radioactive waste management** | 8,671.65 | 9,398.16 | 9,097.81 | 9,988.77 | 10,557.33 | 13,300.00 | 13,873.67 |
| **Decommissioning of NPPs** | 15,686.51 | 14,802.68 | 15,400.42 | 16,216.78 | 16,979.34 | 17,489.00 | 17,282.39 |
| *Of these, provisions for NPPs in operation* | 12,549.42 | 11,424.33 | 11,990.04 | 12,660.96 | 13,277.11 | 12,775.00 | 12,359.88 |
| *Of these, provisions for shutdown NPPs* | 3,137.09 | 3,378.35 | 3,410.39 | 3,555.82 | 3,702.23 | 4,714.00 | 4,922.51 |
| **Last Cores** | 485.38 | 2,397.23 | 2,463.86 | 2,562.63 | 2,630.56 | 2,711.00 | 2,592.85 |
| **Total** | 37,959.23 | 37,769.79 | 38,844.78 | 40,383.19 | 41,824.30 | 44,822.00 | 45,269.52 |

Source: Own compilation of EDF (2018; 2020; 2022) and Assemblée Nationale (2017)

**Table 2-2: Provisions made by Orano for its nuclear operations (in million EUR$_{2020}$)**

| Provision | 2020 | 2021 |
|---|---|---|
| **Dismantling** | 5,173 | 5,679.89 |
| **Waste retrieval and packaging** | 1,202 | 1,322.74 |
| **Long-term waste management and site monitoring** | 1,447 | 1,621.02 |
| **Other non-regulated provisions** | 368 | 392.83 |
| **Total** | 8,189 | 9,015.50 |

Source: Compilation taken from Orano (2022)

[15] Inflation calculated with information taken from inflationtool.com.

*ANDRA*

ANDRA's provisions are to be divided into two separate funds. The "research fund" is intended to finance research on France's long-term storage facility for high-level and long-lived medium level nuclear waste, the Cigéo project. Cash for this fund is collected from nuclear facility operators via a tax. The "construction fund" will be used to account for costs related to the construction and long-term surveillance and maintenance of the long-term storage facility. For its low- and intermediate-level waste storage facilities CSA[16] and CSM[17], ANDRA prepares its own provisions. These funds are to be covered by ANDRA's external segregated fund FCP. Provisions and current fund balance are given in Table 2-3 below. (European Commission 2013; Wealer, Seidel, and von Hirschhausen 2019; ANDRA 2021)

**Table 2-3: Provisions made by ANDRA for its nuclear operations (in million $EUR_{2020}$)**

| Provision | 2019 | 2020 |
|---|---|---|
| **Operation and sealing process monitoring of CSA and CSM** | 29.94 | 36.374 |
| **Waste package management** | 33.90 | 66.195 |
| **Post-sealing surveillance of CSA and CSM** | 6.24 | 6.457 |
| **Total Provisions** | 70.08 | 109.026 |
| **FCP Value** | 83.33 | 126.412 |

Source: Own compilation taken from ANDRA (2021)

*CEA*

In 2004, CEA took over the operating responsibilities at the Marcoule site (Phénix) from EDF and Orano (then Areva) (Orano 2022). Thus, apart from shipping and final waste storage costs that must still be covered by Orano's provisions, CEA must provide funds for dismantling and decommissioning. Additionally, CEA is responsible for several shut down research facilities at Fontenay-aux-Roses, Cadarache and Grenoble (ASN 2021). In 2020, provisions were discounted with an inflation rate of 1.09 % (as opposed to 1.32% in 2019) and a nominal discount rate of 3.75% (CEA 2021). CEA does not provide an overview as detailed as other nuclear operators, see Table 2-4.

**Table 2-4: Provisions made by CEA for its nuclear operations (in million $EUR_{2020}$)**

| Provision | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|
| **Provisions for end-of-lifetime operations** | 16,958.01 | 16,969.54 | 16,923.20 | 16,969.90 |
| **Provisions for Cigéo adjustment** | 16.52 | 16.23 | - | - |
| **Total** | 16,974.53 | 16,985.77 | 16,923.20 | 16,969.90 |

Source: Own compilation of CEA (2019; 2021)

[16] CSA: Centre de stockage des déchets de faible moyenne activitié (low- and intermediate level waste disposal facility)
[17] CSM: Centre de stockage de La Manche (sealed waste disposal facility)

### 2.4.3 Cost assessments

The assessment of future costs for decommissioning tasks underlines significant uncertainty and is highly dependent of discounting assumptions (Dorfman 2017). As was shown in Section 2.4.2, most nuclear operators use different values for discounting, and even seemingly small decimal changes in discount rates heavily influence the year-end estimated costs (Orano 2022). As EDF is the largest nuclear operator in France and other providers offer only information on their provisions, this section will focus on EDF's cost assessments. Table 2-5 provides an overview of the year-end cost estimations made by EDF in annual financial reports that, at the time of writing of these reports, were to be covered by the then made provisions from Table 2-1. Cost estimates for individual NPPs are provided in Section 2.4.4 that discusses the accuracy of historical estimations.

The total estimated inflation-adjusted costs for decommissioning, fuel management and long-term storage have increased by 427.5 million $EUR_{2020}$ (approx. 0.05%) over the last five years. Decommissioning cost assumptions for NPPs in operation have also remained comparatively stable as EDF hopes to reap economies of scale due to the high standardization of its PWR fleet (Dorfman 2017; EDF 2020).

**Table 2-5: End-of year cost assessments by EDF (in million $EUR_{2020}$)**

| Cost component | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|
| **Spent fuel management (incl. waste removal & conditioning)** | 19,349.77 | 20,913.40 | 20,220.00 | 20,749.75 | 18,998.00 | 15,714.01 |
| **Long-term radioactive waste management** | 31,059.21 | 30,342.55 | 31,419.07 | 32,452.93 | 35,580.00 | 35,850.47 |
| **Decommissioning of NPPs** | 27,898.89 | 27,905.53 | 27,727.30 | 27,630.91 | 27,093.00 | 27,485.14 |
| *Of these, costs for NPPs in operation* | 21,157.92 | 21,225.13 | 21,055.95 | 21,186.84 | 19,693.00 | 19,961.98 |
| *Of these, costs for shutdown NPPs* | 6,740.97 | 6,680.40 | 6,671.35 | 6,444.07 | 7,400.00 | 7,523.15 |
| **Last Cores** | 4,553.38 | 4,471.49 | 4,409.02 | 4,341.83 | 4,258.00 | 4,239.20 |
| **Total** | 82,861.26 | 83,632.97 | 83,775.38 | 85,175.41 | 85,929.00 | 83,288.82 |

Source: Own compilation of EDF (2018; 2020; 2022)

### 2.4.4 Cost experience and accuracy of assessments

Over the last few years, several assessments of EDF's cost assumptions have been critical (Assemblée Nationale 2017; Dorfman 2017; Wealer, Seidel, and von Hirschhausen 2019). For shutdown NPPs, being those that are currently undergoing decommissioning, cost assessments have regularly been updated. The last assessment of 2021 shows a real cost increase of approx. 44% from 2001, as shown in Table 2-6. EDF explains these cost differences with unexpected occurrences during dismantling and non-standardization of the shutdown NPP fleet (EDF 2022). Another explanation, at least for a part of the cost increase, might be the above-mentioned uncertainty in combination with discount rate and inflation assumptions that differ between nuclear operators and on a year-to-year basis.

**Table 2-6: Costs assessments for dismantling of shutdown NPPs (in million $EUR_{2020}$)**

| NPPs | 2001 | 2008 | 2012 | 2021 |
|---|---|---|---|---|
| **GCR reactors (Bugey-1, St. Laurent, Chinon-A)** | 2,523.99 | 1,810.47 | 2,320.30 | 5,339.70 |
| **Fessenheim (PWR)** | | | | 808.07 |
| **Chooz-A (PWR)** | 331.67 | 322.46 | 428.88 | 280.73 |
| **Brennilis (HWR)** | 343.71 | 262.85 | 252.96 | 314.85 |
| **Super-Phénix (FBR)** | 1,274.17 | 1,107.74 | 1,084.26 | 520.52 |
| **Total (excl. Fessenheim)** | 4,473.54 | 3,503.53 | 4,086.39 | 6,455.79 |

Source: Own compilation of Cour des Comptes (2012) and EDF (2022)

EDF is also criticized for its low-cost assumptions when compared to other OECD countries, such as Germany, Belgium, or the UK. While each country has different challenges to face during decommissioning, resulting from differences in respective fleets, France has by far the lowest provisions for decommissioning and dismantling when taking the size of the French fleet into account. Even Belgium, whose significantly smaller commercial reactor fleet also mainly consists of standardized PWR reactors[18], estimates decommissioning costs for its complete fleet to be more than 6 billion $EUR_{2010}$ higher than EDF's assumption of 18.1 billion $EUR_{2010}$[19] for the whole French PWR fleet (Assemblée Nationale 2017).

Whether EDF will be able to reap economies of scale from decommissioning its fairly standardized commercial PWR fleet[20] remains to be seen. So far, no reactor has been fully decommissioned and those that are currently in the process, are of different types. Chooz-A itself is a PWR reactor but due to its

[18] Belgium currently operates four WH 3LP PWR reactors, two WH 2LP PWR reactors, and one Framatome 3 loop PWR reactor (IAEA 2022b).
[19] Approx. 6.8 billion $EUR_{2020}$ and 20.4 $EUR_{2020}$, respectively.
[20] France currently operates four CP0, eighteen CP1, ten CP2, twenty P4 REP 1300, four N4 REP 1450 and is building one EPR (all PWRs)(IAEA 2022a).

unique location in a cave, experiences from decommissioning might not be transferable to other PWR reactors. Thus, the first “real” experience will be gathered at the recent shutdown Fessenheim reactors (CP0 type). Decommissioning at these two 900-MW reactors is estimated to cost approx. 400 million $EUR_{2020}$ each. EDF expects average costs for its PWR reactors at 360 million $EUR_{2020}$ per reactor. (EDF 2020; 2022; ASN 2021)

## 2.5 Production

### 2.5.1 Overview

The shutdown reactor fleet in France is diverse in comparison to the current operational PWR fleet. In total, 14 reactors (8 GCR, 3 PWR, 1 HWGCR, 2 FBR) have been permanently shut down, corresponding to approx. 5.5 GW (IAEA 2022a). Apart from the reactors at the Marcoule site that are owned and operated by CEA (Phénix, G-2, G-3), all reactors are being decommissioned by EDF (ASN 2021). Despite France’s strategy of fast-as-possible decommissioning, the process is advancing slowly at most plants, see Table 2-7 (ASN 2021).

In accordance with other country reports, French reactors were classified into commercial and non-commercial reactors following Figure 1-7. All reactors were determined to be commercial reactors due to long lasting connections to the grid.

**Table 2-7: Status of decommissioning NPPs in France**

| France | May 2018 | May 2019 | May 2020 | May 2021 | May 2022 |
|---|---|---|---|---|---|
| **“Warm-up-stage”** | 3 | 3 | 4 | 4 | 4 |
| ***of which defueled*** | *2* | *2* | *1* | *1* | *1* |
| **“Hot-zone-stage”** | 1 | 1 | 2 | 2 | 2 |
| **“Ease-off-stage”** | 0 | 0 | 0 | 0 | 0 |
| **LTE** | 8 | 8 | 8 | 8 | 8 |
| **Finished** | 0 | 0 | 0 | 0 | 0 |
| ***of which greenfield*** | *0* | *0* | *0* | *0* | *0* |
| **Shut-down reactors** | 12 | 12 | 14 | 14 | 14 |

Note: LTE refers to *long-term enclosure*.

Source: 2018-2021 taken from Schneider et al. (2021), 2022 from ASN (2021) and EDF (2022)

### 2.5.2 Progress

***EDF***

EDF is currently responsible for the decommissioning of six first-generation GCR plants at Bugey, Chinon and Saint-Laurent, 3 PWR reactors (Chooz-A, Fessenheim-1 and Fessenheim-2), one HWGCR reactor at Brennilis (EL-4) and the Super-Phénix FBR at Creys-Malville. In the years to come, EDF will also have to manage decommissioning activities of its large PWR fleet still in operation. When exactly these NPPs will enter their decommissioning phases, depends on decisions concerning lifetime extensions (ASN 2021). Due to a high degree of standardization, EDF hopes to use the Fessenheim reactors as test sites to learn best practices that can then be applied to to-be-decommissioned PWR plants and reduce costs and necessary efforts for decommissioning (Martin, Portelli, and Guarnieri 2014; ASN 2021).

The PWR reactor at Chooz-A was shut down in 1991 and has been undergoing decommissioning since 2007. Currently, work on the reactor internal vessels is being conducted. EDF expects these tasks to be completed by 2024, when final decommissioning and decontamination can begin. Initial plans expected Chooz-A to be fully delicenced by 2047, current estimations expect delicencing in 2035. Due to the site's unique location in a cave, unexpected difficulties have led to multiple cost increases, the last amounting to additional 77 million EUR[21] in 2021 (EDF 2022).

For its six GCR reactors at Chinon (Chinon A1, A2, A3), Saint-Laurent-Eaux (St. Laurent A1 & A2) and Bugey (Bugey 1), all in long-term enclosure (LTE) since their respective shutdown, EDF initially adopted a strategy of flooding the reactor vessel with water and then performing decommissioning procedures underwater. All GCR reactors have already been defueled. However, due to France's new decommissioning strategy of fast-as-possible decommissioning and technical issues of underwater dismantling, EDF decided to change the strategy to in-air dismantling in 2016. Thus, initial targets for dismantling no later than 2031 have been scrapped. EDF's current plans include reactor internal vessel and graphite block removal at Chinon A2 to begin in 2033 and last up to 2054. By 2035, all other reactors will have been placed into a so-called "safe storage configuration" (continued LTE) for decommissioning to commence by 2055. ASN however is opposed to this strategy as it would place decommissioning tasks well into the future and contradict the fast-as-possible decommissioning strategy. Thus, all GCR reactors must be apply for new decommissioning decrees in 2022 (ASN 2021; EDF 2022).

The FBR reactor Super-Phénix at Creys-Malville has been undergoing decommissioning since 2006. Currently, reactor vessel internals are being dismantled. This is expected to be completed by 2026, allowing for the whole site to be released from regulatory oversight by 2038. (EDF 2022)

In 2011, the EL-4 reactor at Brennilis (Monts d'Arrée) received a partial dismantling decree for parts outside of the reactor block. Since then, progress has been made, such as fuel removal and machine room dismantling. EDF is currently awaiting approval to begin further work on the reactor itself. These operations are planned to be completed by 2040. (EDF 2022)

The two PWR reactors at Fessenheim were shut down in 2020. EDF currently plans a 5-year preparation phase until the decommissioning decree is obtained in 2025. This includes fuel removal, scheduled to be completed in 2023. Furthermore, work has begun on the removal of old steam generators and transfer to the Cyclife[22] recycling plant in Sweden. This is done to free storage capacities for the steam generators that are still in the plants themselves and must still be decommissioned. (ASN 2021)

[21] Approx. 75.1 million $EUR_{2020}$.
[22] Cyclife is a fully-owned subsidiary of EDF that operates nuclear waste management facilities in France, Sweden and the UK and is tasked with decommissioning work at some of EDF's NPPs, see Section 5.3.

***CEA***

Decommissioning of the demonstration FBR Phénix at Marcoule began shortly after its shutdown in 2009. After disruptions during the Covid19-lockdown in 2020, work on fuel and equipment removal continued. A strategy change, involving a new decommissioning decree, is to set the deadline for decommissioning to be completed to end-2023. (ASN 2021)

The remaining GCR plants G-2 and G-3, also located at Marcoule, are currently in long-term enclosure after having been defueled and partly dismantled. Graphite removal was supposed to begin in 2020, but no indication on further progress could be found. The last known expected completion date is 2040. (CEA 2015a; Schneider et al. 2018)

### 2.5.3 Actors involved

Due to EDF's role as operator of all commercial NPPs and CEA as operator of only a few smaller research reactors, the French nuclear decommissioning industry is limited to a small number of actors. Orano, formally Areva[23], is one of the few actors that is not in direct ownership of EDF. However, Orano is also majority owned by the French state (Orano 2022). In 2015, Orano was tasked with dismantling reactor vessel internals at EDF's Super-Phénix site, initially planned to be completed by 2024 (now 2026) (WNN 2015). Westinghouse is also involved in French decommissioning operations. At Chooz-A, it was tasked with removing the reactor vessel in cooperation with Nuvia France (WNN 2010). Further actors, such as Onet Technologies, are working together with CEA for specific technical research tasks, such as constructing specialized tools and robots for certain decommissioning tasks (WNN 2021). For the decommissioning GCR reactors, EDF consolidated with recycling company Veolia, that is also involved with decommissioning at Marcoule (Veolia Undated), to launch Graphitech (Graphitech 2020). EDF, through its fully owned subsidiary Cyclife, conducts decommissioning at its NPPs (Reuters Events 2018). Cyclife also conducts waste management and recycling operations at its sites in the UK, France and Sweden (Cyclife 2020).

## 2.6 Country specific nuclear and decommissioning developments

### 2.6.1 Hopes for economies of scale and ageing nuclear fleet

France currently operates the second-largest commercial nuclear reactor fleet worldwide. As this fleet is aging and safety problems continue to arise, France faces the challenge of having to decommission these NPPs in the coming decades. All of these operational NPPs are PWR reactors, resulting in EDF hoping to reap economies of scale and learning effects through standardization. However, this stance is debated by regulators and in literature (Assemblée Nationale 2017; Dorfman 2017; Wealer, Seidel, and von Hirschhausen 2019). The idea of reaping economies of scale has been circulating the nuclear

[23] Areva was split into New NP (now Framatome, owned by EDF) and New Areva (now Orano) after filing for bankruptcy in 2016, see Areva (2017) for further details.

industry for some decades, especially in nuclear new build. However, cost data show that nuclear construction cost have actually increased (Koomey and Hultman 2007; Grubler 2010; Koomey, Hultman, and Grubler 2017; Rothwell 2022).

Decommissioning conditions can vary, depending on whether sufficient preparation time was available. Associated with France's ageing fleet are risks of spontaneous and unforeseen decisions to shut down reactors, as occurred in 1997 with the Super Phénix FBR. Here, political decisions to shut down the reactor caught EDF off guard and resulted in poorly prepared decommissioning processes, in technical, financial and organizational terms (Rodriguez, Frith, and Berte 2004; Pelleterat de Borde, Martin, and Guarnieri 2014; EDF 2022). For example, if EDF comes to the conclusion that corrosion in its operational plants is irreparable (WNN 2022a), decommissioning for the PWR fleet might have to commence much sooner than expected, which will likely affect EDF's optimistic average cost estimations of 360 million EUR per reactor (EDF 2022).

### 2.6.2 Financial burdens

These uncertainties, in terms of cost and schedule, are highly relevant for EDF's finances. EDF must make provisions for the decommissioning of its operational fleet and EPRs under construction (Flamanville 3 and Hinkley Point C in UK) whose planned construction costs are rising significantly (EDF 2022; Rothwell 2022). Ongoing uncertainties and cost reassessments have reduced EDF's credit rating over the last years. For example, in 2001, EDF was rated as AAA (prime) by Fitch. In 2009, the rating still stood at A+, but with safety issues, NPPs not reliably operating and rising decommissioning costs, EDF is now rated as BBB+, lower medium grade (Fitch Undated). Other rating agencies have followed this assessment, with S&P reducing EDF's rating from A- in 2020 to BBB in 2022 and Moody's changing EDF's rating from A3 to Baa1 in early 2022. EDF's UK subsidiary EDF Energy was downgraded to BBB- in 2020, the lowest investment grade rating (Kirong 2020; S&P Global 2022; Moody's 2022). EDF is already heavily indebted and will likely be facing further cost increases in the future. However, the French state holds the majority of EDF's shares and may have to bail-out the company if cash-flow problems arise (Dorfman 2017). The final burden of nuclear liability therefore only formally lies with EDF and much more with French taxpayer who will likely have to provide funds for decommissioning and long-term nuclear waste management.

### 2.6.3 Legacy fleet

The fleet of shut down GCR reactors has led to significant problems in the past. The initial strategy of long-term enclosure and underwater dismantling was redacted in 2015. Now, EDF plans to dismantle these NPPs in air – resulting in additional 15 years of necessary operations for the reactor casing, and cost increase of 590 million EUR[24]. This has pushed the need for graphite disposal routes into the second

[24] Approx. 575.1 $EUR_{2020}$

half of the 21st century. ASN opposes this new strategy as it contradicts the goal of "fast-as-possible" decommissioning. Whether EDF will be able to stick to the plan and conduct decommissioning of these reactors in a cost-effective manner, is up for debate. (EDF 2022; ASN 2021)

Just like the UK, decommissioning of legacy NPPs in France is a technically complex and economically expensive activity, that has attracted attention much too late in the process, and that is suffering from a lack of long-term vision back in the early days (1950/60s). Together with the challenge of long-term waste management, it increases the costs of an already expensive technology, and will most likely put further financial burden on the taxpayer, as discussed in Section 2.6.2 above.

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**Appendix**

**Table 2-8: Ownership of shut down nuclear reactors in France (IAEA 2022a)**

| NPP | Type | Model | Owner | Operator | Gross El. Capa. [MW] | Constr. Start Date | Commercial Operation Date | Perm. Shut-down Date |
|---|---|---|---|---|---|---|---|---|
| **Bugey-1** | GCR | UNGG | EDF | EDF | 555 | 01.12.1965 | 01.07.1972 | 27.05.1994 |
| **Chinon A-1** | GCR | UNGG | EDF | EDF | 80 | 01.02.1957 | 01.02.1964 | 16.04.1973 |
| **Chinon A-2** | GCR | UNGG | EDF | EDF | 230 | 01.08.1959 | 24.02.1965 | 14.06.1985 |
| **Chinon A-3** | GCR | UNGG | EDF | EDF | 480 | 01.03.1961 | 04.08.1966 | 15.06.1990 |
| **Chooz-A** | PWR | CHOOZ-A | EDF | SENA | 320 | 01.01.1962 | 15.04.1967 | 30.10.1991 |
| **EL-4 (Monts d'Arrée)** | HWGCR | MONTS-D'ARREE | EDF | EDF | 75 | 01.07.1962 | 01.06.1968 | 31.07.1985 |
| **Fessenheim-1** | PWR | CP0 | EDF | EDF | 920 | 01.09.1971 | 01.01.1978 | 22.02.2020 |
| **Fessenheim-2** | PWR | CP0 | EDF | EDF | 920 | 01.02.1972 | 01.04.1978 | 30.06.2020 |
| **G-2 (Marcoule)** | GCR | | CEA (80%), EDF (20%) | C.G.M.N.. | 43 | 01.03.1955 | 22.04.1959 | 02.02.1980 |
| **G-3 (Marcoule)** | GCR | | CEA | C.G.M.N. | 43 | 01.03.1956 | 04.04.1960 | 20.06.1984 |
| **Phenix** | FBR | PH-250 | CEA | CEA (80%); EDF (20%) | 142 | 01.11.1968 | 14.07.1974 | 01.02.2010 |
| **Saint-Laurent-A-1** | GCR | UNGG | EDF | EDF | 500 | 01.10.1963 | 01.06.1969 | 18.04.1990 |
| **Saint-Laurent-A-2** | GCR | UNGG | EDF | EDF | 530 | 01.01.1966 | 01.11.1971 | 27.03.1993 |
| **Super-Phenix** | FBR | Na-1200 | EDF | EDF | 1242 | 13.12.1976 | 01.12.1986 | 31.12.1998 |

Note: GCR: Gas-cooled reactor; FBR: Fast breeder reactor; PWR: Pressurized water reactor; HWGCR: Heavy water gas-cooled reactor; SENA: Société d'énergie nucléaire franco-belge des Ardennes; C.G.M.N.: Compagnie Generale des Matières Nucléaires

# 3 Germany

Alexander Wimmers, Ben Wealer, Björn Steigerwald, Christian von Hirschhausen

## 3.1 Introduction

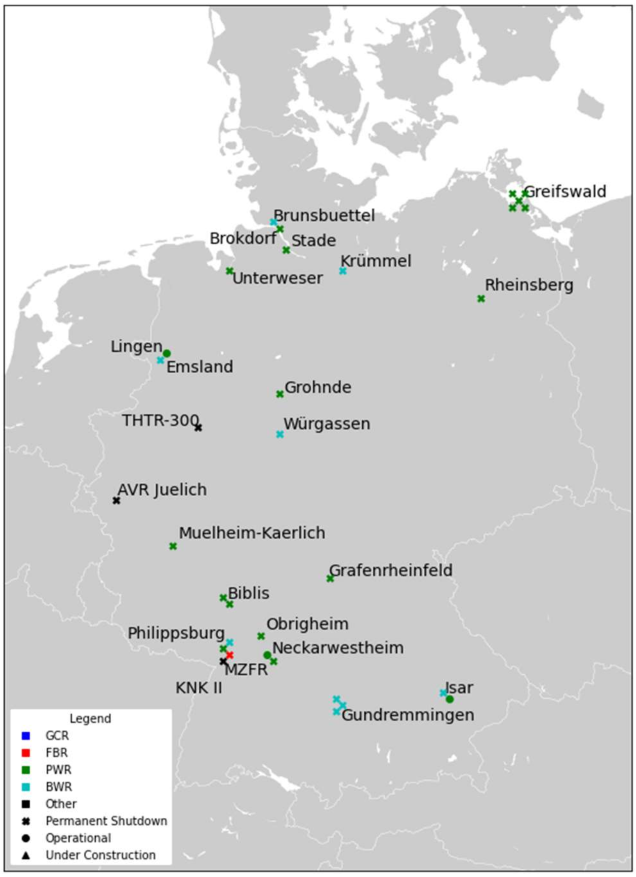
With the closure of three nuclear power plants in 2021, the number of closed nuclear reactors in Germany rose to 30, corresponding to 22.2 GW capacity. Three more reactors are still operational and will be permanently shut down in Spring 2023. Following the Fukushima disaster, the 13th amendment of the Atomic Energy Act of August 2011 withdrew the operating licenses of eight nuclear power plants (NPP), while the remaining eight operational NPPs would be gradually shut down until the end of 2022. The last units to be shut down were Grohnde, Gundremmingen-C and Brokdorf (December 2021), and Isar, Lingen (Emsland) and Neckarwestheim (April 2023) (Deutscher Bundestag 2021; 2022). Figure 3-1 shows the location, type[25] and status for all German commercial NPPs.

For the last twenty years, the German energy sector has been dominated by the *Energiewende*, the transition of the energy system towards renewables, such as solar, wind or biomass. This transition began in earnest when the Renewable Energy Act (*Erneuerbare-Energien-Gesetz, EEG)* was first introduced in 2000. Since then, the share of renewables in the German electricity mix has been steadily increasing, see Figure 3-2. Since the end of World War II, the German energy sector, East and West, had been mostly dominated by coal, especially lignite. In West Germany, the monopolistic energy system, consisting of only eight vertically integrated energy suppliers, was liberalized in 1998, paving the way for decentralized electricity generation from renewables. Electricity generation from nuclear had played a significant role from the 1980s onwards, when most German NPPs had become operational. Both German states had been prohibited from utilizing nuclear energy in any way until the mid-1950s. Consequently, no domestic industry had been able to form and thus early large commercial reactors, Greifswald in East Germany (construction start 1970), and Gundremmingen-A in the West (construction start 1962), relied on foreign technology. In West Germany, the government pursued the development of a domestic industry, against initial resistance from coal-dependent energy suppliers, by adopting nuclear-friendly policies and finally creating a domestic nuclear reactor industry in *Kraftwerksunion* (KWU), jointly owned by Siemens and AEG. Early experiments with heavy water reactors failed and thus, light-water technology became the norm, with BWRs being dominated by PWRs. Opposition towards nuclear grew in the late 1980s after the Chernobyl accident, culminating in first nuclear phase-out plans negotiated by the social democratic-green government in 2001. This phase-out allocated electricity generation allowances (in TWh) to all German NPPs that would have led to a gradual end of commercial nuclear operation by the early 2020s. In 2003 and 2005, NPPs Stade and Obrigheim were shutdown, respectively. In September 2010, the conservative-led government under

[25] Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor, GCR: Gas cooled reactor; FBR: fast breeder reactor; Other includes HTR (High temperature reactor) and PHWR (pressurized heavy water reactor)

Chancellor Merkel retracted the initial phase-out plans and allowed for lifetime extensions of operational NPPs of up to 14 years. When the Fukushima NPP was hit by a tsunami in February 2011, a moratorium, announced in March 2011, halted all nuclear generation in Germany for three months while an ethics commission began work on whether nuclear operation was safe enough to continue. By June 2011, the commission concluded that electricity generation from nuclear power was unsafe and economically unviable and thus, in the summer of 2011, Germany announced the end of electricity generation from nuclear power by the end of 2022, with eight reactors never reassuming operation after the moratorium of March 2011 (von Hirschhausen 2018; Radkau and Hahn 2013). Substantial compensation was paid to nuclear operators for investments that had been made after initial lifetime extensions (142.5 million EUR[26]) and for lost profits from electricity generation (860 million EUR to RWE and 1.4 billion EUR to Vattenfall[27]) (BMJ 2022).

**Figure 3-1: Location, type and status of German NPPs as of May 2022**




Source: Own depiction with data taken from IAEAs Power Reactor Information System (IAEA 2022a)

Over the last ten years, this political decision was widely accepted amongst the general public. With the Russian attack on Ukraine in early 2022 however, concerns about energy security slowly grew, until a debate about life-time extensions of Isar, Lingen and Neckarwestheim and the re-initialization of NPPs

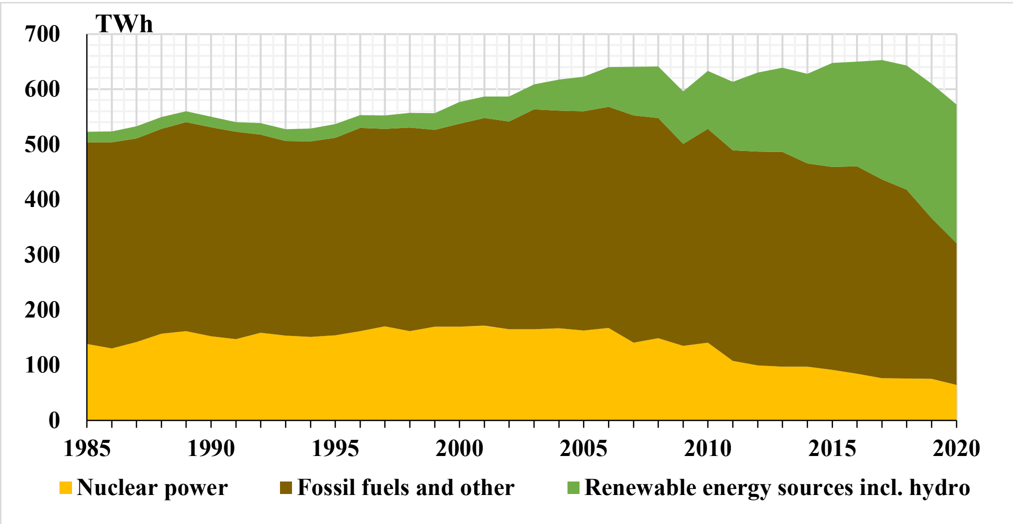
[26] Inflation calculated to 2020 values based on inflationtool.com: 156.5 million $EUR_{2020}$

[27] 944.4 million and 1.5 billion $EUR_{2020}$.

shut down in 2021 arose. Nevertheless, the German government will essentially continue with the planned phase-out and all shutdown NPPs will remain offline. The given reasons were of regulatory, but also of a technical nature. For example, extensive security and maintenance work would be required and additional fuel would have to be procured, which in itself usually takes up to 24 months. This, in combination with the state having to become the owner of the NPPs for liability reasons, as even nuclear opeartors are sceptical of technical feasability, and other issues, would result in extraordninary costs for the lifetime extension of German NPPs that would have to be covered by the German state (BMUV and BMWK 2022; WDR 2022). The three still operational NPPs however will remain on the grid until mid-April 2023 to account for potential short-comings in electricity generation during cold winter months. Then, it is planned to finally end the commercial operation of NPPs for electricity generation in Germany (Deutscher Bundestag 2022).

In 2020, German NPPs generated 64.4 TWh of electricity. The historic maximum generation was 171.3 TWh in 2001 (BP 2021). In 2020, the share of nuclear in the German electricity mix was around 11%. The historic maximum share was 31% in 1997 (Schneider et al. 2020). Figure 3-2 gives an overview of the German electricity generation by source from 1985 to 2020.

**Figure 3-2: German electricity generation by source (1985-2020)**




Source: Own depiction based on data from BP (2021).

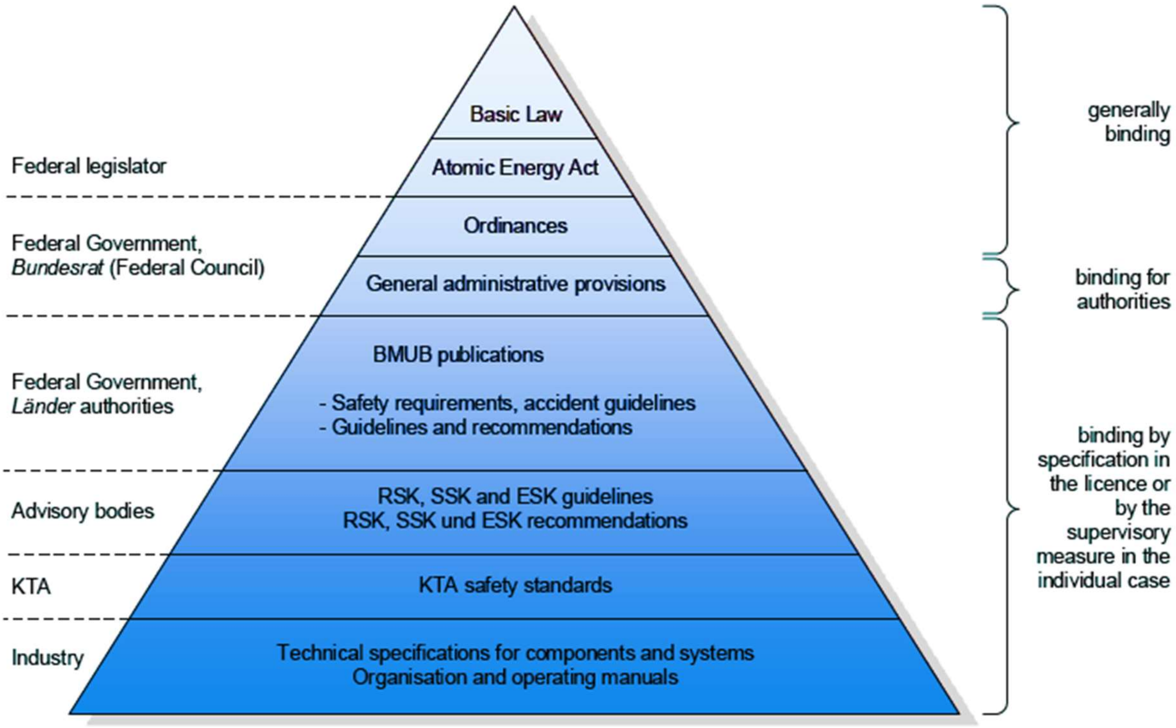
With Germany phasing-out electricity generation from NPPs by spring of 2023, dismantling and decommissioning of the nuclear fleet will be a major undertaking for governmental regulators, involved utilities, operators and other involved stakeholders. This report will provide an overview of the legal framework and regulation for the decommissioning of NPPs in Germany, as well as give an indication on current cost estimates and their accuracy. Additionally, it shows the current progress of the decommissioning process in Germany.

## 3.2 Legal Framework

### 3.2.1 Governmental and regulatory framework

The basic legislation covering nuclear law is the Atomic Energy Act (AtG). This act was promulgated in 1959 by the West German Government and is the core legislation relevant to licensing and safety of nuclear power plants in Germany today. The Radiation Protection Ordinance, the Nuclear Licensing Procedure Ordinance, and six other ordinances support the AtG. The results of the consultations of the Ministry for the Environment (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, BMUV) with the respective advisory bodies are published in the form of recommendations. Figure 3-3 gives an overview of the hierarchy of the national regulations, the authority adopting the regulation and its degree of enforcement (Federal Republic of Germany 2018).

**Figure 3-3: Hierarchy of the national regulations ("regulatory pyramid")**




Source: Own depiction based on Federal Republic of Germany (2018, 108).

In the years following the second attempt of ending commercial nuclear operation in 2011, the German government rearranged the responsibilities of its various agencies. In 2016, a new law, the "Act on the Reorganization of the Organizational Structure of Final Waste Disposal" (EndLaNOG) [28] transferred tasks previously undertaken by the public authority for radiation protection[29] (BfS) to the (at the time) Federal Office for the Safety of Nuclear Waste Management (Bundesamt für kerntechnische Entsorgungssicherheit, BfE) as well as the federal company for radioactive waste disposal BGE (Bundesgesellschaft für Endlagerung mbh), newly founded under private law. In 2020, BfE changed its name to BASE (Bundesamt für die Sicherung der nuklearen Entsorgung). The purpose of the act was "to clearly allocate responsibilities in the fields of radiation protection and disposal, and to ensure a more efficient handling of tasks". The organization of the nuclear sector in Germany is depicted in Figure 3-4 (Federal Republic of Germany 2018).

It was decided that all risks for nuclear related activities, being financial and safety-related, should be borne by the public due to the long-term nature of tasks such as nuclear waste management (KFK 2016). Thus, all federal regulation, licensing, and supervisory tasks are now bundled at BASE. The operational tasks of site selection, building and operation of the deep geological facilities were assigned to BGE, which is also responsible for the construction of the Konrad site for low- and intermediate-level waste (LILW) that is now scheduled to open in 2027, more than half a century after site selection (BGE 2022). Ownership of interim storage facilities for high-level waste was transferred from utility-operated Gesellschaft für Nuklearservice (GNS) and public company Entsorgungswerk für Nuklearanlagen (EWN) to the federally owned company for interim storage BGZ (Bundesgesellschaft für Zwischenlagerung). In the coming years, the LILW storage facilities on the reactor sites will also be transferred to the public company. (Wealer, Seidel, and von Hirschhausen 2019)

**Box 4-1: Legal Framework of the Nuclear Industry in Germany**

**Atomic Energy Act (AtG)**: Core legislation in terms of nuclear licensing and safety. Defines German nuclear phase-out in Article 7 Section 1a.

**Radiation Protection Ordinance (StrlSchV)**: Defines radiation exposure limits to protect workers and clinical staff as well as the general public from ionizing regulation.

**Nuclear Licence Procedure Ordinance (AtVfV)**: Defines the nuclear licensing process in detail.

**Act on Reorganization of Organizational Structure of Final Waste Disposal (EndLaNOG)**: Transfer of tasks from BfS to BASE (then, BfE) and creation of BGE and BGZ.

**Act on Transparency for Costs of Decommissioning of Nuclear Power Plants and Waste Packaging (Transparency Law)**: Tasks BAFA with evaluating the provisions made by NPP operators for decommissioning and waste management. An annual report is issued to Parliament.

**Act on Reorganization of Responsibility for Nuclear Waste Management (VkENOG)**: Transfer of responsibilities for interim and final waste storage from utilities to Federal state and set up of a public fund to finance final waste disposal.

**Act on Site Selection (StandAG)**: Sets the goal of finding a long-term storage facility for high-level radioactive waste by 2031 and defines transparent and inclusive process for this.

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[28] Gesetz zur Neuordnung der Organisationsstruktur im Bereich der Endlagerung (BGBl., I, S. 1843 768/16)
[29] BfS will continue to work on radiation protection.

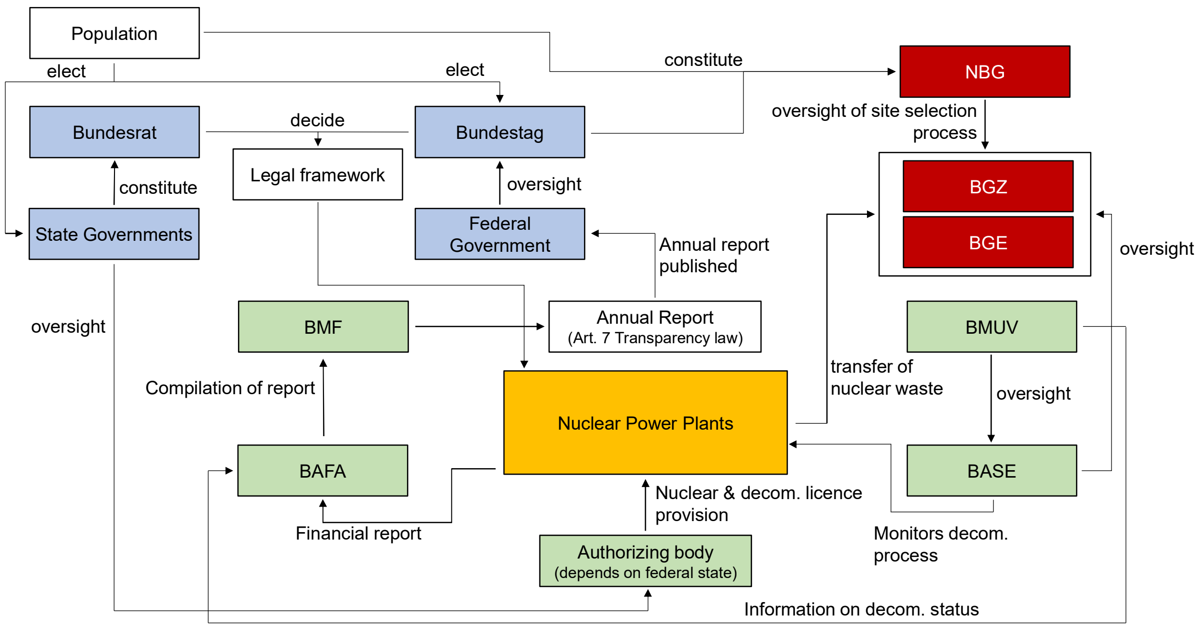
In terms of financial regulation, the “Act on Transparency for Costs of Decommissioning of Nuclear Power Plants and Waste Packaging” (Transparency Act) introduces BAFA (Bundesamt für Wirtschaft und Ausfuhrkontrolle) as the responsible oversight agency. Each year, BAFA reports to the German government and parliament (Bundestag) on the current financial situation of NPP operators and their respective provisions for decommissioning and waste management. This transparency report also includes a detailed description of decommissioning plans at different NPPs. (Deutscher Bundestag 2021)

Finances for final nuclear waste disposal and interim storage were originally planned to be covered by operators, following the polluter-pays-principle. Following the planned phase-out of nuclear electricity generation in 2011, the government installed a commission (Kommission der Überprüfung der Finanzierung der Kernenergieausstiegs, KFK) to determine the best possible way to ensure that operators would retain their liquidity to finance long-term waste management although time for funds to accumulate had been shortened by a substantial margin. The commission concluded in April 2016 that the responsibility for long-term waste management be bundled with one actor – and proposed the state to take over this role. Operators would in turn finance a publicly managed fund to ensure liquidity for waste disposal and storage (Bundesrat 2016). Thus, in 2017, the “Act on Reorganization of Responsibility for Nuclear Waste Management” (VkENOG) transferred full responsibility for nuclear waste storage to the German government. Decommissioning and dismantling of NPPs as well as packaging of nuclear waste remains in the operators’ responsibilities. This transfer of responsibility would occur, once NPP operators paid a certain amount into a public fund designed to cover for future costs of waste storage. Payments amounted to a fixed contribution of about 17.4 billion EUR with additional optional contribution of approx. 6.2 billion EUR.[30] This will be further described in Section 3.4 (BMWI 2016).

In 2013, the “Act on Site Selection” (Standortauswahlgesetz, StandAG) came into legislation. It was amended to its current form in 2016. The goal of this act is to find a suitable site for the long-term storage of high-level radioactive waste by 2031. This is defined in a transparent process and lets the German public participate. The “Nationales Begleitgremium” (NBG) was introduced as one of the actors. It consists of several experts and prominent public figures as well as randomly selected members of the general public. In 2020, the first phase of the process was completed, and geologically favorable areas were presented (Bundesgesellschaft für Endlagerung (BGE) 2020). In the autumn of 2022, BGE announced that the plan to find a suitable location by 2031 was unrealistic and proposed a new target range date of 2046 to 2068. This estimate is still under scrutiny by BASE and BMUV and discussions on this development are still ongoing as of writing. (BASE 2021; 2022)

[30] 17.96 billion and 6.4 billion $EUR_{2020}$.

**Figure 3-4: Governmental and regulatory actors and their connection to German NPPs**




Note: BASE: Bundesamt für Sicherung der nuklearen Entsorgung; BMUV: Federal Ministry for Environment, Nature Conservation, and Nuclear Safety (Bundesumweltministerium); BMF: Federal Ministry of Finance (Bundesfinanzministerium); BAFA: Bundesamt für Wirtschaft und Ausführkontrolle; BGE: Bundesgesellschaft für Endlagerung; BGZ: Bundesgesellschaft für Zwischenlagerung; NBG: Nationales Begleitgremium

Source: Own depiction.

## 3.2.2 Ownership

### 3.2.2.1 Overview

The current NPP fleet is majority-owned by German utilities EnBW, E.ON, and RWE as well as Swedish utility Vattenfall through limited liability companies (LLC)[31] that in turn own operating companies, themselves LLCs, for the specific NPPs. These operating companies are sometimes in shared ownership, as described below. Except for Krümmel, there are clear majority shareholders. This is important for decommissioning, as the decommissioning responsibilty falls into the hands of the majority shareholder. At two NPPs, municipal public utilities are minority-shareholders (i.e. Stadtwerke München at Isar-2, and Stadtwerke Bielefeld at Grohnde). E.ON operates its nuclear business through its subsidiary PreussenElektra GmbH. (Deutscher Bundestag 2021)

Of the 33 listed German nuclear reactors in the IAEAs Power Reactor Information System (PRIS), 23 commercial nuclear reactors (23.755 $GW_e$) are mentioned in the current transparency report on the state of decommissioning provisions by BAFA (Deutscher Bundestag 2021; IAEA 2022b). E.ON and RWE are the majority shareholders for eight reactors each, followed by EnBW for five reactors. Vattenfall is majority shareholder at Brunsbüttel. NPP Krümmel does not have a majority shareholder, which is also reflected in the provisions (see Section 3.4.2). Table 3-7 in the annex gives an overview of the ownership structure of the commercial nuclear reactor fleet in Germany. For the three

[31] In Germany: Gesellschaft mit beschränkter Haftung (GmbH)

reactors at the Gundremmingen site, both PreussenElektra GmbH and RWE Power AG own the nuclear license following Article 7 Section 3 of AtG. For the Grohnde plant, both Gemeinschaftskraftwerk Weser GmbH and Preussen Elektra GmbH hold the nuclear license (Deutscher Bundestag 2018) (see also Section 3.2.2.2 hereunder).

The legacy fleet of reactors situated in former territory of the German Democratic Republic (GDR) consists of the five reactors at Lubmin (Greifswald NPP) and the 62 MW PWR at Rheinsberg. Both facilities have been undergoing decommissioning since the mid-1990s. Ownership and decommissioning responsibilities lie with the publicly owned company Entsorgungswerk für Nuklearanlagen (EWN) GmbH. The German state has full ownership of EWN as the Ministry of Finance (BMF) is the sole shareholder and provider of funds (EWN 2021; Undated).

Research reactors AVR Jülich, KNK II, THTR-300, MZFR are not included in Table 3-7, although we classify them as commercial, see Section 3.5.1. All reactors apart from THTR-300, which is in long-term enclosure, are currently undergoing decommissioning and are owned by the respective research laboratories at Jülich (FZ Jülich) and Karlsruhe (KIT). (Schneider et al. 2022; IAEA 2022b)

The following reactors are not included in PRIS and have been fully decommissioned, but not all released from regulatory control. Thus, they are also excluded from Table 3-7.

Research reactors HDR Großwelzheim and Niederaichbach were owned by KIT and were both released from regulatory control in 1998. Prototype reactor VAK Kahl, released from regulatory control in 2010, was in mixed ownership of RWE (80%) and Bayernwerk AG (20%). Bayernwerk AG is a subsidiary of E.ON (Schneider et al. 2021; Bayernwerk 2021). Construction at the fast breeder reactor (FBR) at Kalkar was completed in 1986. Due to political reasons, the FBR was never loaded with nuclear fuel and the project was abandoned in 1991. Ownership would have been with RWE and E.ON, but in 1995 it was transferred to a Dutch investor for a fraction of the project cost who has since turned the site into an amusement park and convention center (Marth 1992; WDR 2013).

#### 3.2.2.2 Detailed ownership description for utilities

***EnBW AG***

The corporate group EnBW is liable for four nuclear reactors in permanent shutdown and one in operation on three sites. The license for operation (and decommissioning) is held by EnBW Kernkraft GmbH (EnKK), which is majority-owned by EnBW Energie Baden-Württemberg AG with 99,75%[32]. Most shares of ENBW AG are held by NECKARPRI-Beteiligungsgesellschaft mbH (46.75%), owned by the federal state of Baden-Württemberg and OEW Energie- Beteiligungs GmbH (OEW) (46.75%) owned by nine municipalities situated in Baden-Württemberg, see Table 3-1.[33]

[32] 0.05% are held by Kernkraft Obrigheim GmbH (100% EnBW AG), 0.2% by Deutsche Bahn AG, and 1.3% by ZEAG Energie AG (100% EnBW AG).
[33] These municipalities are Alb-Donau-Kreis, Biberach, Bodenseekreis, Freudenstadt, Ravensburg, Reutlingen, Rottweil, Sigmaringen, Zollernalbkreis (OEW Undated).

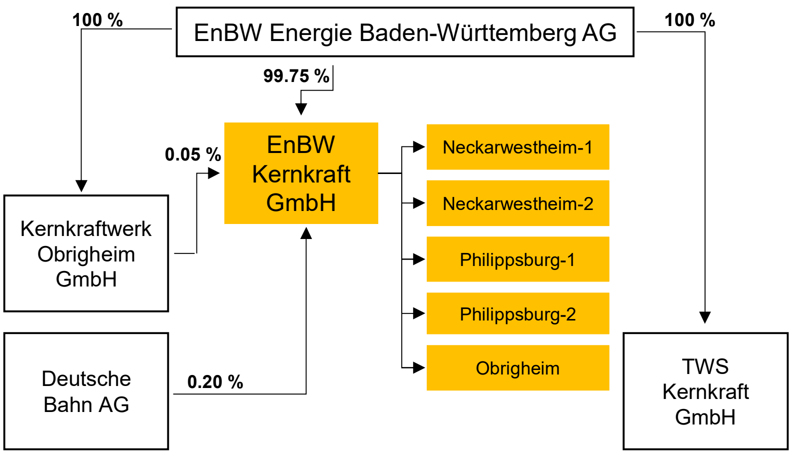
EnKK operates the five reactors Neckarwestheim-1/2 (GKN), Obrigheim (KWO), and Philippsburg-1/2 (KKP) on behalf of the owners of the plants. EnBW AG is the sole shareholder of the two Philippsburg reactors and holds 48.4% of the shares of Neckarwestheim-1 and 62.4% of Neckarwestheim-2. Kernkraftwerk Obrigheim GmbH is the sole owner of Obrigheim and is wholly owned by EnBW Energie Baden-Württemberg AG (Figure 3-5). Both companies are fully included in the consolidated financial statements of EnBW AG. EnBW also owns TWS Kernkraft GmbH that is not involved in any NPP operations. The EnBW Group bears 100% of the dismantling obligations for the plants (Deutscher Bundestag 2021).

**Table 3-1: Shareholders of EnBW AG, as of December 2020**

| Shareholder | Shares |
|---|---|
| NECKARPRI-Beteiligungsgesellschaft mbH | 46.75 % |
| OEW Energie-Beteiligungs GmbH (OEW) | 46.75 % |
| Badische Energieaktionärs-Vereinigung (BEV) | 2.45 % |
| EnBW Energie Baden-Württemberg AG | 2.08 % |
| Gemeindeelektrizitätsverband Schwarzwald-Donau (G.S.D.) | 0.97 % |
| Neckar-Elektrizitätsverband (NEV) | 0.63 % |
| Others | 0.39 % |

Source: Own compilation based on EnBW AG (Undated)

**Figure 3-5: Corporate structure of EnBW Energie Baden-Württemberg and its nuclear subsidiaries**




Source: Own depiction following Deutscher Bundestag (2021)

### *E.ON / PreussenElektra*

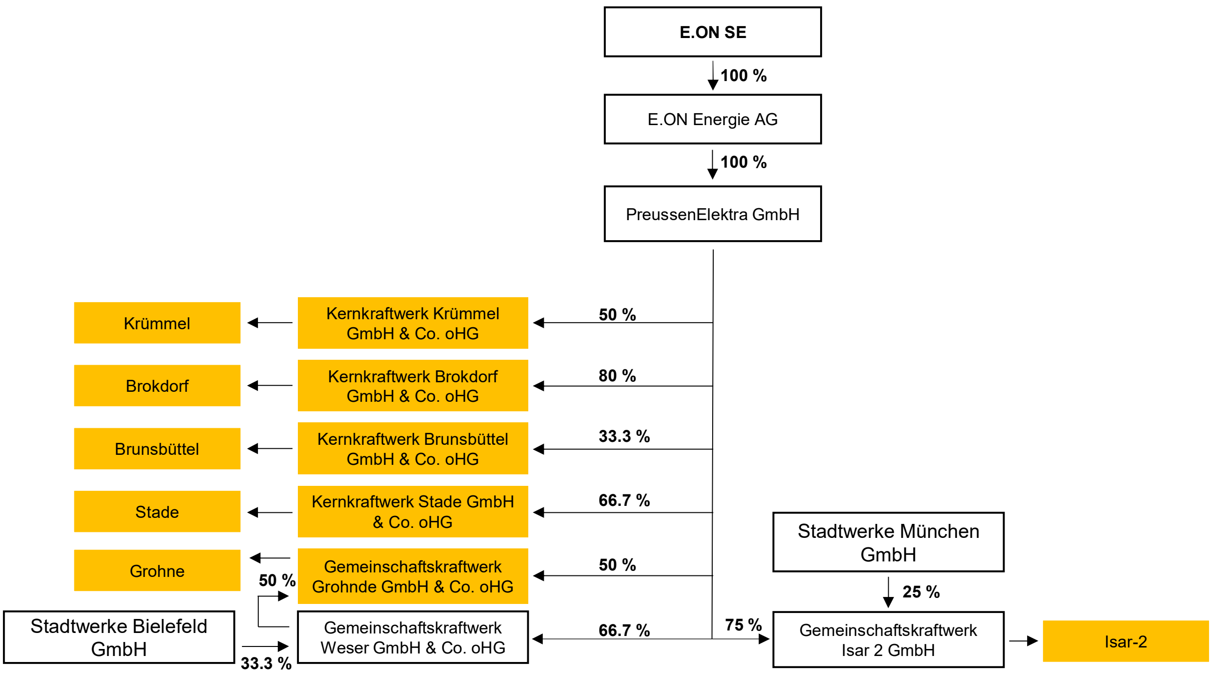
Within the E.ON Group, the nuclear energy business (operation and decommissioning) is managed by the operating unit PreussenElektra GmbH (PEL), of which E.ON SE is the sole owner.[34] PEL is included in the consolidated financial statements of E.ON SE. PEL is the sole nuclear operator of the four shut-

[34] RWE owns 15% of the shares of E.ON Energie AG (RWE and EON 2018)

down reactors Würgassen, Unterweser, Grafenrheinfeld, and Isar-1. Other closed reactors are Stade, Krümmel, and Brunsbüttel. These three reactors are co-owned with Vattenfall Europe Nuclear Energy GmbH (VENE). While Stade and Krümmel are majority-owned by PEL, Brunsbüttel is majority-owned by Vattenfall and therefore also incorporated into the Vattenfall balance sheet. Although PEL has a 50% stake in Krümmel, operational management of the plant is in the hands of VENE, which is also the managing director of the operating companies with sole power of representation. Furthermore, PEL owns two reactors in cooperation with public utilities: Isar-2, and Grohnde. PEL owns 75% of Isar-2, while Stadtwerke München owns 25%, both companies are listed as operator. PEL holds a 50% stake in the operating company Gemeinschaftskernkraftwerk Grohnde GmbH & Co. oHG and is co-holder of the nuclear license and thus co-operator of the Grohnde plant. The other co-operator with a 50% percent share in KWG oHG is Gemeinschaftskraftwerk Weser GmbH & Co. oHG, which in turn is 66.7% owned by PEL. PEL thus holds a total of 83.3% of the shares in KWG oHG (directly and indirectly). The remaining 16.7% are owned by Stadtwerke Bielefeld. PEL is currently involved in two currently operating NPPs, Isar–2 and Emsland.

Until 2019, PEL also held a 25% stake in the operating company Kernkraftwerk Gundremmingen GmbH (KGG GmbH) and was thus both co-holder of the nuclear license and co-operator of units A, B, and C, together with RWE Nuclear GmbH. As part of a transaction between RWE and E.ON, PEL's shares in Gundremmingen as well as in the operating company Kernkraftwerke Lippe-Ems GmbH (12.5%) were transferred in full to RWE. This also relates to the dismantling obligations for these NPPs. Figure 3-6 gives an overview of the corporate structure of E. ON and its nuclear subsidiaries. (Deutscher Bundestag 2021)

**Figure 3-6: Corporate structure of E. ON and its nuclear subsidiaries**



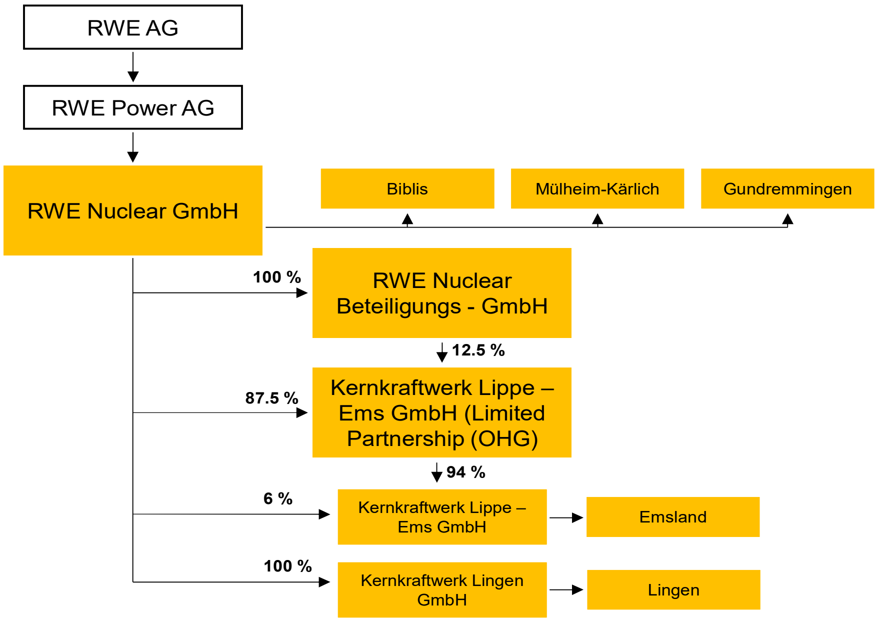

Source: Own depiction following Deutscher Bundestag (2021)

***RWE***

The operation and decommissioning of the German NPPs are part of the RWE Group's "Lignite and Nuclear Energy" segment. RWE Nuclear GmbH is the nuclear operator of the three closed reactors Biblis-A/-B (KWB -A/-B) and Mülheim-Kärlich (KMK). In 2019, E.ON and RWE conducted an wide-ranging transaction of business sectors and subsidiaries, leading to an extensive restructuring of the NPP ownership structure. In this process, RWE took over the shares held by PEL GmbH at Emsland (KKE) (12.5%) and at the Gundremmingen NPP (KRB) (25%). As a result, RWE Nuclear GmbH directly holds a 100% stake in the two operating companies Kernkraftwerk Gundremmingen (KGG) GmbH and in Kernkraftwerk Lingen (KWL) GmbH. RWE Nuclear now also holds a combined 100% stake in the operating company Kernkraftwerk Lippe-Ems (KLE) GmbH directly via RWE Nuclear Beteiligungs-GmbH and indirectly via Kernkraftwerksbeteiligung Lippe-Ems beschränkt haftende OHG.

KGG GmbH is the nuclear operator of the KRB A, B and C plants. KRB A was fully shut down in 1977 and has been undergoing dismantling since 1983. Operation at KRB B ended on December 31, 2017, while operation at KRB C ended in December 2021. There is a contract for electricity generation from nuclear including a supplementary agreement between the shareholder RWE Nuclear GmbH and KGG GmbH. In this contract, which RWE Nuclear GmbH assumed from PEL GmbH with debt-discharging effect in 2019, the release of KGG GmbH from decommissioning and disposal obligations concerning KRB A, B and C was agreed upon. KLE GmbH is the operator under nuclear law of the KKE, for which the end of power operation is scheduled for April 2023. KWL GmbH is the nuclear operator of Lingen NPP, which was finally shut down in 1977. It has been in the process of dismantling since 2015 following a phase of "safe enclosure." The sole shareholder of KWL GmbH is RWE Nuclear GmbH. Both KWL GmbH and RWE Nuclear Beteiligungs-GmbH have concluded a control and profit and loss transfer agreement with RWE Nuclear GmbH. In addition, a control and profit and loss transfer agreement exists between RWE Nuclear GmbH and RWE AG (Deutscher Bundestag 2021; 2022). See Figure 3-7 for an overview of RWE’s nuclear subsidiaries.

**Figure 3-7: Corporate structure RWE and its nuclear subsidiaries**

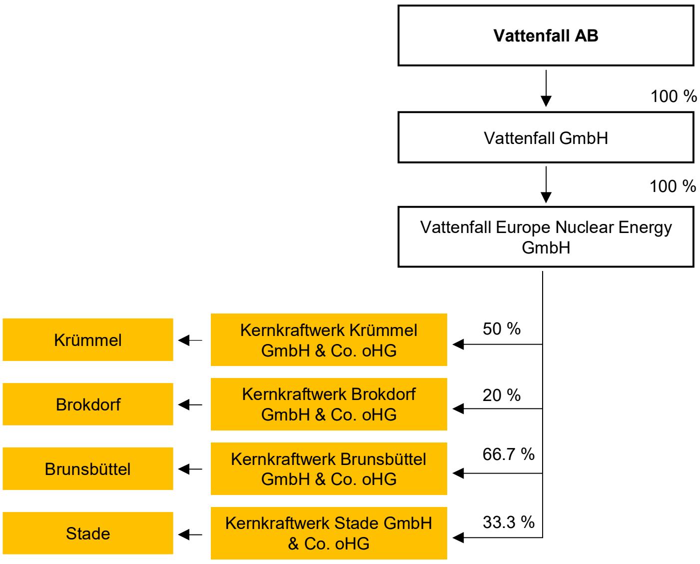



Source: Own depiction following Deutscher Bundestag (2021)

### *Vattenfall*

Swedish utility Vattenfall's German subsidiary Vattenfall GmbH is 100% owner of Vattenfall Europe Nuclear Energy GmbH. This company holds shares of four German NPP operators, namely 50% at Krümmel (KKK), 20% at Brokdorf (KBR), 66.7% at Brunsbüttel (KKB) and 33.3% at Stade (KKS). The majority share at KKB also implies the obligation to decommissioning this NPP. KKK is partly owned with E.ON, and both utilities thus incorporate half of the provisions in their respective balance sheets. VENE is the operator of KKK and thus responsible for decommissioning (Vattenfall 2022). Provisions for KBR and KKS are included in E.ON's balance sheet (Deutscher Bundestag 2021). Figure 3-8 depicts the corporate structure of Vattenfall and its nuclear subsidiaries.

**Figure 3-8: Corporate structure Vattenfall and its nuclear subsidiaries**




Source: Own depiction following Deutscher Bundestag (2021)

***Stadtwerke München***

Stadtwerke München Gmbh (SWM) is a communal utility and fully owned by the city of Munich. SWM makes provisions for the NPP Isar-2 that is co-owned with E.ON, see Figure 3-6. Provisions had amounted to 407.8 million EUR[35] by December 2020 (Deutscher Bundestag 2021).

### 3.2.3 License provision and extension

Following Article 24 AtG, the individual federal states are the licensing authorities for operation as well as decommissioning and are, in addition to the federal authority BASE, responsible for the continuous regulatory supervision of the facilities on their territory.[36] In the decision process, all instances of the federal system (local municipalities (Gemeinden), counties (Landkreise), and federal states) must be included in some form. Article 7 AtG regulates the licensing requirements for nuclear facilities, in particular NPPs. The 13th amendment of the AtG in 2011 restricted new licenses for construction and operation. (BMJ 2022)

### 3.2.4 Oversight

Oversight responsibilities are split in two: oversight regarding the decommissioning process itself lies with the BMUV and its subsidiary agencies BASE and BfS as well as the respective authorizing bodies of the federal states involved. In terms of financial oversight, the Federal Ministry of Finance (BMF, Bundesministerium der Finanzen) and its subsidiary agency BAFA (Bundesamt für Wirtschaft und Ausführkontrolle) are responsible. BAFA publishes the annual transparency report following Article 7 of the "Act on Transparency for Costs of Decommissioning of Nuclear Power Plants and Waste Packaging", also known as "Transparency Act" (TransparenzG). The last report was published in November 2021. (Deutscher Bundestag 2021)

Nuclear licensing is conducted by the federal states' authorities. In terms of nuclear law and regulation however, cooperation between the federal and states' governments and authorities is necessary. For this, the *Länderausschuss für Atomkernenergie* (LAA) was introduced. The LAA is a continuously active cooperation committee to coordinate amendments to nuclear law to provide standardized practice in the nuclear field in Germany (BMUV 2019).

Additionally, operators are mandated to publish separate transparency reports on their own respective websites, following Article 4 TransparenzG and Article 9 of the "Act on the Transparency of Decommissioning Provisions" (RückBRTransparenzV). These reports are to be published by 30th November of each year and must describe operators' plans on how to complete decommissioning of NPPs in such a manner that is understandable for the general public. (Deutscher Bundestag 2021)

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[35] Already in $EUR_{2020}$

[36] For example, in Schleswig-Holstein, where NPPs Brokdorf, Brunsbüttel and Krümmel are located, the state's Ministry for Energy Transition, Climate Protection, Environment and Nature is responsible for nuclear licensing, see https://www.schleswig-holstein.de/DE/landesregierung/ministerien-behoerden/V/v_node.html.

### 3.3 Decommissioning Regulation

#### 3.3.1 Decommissioning policy

Article 7 Section 3 of AtG stipulates that a license is required for the decommissioning, dismantling and long-term containment of a nuclear facility or parts thereof. The licensing procedure is governed by the Nuclear Licensing Procedure Ordinance (AtVfV, Atomrechtliche Verfahrensordnung). The main features are the submission of applications and documents, public participation, the possibility of splitting the procedure into several licensing steps and an environmental impact assessment. Licensing applications are submitted to, processed and reviewed by the relevant state authority. In this process, the state ministry works with an independent technical expert organization such as the TÜV (German Technical Inspection Association), and in individual cases can also commission subordinate authorities with supervisory tasks. (Scherwath, Wealer, and Mendelevitch 2020)

After the operating license of a reactor expires, it enters the post-operational phase (POP). Most security measures must remain active. Before the reform in 2017, the operator had to decide between the two possible decommissioning strategies *Immediate Dismantling* and *Deferred Dismantling* in their decommissioning application. At the end of the decommissioning process both strategies must lead to a status that allows all buildings and the site to be released from nuclear regulation. However, the “Act on the Reorganization of Responsibility in Nuclear Waste Management”, which entered into force in 2017, included in Article 3 an amendment of Article 7 Section 3 AtG, which concludes that deferred dismantling is no longer an option for decommissioning of NPPs.[37] The end of the POP is generally determined by the removal of the spent fuel from the reactor building. This significantly reduces radiation and means that security measures can be reduced and dismantled, respectively. Dismantling can start even if some of the defected rods remain in the facility, as these have significantly lower radiation. For Germany, the manual accompanying the AtG, known as “Stilllegungsleitfaden”, provided by BASE and BMUV, prohibits entombment, a strategy chosen for, e.g., the Chernobyl power plant (Scherwath, Wealer, and Mendelevitch 2020; BMUV 2021).

#### 3.3.2 Regulatory and legal process

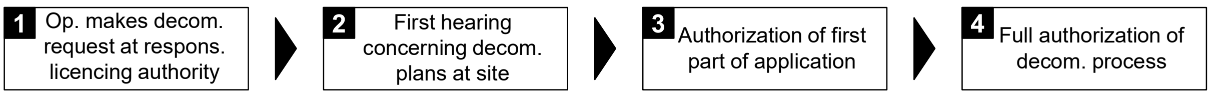
Once the operating life of an NPP ends, the plant enters the POP. According to Article 7 Section 3 AtG, an approval from the regulatory authority is needed for the closure and the actual dismantling of a reactor or parts of the facility. The course of the licensing procedure is regulated in the above mentioned AtVfV. Essential features are the application with submission of documents, public participation, the possibility of splitting the application into several approval steps and the environmental impact assessment (BMUV 2013). The decommissioning requests are sent to the licensing authorities of the responsible federal states. The licensing authority then works on their part–if needed—with a technical inspection

[37] “In individual cases, the competent authority may permit temporary exceptions for plant components as far and as long as this is necessary for reasons of radiation protection” (Federal Republic of Germany 2018, 114).

association, like TÜV. In certain cases, subordinate agencies like the Reactor Safety Commission (RSK) or the Radiation Protection Commission (SSK) can be charged with supervisory tasks (Seidel and Wealer 2016).

This decommissioning approval process consists of four milestones, defined by BAFA, that are depicted in Figure 3-9. The first milestone is the above-mentioned request for decommissioning which must be made with the responsible licensing authority. Once the initial hearing is completed, the second milestone is completed. As the authorization might be split into several authorization procedures for different parts of the decommissioning process, the third milestone marks the point in time when the first authorization for any part of the process is granted. Finally, the last milestone is reached when the application process is completed and full authorization for decommissioning is granted. This regulatory licensing process takes three to five years, on average. (Deutscher Bundestag 2021)

**Figure 3-9: Milestones in the application process to commence with decommissioning of NPPs**

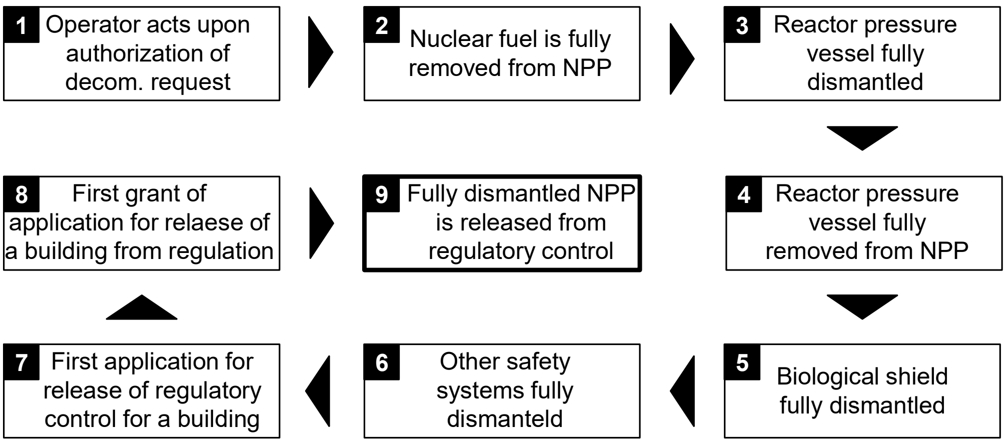



Source: One depiction following Deutscher Bundestag (2021)

Instructions for decommissioning NPPs are outlined in the Guidelines for Decommissioning (“Stilllegungsleitfaden”). From these guidelines, it can be deduced that all information concerning the entire decommissioning process of the plant must be included within the request for the first submission of the decommissioning application. This information should enable the involved authorities to judge if the proposed decommissioning steps are planned in a reasonable manner and if certain planned activities can hinder further or future decommissioning steps, especially under radiation protection aspects. The states have some expertise as they were responsible for supervision since the beginning of the nuclear age (whereas the federal level sets the general rules). As the plant is in POP, which is still covered by the operating license, only works that are covered by this license can be realized. The defueling of the reactor core as well as decontamination works of systems and installations are possible working steps in this phase. Because this amendment annulled a possible return of the NPPs into a phase of power operation, all requests for measures or actions that might infringe the power plant operation state could now basically be granted. Once the request is granted and the plant is legally considered permanently shut down, the operator begins the dismantling process. For certain exceptions that are decided on a case-by-case basis by BASE, the operator can also follow the deferred dismantling strategy that allows larger components to be stored for about 30 years, see Footnote 37. The decommissioning process ends with the release of the regulatory control. This release can only occur once the responsible nuclear authority conducts extensive measurements and deems the site to be safe, following Articles 31 to 42 of the Ordinance on the Protection from Radiation (Strahlenschutzverordnung, StrlSchV). The site or respectively single facilities, i.e. used for interim storage, can be put under a new nuclear license. There is no mandate to demolish the complete site to a greenfield status. Instead, once the site has been released from nuclear regulatory oversight and control, it can be used for other purposes, as was done at the FBR Kalkar, see Section 3.2.2, or it may be "conventionally" demolished (Scheuten 2012; BMUV 2021).

To monitor the status of the decommissioning process, BAFA defines nine milestones, following a similar approach to the milestones of the application process. Figure 3-10 shows these milestones. The first milestone is reached when the operator acts upon the granted authorization and commences the decommissioning process of the NPP. Once all nuclear fuel, corresponding to 99% of radiation levels of all contaminated waste on site, is removed from the premises, the second milestone is completed. Milestones 3 and 4 relate to the dismantling and removal of the reactor pressure vessel. The removal of the biological shield corresponds to the fifth milestone. Milestone 6 is completed once all security measures have been dismantled. The seventh milestone constitutes the first application for release of regulatory control for a building on the premises of the NPP. Once this application is approved, milestone 8 is completed. The final milestone is completed, once the NPP and the whole premises are released from regulatory control. (Deutscher Bundestag 2021)

**Figure 3-10: Milestones of decommissioning process**




Source: Own depiction following Deutscher Bundestag (2021)

### 3.3.3 Oversight

The Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) oversees nuclear safety and radiation protection. BMUV specifies the licensing procedures of NPPs and other facilities, which are implemented by the governmental authorities in the federal states. Subordinate authorities to the BMUV are the Federal Office for the Safety of Nuclear Waste Management (Bundesamt für die Sicherheit der nuklearen Entsorgung, BASE) and the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS). The advisory bodies of the BMUV are (BMUV 2019):

- Reactor Safety Commission (RSK) in matters of nuclear safety,
- Commission on Radiological Protection (SSK) in the matters of radiation
- Nuclear Waste Management Commission (ESK) in matters of nuclear waste management

The Federal Ministry of Finance (Bundesfinanzministerium, BMF) and its subsidiary agency BAFA (Bundesamt für Wirtschaft und Ausführkontrolle) are responsible for financial oversight (Deutscher Bundestag 2021).

### 3.3.4 Liability

There are two organizational models for the decommissioning of German NPPs. The first model was chosen for the NPPs of the former GDR, that being Rheinsberg and the five Greifswald reactors. They are being decommissioned by EWN GmbH. The sole shareholder of the company is BMF. For the other commercial NPPs, the second model applies. Here, majority shareholders, i.e. the utilities, are responsible for the decommissioning of their NPPs and tender the work, especially the complex activities of the "hot-zone stage" to specialized nuclear companies (e.g. Areva for Würgassen and Stade, EWN for Obrigheim). (Deutscher Bundestag 2021; EWN 2021)

## 3.4 Financial Regulation

### 3.4.1 The funding of decommissioning

The funding system in Germany differs between purely public-owned facilities, facilities with mixed-ownership, and facilities in private ownership. Decommissioning costs of public-owned nuclear facilities are generally financed from the current public budget, with no provisions for future payments. The Federal Government covers the majority of the costs, while some are covered by State Governments (European Commission 2013). Examples for public funding are the former German Democratic Republic (GDR) NPPs Greifswald and Rheinsberg, where decommissioning is fully funded by the Ministry of Finance. At two NPPs, communal utilities are co-owners resulting in special provisional arrangements (European Commission 2013). At Grohnde, Stadtwerke Bielefeld own a 16.7% stake of the operating LLC, but make no provisions, as they are covered by E.ON, see Section 3.2.2.2. At Isar-2, Stadtwerke München are co-owner and co-operator and must therefore make provisions for decommissioning of their ownership proportion (Deutscher Bundestag 2021).[38]

#### 3.4.1.1 … before the reform

Legal foundations for the financing of the nuclear back-end in Germany are the Commercial Law ("Handelsgesetzbuch", HGB) and the AtG. The operators of nuclear facilities were obliged to set up provisions for decommissioning and waste management according to Article 249 HGB. These funds were collected from the consumers via the electricity price (Irrek and Vorfeld 2015). These provisions were internal, unrestricted and non-segregated funds, which needed to be set up with the start of operation. Commercial Law defines provisions as financial liabilities, which will have to be paid, but it is not exactly defined how high they should be and when they must be paid. The Commercial Law thus

[38] There also some facilities, whose decommissioning is financed by the European Union (e.g. the ITU European Commission JRC research facilities in Karlsruhe) (European Commission 2013).

forced the operator to act prudently and to include all known obligations immediately into their balance sheet but set no target cost or defined rules on how provisions were to be managed. The provisions had to be reported in the balance sheets and be verified by auditing companies, but not made available to the public (Müller-Dehn 2008). The underlying cost estimates were regularly checked by state ministries, but there were only limited possibilities to confirm the technical basis on which assessments had been made (European Commission 2013). The estimated costs (settlement amounts) were inflated using the expected inflation rate until the settlement date and then discounted using a fixed discount rate. Operators published neither the estimated settlement amounts, the settlement date, nor the underlying discount rates (Irrek and Vorfeld 2015).

The financial resources to cover the future costs were managed by the private utilities, and they were free to choose where to invest funds within the framework of above-mentioned accounting rules. These funding regulations led to misuses of the funds and inappropriate accounting of the actual decommissioning liabilities. Initially, this represented a “recognized major source of internal finance” (European Commission 2013), which was mostly used for corporate activities. Other advantages were interest benefits from deferring tax payments into the future, and the reduction of borrowing requirements and improvement of the rating position of the utilities (FÖS - Forum Ökologisch-Soziale Marktwirtschaft 2014). As the provisions were used for corporate investments, decommissioning or waste management expenses were supplied through the operating cash flow or by liquidating assets. Companies then reduced the liability on the balance sheet. If the cash flow or the liquidated assets were insufficient, activities would have needed to be postponed or insolvency declared (Wealer, Seidel, and von Hirschhausen 2019).

OECD/NEA (2016) highlighted the unregulated and uncontrolled system of internal non-segregated funds as the most critical aspect of the German system. In addition, due to the non-transparent nature of the German decommissioning funding systems, there was a risk that the tangible assets would continue to decline in value in the years (Irrek and Vorfeld 2015). This increased the risk of a possible insolvency of the German utilities. In this case, the financial resources to cover future costs would probably have been lost and the responsibility to cover for future costs would have been transferred to the public budget (Wealer, Seidel, and von Hirschhausen 2019). A study conducted on behalf of the Ministry of Economy in 2014 concluded that funds would not necessarily suffice in the case of operator insolvency (Weins and Fährmann 2015).

#### 3.4.1.2 … after the reform

On behalf of the government, an expert commission reviewed the financing system and provided reform proposals to meet the actual risk related to the system of internal non-segregated funds (KFK 2016). In June 2017, the “Act on the Reorganization of Responsibility in Nuclear Waste Management” entered into legislation. The aim was to secure the financing of decommissioning without passing on the costs incurred for this purpose to society but also to not jeopardize the economic situation of the operators

(Federal Republic of Germany 2018). The latter was achieved with the act allowing the utilities to transfer liability and financial responsibility for interim and final storage to the government. In return, 23.556 billion EUR[39] were transferred into a public fund. The operators of NPPs are now responsible only for the financing of decommissioning, (immediate) dismantling, and waste conditioning (BMWI 2016).

Included in the act, was in article 7 the "Act on Transparency Regarding the Costs of Decommissioning and Dismantling Nuclear Power Plants and the Packaging of Radioactive Waste (Transparency Act)". This act requires operators of NPPs to report an overview of their remaining provisions for nuclear decommissioning and their available funds to finance future costs of decommissioning to BAFA (see Scherwath, Wealer and Mendelevitch (2020) for more details). The Act was also thought to provide clarity on the underlying cost estimates for the provisions.

Article 8 of the act included the "Act on the Follow-up Liability for Dismantling and Waste Management Costs in the Nuclear Energy Sector (Follow-up Liability Act)". This act ensures that payment obligations for 1) the costs for decommissioning and dismantling of the facilities, 2) the payment obligations to the fund according to the Waste Management Fund Act, and 3) the payment obligations for cost increases in radioactive waste management remain with the operating and so-called controlling companies. This means that nuclear utilities cannot rid themselves of the financial responsibility for nuclear decommissioning through restructuration (Federal Republic of Germany 2018).

### 3.4.2 Current balance in funds

Provisions made by the utilities for nuclear decommissioning and dismantling are reported in the annual transparency report, published to the German parliament (Bundestag) by BAFA (Deutscher Bundestag 2021). The current provisions for decommissioning are shown in Table 3-2.

At the end of 2020, EnBW reports 4.8 billion EUR of provisions for decommissioning its five reactors (including waste conditioning).

E.ON incorporates provisions for all its operators into its balance sheets, with the exception of Brunsbüttel. Only 50% of the provisions of Krümmel are represented in the balance sheet, as this NPP is in shared ownership with Vattenfall. Following the owner structure, 75% of the provisions for Isar-2, as well as 100% of the provisions for Brokdorf (80% legal share), Stade (66.7% legal share), and Grohnde (83.3% legal share), are included in the E.ON balance sheets. The overall provisions for decommissioning (including conditioning) were around 8.6 billion EUR in 2020. This still includes 25% of the costs for returning waste from reprocessing for the three Gundremmingen units (now part of RWE).

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[39] 24.3 billion $EUR_{2020}$

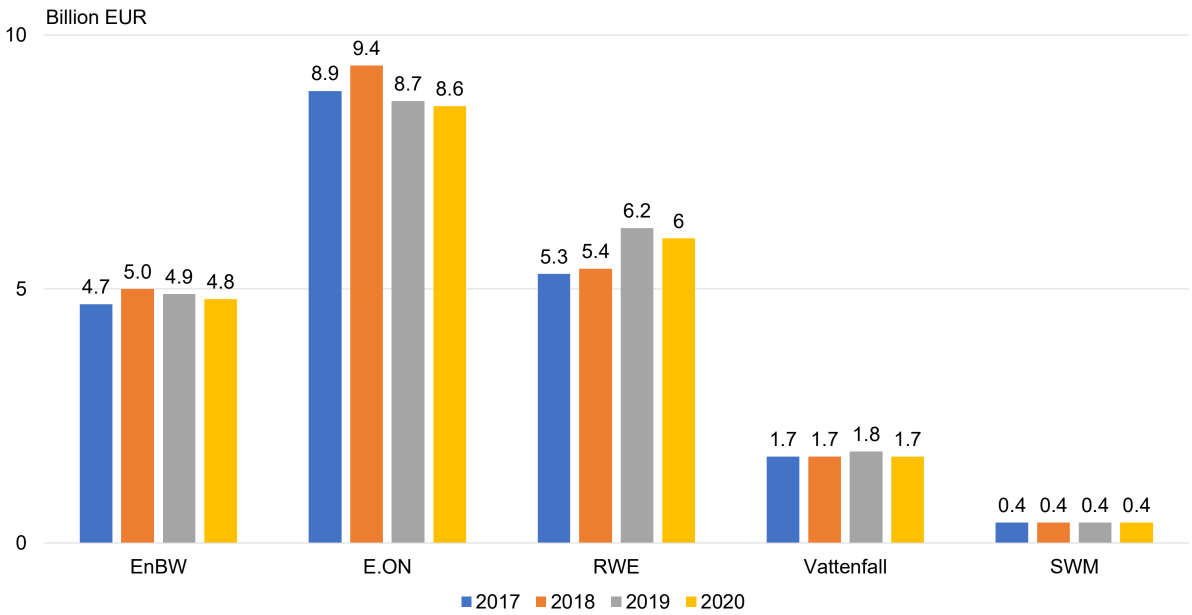
As of December 2020, total provisions made by RWE amounted to 6 billion EUR, distributed amongst RWE Nuclear GmbH, KKE GmbH and KWL GmbH

Vattenfall had made provisions for KKB and KKK, amounting to 2.4 billion EUR in December 2020.

Public utility Stadtwerke München (SWM) holds a 25% stake in the ownership of Isar-2 (KKI-2). Provisions for this NPP are included in SWM's balance sheet and amounted to 407.8 million EUR in 2020.

Figure 3-11 gives an overview of the reported provisions of the utilities. In 2019, falling discount rates meant that the utilities had to make additions to the nuclear provisions. Even after the reform and the implementation of the transparency law it is not possible to earmark the provisions to the reactors. Preussen Elektra, for example, gives an estimated 5,649.2 Mio. EUR which are spread over 100 percent for Würgassen, Unterweser, Grohnde, and Isar-1, for 75 percent for Isar-2, and 25 percent for Gundremmingen A-B-C (Deutscher Bundestag 2018).

**Figure 3-11: Provisions of the utilities on the due dates in 2017-20 in billion EUR**




Source: Compiled from Deutscher Bundestag (2020; 2021), values not inflation-adjusted.

As this report focusses on decommissioning of NPPs, the German fund to finance long-term nuclear waste disposal KENFO (Fonds zur Finanzierung der kerntechnischen Entsorgung) shall only be mentioned briefly. This fund was set up during the above-mentioned reform (see Section 3.4.1.2) that allowed utilities to rid themselves of the responsibility of long-term nuclear waste disposal by paying 23.5 billion EUR[40] into the state-owned fund. The goal of KENFO is to ensure that the disposal of nuclear waste in long-term storage is financially secured. In 2020, 73% of assets were invested and

[40] 24.3 billion $EUR_{2020}$

returned profits of 1.6 billion EUR. Since set-up, KENFO achieved 8.2% annual return on investment. Nevertheless, due to the long timeframe of nuclear waste disposal, fund performance risks remain. (KENFO 2021; Narat 2021)

**Table 3-2: Provisions of German NPP operators as of 31 December 2020**

| Ownership companies | Post-operational stage | Dismantling (incl. preparation), i.e. decommissioning | Waste conditioning & packaging |
|---|---|---|---|
| **EnBW Group** | | **4.789 billion EUR** | |
| EnBW AG | 1,403 million EUR | 836 million EUR | 1,263 million EUR |
| TWS Kernkraft GmbH | 428 million EUR | 252 million EUR | 414 million EUR |
| Kernkraftwerk Obrigheim GmbH | 77 million EUR | 54 million EUR | 62 million EUR |
| **E.ON Group** | | **8.622 billion EUR** | |
| PreussenElektra GmbH | 1,684 million EUR | 955 million EUR | 2,029 million EUR |
| KBR oHG | 654 million EUR | 315 million EUR | 589 million EUR |
| KKS oHG | 44 million EUR | 39 million EUR | 175 million EUR |
| KWG oHG | 608 million EUR | 303 million EUR | 573 million EUR |
| KKK oHG (50%) | 224.05 million EUR | 235.5 million EUR | 194.8 million EUR |
| **RWE Group** | | **6.031 billion EUR** | |
| RWE Nuclear GmbH | 1,814 million EUR | 1,325 million EUR | 1,328 million EUR |
| KKE | 741 million EUR | 347 million EUR | 274 million EUR |
| KWL | 64 million EUR | 99 million EUR | 39 million EUR |
| **Vattenfall Group** | | **1.747 billion EUR** | |
| KKB oHG | 329.8 million EUR | 347.8 million EUR | 415 million EUR |
| KKK oHG (50%) | 224.05 million EUR | 235.5 million EUR | 194.8 million EUR |
| **Stadtwerke München (SWM)** | | **407.8 million EUR** | |
| KKI 2 | 172.3 million EUR | 108.9 million EUR | 126.6 million EUR |
| **Total** | **8.467 billion EUR** | **5.453 billion EUR** | **7.677 billion EUR** |

In this depiction, provisions for KKK are divided between E.ON and Vattenfall, but are reported in full in Vattenfall's balance sheet. All values in $EUR_{2020}$.

Source: Own depiction based on Deutscher Bundestag (2021).

### 3.4.3 Cost assessments

In Germany, cost assessments for decommissioning and long-term waste management are based on expert opinions and cost models. On behalf on the utilities, the private company NIS (Siempelkamp) applied cost models for both light water reactor types used in German NPPs by adjusting the strategy and the reactors in question, for decommissioning cost estimates.[41] The cost estimates produced by the private company for the utilities are not publicly available (Irrek and Vorfeld 2015). In 2015, the auditing company Warth & Klein Grant Thornton AG provided, on behalf of the German government, an estimation of the whole costs for the nuclear back-end of 23 commercial NPPs: 47.5 billion in $EUR_{2014}$[42], of which 19.7 billion were explicitly attributed to decommissioning and dismantling.[43] Provisions for these tasks have amounted to 21.6 billion EUR as of December 2020. The different cost categories are presented in Table 3-3. (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015; Besnard et al. 2019)

**Table 3-3: Estimated decommissioning and waste management cost in Germany (million $EUR_{2014}$)**

| Cost Categories | Undiscounted costs 2015-99 in prices of 2014 (Mio. EUR) | Discounted costs 2015-99 with nuclear specific discount rate of 1.97% (Mio. EUR) |
|---|---|---|
| **Decommissioning and dismantling** | 19,719 | 30,214 |
| **Casks, Transport, Operational Wastes** | 9,915 | 52,840 |
| **Interim Storage** | 5,823 | 26,770 |
| **Low and Medium Waste Disposal (Schacht Konrad)** | 3,750 | 9,016 |
| **High Level Waste Disposal** | 8,321 | 50,966 |
| **Total costs** | **47,527** | **169,808** |

Source: Own depiction based on Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft (2015).

In addition, there are costs for the public funded decommissioning of Greifswald and Rheinsberg and for research facilities: The initial decommissioning costs for Greifswald were initially at about 4 billion EUR and for Rheinsberg 600 million EUR; the latest cost estimate in 2016 was around 6.5 billion[44] for both facilities. (Besnard et al. 2019)

[41] Also, on behalf of the utilities, the private and utilities-owned GNS estimates the costs for waste management based on schedules and cost estimates produced by the German Federal Office for Radiation Protections (BfS, now BASE) for the disposal facilities.

[42] Inflation calculated with information taken from inflationtool.com.

[43] 50 billion $EUR_{2020}$ of which 20.7 billion for decommissioning.

[44] 6.8 billion $EUR_{2020}$

Additional costs not mentioned in Table 3-3 are further 400 million EUR for greenfield decommissioning[45] and another 900 million EUR for not yet made provisions for burnt fuel, as more NPPs were still operational at the time of writing of the study by Warth & Klein Grant Thornton.[46] As always, all cost estimations are subject to many uncertainties related to expectations about future inflation rates, cost increases, and time delays. The estimation of Warth & Klein Grant Thornton considered this by a computation of the estimated costs with a nuclear specific inflation rate of 1.97% until 2099, which resulted in total discounted costs of around 169.8 billion EUR[47].

The audit concluded that the effect of changing the estimated nuclear-specific inflation rate on future costs is strong and causes the most uncertainties. The auditors stress that risks lie in the underestimation of costs and a too small liquidity of utilities from 2070 onwards. (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015)

However, since the responsibility of long-term waste disposal was transferred to the state during the above-mentioned reform (see Section 3.4.1.2), this assessment might no longer be accurate. Long-term waste management must be discounted for the longest timeframe of all cost categories and is therefore influenced strongly by discount rate assumptions. Whether this change has affected the provisions made by the utilities and can guarantee that all other cost categories are accounted for, can currently not be accurately determined.

### 3.4.4 Cost experience and accuracy of assessments

Table 3-4 provides an overview of cost estimations for decommissioning projects in Germany, including prototype and research reactors (VAK Kahl, Niederaichbach, THTR-300, AVR Jülich, KNK II).

In Germany, only one large commercial reactor has completed decommissioning: Würgassen was decommissioned after 17 years with a five year delay at costs of around 1.1 billion $EUR_{2013}$ or 1,700 $EUR_{2013}$/kW.[48] Initial estimations had calculated costs of 0.5 billion EUR (Klooß 2012). At Gundremmingen-A, which has been undergoing decommissioning since 1983, work is ongoing and costs have been estimated at 2.2 billion $EUR_{2015}$[49] (Wealer et al. 2015). As shown in Section 3.4.2, RWE, responsible for Gundremmingen-A, has made provisions of 6 billion $EUR_{2020}$ to decommission further seven NPPs. In 2014, overall costs to decommission (without casks, transport etc.) the German fleet were estimated at 19.72 EUR billion or 830 EUR/kW[50] (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015).

45 Greenfield decommissioning is not mandated, and "conventional" demolition of structures might cause additional cost.
46 421 million for greenfield decommissioning and 947.3 million $EUR_{2020}$ for burnt fuel.
47 178.7 billion $EUR_{2020}$
48 1.2 billion $EUR_{2020}$ or approx. 1,800 $EUR_{2020}$.
49 2.3 billion $EUR_{2020}$
50 20.7 billion $EUR_{2020}$ or 874 $EUR_{2020}$/kW.

**Table 3-4: Cost estimations for decommissioning projects in Germany**

| NPP/Reactor | Operational lifetime | Decommissioning process | Decommissioning costs in million $EUR_{2020}$ |
|---|---|---|---|
| **VAK Kahl** | 1962-1985 | 1988 – 2010 | 157.6 |
| **Würgassen** | 1975-1994 | 1997 – 2014 | 1,050.6 |
| **Gundremmingen A** | 1967-1977 | Since 1983 | 2,311.3 |
| **Stade** | 1972-2003 | 2005 – 2026 (estimate) | 525.3 |
| **Obrigheim** | 1969-2005 | 2008 until mid-2020s (estimate) | 630.4 |
| **Mülheim-Kärlich** | 1987-1988 | 2004 – 2030s (estimate) | 761.7 |
| **Greifswald 1-5** | 1974-1990 | Since 1995 | >4,202.4 for Greifswald and 630.4 Rheinsberg; new calculations estimate around 6.8 bn for both projects |
| **Rheinsberg** | 1967-1991 | 1995 – 2069 | |
| **Niederaichbach** | 1973-1974 | 1987 – 1995 | 147.1 |
| **THTR-300** | 1987-1988 | Begin in 2030 | 709.2 |
| **AVR Jülich** | 1969-1988 | 2003 – 2022 | 378.2 |
| **KNK II** | 1979-1991 | 1993 – 2019 | 367.7 |

Source: Own depiction based on Wealer et al. (2015) and (Deutscher Bundestag 2021)

## 3.5 Production

### 3.5.1 Overview

By the end of 2021, Germany had a total of 30 closed commercial nuclear reactors corresponding to the second largest fleet of closed reactors worldwide. Including prototype and research reactors, it also has the second highest number of fully decommissioned units. The latest closures were Brokdorf, Grohnde (both operated by Preussen Elektra) and Gundremmingen-C (operated by RWE) on 31 December 2021 after an average time of operation of 36 years. In this and the accompanying country reports, reactors were classified as commercial and non-commercial following the classification scheme depicted in Figure 1-7 in the annex of Chapter 1. German reactors have all been classified as "commercial" – even reactors originally designed as research reactors supplied electricity to the grid for many years, e.g., AVR Jülich. An overview of the current decommissioning status of German NPPs is provided in Table 3-8 in the annex. All reactors were determined to be commercial reactors due to long lasting connections to the grid. (Wealer et al. 2015; Kunz et al. 2018; Wealer, Seidel, and von Hirschhausen 2019; Besnard et al. 2019; Schneider et al. 2018; 2019; 2020; 2021; 2022; WNN 2021)

### 3.5.2 Progress

Of the large commercial reactors, only Würgassen has de facto completed the technical decommissioning process. Several commercial reactors have completed the "Hot-Zone-Stage" and have transferred into the "Ease-Off-Stage". However, it cannot be released from regulatory control as buildings on site are used as interim nuclear waste storage. Smaller reactors, HDR Großwelzheim, Niederaichbach and VAK Kahl, have all been fully decommissioned and released from regulatory control. The prototype reactor THTR-300 is the only German reactor still in long-term enclosure (Schneider et al. 2022).

Since 1983, decommissioning has been underway at Gundremmingen. This NPP consists of two parts: KRB I or Gundremmingen-A, a BWR that was shut down in 1977, and KRB II, incorporating Gundremmingen-B and -C, two BWR reactors commissioned in 1984 and 1985, respectively. Gundremmingen-A can be placed into the "Ease-Off-Stage" of decommissioning as the site has been free of fuel since 1988 and the most critical components have been dismantled successfully. In 2020, demolition at the reactor building continued and is expected to be completed sometime in the early 2030s. Individual buildings of the Gundremmingen-A site have been reassigned to KRB II and are currently being used as a facility for dismantling and decontamination of components from KRB II. Furthermore, the site includes an interim storage facility that is being managed by BGZ. A decommissioning license for Gundremmingen-B and -C was granted in May 2021. With Gundremmingen C only having been shut down in December 2021, decommissioning works will continue to the 2040s. (Deutscher Bundestag 2021; RWE 2022)

The BWR reactor at Lingen was shut down in 1977 and was placed into long-term enclosure in 1988 after having been fully defueled in 1986. Since 2015, it has been released and decommissioning work on contaminated buildings has begun following the grant of the first part of a two-part decommissioning authorization request. The second part is still awaiting approval. When decommissioning will be completed is debated, with RWE aiming at mid-2020s and official reports stating early 2030s. (RWE 2020; Deutscher Bundestag 2021)

Decommissioning at Stade (640 MW) was thought to have been achieved by 2014. However, issues resulting from unexpected contamination have led to significant delays. The current target is to achieve a greenfield site by 2026. (Deutscher Bundestag 2021)

The legacy fleet of the former German Democratic Republic (GDR), consisting of Rheinsberg and the five units at Greifswald, is currently in the "Ease-Off-Stage". But hot-zone works were somewhat deferred for both sites: The six reactor pressure vessels, 17 steam generators and parts of the primary cooling system were transported to the "Interim Storage Facility North", also operated by EWN. (EWN 2021)

The NPP Krümmel was shut down in 2011, after having been offline since June 2007, apart from several days in 2009. In 2015, the operator applied to the local authority in Schleswig-Holstein to fully shut down and decommission the plant. However, the permit has not yet been granted. During the application process, the operator planned to defuel the plant, which was achieved in late 2019. Whether the plan to decommission Krümmel by 2038 can be achieved, remains uncertain as the permission to fully begin decommissioning was expected to be granted in early 2022. As a major step of the warm-up stage was thus already completed, this report considers Krümmel to be in this stage, although a permit has not yet been granted. (Deutscher Bundestag 2021; KKK 2015; Schleswig-Holsteinisches Ministerium für Energiewende, Klimaschutz, Umwelt und Natur Undated)

All plants that were shut down following the Fukushima accident in March 2011 have submitted their decommissioning proposal to the regulatory authority, which have not yet all been granted (Deutscher Bundestag 2021). But the German operators currently face several obstacles in order to be able to conclude the decommissioning process in a timely manner without excessive costs. These obstacles included insufficient numbers of transport and storage casks being produced to defuel the reactors that have been, according to reports by GNS, partially been resolved (Ismar 2012; Uken 2012; GNS 2014). In addition, the early shutdown of reactors after the phase-out decision caused a high number of "special" fuel rods—not completely burnt-up fuel—in the reactor core, for which no casks have yet been approved by the regulatory authorities (Bannani et al. 2015; Bechtel et al. 2019). Defueling and subsequent interim storage cannot be achieved until the required casks are available. Table 3-5 shows the development in the decommissioning process since 2015 as of June 2022.

**Table 3-5: Current Status of Reactor Decommissioning in Germany (as of June 2022).**

| Germany | 2015 | May 2018 | May 2019 | May 2020 | May 2021 | May 2022 |
|---|---|---|---|---|---|---|
| **"Warm-up-stage"** | 10 | 11 | 11 | 8 | 8 | 8 |
| ***of which defueled*** | *0* | *3* | *6* | *4* | *6* | *5* |
| **"Hot-zone-stage"** | 3 | 4 | 4 | 8 | 8 | 9 |
| **"Ease-off-stage"** | 9 | 8 | 8 | 8 | 8 | 9 |
| **LTE** | 2 | 1 | 1 | 1 | 1 | 1 |
| **Finished** | 4 | 5 | 5 | 5 | 5* | 4 |
| ***of which greenfield*** | *3* | *3* | *3* | *3* | *3* | *3* |
| **Shut-down reactors** | **28** | **29** | **29** | **30** | **30** | **33** |

*Schneider et al. (2021) mistakenly placed Gundremmingen-A amongst the completely decommissioned NPPs..

Sources: Schneider et al. (2018; 2019; 2020; 2021; 2022) and Deutscher Bundestag (2021)

### 3.5.3 Actors involved in the decommissioning process

Experiences from past and ongoing decommissioning projects show that specialized companies are especially active in the hot-zone stage, where the reactor pressure vessel and the vessel internals are dismantled (Scherwath, Wealer, and Mendelevitch 2020). As these tasks constitute very complex and specific tasks, they can only be provided by a few specialized nuclear firms, e.g. Westinghouse or Framatome. Some companies are also trying to achieve economies of scale: In January 2018, PreussenElektra awarded a decommissioning contract to ZerKon (a consortium led by the German utilities-owned waste management company GNS (Preussen Elektra is the major shareholder of GNS with 48% of the shares) and Westinghouse Electric Sweden) to dismantle the ractor vessel internals (RVI) of its six plants (Schneider et al. 2018). Vattenfall awarded the contract for the dismantling of the RVI to a consortium of EWN and Areva, with an option for the Krümmel plant (Areva 2017). EnBW awarded a contract for the dismantling of the reactor pressure vessels (RPV) and RVI to a Westinghouse-led consortium with Nukem Technologies and GNS (WNN 2015).

In 2021, Westinghouse was tasked with dismantling the RPVat the units at the Gundremmingen B and C sites by RWE. For RWE's Emsland site, a consotrium of Framatom and Transnubel is currently operational. (RWE 2021)

The following companies have already worked in Germany or have concrete plans to enter the German market: Nukem Technologies, Framatome, EWN, Siempelkamp, GEH, Westinghouse and Babcock. Until now, only EWN, Nukem, and Framatome have been active in the hot-zone-stage. The companies prefer to act in a consortium, bundling knowledge and sharing risks (Scherwath, Wealer, and Mendelevitch 2020).

A special feature of the German market is the interconnection of service providers and operators, as the utilities - through the ownership of GNS - also act on the supply side of the market. Utilities-owned GNS was founded in 1977 and provides transport, waste management, and disposal of waste services. GNS is the main supplier of casks and developed the storage and transport casks CASTOR (GNS Undated). The directly contracted consortia then often hire subcontractors to perform specific tasks. For example, engineering company Bilfinger was tasked with the dismantling of reactor internals and radiation shielding at Mülheim-Kärlich and Brunsbüttel (Bilfinger Undated).

#### 3.5.4 Focus on decommissioning in the hot zone

Apart from the USA and Japan, Germany is the only country that has managed to fully decommission several NPPs to greenfield status (Schneider et al. 2021). With Germany planning the commercial operation of its NPPs to end in 2023, and with most NPPs already having been shut down, the country's utilities are tasked with the parallel decommissioning of German NPPs – with some already having reached the "hot-zone-stage", see Section 3.5.2. This stage of decommissioning constitutes the removal of the reactor pressure vessel (RPV) and vessel internals (RVI) (Schneider et al. 2021). Initially, concerns were stated that the parallel dismantling and decommissioning at several German NPPs would lead to a bottleneck situation due to too few companies being able to offer the necessary skills for hot-zone-stage work (Scherwath, Wealer, and Mendelevitch 2020). It seems however, that German utilities are aiming to reap economies of scale by awarding hot-zone-decommissioning tasks to few large consortia, as shown below in Table 3-6 (Schneider et al. 2021; 2022).

**Table 3-6: Hot-zone contractors & consortia**

| Contractor | Hot-Zone-Task | NPPs |
|---|---|---|
| **Orano & EWN** | RVI Dismantling | Biblis A & B, Mülheim-Kärlich, Brunsbüttel, Krümmel, Philippsburg-2, Neckarwestheim-2 |
| | RPV Dismantling | Mülheim-Kärlich |
| **Kraftanlagen Heidelberg & STEAG** | RPV Dismantling | Biblis A & B |
| **Atkins** | RPV Dismantling | Lingen |
| **EWN** | RPV & RVI Dismantling | Obrigheim |
| **Westinghouse, Nukem Technologies, GNS** | RPV & RVI Dismantling | Philippsburg-1 |
| **ZerKon (GNS, Westinghouse Electric Sweden, Westinghouse Electric Germany)** | Internal Structures | Würgassen, Unterweser, Grafenrheinfeld, Isar-1, Krümmel, Brunsbüttel |
| **Cyclife & Framatome (EDF subsidiaries)** | Steam Generator Dismantling | Unterweser, Grafenrheinfeld, Grohnde, Brokdorf |

Sources: Own compilation of Schneider et al (2021; 2022), Scherwath,Wealer and Mendelevitch (2020), Areva (2019), RWE (2019), Orano (Undated), Preussen Elektra (2022) and Maksimenko (2021)

## 3.6 Country specific nuclear and decommissioning developments

Even though Germany is relatively advanced in its decommissioning process, the analysis shows significant delays in the timing, and thus mirrors a trend that is similarly observable in other country cases such as France of the UK. In Germany, the external conditions for nuclear decommissioning are quite favorable, though: With the decision to end the commercial use of nuclear power in 2023, and the decision for a final repository to be decided in 2031, there is a clear commitment to move towards the back-end of the sector. However, a couple of factors might turn out slow down the overall process.

### 3.6.1 Lack of incentives for timely decommissioning

The structure for decommissioning described above provides in theory sufficient funds overall but foresees no incentive mechanism for timely and cost-efficient processes. Since the major decision for closing down all reactors, back in 2011, several delays have already occurred, mainly in the defueling process, see Section 3.5.2.

Project timelines have been systematically extended. At present, most plants only plan the end of their respective decommissioning in the late 2030s or even early 2040s (e.g., Emsland, Neckarwestheim), two decades from now. Special cases are the first larger commercial reactors of Stade, closed down in 2003 and expected to finish decommissioning in 2026, and Würgassen, closed down in 1994 and now expected to be fully released from regulatory oversight by 2030 (Deutscher Bundestag 2021). Würgassen particularly shows the difficulty in respecting delays both due to the lack of internal incentives, and delays in the downstream development of intermediate waste storage.

### 3.6.2 Delays and uncertainties in intermediate and final storage of low- and medium-level waste

Among the reasons for the delay from the downstream side are the uncertainties of the logistics of low- and medium-level waste and the systematic delay of the opening of the final storage site "Schacht Konrad". The old iron ore mine was identified as a potential site for storing 303.000 $m^3$ of low- and intermediate-level waste in 1982, but it took until 2002 for the licensing authority to grant permission for Konrad. Initially planned to open in the 2010s, the date was regularly extended. At present (2022), opening is planned for 2027 (BGE 2022).

Logistical challenges in filling the depository Konrad add to the delays. As of 2022, there was no decision about the timeline of delivering waste to Konrad, and how the intermediate logistical platform at Würgassen (on the site of the former NPP) will be deployed. BGZ, the company in charge of intermediate storage, is currently planning a logistical centre that should be operational in 2027. At present, different forms of containment of waste are being debated, such as cylindrical concrete canisters, cylindrical iron canisters, or steel containers (BGZ Undated). Even though the packaging is not a complicated process by itself (planned expenses for "treatment of remaining materials and packaging" make up about a third of total expenses), these delays might have repercussions upstream and potentially lead to costs and time overruns in the entire process as decommissioning utilities have nowhere to send nuclear waste or have to store it on-site, delaying greenfield releases.

### 3.6.3 Upcoming challenges

An important issue for the decommissioning process as a whole is the logistics and the handling of the high-level waste accumulated on site. Legally, the responsibility for the high-level waste was moved from the companies to the federal government, where the Ministry of the Environment is in charge of the process, see Section 3.4.1.2. However, two potential issues interfere with the decommissioning process:

- Defueling of existing reactors has taken longer than planned. Situated at the intersection of decommissioning and intermediate fuel storage, this is the first critical step of the process that is cost- and time-intensive.
- There are technical interdependencies between the site of the reactor and the close-by intermediate storage site. Examples are energy supply, internal logistics (rail, transport, etc.),

and personnel and administration. Cutting these into two separate pieces raises transaction costs and may lead to strategic behavior by the incumbents, which may further delay decommissioning.

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## Appendix

**Table 3-7 Ownership of German Nuclear Power Plants**

| Nuclear Power Plant | Operator | Owner |
|---|---|---|
| | *NPPs in Single Ownership Structure* | |
| **Biblis A & B** | RWE Power AG | RWE |
| **Emsland** | Kernkraftwerke Lippe-Ems GmbH | RWE |
| **Grafenrheinfeld** | PreussenElektra GmbH | E.ON |
| **Greifswald 1-5** | EWN GmbH | EWN |
| **Gundremmingen A, B & C** | Kernkraftwerke Gundremmingen Betriebsgesellschaft mbH | RWE |
| **Isar-1** | PreussenElektra GmbH | E. ON |
| **Lingen** | RWE | RWE |
| **Mülheim-Kärlich** | RWE | RWE |
| **Neckarwestheim 2** | EnBW | EnBW |
| **Obrigheim** | Kernkraftwerk Obrigheim GmbH | EnBW |
| **Philippsburg 1 & 2** | EnBW | EnBW |
| **Rheinsberg** | EWN GmbH | EWN |
| **Unterweser** | E. ON | E. ON |
| **Würgassen** | PreussenElektra GmbH | E. ON |
| | *NPPs in Mixed Ownership Structure* | |
| **Brokdorf** | PreussenElektra GmbH | E. ON (80%), Vattenfall (20%) |
| **Brunsbüttel** | Kernkraftwerk Brunsbüttel GmbH & Co. oHG | Vattenfall (66.7%), E.ON (33.3%) |
| **Grohnde** | PreussenElektra GmbH | E.ON (83.3%), Stadtwerke Bielefeld (16.7%) |
| **Isar-2** | PreussenElektra GmbH | E.ON (25%), Stadtwerke München (25%) |
| **Krümmel** | Kernkraftwerk Krümmel GmbH & Co oHG | Vattenfall (50%), E.ON (50%) |
| **Neckarwestheim 1** | EnBW | EnBW (98.45%), 4 other owners (1.55%) (see Figure 3-5) |
| **Stade** | Kernkraftwerke Stade GmbH | E. ON (66.7%), Vattenfall (33.3%) |

Source: Own compilation of Deutscher Bundestag (2021, xi), EWN (2021, 2) and IAEAs Operating Experience (IAEA 2022a)

**Table 3-8: Reactors undergoing decommissioning in Germany, as of May 2022**

| Reactor | Capacity in MW | Reactor Type | Operational Time | Owner / Operator | Decommissioning Stage | Defueled |
|---|---|---|---|---|---|---|
| **AVR Jülich** | 13 | HTGR | 19.05.1969 - 31.12.1988 | Arbeitsgemeinschaft Versuchsreaktor GmbH / Arbeitsgemeinschaft Versuchsreaktor GmbH | Hot – zone Stage | Yes |
| **Biblis-A** | 1,167 | PWR | 25.08.1974 - 06.08.2011 | RWE / RWE | Warm – up Stage | Yes |
| **Biblis-B** | 1,240 | PWR | 06.04.1976 - 06.08.2011 | RWE / RWE | Warm – up Stage | Yes |
| **Brokdorf** | 1,410 | PWR | 14.10.1986 – 31.12.2021 | 80% E.ON, 20 % VENE / E.ON | POP | Yes |
| **Brunsbüttel** | 771 | BWR-69 | 13.07.1976 - 06.08.2011 | 66.6% VENE, 33.3% E.ON / Krankraftwerk Brunsbüttel GmbH & Co. OHG | Hot – zone Stage | Yes |
| **Grafenrheinfeld** | 1,275 | PWR | 21.12.1981 - 30.06.2015 | E.ON /E.ON | Warm – up Stage | Yes |
| **Greifswald (I)** | 408 | VVER-230 | 17.12.1973 - 14.02.1990 | Energiewerke Nord GmbH / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Greifswald (II)** | 408 | VVER-230 | 23.12.1974 - 16.04.1975 | Energiewerke Nord GmbH / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Greifswald (III)** | 408 | VVER-230 | 24.10.1977 - 28.02.1990 | Energiewerke Nord GmbH / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Greifswald (IV)** | 408 | VVER-230 | 01.04.1972 - 22.07.1990 | . / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Greifswald (V)** | 408 | VVER-230 | 24.04.1989 - 24.11.1989 | VEB KKW "Bruno Leschner" / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Grohnde** | 1360 | PWR | 05.09.1984 – 31.12.2021 | 83.3% E.ON, 16.7% SW Bielefeld / E.ON | POP | No |
| **Gundremmingen-A** | 237 | BWR | 01.12.1966 – 13.01.1977 | Kernkraftwerke Gundremmingen Betriebsgesellschaft mbH | Ease – off Stage | Yes |
| **Gundremmingen-B** | 1,284 | BWR-72 | 16.03.1984 - 31.12.2017 | 75% RWE, 25% E.ON / Kernkraftwerk Gundremmingen GmbH | Warm – up Stage | No |
| **Gundremmingen-C** | 1,288 | BWR-72 | 02.11.1984 - 31.12.2017 | 75% RWE, 25% E.ON / Kernkraftwerk Gundremmingen GmbH | Warm – up Stage | No |
| **Isar-1** | 878 | BWR-69 | 03.12.1977 - 06.08.2011 | E.ON / E.ON | Hot – zone Stage | Yes |
| **KNK II** | 17 | FBR | 03.03.1979 - 23.08.1991 | Karlsruher Institute für Technologie (Kernforschungszentrum Karlssruhe – KFK) / Kernkraftwerk Betriebsgesellschaft MBH | Hot – zone Stage | Yes |
| **Krümmel** | 1346 | BWR-69 | 28.09.1983 – 06.08.2011 | 50% VENE, 50% E.ON / Kernkraftwerk Krümmel Gmbh & Co oHG | Warm – up Stage | Yes |
| **Lingen** | 183 | BWR | 01.10.1968 - 05.01.1977 | RWE / Kernkraftwerk Lingen GmbH | Warm – up Stage | Yes |
| **Mülheim-Kärlich** | 1219 | PWR | 18.08.1987 - 09.09.1988 | SCN / Kernkraftwerk Gundremmingen GmbH | Hot – zone Stage | Yes |
| **MZFR** | 52 | PHWR | 09.03.1966 - 03.05.1984 | Kerntechnische Entsorgung Karlsruhe GmbH / Kernkraftwerk – Betriebsgesellschaft MBH | Ease – off Stage | Yes |

| Reactor | Capacity in MW | Reactor Type | Operational Time | Owner / Operator | Decommissioning Stage | Defueled |
|---|---|---|---|---|---|---|
| **Neckarwestheim-1** | 785 | PWR | 03.06.1976 - 06.08.2011 | 98,45 % EnBW, 1,55 four other owner / EnBW Kernkraft GmbH | Hot – zone Stage | Yes |
| **Obrigheim** | 340 | PWR | 29.10.1968 - 31.03.1969 | Kernkraftwerk Obrigheim GmbH / EnBW | Hot – zone Stage | Yes |
| **Philippsburg-1** | 890 | BWR-69 | 05.05.1979 - 06.08.2011 | EnBW / EnBW Kernkraft GmbH | Hot – zone Stage | Yes |
| **Phillipsburg-2** | 1402 | PWR | 18.04.1985 - 31.12.2019 | EnBW / EnbW Krankraft GmbH | Warm – up Stage | No |
| **Rheinsberg** | 62 | PWR | 06.05.1966 - 01.06.1990 | Energiewerke Nord GmbH / Energiewerke Nord GmbH | Ease – off Stage | Yes |
| **Stade** | 640 | PWR | 29.01.1972 - 14.11.2003 | Kernkraftwerk Stade GmbH / E.ON | Ease – off Stage | Yes |
| **Hamm - Uentrop** | 296 | HTGR | 16.11.1985 – 29.09.1988 | Hochtemperatur Kernkraftwerk GmbH / Hochtemperatur Kernkraftwerk GmbH | LTE Stage | Yes |
| **Unterweser** | 1,345 | PWR | 29.09.1978 - 06.08.2011 | E.ON / E.ON GmbH | Hot – zone Stage | Yes |

Source: Own depiction based on Schneider et al. (2019; 2021), Wealer et al. (2018), Deutscher Bundestag (2021), and IAEA (IAEA 2022b).

# 4 Sweden

Rebekka Bärenbold

## 4.1 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 4-1 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.

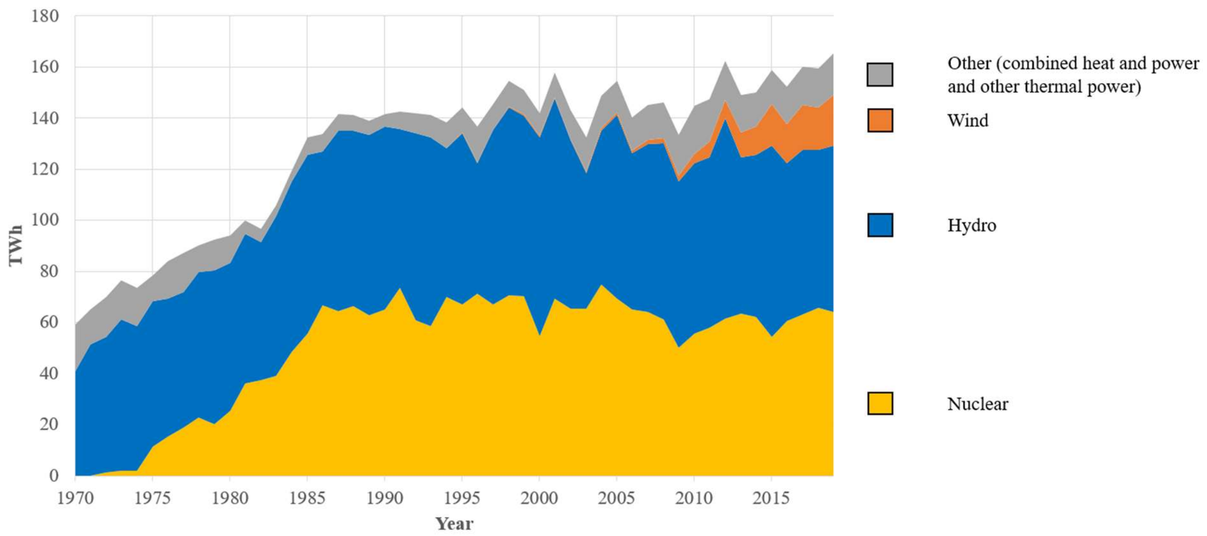
Figure 4-1 shows the development of the shares of different electricity sources over time. It can be seen that the share of wind power in the electricity mix has been increasing in the last couple of years, whereas the shares of nuclear and hydropower remain relatively constant since the 1980s. However, 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 4-1: 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 4-1: Swedish electricity generation by source (1970-2019)**




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

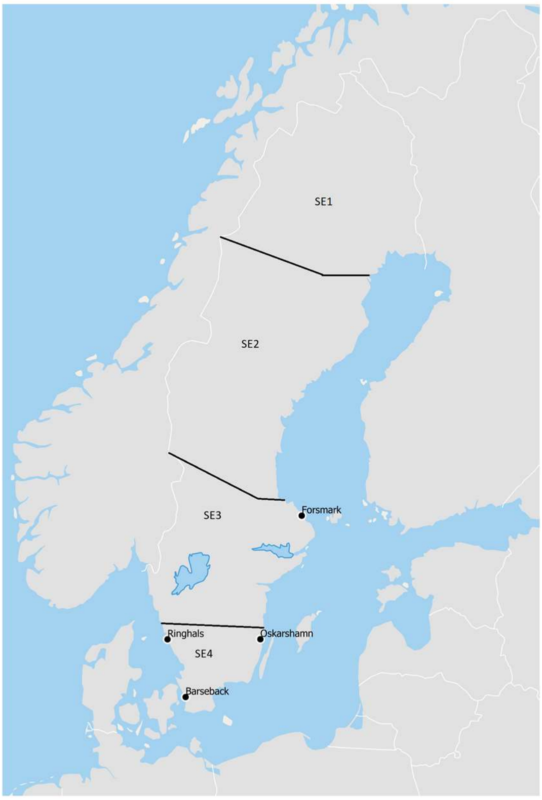
During the last couple of years, operating NPPs in Sweden was unprofitable, as the costs of operating an NPP were higher than the prices received for electricity by the operators. The decline in nuclear electricity prices in Sweden can partly be attributed to subsidies for renewable energies reducing 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 4.5.2. In 2022, six nuclear power reactors are still operating in Sweden distributed among three 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 seven 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 4-2).

**Figure 4-2: 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.

## 4.2 Legal and Regulatory Framework

### 4.2.1 Governmental and regulatory framework

The main guiding laws in Sweden are the Swedish's Radiation Protection Act and the Act on Nuclear Activities (Box 5-1). 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 4-3 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,

**Box 5-1: 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.

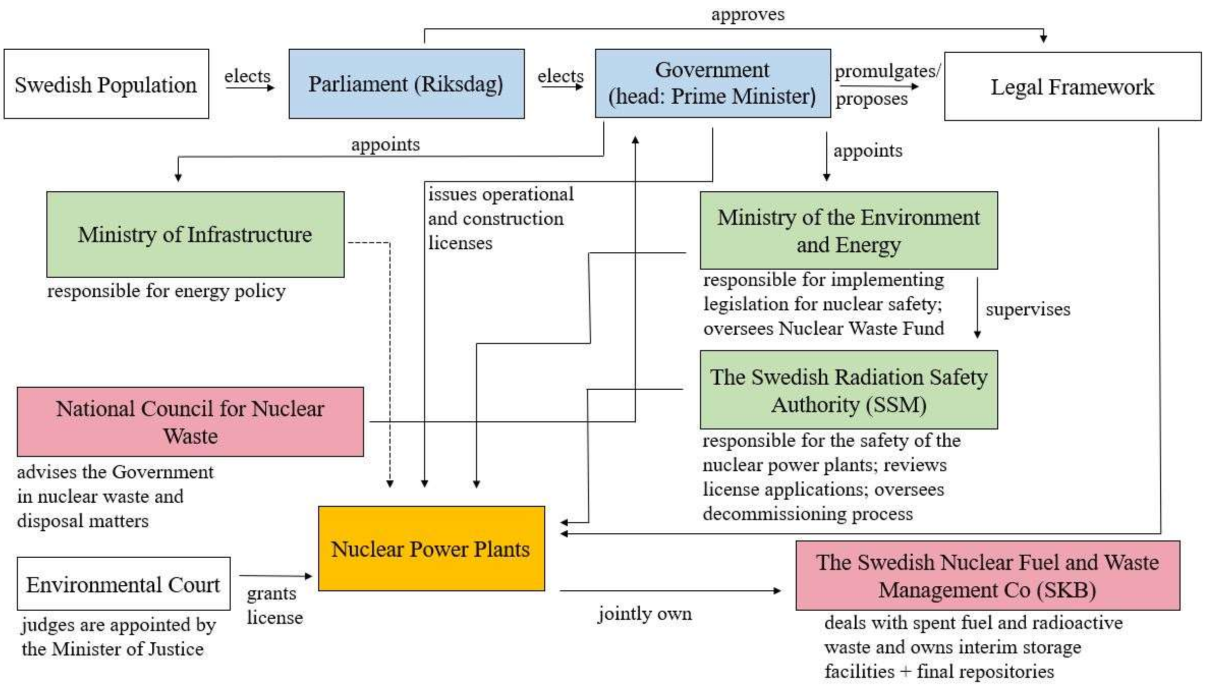
**The Environmental Code, SFS 1998:808:** The objective of the Code is to promote sustainable development and ensure a healthy environment for current and future generations. It includes general provisions on environmental protection.

**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.

it grants and approves licenses for the operation and construction of NPPs as well as for the repository of spent nuclear fuel (IAEA 2022a).

**Figure 4-3: 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 4.2.6.

### 4.2.2 License provision and extension

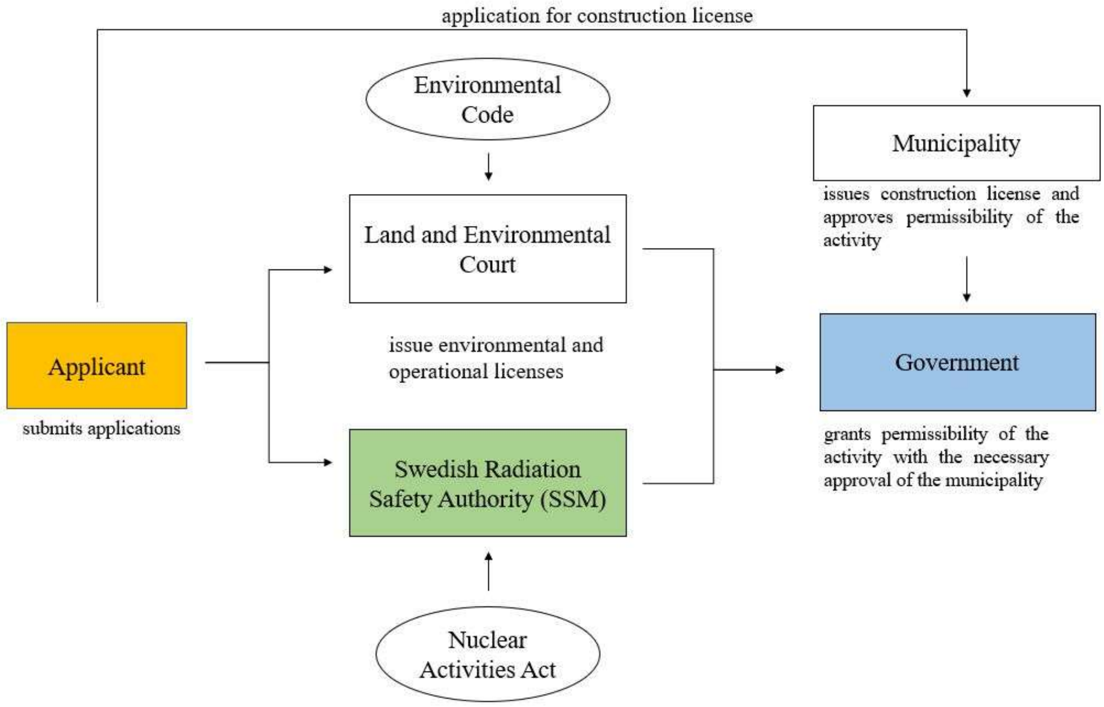
The main legal framework of the licensing process consists of the Environmental Code (1998:808), the Nuclear Activities Act (1984:3) and the Radiation Protection Act (1988:220) (Kärnavfallsradet 2013).

The licensing process shown in Figure 4-4 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 4-4: Licensing process**




Source: Own figure.

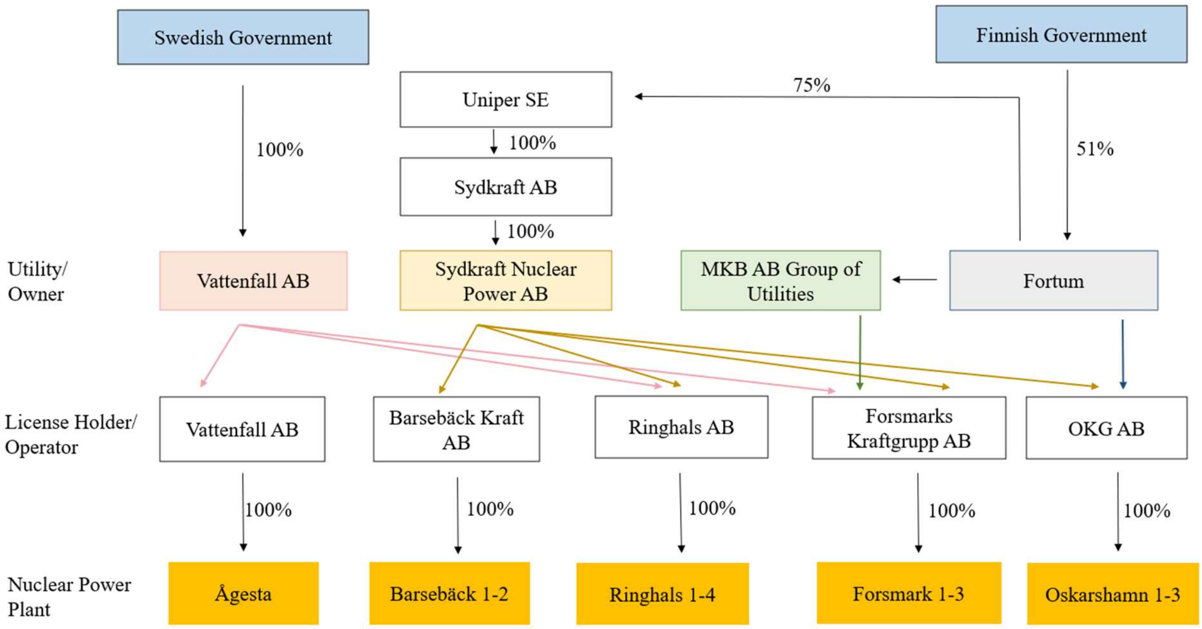
### 4.2.3 Oversight

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).

### 4.2.4 Ownership

The ownership of NPPs in Sweden consists of private and public ownership (World Nuclear Association 2020). Figure 4-5 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 4-5: Swedish NPPs and their owners and operators**




Source: Own figure.

In the following, the utilities depicted in Figure 4-5 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 4-2 reports the distribution of shares of power plants in Sweden.

**Table 4-2: 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).

### 4.2.5 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).[51] 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 1956 with the purpose to provide financial insurance to the Swedish nuclear industry. In 2002, the

[51] 50 million SEK correspond to 9.7 million USD in 1968; 3,300 million SEK correspond to 319.5 million USD in 2001.

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).

#### 4.2.6 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[52]. 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 medium levels of waste (e.g., operational wastes like protective clothing, etc.) that do not need to be

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

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).

## 4.3 Decommissioning Regulation

### 4.3.1 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).

#### 4.3.2 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).

#### 4.3.3 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.

### 4.4 Financial Regulation

#### 4.4.1 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[53] 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).

[53] 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).

#### 4.4.2 Current balance in funds

As of 31.12.2021, the total capital of the fund stood at 80.8 billion SEK (2020 price level)[54] (Nuclear Waste Fund 2021). Table 4-3 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 4-3: 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).

#### 4.4.3 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 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

[54] 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020).

management and decommissioning for all the reactors and waste is 110.5 billion SEK.[55] 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).

#### 4.4.4 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.

#### 4.4.5 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).

### 4.5 Production

#### 4.5.1 Overview

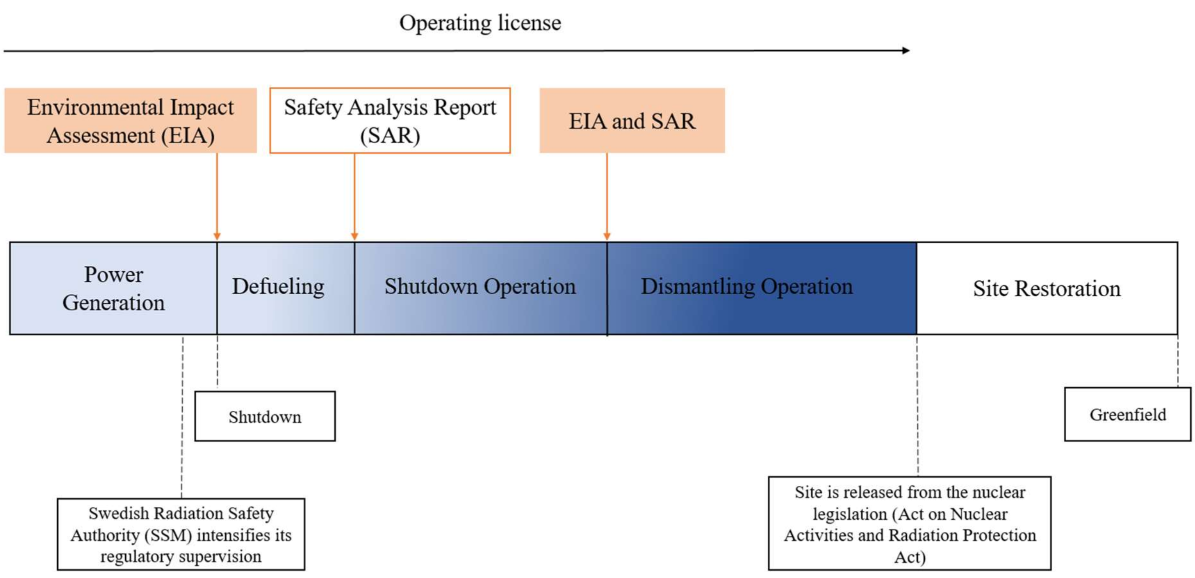
Sweden has very limited experience in the decommissioning of nuclear reactors overall and no experience in the decommissioning of commercial nuclear reactors. The only completed decommissioning work is the decommissioning of the research reactor R1 at the Royal Institute of Technology in Stockholm. Even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

[55] 1 SEK corresponds to 0.0954 EUR and 0.109 USD (yearly average exchange rate 2020).

### 4.5.2 Progress

Figure 4-6 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 4-6: 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).

### 4.5.3 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.

### 4.6 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 $CO_2$ 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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# 5 Switzerland

Rebekka Bärenbold

## 5.1 Introduction

Similar to other countries, Switzerland started to pursue nuclear energy after the end of the Second World War (IAEA 2022a). The Manhattan-project and the American nuclear technology development had a decisive influence on the development of nuclear technology in Switzerland (Wildi 2003). The state was heavily involved in the early stages of nuclear technology development but it soon moved to the peripheral role of a moneylender. The construction of the five commercial nuclear reactors in Switzerland was therefore initiated by the private industry and not by state-governed projects (Wildi 2003). In 1969, Beznau 1 started operating commercially as the first official Swiss nuclear power plant (NPP)[56] (swissinfo 2016). Currently, the NPP fleet of Switzerland is among the oldest worldwide (Schneider et al. 2021). Table 5-1 shows the Swiss nuclear power reactors in detail.

**Table 5-1: Nuclear power reactors in Switzerland**

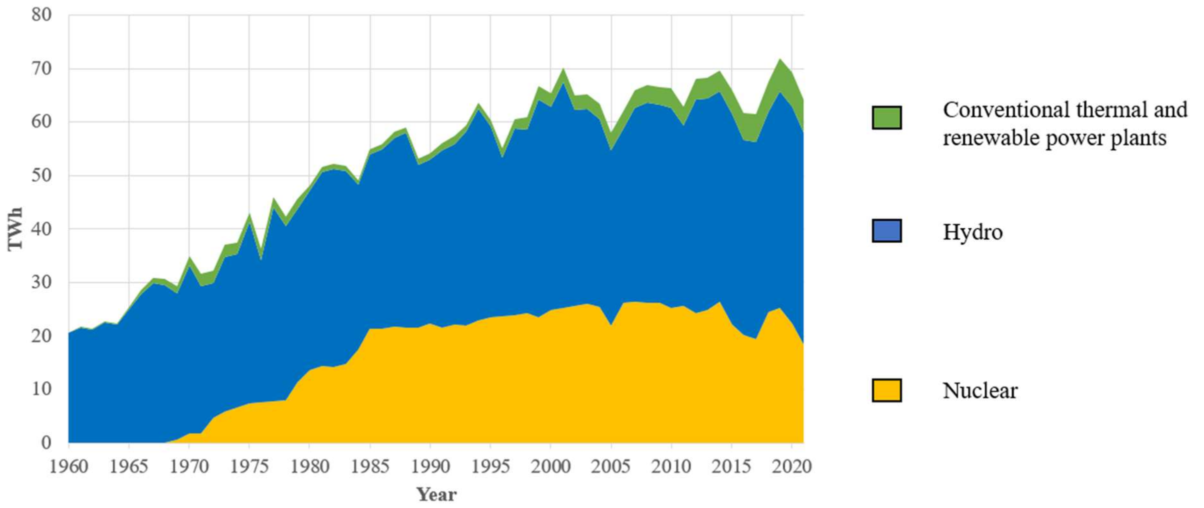
| Nuclear Power Reactor | Grid connection | Type[1] | Net Capacity [MW(e)] | Status |
|---|---|---|---|---|
| **Beznau-1** | 1969 | PWR | 365 | Operational |
| **Beznau-2** | 1972 | PWR | 365 | Operational |
| **Gösgen** | 1979 | PWR | 1010 | Operational |
| **Leibstadt** | 1984 | BWR | 1220 | Operational |
| **Mühleberg** | 1972-2019 | BWR | 373 | Permanent shutdown |

[1] *There are two types of Light Water nuclear reactors in Switzerland: Pressurized water reactors (PWR) and boiling water reactors (BWR).*
Source: Own compilation based on IAEA (2022b).

NPPs are still an important source of electricity in Switzerland today. In 2020, the share of nuclear energy in the electricity production mix was around 32.9%. In addition to nuclear energy, Switzerland also generates electricity from hydropower plants (58.1%), fossil fuels (2.3%) and various renewables such as solar, wind and biomass (6.7%) (BFE 2021). As visible in Figure 5-1, the share of non-hydro based renewable electricity in the mix has been increasing slightly in recent years.

[56] Note that even though Beznau-1 is the first official commercial Swiss NPP it was not the first Swiss NPP connected to the electric grid. In 1960, a Swiss NPP was constructed in an underground rock cavern in Lucens (VD). The reactor was a heavy-water reactor and was connected to the electric grid in 1968 (Buser, Lambert, and Wildi 2020; Wildi 2003). However, the project was abandoned after a collapse of the cooling system released a high amount of radioactivity in the cavern in 1969. After the accident, the decommissioning process started right away and was finished in 1995 (Wildi 2003). For more information about Lucens, see Buser, Lambert, and Wildi (2020); ENSI (2012) and Wildi (2003).

**Figure 5-1: Swiss electricity generation by source (1960-2021)**




Source: Own depiction based on data from Bundesamt für Energie (BFE) (2022c).

Swiss electricity consumers face a mixed electricity market structure, both monopolistic and competitive. The market for large-scale consumers[57] was liberalized in 2009. Thus, these consumers are able to freely choose their electricity provider and buy the electricity they need on the electricity market (AEW 2021). In contrast, small consumers (which correspond to 99% of all end users) cannot buy their electricity on the market. They are bound to their local electricity provider (AEW 2021). However, plans exist for a possible full liberalization of the Swiss residential electricity market in the near future (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation (UVEK), 2020).

In the monopolistic market structure for private consumers, the price of nuclear energy is regulated and determined by the electricity generation costs (“LCOE”) of the NPP. These costs include the degree of capacity utilization; construction and capital costs; operating costs; and fuel costs (mainly disposal costs). The electricity generation costs of NPPs in Switzerland have decreased over time as the capital costs are being repaid. Currently, the costs are approximately 0.04 CHF/ kWh[58] for the older Swiss NPPs (swissnuclear 2018). Large-scale consumers can purchase electricity at market prices which are not regulated and NPPs acting in the market receive the respective wholesale market price which is subject to fluctuations. Consequently, future market developments might improve or damper the profitable production of nuclear electricity (swissnuclear 2017a). For 2022, the Swiss Federal Electricity Commission ElCom reports a slight increase in electricity prices (ElCom 2021).

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

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57 Annual consumption of more than 100’000 kWh (AEW 2021).
58 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).

## 5.2 Legal and Regulatory Framework

### 5.2.1 Governmental and regulatory framework

The first act on nuclear energy dates back to 1959 when the Swiss government passed a bill concerning the peaceful use of nuclear energy (Schweizerisches Bundesarchiv (BAR) 2020). Today, there are six main acts about the usage and organization of the nuclear industry in Switzerland (see the box for details). The main laws that govern the nuclear industry are a part of the Nuclear Energy Act (KEG). The KEG regulates the construction, operation, and decommissioning of NPPs (Bundesrat 2005).

**Box 6-1: Legal framework of Swiss nuclear industry**

**Energy Act (EG), SR 730.0:** formulates Switzerland's requirements for its energy supply.

**Electricity Supply Act (StrVG), SR 734.7:** lays out the framework and tasks for all Swiss electricity providers.

**Nuclear Energy Act (KEG) and Nuclear Energy Ordinance (KEV), SR 732.1 and SR 732.11:** KEG regulates the usage of nuclear energy in Switzerland and determines the safety principles. KEV adds on to KEG and makes it more specific, e.g., concerning the transport of nuclear waste.

**Radiation Protection Act (StSG), SR 814.50:** regulates the radiation protection aspects for operators of nuclear facilities and for nuclear energy users in medicine, industry and research.

**Nuclear Energy Liability Act (KHG), SR 732.44:** regulates, among other things, who is liable for damages/ accidents tied to nuclear power plants.

**Act on the Swiss Federal Nuclear Safety Inspectorate (ENSIG), SR 732.2:** regulates the organization and tasks of the national inspectorate for nuclear safety (ENSI).

Figure 5-2 shows all the important regulatory and governmental bodies and their respective influence on Swiss NPPs. Concerning governmental and regulatory bodies guiding the nuclear industry, the **Federal Council**, the Swiss executive branch, and the **Federal Assembly,** the Swiss legislative branch, are responsible for the peaceful usage of nuclear energy in Switzerland. Together, they define the regulatory and legal framework. The Federal Council and the Federal Assembly are also involved in the license approval process of Swiss NPPs as they grant the general license (Kernkraftwerk Gösgen 2020b).

The **Department of the Environment, Transport, Energy and Communication (DETEC),** whose head is one of the federal councilors, regulates the issuing of licenses concerning the construction and operation of NPPs (IAEA 2022a). The **Federal Office of Energy (SFOE)** has the competence to answer nuclear energy related questions on a political level. It is subordinate to DETEC (BFE 2022a).

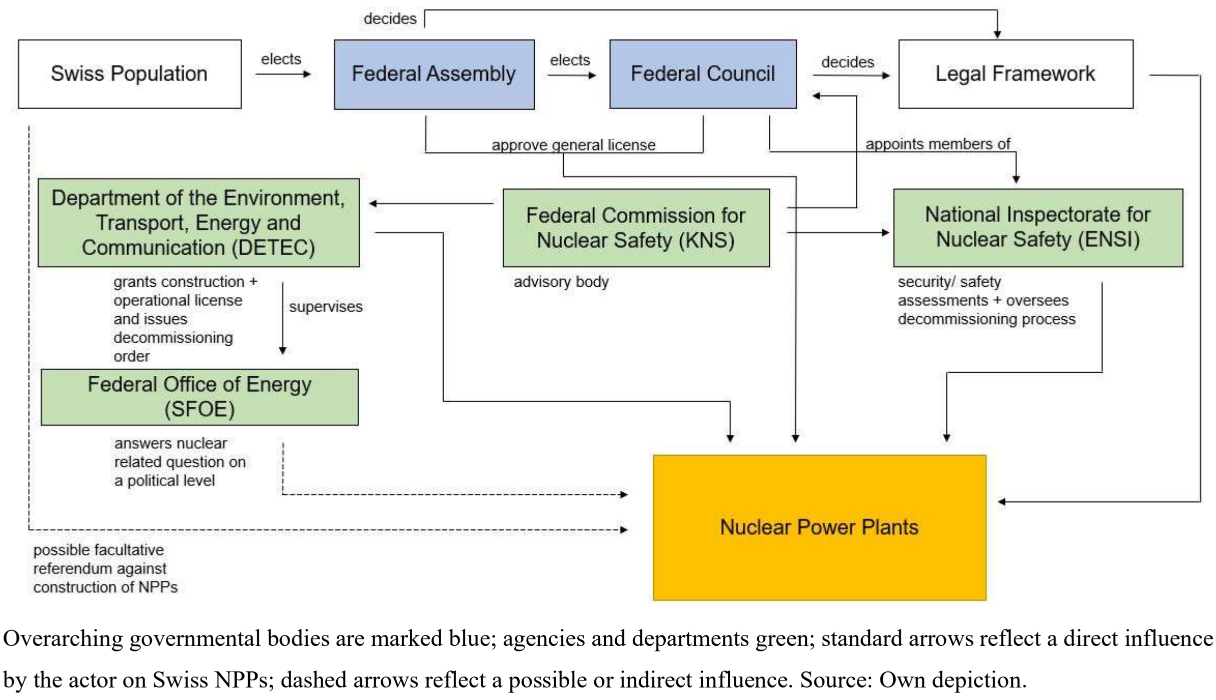
The main supervisor of the nuclear industry on a national level is the **National Inspectorate for Nuclear Safety (ENSI).** ENSI is independent from SFOE and supervised by an independent board whose members are appointed by the Federal Council (ENSI 2020a). Its tasks include inspections of the Swiss NPPs, surveillance of revisions, radiological survey, and safety assessments of the nuclear facilities. Thus, its area of competence is quite extensive, ranging from surveying operation and decommissioning NPPs to the transport of radioactive waste to nuclear research (ENSI 2020a).

Throughout the year, ENSI conducts over 400 on-site inspections and monitors the operation and organization of the nuclear facilities (ENSI 2020a; 2020b). In general, inspections are carried out without notifying the operator first (ENSI 2015b). Every ten years, the NPP operators must carry out a periodic safety review (a so-called "PSÜ"). The objective is a holistic safety assessment of the NPP by the operator. The task of ENSI is to examine the PSÜ thoroughly and to point out where retrofitting measures are necessary (ENSI 2012a).

Another regulatory body involved is the **Federal Commission for Nuclear Safety (KNS)**. KNS holds an consultative role and thus, advises the Federal Council, DETEC and ENSI in nuclear related issues (BFE 2020). There is no overlap between the membership of the boards of KNS and the independent board of ENSI (BFE 2020; ENSI 2020). As shown in Figure 5-2, the **Swiss population** also has the possibility of opposing the construction of an NPP by taking a facultative referendum. Further opposition measures include direct demonstrations as happened in Kaiseraugst.[59]

On an international level, Switzerland is a founding member of **IAEA** (International Atomic Energy Agency) and follows its regulations (Eidgenössisches Departement für auswärtige Angelegenheiten (EDA) 2017). For a complete overview over all the international treaties and conventions followed by Switzerland, see (IAEA 2022a).

**Figure 5-2: Governmental and regulatory actors and their connection to Swiss NPPs**




Overarching governmental bodies are marked blue; agencies and departments green; standard arrows reflect a direct influence by the actor on Swiss NPPs; dashed arrows reflect a possible or indirect influence. Source: Own depiction.

[59] The project of an NPP in Kaiseraugst began in 1969. In 1972, the official location permit was granted by the federal government. This decision was met by strong opposition of the local population that lasted for several years. On April 1st 1975 the conflict came to a head when around 18'000 activists occupied the site of the planned NPP in Kaiseraugst for eleven weeks. The goal was to stop construction work. Given the strong and well-organized local opposition, it became evident that the construction of an NPP in Kaiseraugst would not be feasible. The project was officially abandoned in 1988 (Kupper 1998).

### 5.2.2 License provision and extension

Art. 12-25 in the Nuclear Energy Act regulates the policies with regards to licenses for nuclear plants. The construction of a NPP demands three licenses: a general (Art. 12-14), a construction (Art. 15-18) and an operating license (Art. 19-25) (Bundesrat 2005). A particularity of the Swiss legal process is that the Swiss people may call for an optional referendum and therefore, decide on the construction of new nuclear facilities (IAEA 2022a).

The general license defines the holder of the authorization, location/ site, purpose of the unit, main features of the project (for NPPs this includes the type of reactor, capacity and type of main cooling system) and maximum radiation exposure for people living close-by. It is approved by the Federal Assembly and the Federal Council. However, the general license itself does not allow the NPP owners to begin construction. For that, DETEC must grant a construction license (Bundesrat 2005). DETEC will grant a construction license if the protection of humans and the environment is all but guaranteed; the project fulfills the nuclear safety requirements; no conflicts of interest are present (e.g., envisioned site of plant is not in a protected area); professional execution of the project is present; and there exists a plan for decommissioning. The construction license defines the holder of the authorization, site/ location, planned reactor output, relevant elements of technical realization, basic features of emergency protection, units and system parts that may only be built after approval of inspecting authorities such as ENSI (Bundesrat 2005).

The last license necessary for the actual operation of a NPP is the operating license. Again, DETEC is responsible for granting this license. The operating license defines the holder of the authorization, allowed reactor output, limits for radiation exposure of the surrounding environment, measures for surveillance of the surrounding environment, safety, and emergency measures that the holder of the authorization has to meet during the operation of the plant (Bundesrat 2005). There is no maximum duration of licenses, meaning that all currently active Swiss NPPs (Beznau 1 + 2, Gösgen and Leibstadt) have unlimited operating licenses. As long as the NPPs are deemed to be safe by inspections through ENSI, they are allowed to keep operating (ENSI 2020a; IAEA 2022a; UVEK 2017). In addition to safety issues, the Federal Council has the right to revoke the license if the requirements for issuance stated by the law are not currently, or no longer, met. The Federal Council may also revoke the license if the licensee fails to comply with a condition or an ordered measure despite a reminder (SR 732.1, Art. 67). Note, that the construction of new Swiss NPPs is forbidden by law (Art. 12a in SR 732.1) as of May 2017 (Bundesrat 2005).

Decommissioning law and regulations are also governed by ENSI, KNS, and DETEC under the Art. 26-29 of the Nuclear Energy Act determined by the Federal Council and Federal Assembly. A detailed discussion of the decommissioning process and its laws follows in Section 4.3.

### 5.2.3 Oversight

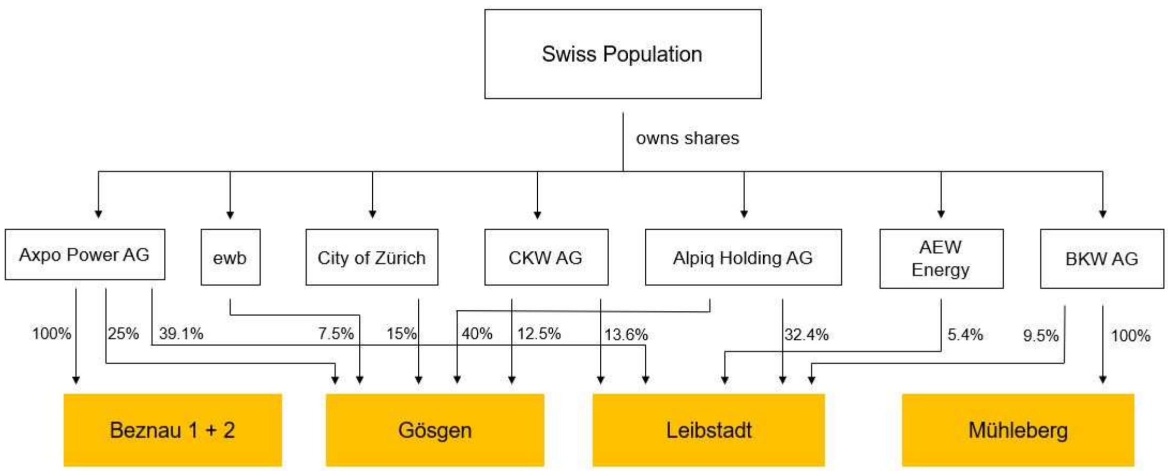
The main oversight in terms of granting licenses belongs to the Federal Council, the Federal Assembly, and DETEC, as they make the decision whether to issue a license or not (IAEA 2022a). While SFOE and ENSI are not part of the final decision to grant a license, they are both heavily involved in the supporting processes. For example, SFOE is the lead in all authorization procedures with respect to the three licenses and ENSI is involved in the safety assessments and examinations of the nuclear facilities (IAEA 2022a).

Oversight during operations is largely the responsibility of ENSI, which conducts safety and security inspections (ENSI 2020a). All NPPs are additionally subject to international inspections conducted by the International Atomic Energy Agency (IAEA).

### 5.2.4 Ownership

Eighty-two percent of the Swiss NPPs belong to public authorities, in other words, these facilities indirectly belong to the Swiss citizens. Most shares in the operating electricity companies of the NPPs belong to the cantons. Foreign investors are not directly involved in the ownership of Swiss NPPs (Kernkraftwerk Gösgen 2020a). Figure 5-3 shows the operators and shareholders of the Swiss NPPs. Note that the nuclear reactors Beznau 1 + 2 are fully owned by Axpo Power AG and Mühleberg by BKW AG whereas Gösgen and Leibstadt are so-called partner plants (i.e., under shared ownership by multiple shareholders).

**Figure 5-3: Swiss NPPs and their owners**




Source: Own depiction based on Seidel and Wealer (2016).

In the following, the different owners of the Swiss NPPs (visible in Figure 5-3) are shortly described in more detail:

- **AEW Energie AG** is a public company and belongs to the canton of Aargau (AEW 2020).
- **Alpiq AG** is an international energy company, owned and controlled by different shareholders (Alpiq 2020). Major shareholders are EOS Holding SA and Swiss Power Plant Holding Ltd. (subsidiary company of CSA Energy Infrastructure Switzerland) with both owning 33.33% of Alpiq's shares (Alpiq 2020b).
- **Axpo Holding AG, Axpo Power AG, Axpo Solutions AG, Avectris AG** and **CKW AG** all belong to the Axpo group. The Axpo group belongs 100% to the North-East Swiss cantons and utilities (Axpo 2020).
- **BKW AG** is a public company. The majority of shares (52.54%) belong to the Canton of Bern (Kernkraftwerk Gösgen 2020). 10% belong to the Swiss energy utility company Groupe E AG (BKW 2019).
- **ewb** is a public company and belongs to the city of Bern (EWB 2020).
- **City of Zürich** is publicly organized. The City Council forms the government and is elected by the people of Zürich.

All utility holding companies described in this subsection also either operate their own or have shares in renewable energy sources such as hydropower, solar, wind power, and biomass. The companies are thus diversified in terms of their electricity sources. Further, the companies also have an international aspect to their portfolio as they own and invest in energy sources abroad (AEW 2020; Alpiq 2020a; 2020c; Axpo 2020; BKW 2020b; EWB 2020).

### 5.2.5 Liability

In general, the operators of the NPPs are liable for damages and events tied to the power plant (Art. 1, SR 732.44). The liability is unlimited (Art. 3, SR 732.44). It is valid for the operation of the power plant as well as when transporting fuel (e.g., from the power plant to the interim storage facility "Zwilag"). Furthermore, the unlimited liability is independent of negligence; in other words, it does not matter whether external factors or the operator were responsible for the damage, the operators are always liable (Art. 3, SR 732.44). Contrary to other countries, the operators are liable even when warlike events, terrorist attacks or extraordinary natural phenomena cause the damage (BFE 2011).

In the case of a nuclear accident, the operator of the power plant is fully liable for all costs related to the accident, also including the subsequent decommissioning of the plant. The mandatory liability insurance coverage for nuclear accidents currently lies at around EUR 1.2 billion for the operators of Swiss NPPs. The coverage is provided by the nuclear insurance pool, which was established in 1957. The members of the nuclear insurance pool are several private Swiss insurance companies such as Helvetia, Basler Versicherungen, AXA, die Mobiliar etc. (Nuklearpool 2021a; 2021b). If the damage exceeds the insurance coverage, the operator is liable with its complete company assets. To give an example, for hypothetical accidents at NPP Beznau and Mühleberg it is Axpo Power AG and BKW AG, respectively, who would be liable. According to the legislation, the law does not provide for any recourse to the shareholders (swissnuclear 2021a; BFE 2011).

In addition to the mandatory liability insurance coverage, the federal government set up a nuclear damage fund. The fund was established to cover the risks that the private insurance pool cannot insure, or cannot insure fully. Thus, these risks are expected to be covered or partly covered by the federal government. An example for such a risk is a core meltdown with an uncontrolled release of radioactivity (Bundesrat 2015). Furthermore, the federal fund operates as a risk hedge in the event of insolvency of the insurers and the liable operators. To secure the coverage, operators pay premiums, which flow into the federal nuclear damage fund. The fund contained around 520 million CHF at the end of 2020 (Bundesrat 2021). [60]

Switzerland also ratified two nuclear energy liability agreements of Brussels and Paris. With the additional agreement of Brussels, 1.5 billion EUR is now covered by private liability insurance and available to cover nuclear damages (compared to 1.2 billion EUR before) (BFE 2022b; Bundesrat 2021). There also exists a bilateral agreement with Germany on liability towards third parties in the field of nuclear energy dating back to 1986, which regulates the principle of equal treatment of nationals of both countries (BFE 2022b).

### 5.2.6 Nuclear Waste Management

Nuclear waste management is regulated by Art. 30-34 of the Nuclear Energy Act. According to the law, radioactive waste produced in Switzerland must *generally* be disposed of domestically. The operators of NPPs are obliged to dispose of their nuclear waste in a safe manner and assume the costs for disposal. The disposal obligation of the operators is fulfilled when a) the waste is disposed of in a deep geological repository and the financial means for its monitoring and closure are secured; b) the waste is disposed of in a disposal facility abroad[61] (Bundesrat 2005). ENSI makes sure that the operators meet these requirements and has therefore the main oversight with respect to nuclear waste management (e.g., transport of nuclear waste, interim storage, final repository) (ENSI 2020a).

All of the five Swiss NPPs have their own facilities to store all categories of radioactive waste (high, medium and low) on site. Spent fuel elements are first stored for a few years in the cooling pool at the power plant. Once the spent nuclear fuel has sufficiently cooled, it is packed into dry casks and transported to the interim storage facility “Zwilag” where it will be stored until its final deposition in the geological repository (Zwilag 2021b). The only exception is Beznau. Beznau has its own interim

[60] 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).
[61] The conditions under which disposal abroad is sanctioned are not clearly stated in the law. For the purposes of commercial reactors, it is our understanding that waste must be disposed of domestically.

storage facility on-site “Zwibez”, where spent fuel elements and lower level waste are temporarily stored (Nagra 2022b). The construction of Zwilag began in 1996 and it started to operate gradually from 2001 onwards. The construction was financed by its shareholders, i.e., the operators of the Swiss NPPs[62], and to a lesser extent, the Swiss Confederation (Zwilag 2021a). The capital stock of Zwilag is proportionally distributed according to the individual capacity of the NPPs (Nagra 2020e). NPPs with higher capacity use more spent fuel and thus, produce more waste. Zwilag can be seen as a link between the generation of nuclear waste and its final long-term storage. It was built to store and process all categories of radioactive waste generated in Switzerland (Zwilag 2021b). The storage facility includes a plasma plant, which is the first of its kind to be used for nuclear waste vitrification. In the plasma plant, the lower-level radioactive waste is thermally decomposed. Through this process, the volume of the waste is reduced and thus, is made more compact and stable for final storage. The process does not reduce the radioactivity of the waste (Zwilag 2020).

As of right now, Switzerland does not have any final repository for radioactive waste. Nagra (the National Cooperative for the Storage of Radioactive Waste) proposed two possible construction plans for the final disposal of radioactive waste: (1) a combination repository for high active (HAA) and low/ medium active (SMA) nuclear waste and (2) two separate repositories for HAA and SMA waste, respectively (Nagra 2020d). The process of choosing a site for the final repository or repositories took around 15 years. In September 2022, Nagra made its final choice and selected the site “Nördlich Lägern” to host a combination repository. According to Nagra, they choice the site over the other two candidate sites because of the superior geological conditions. Currently, Nagra is working on the procurement of general licenses, which have to be submitted to the Government until 2024. It is expected that the first waste will be stored in the final repository in 2050 (Nagra 2022a).

## 5.3 Decommissioning Regulation

### 5.3.1 Decommissioning policy

In Switzerland, two types of decommissioning strategies are allowed: “direct dismantling” and “deferred dismantling after safe enclosure.” Mühleberg, the first commercial NPP being decommissioned in Switzerland is using the direct dismantling strategy.

The strategy of direct dismantling requires that the power plant be dismantled right after it’s shutdown. The entire decommissioning process is estimated to take around 10-15 years. Advantages of this strategy include expediency; the presence of the long-term working force who have a deep knowledge about the specific NPP; and the fact that the infrastructure is still in good condition. But,

[62] BKW Energie AG (10.7%), Kernkraftwerk Gösgen-Däniken (31.2%), Kernkraftwerk Leibstadt (33.8%) and Axpo Power AG (24.3%).

because there is little time for the short-lived radioactivity to decay, costs may be higher[63] and workers are exposed to greater amounts of radioactivity (TÜV 2016).

In the strategy of deferred dismantling, the dismantling of the NPP starts later on (around 30-60 years after the shutdown). This strategy allows radioactivity levels to decrease over time and therefore, the workers are subject to less radioactivity than in the direct dismantling strategy. Further, the strategy also bears the advantage that money in the decommissioning fund can accrue more interest. A big disadvantage of safe enclosure is uncertainty about future conditions (i.e., continued financial viability of the business owning the liability; political environment; being able to retain and recover the relevant knowledge after a long period) (Pomfret, Nash, and Woollam 2002; TÜV 2016).

There is also a third strategy that is sometimes used in decommissioning NPPs called "safe entombment." According to this strategy, the NPP is safely enclosed in cement and encapsulated from the natural environment. In Switzerland, the method has previously been used to decommission an experimental reactor in a rock cavern in Lucens (ENSI 2012b). Currently, safe entombment is not allowed as a strategy for the decommissioning of commercial reactors in Switzerland.

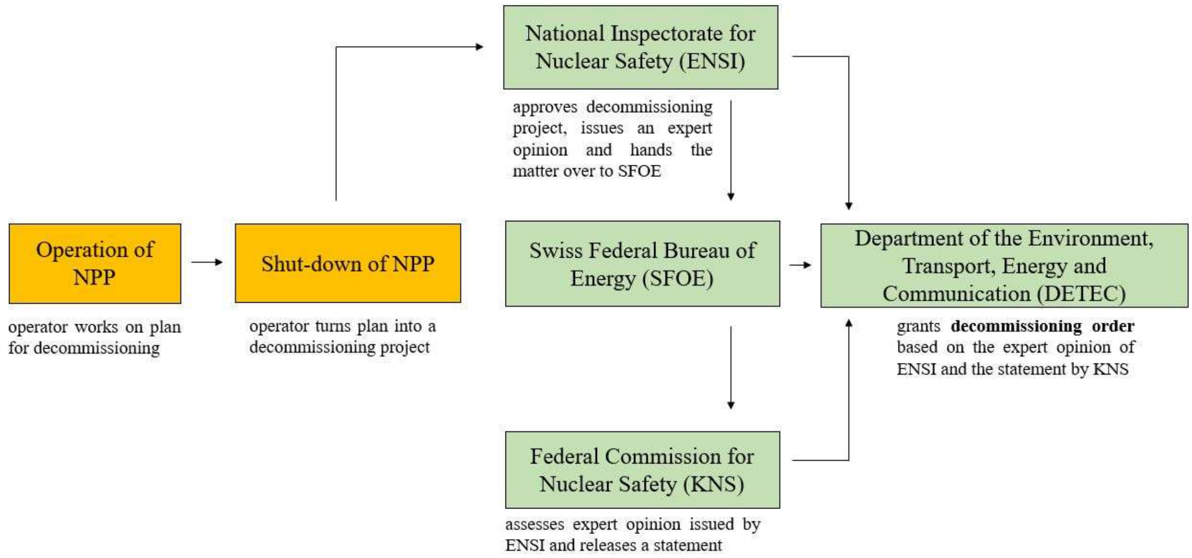
### 5.3.2 Regulatory and legal process

The decommissioning of nuclear plants is regulated in Art. 26-29 of the Nuclear Energy Act. According to Art. 26, the operator must decommission its plant if it decides to shut the plant down or if the operational license has been revoked. Throughout operation, the operator of the power plant is working on the decommissioning plan. The plan needs to be detailed and specify aspects such as the planned decommissioning work, the time required, a radiation protection plan, and information on the type and quantity of radioactive waste expected (Bundesrat 2005). When the shutdown is near, the operator concretizes its plan and turns the plan into a decommissioning project, which ENSI must approve. After that, ENSI issues an expert opinion and hands it over to the SFOE. The expert opinion of ENSI is assessed by KNS who then releases a statement. Based on the expert opinion of ENSI and the statement released by KNS, DETEC issues the decommissioning order (BFE 2018; BKW 2020). The regulatory and legal steps necessary are summarized in Figure 5-4.

Once the NPP is shut down and no longer generates any electricity, the power operation of the NPP is considered to be permanently discontinued. The operator then prepares the power plant for dismantling and the post-operational phase. When this work is finished, and the operator has obtained the necessary legal document (the decommissioning order), the actual decommissioning process commences (ENSI 2021) .

[63] There are other studies suggesting that the costs of immediate dismantling will be lower (e.g., Park et al. 2022; Suh, Hornibrook, and Yim 2018; OECD/NEA 2006; Short et al. 2011).

**Figure 5-4: Regulatory and legal steps necessary for decommissioning**




Source: Own figure.

The post-operational and radiological decommissioning phases are scheduled to take approximately twelve years following shut down, after which conventional dismantling starts. Conventional dismantling no longer falls under the decommissioning order and thus, a second application must be submitted to the SFOE outlining how the operator intends to use the site in the future (BKW 2021; swissnuclear 2017b). The site of the former NPP may be reused for other purposes. If there are no parts left of the NPP on site, the location is called a “greenfield”. In contrast, a “brownfield” categorization indicates that there are still some remaining, though entirely decontaminated, structures from the power plant (BKW 2021). In Switzerland, there are three defined decommissioning targets, which are more nuanced. Target 1 foresees the release of the site from nuclear energy legislation, that is, only radiological decommissioning. Target 2 corresponds to the complete dismantling including the removal of foundations and concrete construction down to two meters from the top edge of the terrain. Lastly, target 3 requires the complete deconstruction including removal of all foundations of all facilities (= greenfield). There is no legal obligation to officially adopt a specific target beyond Target 1, which is required by law. However, Target 3 is indicated as the base project in the cost study (see Subsection 1.4.1 for details on the cost study) (swissnuclear 2021b).

### 5.3.3 Oversight

In terms of decommissioning and the dismantling of Swiss nuclear facilities, ENSI has the main oversight. The decommissioning plans are reviewed regularly by ENSI and as steps in the decommissioning plan are undertaken, ENSI makes regular inspections (ENSI 2020a). Furthermore, the decommissioning work done in Switzerland follows the international recommendations of the IAEA and WENRA (Western European Nuclear Regulators Association) (ENSI 2015a).

## 5.4 Financial Regulation

### 5.4.1 The funding of decommissioning

The financing of decommissioning and waste disposal is established in Art. 77-82 of the Nuclear Energy Act and further in the Ordinance on the Decommissioning Fund and the Waste Disposal Fund for Nuclear Facilities (Bundesrat 2005; 2008). The operators of the NPPs are financially responsible for the disposal of spent nuclear fuel elements as well as the disposal of radioactive waste from operation (e.g., contaminated clothes) and decommissioning of their power plants. To ensure the financing of decommissioning and disposal of waste, two separate funds are in place: a decommissioning fund (established in 1985) and a waste disposal fund (established in 2001) (STENFO 2020).

These funds are centrally managed by STENFO's management body, the Administrative Commission, which collects, pools, and manages the individual contributions from each NPP. The pooled decommissioning funds must cover all decommissioning and dismantling costs, including associated decommissioning waste (i.e., contaminated concrete, etc.), of the NPPs (STENFO 2021g). The pooled waste disposal funds cover the costs of the final disposal of operational waste and spent fuel elements. The main cost elements are: transport and storage, processing, disposal of fuel elements, interim storage, and deep geological disposal of radioactive waste in one or two deep geological repositories (STENFO 2021b). Disposal costs that occur during the operation of NPPs must be paid by the operators on an ongoing basis and are not covered by the funds (Subsection 4.4.3). Similarly, the operators must also pay directly for the costs during the post-operational phase (i.e., the period from the decommissioning of a plant to the start of the defined decommissioning work) (STENFO 2021c).

The operators of the Swiss NPPs contribute yearly to these decommissioning and waste disposal funds. Zwilag only contributes to the waste disposal fund (STENFO 2020). The money from all contributors is collected in one account (one account each for decommissioning and waste disposal) and managed collectively by the Administrative Commission. The Administrative Commission is the management body of the funds. The supervision of the two funds belongs to the Swiss government. Fees for the decommissioning fund and the waste disposal fund are calculated based on routine cost studies. Every 5 years, each operator of a Swiss NPP reports its decommissioning and waste disposal costs to swissnuclear. After that, swissnuclear prepares a comprehensive cost study detailing the estimates for the plans for decommissioning the individual plants and for the deep geological repository that it submits to the Decommissioning Fund for Nuclear Facilities and Waste Disposal Fund for Nuclear Power Plants (STENFO). STENFO then releases a summarized cost study that includes all the relevant details reported by the operators (STENFO 2021d). The cost assessment will be discussed in more detail in Subsection 5.4.3. If there is money left over in the fund, i.e., if the decommissioning costs of an operator are lower than previously calculated, the money will be redistributed to the operator. However, this can only happen at the time when all of the NPPs have been fully radiologically decommissioned. No premature reimbursements are allowed (UVEK 2019).

### 5.4.2 Current balance in funds

As of December 31, 2020, the accumulated *decommissioning* fund capital, including annual contributions, amounted to CHF 2,822 million (previous year: CHF 2,724 million). This corresponds to an increase of 7.55% or CHF 198.2 million above the set target amount per 31st of December 2020 (STENFO 2021e). The accumulated funds for *waste disposal* (current amount), including annual contributions, amounted to CHF 6,030 million (previous year: CHF 5,768 million). This corresponds to an increase of 12.49% or CHF 669.5 million above the set target amount per 31st of December 2020 (STENFO 2021e).[64] Table 5-2 shows the current balances in the decommissioning and the waste disposal fund. As the Zwilag itself does not produce any radioactive content but stores the radioactive material of the NPPs, it does not need to contribute to the waste disposal fund.

**Table 5-2: Current balance in the funds for individual NPPs and Zwilag (in million CHF, price level 2020)**

| Current balance as of 31/12/2019 | Beznau (1&2) | Gösgen | Leibstadt | Mühleberg | Zwilag | Total |
|---|---|---|---|---|---|---|
| **Decommissioning fund** | 895 | 602 | 678 | 486 | 45 | **2,706** |
| **Waste disposal fund** | 1,855 | 1,594 | 1,473 | 808 | - | **5,730** |
| **Total** | **2,750** | **2,196** | **2,151** | **1,294** | **45** | **8,436** |

Note: 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020). Source: STENFO (2021f).

### 5.4.3 Cost assessments

Every five years, the operators of the Swiss NPPs estimate the decommissioning and waste disposal costs of their respective NPP and report the costs to STENFO. The cost studies serve as the basis for determining the contributions to the funds. The contributions to the funds are calculated with the help of a financial model, which is reviewed by an external expert and approved by the Administrative Commission. The model is based on an operating life of 50 years, an investment return of 2.1% and an inflation rate of 0.5% per year (STENFO 2021f; 2021d). The Administrative Commission submits a proposal on the amount of the provisional fund contributions to DETEC. Once DETEC accepts the proposal, the fund contributions are binding for the NPP operators (swissnuclear 2016). Currently, the operators of the Swiss NPPs are paying their contributions to the funds based on the 2016 cost study. The new cost study 2021 will serve as the basis for the contributions for the years 2022-2026 (STENFO 2021a). The following Table 5-3 shows the cost elements covered by the decommissioning fund and the waste disposal fund respectively.

[64] 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).

**Table 5-3: Cost elements included in decommissioning and waste disposal funds**

| Decommissioning costs | Waste disposal costs |
|---|---|
| Administration costs | Administration costs |
| Insurance | Insurance |
| Official authorizations and supervision | Official authorizations and supervision |
| Radiation and occupational safety measures | Radiation and occupational safety measures |
| Planning, design, project management and supervision | Planning, design, project management, construction, operation, dismantling and monitoring of waste disposal plants |
| Plant-related preparation for decommissioning | Transport and disposal of radioactive operational waste |
| Containment, maintenance and guarding of the facility | Transport, reprocessing and disposal of spent fuel |
| Decontamination or disassembly and crushing of activated and contaminated parts | A 50-year monitoring phase for a deep geological repository |
| Transport and disposal of radioactive waste as a result from decommissioning | |
| Demolition of all technical equipment and buildings and the dumping of inactive waste | |
| Decontamination of the site | |

Source: STENFO (2021b).

Waste disposal costs that arise during the operation and during the post-operational phase are covered directly by the operator. This includes the following cost (STENFO 2020):

- The processing of spent fuel elements
- Research and preparatory work by the National Co-operative for the Disposal of radioactive waste (Nagra)
- Construction and operation of a central interim storage facility (Zwilag in Würenlingen)
- Construction and operation of the fuel element wet storage facility at Gösgen NPP
- Measures after the decommissioning of a plant to maintain nuclear safety and radiation protection and to operate the infrastructure until the fuel elements have been safely removed

Table 5-4 shows the total estimated costs for decommissioning and waste disposal based on the latest estimates of the cost study 2021. In the table, the costs for decommissioning reflect the costs for the base project “Target 3”. Similarly, waste disposal costs are indicated for the base project “waste disposal with a 75% chance for a combination repository.”

**Table 5-4: Total costs for decommissioning and waste disposal (in million CHF, price level 2020)**

| Costs for decommissioning and waste disposal | Beznau | Gösgen | Leibstadt | Mühleberg | Zwilag | Total |
|---|---|---|---|---|---|---|
| **Decommissioning costs target 3 (green field)** | 950 | 894 | 1,016 | 591 | 184 | **3,635** |
| **Waste disposal costs for disposal with a 75% chance for a combination repository** | 4,462 | 5,086 | 5,453 | 2,070 | . | **17,071** |
| **Total** | **5,412** | **5,980** | **6,469** | **2,661** | **184** | **20,706** |

Note: 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020). Source: swissnuclear (2021b).

### 5.4.4 Cost experience and accuracy of assessments

As no commercial NPP has been completely decommissioned in Switzerland, it cannot be said whether the costs assessments are accurate. So far, only one commercial NPP (Mühleberg) is undergoing decommissioning. According to the operator of Mühleberg, BKW AG, the financing is on track so far (BKW 2020; VSE 2020). In terms of determining the accuracy of their cost studies, STENFO recruits independent external experts to verify the cost estimates. By doing so, STENFO aims at making sure that experience from home and abroad is considered (STENFO 2022).

### 5.4.5 Funding Liability

In terms of costs for decommissioning and waste disposal, the operators are fully financially responsible. If the money that the operator has put in the fund is not enough the operator has to pay out of his pocket. If this is still not enough, the pooled fund is used to make up the missing amount. Then, the operator must pay back the money plus interest within a certain timeframe set by the Federal Council. If the operator of a power plant is insolvent, or no longer exists, and cannot pay the money back, the operators of the other Swiss NPPs are liable. If the other operators do not have the means to pay the debts the government is liable as a last resort (swissnuclear 2020).

## 5.5 Production

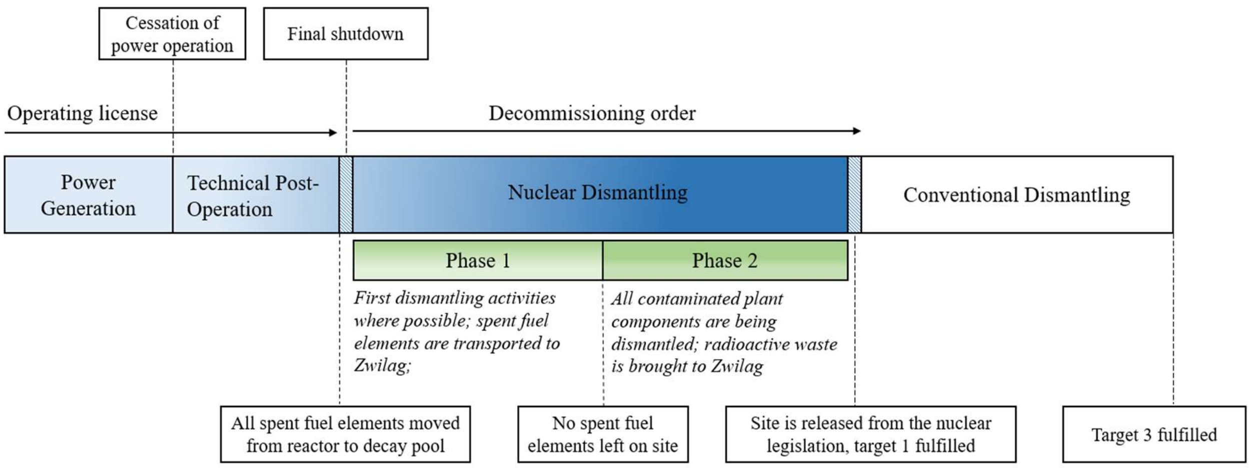
### 5.5.1 Overview

As of 2022, Switzerland has shut down one commercial nuclear plant: Mühleberg in December 2019. Since the shutdown of Mühleberg is very recent, decommissioning work only just begun and is in its early stages (BKW 2020a). Switzerland has some limited decommissioning experience with respect to research reactors. However, it must be made clear here that decommissioning a commercial reactor and decommissioning a research reactor differ greatly in terms of scale, financial incentives, regulation, and difficulty. Even so, some valuable decommissioning experience can be gathered from decommissioning projects of research reactors. Up until now, two research NPPs (AGN-201-P of the University of Geneva and AGN-211-P at the University of Basel) and one experimental reactor in Lucens, Canton of Vaud, have been successfully decommissioned (Hoskyn 2021; ENSI 2012b; 2013). Further, three research reactors are currently being decommissioned: DIORIT at the Paul-Scherrer-Institute (PSI) (since 1994; biological shield was dismantled in 2013), SAPHIR at PSI (since 2002; decommissioning process is almost finished) and PROTEUS at PSI which has been shut down and is currently in the first phases of decommissioning, i.e., the nuclear dismantling of the plant has begun (ENSI 2013; PSI 2022).

### 5.5.2 Progress

Figure 5-5 shows the different stages of decommissioning. After the NPP has been shut down, i.e., stopped its electricity production, the NPP is in the technical post-operational phase. During this time, the plant is prepared for decommissioning. Further, spent fuel elements are unloaded from the reactor pressure vessels and moved to decay pools. There, they are stored to cool down. All of this work still falls under the operating license of an NPP. With the commissioning of the independent cooling of the decay pool, the plant is considered to be "finally put out of operation" (swissnuclear 2021b; ENSI 2022). The final shutdown of the plant marks the expiration of the operating license and the decommissioning order attains full legal effectiveness. The decommissioning order is needed to start the actual dismantling of the plant (swissnuclear 2021b). During nuclear dismantling, the plant is dismantled step-by-step.

**Figure 5-5: Overview over the decommissioning process**




Source: Own depiction based on BKW (2022); swissnuclear (2021b); ENSI (2021).

In phase 1, first dismantling activities are carried out where possible. Also, spent fuel elements are packed into containers and brought to Zwilag. After all spent fuel elements have left the site, the NPP moves from phase 1 to phase 2 in the dismantling process. During phase 2, all contaminated parts of the plant (e.g., the reactor pressure vessel) are removed. If possible, the removed parts are cleaned and either brought to an interim storage facility or, after being tested for radioactivity, disposed of as regular waste

(BKW 2022). At the end of the nuclear dismantling phase (around 10 years after final shutdown), the site is completely free of radioactive material. After ENSI has inspected and approved the site, DETEC officially releases it from nuclear legislation as the site no longer poses a radiological hazard. Then, conventional dismantling begins, which no longer falls under the decommissioning order (swissnuclear 2017b).

The entire decommissioning process (including technical post-operation and conventional dismantling phase) is estimated to take around 15-20 years (swissnuclear 2017b). However, the time varies according to the specific decommissioning target chosen (see Subsection 1.3.2 for details on the targets).

***Mühleberg***

BKW AG decided in 2013 to shut down and decommission its plant, Mühleberg, due to business reasons by the end of 2019 (BKW 2022). Phase 0, the technical post-operational phase, started on January 6th 2020 approximately three weeks after the final cessation of power production of the plant. The concept for phase 0 has been approved by ENSI in 2015 (swissnuclear 2021b). In 2020, all spent fuel elements were removed from the reactor into the decay pool (BKW 2022). ENSI confirmed the end of the technical post-operation phase with a final inspection in September 2020. The NPP moved from phase 0 to phase 1 in the decommissioning process. Currently, in 2022, Mühleberg is in phase 1. In this phase, dismantling activities in the reactor building are carried out where possible and spent fuel elements are transported from the decay pool to Zwilag. It is to be expected that all spent fuel will have left the plant by spring 2024 which will mark the end of phase 1 (BKW 2022).

### 5.5.3 Actors involved in the decommissioning process

Actors involved in the decommissioning process are the operator(s) of the specific plant (in the case of Mühleberg this would be BKW AG), the Zwilag, where most radioactive waste is stored, DETEC who issues the decommissioning order and finally, ENSI who oversees the entire process. While there is discussion of hiring external contractors to conduct some decommissioning work, as of this writing, no official plans or contracts are available to the public.

## 5.6 Country specific nuclear and decommissioning developments

An important turning point for the nuclear industry in Switzerland was the Fukushima nuclear accident in 2011. Following this accident, the political climate for Swiss NPPs has distinctively worsened and the public's resentment toward nuclear energy increased (ENSI 2012c). Shortly after the accident, the Federal Council introduced its "Energiestrategie 2050" which includes the support for the development and production of renewable energy with various measures including the phase-out of nuclear power (UVEK 2020). One of the measures is called the "cost oriented buy-back price." With this instrument, new biomass facilities, wind power plants, geothermal power plants, small waterpower plants and big photovoltaic facilities get a premium on their power input. Further instruments include federal investment contributions for biomass facilities and small hydro power plants and the introduction of a market premium for large hydro plants, which have to sell their power below their production costs. The Energiestrategie also requires all NPPs to be phased out at the end of their safe operating lifetime and prohibits the construction of new NPPs by law (Art. 12a SR 732.1) (BFE 2017; Verband Schweizerischer Elektrizitätsunternehmen (VSE) 2020).

Concerning nuclear decommissioning, Switzerland has limited experience. So far, only one commercial reactor, Mühleberg, has been shut down (BKW 2020a). The combination of the advanced age of the Swiss NPPs and the approved new federal energy strategy might encourage the shutdown of nuclear reactors in the near future. An additional push in that direction is given through high investment costs of nuclear power reactors (UVEK 2017). Axpo Power AG, the owner of Switzerland's oldest commercial NPP, Beznau, announced that they plan to definitely shut down their plant around 2030. To prepare Beznau for decommissioning, 10-12 people are working already today solely on this matter. As the NPPs Gösgen and Leibstadt are considerably younger than Beznau 1 + 2, it is expected that they will keep operating until the 2040s (SRF 2019). According to this information, Switzerland will have phased out of nuclear energy by 2050. However, recent global developments, especially related to energy security, sparked a discussion about constructing new NPPs in Switzerland and thus, challenging parts of the Energiestrategie 2050 (Hägler 2022).

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# 6 United Kingdom

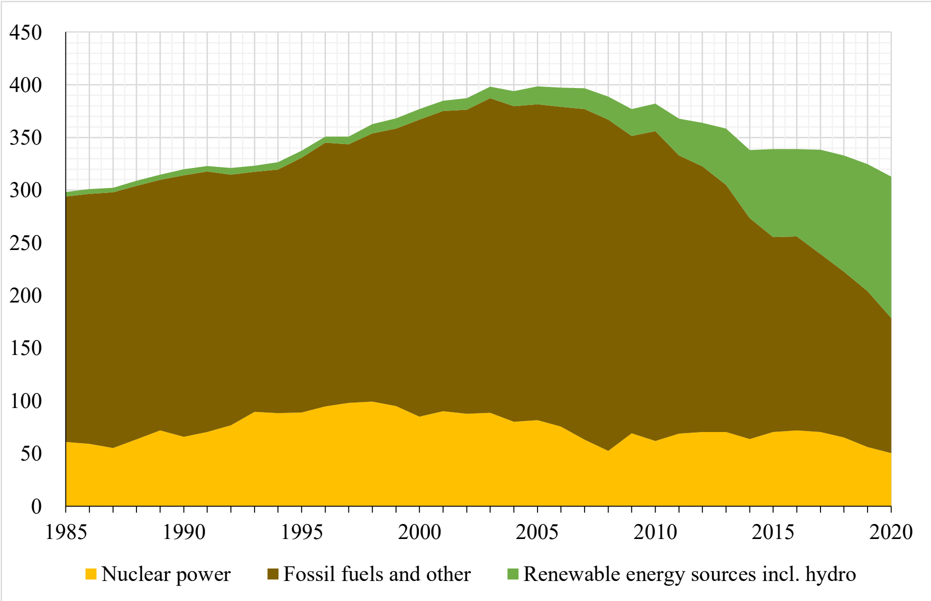
Alexander Wimmers, Björn Steigerwald, Christian von Hirschhausen

### 6.1 Introduction

The United Kingdom (UK) was amongst the first countries to experiment with electricity generation from nuclear power and was one of the first to implement its commercial use (Hirose and McCauley 2022). During the planning and construction of these early reactors, the necessity for safe and cheap nuclear decommissioning was neglected, resulting in an extensively complicated process experienced today (MacKerron 2012; Laraia 2018; Foster et al. 2021; NDA 2021a). During this time, nuclear waste management experienced similar neglect (MacKerron 2015). Additionally, the UK's governmental agency, the Nuclear Decommissioning Authority (NDA), has only recently regained control of the decommissioning process in the country, after an initial approach involving private consortia (so-called Parent Body Organizations, PBOs*)* failed to fulfill its goal (NDA 2015; Holliday, HM Government, and BEIS 2021; Schneider et al. 2021). Furthermore, as it was learnt that decommissioning experiences from one nuclear site might not be directly transferrable to others, the NDA has changed its decommissioning strategy from a high-level strategy applying the same criteria to most nuclear power plants (NPP) to one that aims at individual approaches for its Magnox fleet to achieve decommissioning as soon as possible. The envisioned release date for its last English NPP from regulation is 2125 (NDA 2021a).

Historically, the UK's electricity mix was characterized by a large share of fossil fuels such as coal and oil. The decline of the share of coal in the electricity mix has so far been mostly compensated by gas, wind and solar. Nevertheless, nuclear power has always played a major role with a share of about 20 – 25 % in electricity generation. However, in recent years one observes a steady decline, resulting from the rise of renewable energies and the subsequent shutdown of ageing NPPs, with a current share around 15 % (BP 2021). Figure 6-1 shows the development of the British electricity mix from 1985 to 2020. As of June 2022, eleven advanced gas-cooled reactors (AGR) and one pressurized water reactor (PWR), all operated by EDF Energy, a subsidiary of French majority state-owned utility Éléctricité de France (EDF), are still operational. Construction begun at two PWRs (EPR type) in 2018 and 2019, respectively (IAEA 2022c). The project is already experiencing delays and cost overruns (EDF 2022; Rothwell 2022).

**Figure 6-1: Electricity generation by source in UK from 1985 to 2020**




Source: Own depiction taken from BP (2021)

The UK's electricity market underwent three major reforms in the last three decades that ultimately resulted in the complete capitalization of former state-owned British utilities. The first reform, conducted in the early 1990s, created the so-called "Wholesale Pool Market", limited to England and Wales. Here, regardless of market prices and individual contracts, a single price was passed on to consumers. Initially, this led to a decrease in electricity prices, but soon resulted in very high prices and vertical integration along the electricity supply chain. This trend resulted in the creation of the Office of Gas and Electricity Markets (Ofgem) in 1999. (Thomas 2006; Liu, Wang, and Cardinal 2022)

Monopolistic tendencies and high prices that formed despite Ofgem's oversight led to the second reform that was introduced with the Energy Act of 2004. The New Electricity Trading Arrangement (NAFA) introduced bilateral contracts and an electricity market that allowed for intraday, day-ahead and future market trading. The British Electricity Transmission and Trading Arrangement (BETTA) extended this market design to Scotland in 2005. First, this reform again reduced consumer electricity prices due to fierce competition, but then again, prices began to rise and the "Big Six"[65], an oligopolistic market with over 70% market share, resulted in a steep rise in British electricity bills. (Liu, Wang, and Cardinal 2022)

The third reform, that introduced the current electricity market design, was proposed in a 2011 White Paper and later implemented (DECC 2011). This market design includes a capacity market for grid stability and contracts for difference for renewable energy promotion. The oligopolistic structure has not been touched, and consumer electricity prices have further increased, likely due to the costly

[65] Britsh Gas, EDF Energy, E.ON, Npower, Scottish Power and Scottish Southern Electricity (now Ovo Energy).

capacity market, that is also criticized for its favoring of conventional fossil fuel generation (Liu, Wang, and Cardinal 2022).

As mentioned above, the UK was one of the first countries to commercialize nuclear power production. Since the mid-1940s, the UK has built several research and commercial sites that today form the infamous legacy fleet, a fleet of mainly gas-cooled reactors (GCR) of Magnox type, built in the 1950s and 1960s, during a time when decommissioning and waste management were of low priority (MacKerron 2012; Laraia 2018; Foster et al. 2021; NDA 2021a). Later, AGRs were built, of which some are still operational today. In 1988, construction on the UK's currently only PWR Sizewell B began (Foster et al. 2021). In 1995, parallel to privatization efforts in the whole electricity sector, the decision was made to commercialize this, in comparison to the Magnox fleet, productive and more modern fleet of AGRs and the Sizewell PWR. Thus, by 1997, shares of British Energy were tradeable on the stock market, although this did not go without opposition (e.g. NAO (2004)). Ownership of the Magnox fleet was assumed by Magnox Electric, that was later incorporated to nationally owned fuel cycle company BNFL. After initially prospering, British Energy had to receive its first governmental loan in 2002 due to low wholesale electricity prices and required continuous governmental support from thereon (Thomas 2006; House of Commons 2007). After struggling for several years, British Energy was acquired by EDF in 2009, transferring ownership of all operational British NPPs to EDF Energy (EDF 2022). Figure 6-2 shows the location of British nuclear reactors, their type and current operational status.

Hand in hand with the privatization came the halt of nuclear new build under a Conservative government, as it was deemed that additional NPPs were too costly. In 2008 however, this policy was changed, when construction of further NPPs was announced by the acting Labour government (Foster et al. 2021). Plans in 2013 envisioned the construction of 16 new reactors (Hirose and McCauley 2022). However, new construction began only in 2018, when the Hinkley Point C project (two reactors) was launched (EDF 2022).

In its recently published *Energy Security Strategy 2022*, the British Government announced that it will increase funding for nuclear power in the UK and has set a target of 24 GW nuclear capacity by 2050, corresponding to approx. 25% of projected electricity demand (HM Government 2022). It remains unclear, which nuclear technology, whether existing or under development, shall be used to implement this ambitious target. The only NPP currently under construction in the UK, Hinkley Point C, had to reschedule its planned commissioning date from end-2025 to mid-2026 and financing needs already exceed original shareholder obligations, from an initial estimate of 18 billion GBP in 2016 to approx. 23 billion GBP[66] today (EDF 2022; Rothwell 2022).

In contrast to the UK government's plans, reactors at Dungeness-B and Hunterston-B were permanently shut down in 2021 and 2022, respectively, corresponding to 2.5 GW of gross electrical capacity, see Table 6-7 (EDF Energy Undated; 2021).

[66] From approx. 26.1 to 33.3 billion $EUR_{2020}$.

In this report, we show how nuclear decommissioning is governed in the UK. We describe the current legal framework and regulations and provide insight on liabilities and oversight. Furthermore, we provide information on the financial situation and regulations and give a short status report on the progress of decommissioning NPPs in the UK.

**Figure 6-2: Location of British Nuclear Reactors**


Source: Own depiction with information gathered from (IAEA 2022b).

## 6.2 Legal Framework

To tackle the issue of nuclear decommissioning, the UK government founded the Nuclear Decommissioning Authority (NDA) in the early 2000s. The NDA is the main authority when it comes to nuclear decommissioning and waste management in the UK. However, other actors are also involved (Laraia 2018). Therefore, in this chapter, we will describe this current regulatory framework, the structurization of oversight, liabilities and the ownership of decommissioned NPPs in detail.

### 6.2.1 Governmental and regulatory framework

The long history of nuclear technology utilization in the UK has resulted in a vast regulatory framework concerning mostly the safety and security of the construction, operation and decommissioning of NPPs as well as nuclear waste management. An overview is provided in Box 7-1. Figure 6-3 shows the relations of different actors in the British nuclear industry.

The Nuclear Installations Act (NIA) of 1965 lays the foundation for nuclear industry regulation in the UK. It incorporates many features of the Nuclear Installations and Insurance Act of 1959 and describes which nuclear installations require a license to operate. This was defined more precisely in the Nuclear Installation Regulations of 1971 (Statutory Instrument 1971/381): all nuclear sites – apart from few military sites under the control of the Ministry of Defense – require a nuclear license to be installed and operated. Additionally, the NIA provides oversight for the processing of uranium and plutonium and provides a special legal regime to monitor liability provisions of nuclear licensees. (ONR 2021b)

The Energy Act (TEA) of 2004 created the Nuclear Decommissioning Authority (NDA) and in its 2013 amendment established the Office for Nuclear Regulation (ONR) that, following its predecessors that had been in place since the 1960s, incorporates the role of licensing authority in England, Scotland and Wales. In Northern Ireland, this role is assumed

**Box 7-1: Legal Framework of the Nuclear Industry in the UK**

**Nuclear Installations Act** (NIA): requires licensing of nuclear installations, provides control for uranium processing and provides legal regime for liability governance of licensees

**Energy Act** (TEA) 2004 & 2013: establishment of the NDA in 2004 and of the ONR in 2013

**Health and Safety at Work Act** (HSWA): definition of regulation to reduce risks at all workplaces. Acted upon by ONR

**Ionising Installations Act** (IRR17): defines radiation exposure limits for workers at NPPs

**Nuclear Industry Security Regulations** (NISR 2003): ONR may act upon this to conduct regulatory activities and assess security arrangements

**Nuclear Reactors (Environmental Impact Assessment for Decommissioning) Regulations** (EIADR): requires a full-scale environmental impact assessment and a grant by the ONR before decommissioning of NPPs can begin

**Radiation (Emergency Preparedness and Public Information) Regulations** (REPPIR19): requires licensees and local authorities to share information and provide plans in case of radiation emergencies

**Nuclear Safeguards Regulations** (NSR19): implemented in wake of Brexit, this regulation ensures that nuclear material is not used in military context by the Secretary of State. Further information on the NDA is provided below. (ONR 2021b)

The Health and Safety at Work Act (HSWA) of 1974 sets regulation to reduce risks at all workplaces, including nuclear installations, and ensure safety of workers and the public. The HSWA is the basis on which the ONR acts upon. (ONR 2021b).

The Ionising Installations Act (IRR17) of 2017 guarantees further protection for workers in industries involved with ionizing radiation. A main part of this act is the definition of exposure limits. This is also enforced by the ONR at nuclear sites. (ONR 2021a; 2021b)

Furthermore, the Nuclear Industry Security Regulations of 2003 (NISR 2003) enable the ONR to conduct regulatory activities, enforce compliance in the industry and assess security arrangements. For example, they provide definitions of nuclear material and so-called other radioactive material. Applicants for nuclear licenses must provide a security plan that meet certain criteria. (ONR 2021b)

The Nuclear Reactors (Environmental Impact Assessment for Decommissioning) Regulations (EIADR) came into force in 1999. Following these regulations, an environmental impact assessment must be conducted before the dismantling and decommissioning of NPPs or other nuclear installations can commence. They also define various procedural requirements. This environmental assessment is conducted by the ONR and includes various stakeholders, such as environment agencies, local authorities, and members of the public. Only when the ONR grants permission, may nuclear and non-nuclear decommissioning begin. (ONR 2021b)

The Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR19) of 2019 require the licensees to prepare on- and off-site emergency plans after having conducted a hazard evaluation. Duties are also placed on the local authority to prepare for the occurrence of a radiation emergency. Both licensee and local authority must guarantee that all necessary information is provided to the affected population and amongst one another. (ONR 2021b)

On 31 January 2020, the UK left the European Union (EU). With this process, commonly referred to as Brexit, it also left the European Atomic Energy Community (Euratom). Euratom was established to create a common market for nuclear goods, services, capital, and specialized personnel. The UK has passed legislation to implement European regulations nationally (e.g., Nuclear Safeguards Regulations (NSR19) in 2019), signed nuclear cooperation agreements with Australia, Canada, the USA and the International Atomic Energy Agency (IAEA), and joined a new nuclear cooperation agreement with the EU in December 2020, which took effect from 1 January 2021. (World Nuclear Association 2022; ONR 2021b)

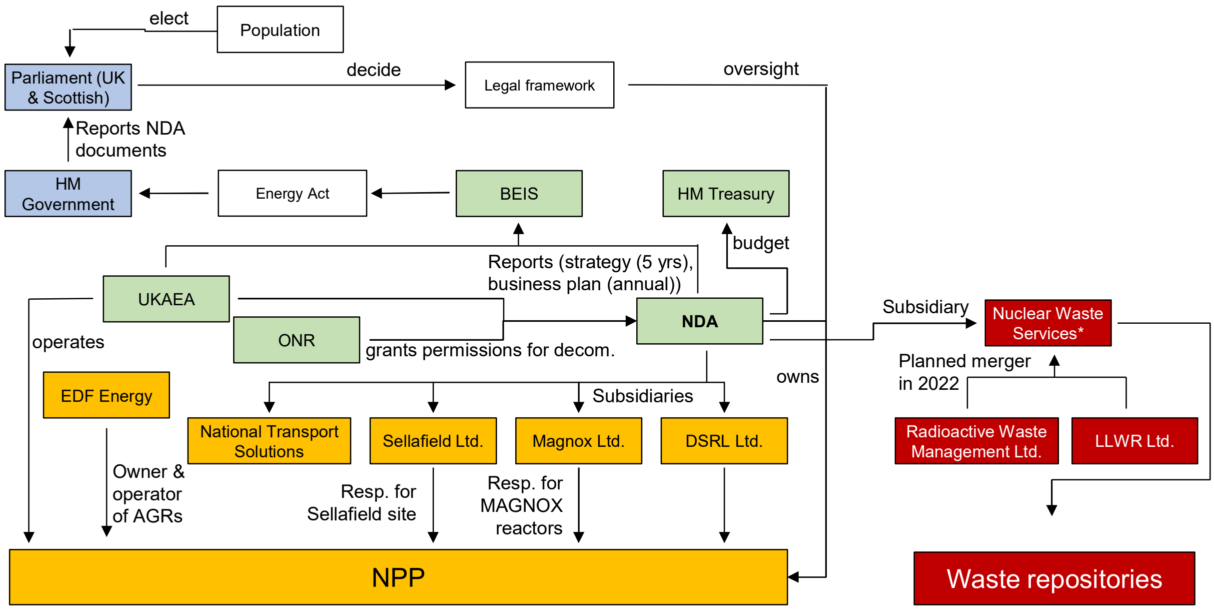
Further regulations, such as the Construction (Design and Management) Regulation of 2015, also influence NPPs. A full overview is provided at ONR (2021b).

In 2004, the Energy Act (TIA04) established the legal framework to establish the NDA in 2005. The agency was initially tasked with decommissioning the UK's legacy fleet (mostly Magnox reactors). It is funded by the Department of Business, Energy and Industrial Strategy (BEIS), but also has additional responsibilities towards Scottish ministers regarding NPPs in Scotland (NDA 2021a). The

NDA is required to publish a strategy report every five years that is presented to Parliament and a business plan every three years, while other reports, such as an annual mission progress report are published for increased transparency (NDA 2022). Initially, the UK followed a PBO (Parent Body Organisation) approach to decommissioning. In this scheme, private firms (PBO) would assume temporary control of the NDA's nuclear subsidies, so-called Site License Companies (SLC). These SLCs were – and still are – the operators of the British nuclear legacy fleet, as shown in Section 6.2.2. The PBO would perform management operations to reduce complexity and increase efficiency and earn a fee depending on performance after a certain period of time. Due to ineffectiveness and NDA oversight failure, the PBO scheme has been replaced by full NDA ownership and oversight (House of Commons 2020; Holliday, HM Government, and BEIS 2021; NDA 2021a). In Section 6.5.4 of this chapter, the PBO scheme is explained in more detail and closely examined. Following the PBO scheme's failure, the NDA now has multiple subsidiaries that are responsible for different sites and tasks concerning decommissioning. A short description of each subsidiary shall be given below, following NDA (2022).

- Sellafield Ltd is tasked with operating and decommissioning the large nuclear site at Sellafield (incl. Windscale) that also includes an interim storage facility. Nuclear waste from other sites, for example those operated by EDF Energy, will be transferred to Sellafield.
- Magnox Ltd is responsible for 12 nuclear sites across the UK, corresponding to all Magnox reactors, except for Sellafield, with a total electrical capacity of 4.7 GW, see Table 6-7 for details.
- The responsibilities of Dounreay Site Restoration Ltd (DSRL) lie in the clean-up of the Dounreay site in northern Scotland (two fast-breeder reactors (FBR)). DSRL also operates a disposal facility for low-level waste from its designated site and became a full NDA subsidiary only in April 2021.
- Nuclear Waste Services was announced in January 2022 and will be comprised of LLWR Ltd, a fully owned NDA subsidiary since July 2021, Radioactive Waste Management Ltd, that is tasked with building a geological disposal facility, and the NDA's Integrated Waste Management Programme.
- Finally, Nuclear Transport Services (NTS) was founded in 2021 as an excellence center to establish strategic capabilities for transport of radioactive waste and other hazardous materials.

**Figure 6-3: Legal framework and actors in UK**




Source: Own depiction.

### 6.2.2 Ownership

The four reactors at Dungeness and Hunterston were only recently shut down and are still owned by EDF Energy. EDF Energy is the British subsidiary of French state-owned utility-operator Éléctricité de France (EDF). It operates the British AGR fleet, formally owned by British Energy (EDF 2022; Hirose and McCauley 2022). Following an agreement between EDF Energy and the UK government, ownership of the AGRs will be transferred to the NDA once they are defueled, ideally saving up to one billion GBP[67] of taxpayer money[68]. EDF Energy also owns and operates the Sizewell B plant, Britain's only operational pressurized water reactor (PWR), and is, together with China General Nuclear Power Corporation (CGR), building two new EPRs at Hinkley Point C (EDF 2022).

The United Kingdom Atomic Energy Authority (UKAEA) owns two reactors, Windscale AGR and Winfrith SGHWR, and is the formal operator at the Dounreay FBR reactors. Decommissioning at Dounreay is conducted by DSRL, while Windscale and Winfrith are both attributed to the Sellafield site and are thus decommissioned by Sellafield Ltd (NDA 2022).

For all other shut down reactors, the NDA has assumed ownership. As described above, the operation is managed depending on the type of reactor and location. While Sellafield Ltd is the nuclear operator and thus responsible for decommissioning at the old reactors at Calder Hall (i.e., Sellafield site), all other Magnox reactors are decommissioned by Magnox Ltd. Once the reactors still in operation (currently operated by EDF Energy) reach a certain stage in the decommissioning process (once they have been defueled), ownership will be transferred to the NDA and Magnox Ltd. This is expected to

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[67] Approx. 1.13 billion $EUR_{2020}$.
[68]BEIS (2021) Decommissioning agreement reached on advanced gas cooled reactor (AGR) nuclear power stations. https://www.gov.uk/government/news/decommissioning-agreement-reached-on-advanced-gas-cool-reactor-agr-nuclear-power-stations. Accessed on 22.04.2022.

happen in the next 10 years. An overview of all shut down reactors is provided in Table 6-7 in the appendix of this chapter (NDA 2022; IAEA 2022a).

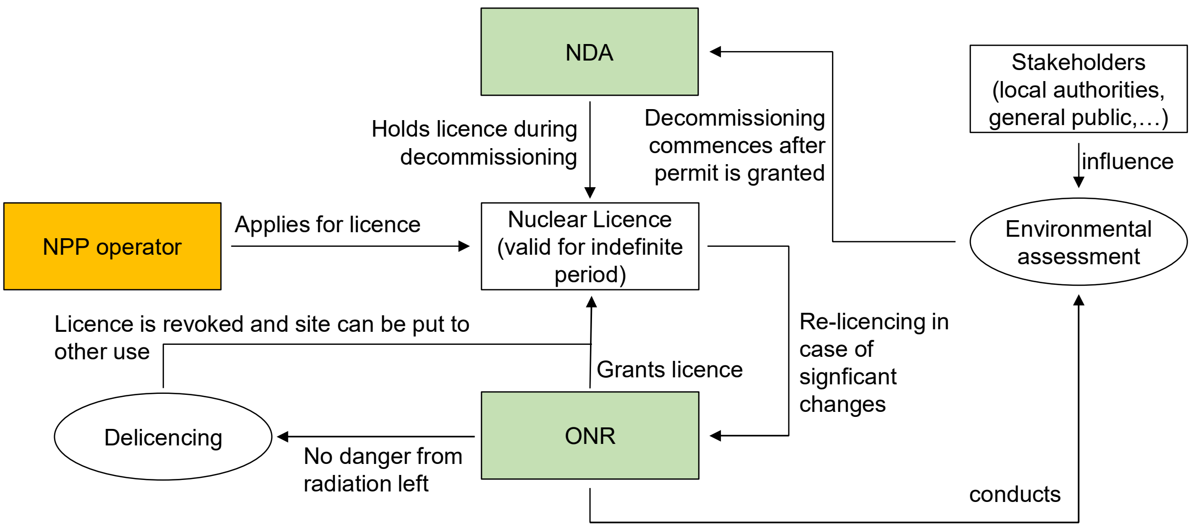
### 6.2.3 License provision and extension

The Nuclear Installations Act of 1965 requires the licensing of sites where nuclear reactors, and other nuclear installations, such as enrichment plants will be located and operated. Thus, in the UK, no site is to be used for this purpose unless a nuclear site license (from here on shortened to "license") has been granted by the ONR or, in the case of Northern Ireland, the Secretary of State[69]. (ONR 2021b)

A license is granted for an indefinite period to a particular legal entity as operator. License renewal may become necessary if the operator changes, new or other nuclear installations that are not included in the original license are to be built at the site, or the site is to be expanded over its initial boundaries. If none of these instances occur, the license is effective for the entire lifetime of the site, from construction to decommissioning and final site clearance. Most sites, however, will have to request replacement licenses multiple times over their lifetime. Note that before any decommissioning work can begin, the ONR must conduct an environmental assessment and grant a permit. This is not part of the license, although new NPPs must now provide plans for later decommissioning in their license application. (ONR 2021b)

Once the ONR approves that the danger from ionizing radiation from the site or material on the site to have ceased, the site can be released from regulatory control and used for other purposes. Alternatively, the site can be relicensed or put to another use that does not require a nuclear site license (brownfield). Thus, some form of licensing, be it de- or relicensing must be conducted by the ONR before the land can be put to another use (NDA 2021c; ONR 2021b).

**Figure 6-4: Licensing process**




Source: Own depiction.

[69] As of today, there are no operational or shutdown NPPs in Northern Ireland. The authors are unaware of any plans to change this in the future.

### 6.2.4 Oversight

Following the Energy Act of 2004, the NDA is required to provide an extensive status report to the British and Scottish Parliaments every five years, titled "NDA Strategy". The last report was published in March 2021. It contains reports on past activities, occurred and expected challenges and how these will be tackled in the upcoming years. Additionally, a "Mission Progress Report" is published every five years. The last issue was provided in 2019. The NDA must also publish several annual reports. These are the "NDA Business Plan" that covers three years and is an Energy Act requirement, the "NDA Mid-Year Performance Report" and the "NDA Annual Report and Accounts", the latter also being an Energy Act requirement (NDA 2021a).

In terms of safety on the to-be-decommissioned sites, the ONR's sub-division for Decommissioning, Fuel and Waste is responsible. This division also oversees the transport of radioactive materials between the NPPs and other nuclear sites. (ONR 2021c)

## 6.3 Decommissioning Regulation

Historically, nuclear decommissioning or waste management were not prioritized in British nuclear policies (MacKerron 2012; Laraia 2018; Hirose and McCauley 2022). The foundation of the British nuclear sector was built within a military framework: the first commercial NPP at Calder Hall was financed by the Ministry of Defense. Decommissioning was placed on the government's agenda only in 2002, with the White Paper "Managing the Nuclear Legacy" being published. Here, plans for the creation of a Liabilities Management Authority were laid out. With the ratification of the Energy Act (TEA 04) in 2005, the NDA was founded and tasked with decommissioning the UK's legacy fleet. For the AGR fleet, the operator, EDF Energy, is also partly responsible with financial obligations managed in the Nuclear Liabilities Fund created in 1996. After defueling, decommissioning responsibility will be transferred to the NDA. (MacKerron 2012; Department of Trade and Industry 2002; Nuclear Liabilities Fund 2021)

### 6.3.1 Decommissioning policy

In general, there are three technical strategies to decommission an NPP. These are immediate dismantling, long term enclosure and deferred dismantling, and entombment. Following the strategy of entombment has however been discouraged by the IAEA and should only be considered a solution in certain circumstances, such as when accidents occur (Laraia 2018).

For all its nuclear decommissioning practice, the UK applies a concept called ALARP ("As Low As Reasonably Practicable"). ALARP follows the legal requirement to reduce risks "so far as reasonably practicable" (SFAIRP) (ONR 2020, 2). This concept was introduced to reduce cost and increase efficiency by avoiding the application of duties that cannot be fulfilled as "absolute safety cannot be guaranteed" (Health & Safety Executive 2001, 8). As will be shown in Section 6.5, the NDA is currently applying the "lead and learn" initiative to determine the optimal decommissioning approach for its extensive legacy fleet. This leads to the question, what "reasonable" means in the context of ALARP. This is discussed in detail by Hirose and McCauley (2022).

For its large fleet of MAGNOX reactors, the UK, i.e., the fully responsible NDA, initially adopted a strategy of deferred dismantling, planning on enclosing radioactive components for 85 years after shutdown at all NPPs. First experiences at the Bradwell site however have shown that not all sites are suitable for this strategy and after an inquiry, the NDA adopted an approach to decommission "as fast as possible" (NDA 2021a, 35) and follow site-specific strategies. Thus, at some sites, decommissioning work will commence earlier, while at other sites, long term enclosure (LTE) will continue for the next decades (NDA 2021a; MacKerron 2012).

Currently, EDF Energy is formally responsible for decommissioning a total of 14 AGRs at seven individual sites. For Hunterston B and Hinkley Point B, plans have been made for defueling to commence in 2022 and decommissioning to proceed as fast as possible. At Dungeness-B, defueling has begun. This shall be conducted by EDF Energy itself, before the plants are transferred to the NDA and its subsidiary Magnox Ltd. Defueling shall be conducted in coordination with the NDA for all other AGR sites that are planned to be shut down successively until 2030. (EDF Energy Undated; 2021)

In the early 2000s, decommissioning policy followed an approach that initially aimed at making the process as cost-effective as possible. Hereby, the NDA acted as a contractor and awarded the tasks of decommissioning NPPs to private site license companies (SLC) that were temporarily owned and controlled by separate legal entities, named parent body organizations (PBO), through share transfer. PBOs did not conduct any decommissioning activities themselves, but rather guaranteed sufficient financial resources for the process and ensured that SLCs complete their assigned tasks according to criteria defined by the NDA by essentially taking over upper management roles and tasks of the SLC. Companies had to compete in tenders in order to be awarded the rights to become a PBO. SLCs are still legally independent today and can outsource tasks to third parties for efficiency increases and cost reduction reasons. However, the PBO approach was proven to be unsuccessful in some cases. For example, information on sites was often inadequate, e.g., in terms of how much nuclear waste was actually stored at the site, complicating the exact definition of the task in the necessary contracts. Furthermore, merging actors from private and public sectors did not go as smoothly as planned with conflicts arising between SLC employees, often formerly employed at public operators such as UKAEA, and PBO management tasked with making profits. Refer to Section 6.5.4 for a more detailed description of the PBO scheme and its failure (MacKerron 2012; NDA 2021c; Holliday, HM Government, and BEIS 2021; House of Commons 2020).

Thus, in recent years, the NDA has retracted the original PBO model and has continuously reassumed control of the SLCs, with Sellafield Ltd becoming an NDA subsidiary in 2016, followed by Magnox Ltd in 2019 as well as DSRL and LLWR in 2021. After the restructuration, the NDA group with consist of the NDA itself and four key subsidiaries Sellafield Ltd, Magnox Ltd, which is to be merged with DSRL, Nuclear Waste Services Ltd, a newly formed subsidiary consisting of Radioactive

Waste Management Ltd and LLWR Ltd, and finally the excellence center Nuclear Transport Solutions, see Section 6.2.1 (NDA 2022).

### 6.3.2 Regulatory and legal process

Before the approval of a nuclear site license, applicants must present to ONR their detailed and suitable strategies and plans for decommissioning of the NPP and corresponding facilities as well as programs for waste treatment and disposal. Additionally, a funded decommissioning plan must be set up and be approved by BEIS. So, in order to begin decommissioning, the original nuclear site license need not necessarily be renewed, unless the operator changes. This is usually the case before decommissioning, e.g., when ownership transfers to the NDA, and thus a license renewal becomes necessary. Before decommissioning work itself can begin, the ONR conducts an extensive environmental assessment, following EIADR, see Section 6.2.1 for details. (ONR 2021b)

When decommissioning is completed, sites are considered to be in the “Site End State” and the site is suitable for other uses. The NDA encourages “the reuse of brownfield land over the development of greenfield land” (NDA 2021a, 44). To allow for land re-use (brownfield), the nuclear site license (from here on shortened to “license”) must be terminated and ONR must declare the so-called “Period of Responsibility” to be over. The license and this period are independent from one another. The period of responsibility begins with the grant of the license and ends when ONR gives a written notice that there is no further hazard from ionizing radiation, a new license is granted for the site in question (e.g., when the site is transferred into NDA ownership) or when a license is no longer required. Therefore, a licensee is responsible for the entirety of the decommissioning process until their period of responsibility is officially declared to be over. Apart from this, no regulation in terms of decommissioning exists (ONR 2021b). According to many decommissioning plans of British NPPs, complete decommissioning will take several decades. Therefore, the NDA defines several “Interim States” to measure the achievement of interim goals without finally committing to an end state (NDA 2021a).

### 6.3.3 Oversight

Decommissioning of the legacy fleet is carried out by the NDA’s SLCs, Sellafield Ltd., Magnox Ltd and DSLR Ltd. These SLCs report to the NDA who in turn provides transparent information to the public on the decommissioning progress in the form of reports, see Section 6.2.4. EDF Energy, BEIS and the NDA are working closely together to establish optimal strategies for the decommissioning of the AGR fleet. Thus, in time, the NDA’s reports will contain information on these reactors, too. (NDA 2021a)

### 6.3.4 Liability

The Nuclear Installations Act of 1965 (see Section 6.2.1), places full liability on the nuclear license holder in case of damage to persons or property caused by nuclear materials from or on the nuclear site. This happens without proof of fault. To ensure possible damages can be compensated, the licensee must prove that sufficient funds are available, either by insurance or other means. Thus, when the owner of an NPP changes, e.g., when the NPP is transferred to the NDA, liability is transferred, too (ONR 2021b).

As of 1 January 2022, amendments of the Nuclear Installations Act, originally proposed in September 2015, came into effect. These amendments adopted the so-called "Paris and Brussels Conventions" on third party liability in the nuclear field and raised maximum operator liability in the case of a nuclear incident from a mere 140 million EUR to 1.2 billion EUR over a period of 5 years (DECC 2012). Further, the period during which claims can be made is raised from 10 to 30 years. The NDA, as governmental agency, is insured by the government. The contingent liability was therefore increased from 700 million EUR to 1.2 billion EUR per site (Hands 2021).

## 6.4 Financial Regulation

### 6.4.1 The funding of decommissioning

Note that all monetary values are provided in the text as stated in the original sources and are referenced in footnotes in 2020 EUR to make values comparable to other country reports. For this UK report, inflation and currency conversion were taken from sources stated in the footnote below.[70]

The NDA is mostly funded through BEIS. Other income is generated from the NDA's business activities, as shown below in

Table 6-1. Planned expenditure is voted upon each year by Parliament (NDA 2022). The UK government makes provisions for its long-term energy policies that, in 2015, included 7.5 billion GBP[71] for oil and gas field decommissioning and 82.9 billion GBP[72] for nuclear decommissioning (NAO 2016). In 2021, the provisions for nuclear decommissioning had amounted to 135.8 billion GBP[73] (NDA 2021b). Given the long-term perspective of nuclear decommissioning of over 100 years, it is highly uncertain whether these provisions can cover future costs. This is shown by reflections from 2015 by the NDA that report a range of necessary provisions from 95 to 218 billion GBP[74] (NAO 2016).

For the decommissioning of the AGR fleet (currently owned by EDF Energy), the Nuclear Liabilities Fund (NLF), an external segregated fund, was created by the UK government in 1996 with an initial endowment of 223 million GBP[75]. The NLF will also cover some liabilities of spent fuel management for the Sizewell B plant. The goal was to reduce the costs for British taxpayers by planning ahead and setting aside provisions that can be invested to cover future decommissioning costs for the – at the time – modern AGR fleet, then owned by British Energy. British Energy, formally the largest British utility filed for bankruptcy, despite controversial governmental aid (supplied through the NLF)

[70] Inflation taken from inflationtool.com. Currency conversion completed with values from https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/.

[71] Approx. 10.86 billion $EUR_{2020}$

[72] Approx. 120 billion $EUR_{2020}$)

[73] Approx. 153.95 billion $EUR_{2020}$

[74] Approx. 137.53 to 315.6 billion $EUR_{2020}$

[75] Approx. 398.69 million $EUR_{2020}$

and was acquired by EDF in 2009. Since then, the NLF has received significant capital injections from the UK government, the last accumulating to 5.1 billion GBP[76] in 2020. It is expected that more taxpayer money, additional 5.6 billion GBP[77], will be injected into the fund in the financial year 2021-2022. (Thomas 2006; Wealer, Seidel, and von Hirschhausen 2019; Nuclear Liabilities Fund 2021; House of Commons 2022; EDF 2022)

EDF, the parent company of EDF Energy, also makes provisions for decommissioning and waste management, shown in Table 6-4. These provisions will cover the cost of defueling and waste transfer for the AGR fleet before the NDA assumes ownership following the recent agreement between NDA and EDF Energy, see Section 6.2.2. Further, they are to cover costs associated with the decommissioning of Sizewell B, the only operational British PWR. These provisions are calculated with a discount rate of 1.9%, but are separate from the NLF. (EDF 2022; House of Commons 2022)

### 6.4.2 Current balance in funds

For 2022/2023, total planned yearly expenditure for NDA activities is expected at 3.645 billion GBP, of which 2.825 billion GBP are funded by the UK government that makes provisions on this behalf. The NDA also funds itself to some extent through income from its commercial nuclear activities, such as spent fuel and nuclear materials management or transportation services. Most of the money is spent on site-specific expenditure, divided amongst the NDA's SLCs. In total, 3.389 billion GBP will be spent at SLCs, of which 71% are dedicated for decommissioning. Sellafield Ltd is by far the most expensive SLC, requiring a total of 2.345 billion GBP. About half of the decommissioning budget (1.196 of 2.410 billion GBP) is planned for decommissioning at Sellafield alone. In the upcoming years, government funding is expected to increase, while income from commercial activities will likely decline. By 2024/2025, the NDA's budget will have accumulated to 3.864 billion GBP. An overview is provided in

Table 6-1 and Table 6-2 below. Refer to the bottom row in each table for $EUR_{2020}$ values. (NDA 2022)

**Table 6-1: Historical and planned NDA funding from 2021 to 2025 (values in million GBP)**

| Fiscal year | 2021/2022 | 2022/2023 | 2023/2024 | 2024/2025 |
|---|---|---|---|---|
| **Income** | 964 | 820 | 802 | 924 |
| **Government funding** | 2,530 | 2,825 | 2,963 | 2,940 |
| **TOTAL** | **3,494** | **3,645** | **3,765** | **3,864** |
| **TOTAL in $EUR_{2020}$** | **3,961** | **4,132** | **4,268** | **4,380** |

Source: Own depiction following NDA (2022)

[76] Approx 5.74 billion $EUR_{2020}$
[77] Approx. 6.35 billion $EUR_{2020}$

At the end of the fiscal year of 2020-21, the NLF's assets were valued at 14.77 billion GBP. This increase from a starting value of 9.37 billion GBP came mostly from a capital injection of over 5 billion GBP by BEIS. Other income came from ordinary activities (428.77 million GBP) and contributions from EDF Energy (13 million GBP), see

Table 6-3. Liabilities estimated from 2021 to 2130 accumulate to 23.506 billion GBP[78] of which 18.584 billion GBP[79] are directly linked to decommissioning. The NDA acts as the administrator of the NLF and approves of payments for decommissioning and waste management. (Nuclear Liabilities Fund 2021)

**Table 6-2: Planned site-specific expenditure from 2021 to 2023 (values in million GBP)**

| SLC / Site | Decom. Costs 2022/2023 | Operations Costs 2022/2023 | Planned Total Costs 2022/2023 | Planned Total Costs 2021/2022 |
|---|---|---|---|---|
| **Sellafield Ltd** | 1,196 | 1,149 | 2,345 | 2,220 |
| **Magnox Ltd** | 515 | - | 515 | 505 |
| **DSRL** | 205 | - | 205 | 200 |
| **RWM** | 92 | - | 92 | 78 |
| **LLWR** | 85 | - | 85 | 77 |
| **Others** | 61 | 86 | 147 | 175 |
| **Non-Site Expenditure** | 256 | - | 256 | 249 |
| **TOTAL** | **2,410** | **1,235** | **3,645** | **3,494** |
| **TOTAL in $EUR_{2020}$** | **2,732** | **1,400** | **4,132** | **3,961** |

Note: DRSL: Dounreay Site Restauration Ltd; RWM: Radioactive Waste Management Ltd; LLWR: LLW Repository Ltd. See Section 6.2.2 for further information on NDA subsidiaries.

Source: Own depiction following NDA (2022)

**Table 6-3: Overview of NLF assets in 2020 and 2021 (values rounded to million GBP)**

| Year | 2020 | 2021 |
|---|---|---|
| **Asset value at start of the year** | 9,403 | 9,374.3 |
| **Contributions from EDF** | 22.5 | 13 |
| **Amounts payable to EDF** | - 58.1 | - 65.2 |
| **Funding from BEIS** | - | 5,070 |
| **Operating profit on ordinary activities before tax** | 16.9 | 428.8 |
| **Tax on profit on ordinary activities** | - 10 | - 49.3 |
| **Asset value at end of the year** | **9,374.3** | **14,771.6** |
| **Asset value in $EUR_{2020}$** | 10,542 | 16,746 |

Source: Own depiction following Nuclear Liabilities Fund (2021)

[78] Approx. 26.647 billion $EUR_{2020}$
[79] Approx. 21.067 billion $EUR_{2020}$

As mentioned above, EDF itself makes provisions for fuel management, waste removal and long-term waste management. These provisions, shown in Table 6-4, are made solely for its UK NPPs, operated by EDF's subsidiary EDF Energy. They are, to some extent dedicated for AGR defueling and waste transport, but most will be used to decommission Sizewell B, which will not be transferred into NDA ownership. Fuel from Sizewell B will be stored on-site and not be transferred to Sellafield. These costs are based on year-end economic conditions and include spent fuel and waste management over the whole operating life of the NPPs. The costs are assessed each year and are discounted with a rate of 1.9%. (EDF 2022)

**Table 6-4: Provisions for the back-end of the nuclear cycle by EDF (all values in million $EUR_{2020}$)**

| Year | 2021 | | 2020 | |
|---|---|---|---|---|
| | Costs based on year-end economic conditions | Amounts in provision at present value | Costs based on year-end economic conditions | Amounts in provision at present value |
| **Spent fuel management** | 2,725 | 1,401 | 2,318 | 1,286 |
| **Waste removal and conditioning** | 2,154 | 639 | 1,875 | 546 |
| **Long-term radioactive waste management** | 5,126 | 1,415 | 3,724 | 1,106 |
| **Back-end nuclear cycle expense** | 10,005 | 3,455 | 7,917 | 2,938 |

Source: Taken from EDF (2022)

### 6.4.3 Cost assessments

Today, provisions made by the UK government on behalf of nuclear decommissioning have amounted to 135.8 billion GBP[80]. These funds are to be used for the legacy fleet currently overseen by the NDA and are "the best estimate of how much our mission will cost over approximately 120 years". (NDA 2021b, 110–11)

Capital in the NLF is to be used for the current AGR fleet, operational and shut down, owned by EDF Energy and will also have to serve for the decommissioning of new NPPs in planning or under construction. NLF estimates liabilities directly linked to decommissioning will amount to 18.6 billion GBP[81] by 2130. For its British nuclear fleet, EDF Energy's parent company EDF also makes provisions of currently 10 billion GBP[82]. This includes provisions for the Sizewell B plant. (Nuclear Liabilities Fund 2021; EDF 2022)

[80] Approx. 153.95 billion $EUR_{2020}$
[81] Approx. 21.07 billion $EUR_{2020}$
[82] Approx. 11.34 billion $EUR_{2020}$

### 6.4.4 Cost experience and accuracy of assessments

In 1993, the National Audit Office (NAO) estimated the total undiscounted costs for the decommissioning of nuclear facilities at 17.916 billion GBP[83] after initial estimates by the Atomic Energy Authority, made in 1991, ranged between 3 and 4 billion GBP[84] were deemed too low. (NAO 1993)

As discussed above in Section 6.4.3, current cost estimates of the NDA and NLF amount to a total of over 154 billion GBP[85]. This is evidence that, historically, the costs for decommissioning have been strongly underestimated. Even after correcting the initial estimation of the Atomic Energy Authority of 1991, the NAO still underestimated the costs by a factor of 4.5. Given the timeframe of over 100 years, the uncertainty underlying any cost prediction is substantial (NAO 2016; NDA 2021b). Uncertainties include technical issues and delays but also economic developments, such as inflation and discounting assumptions. Social risks, such as the underestimation of socio-economic costs from staff retraining, redeployment or organizational changes, can also influence actual cost (Invernizzi, Locatelli, and Brookes 2017).

Further uncertainty comes from the investment of provisions in the NLF, a managed fund. The NLF was set up to reduce the cost of decommissioning NPPs for the taxpayer. This can only be achieved when the fund performs according to the defined performance goals. The NLF is structured in two sections with cash in the National Loans Fund (NatLF) and investments in the Mixed Asset Portfolio (MAP). Assets in the NatLF can be accessed on a short notice and accounted for 80% of total assets in 2021 after a 5.07 billion GBP injection by BEIS. These assets however perform with lower returns compared to the MAP portfolio. Thus, the NLF has not been able to achieve its targeted return. Target return over the last three years was set to 5.4%, but the NLF was only able to return 1.7% on investments. When regarding the MAP portfolio separately, the picture is more favorable. On the one hand, MAP portfolio return also missed its three-year target but it was able to surpass the target return set for the fiscal year of 2020-2021 by 2.5%. Target returns in 2021-2022 are 4.9% and 7.3% for the total fund and MAP, respectively. An overview of the NLF fund performance is provided in Table 6-5 (Nuclear Liabilities Fund 2021).

For investments held in the MAP, for which the NLF has more investment flexibility compared to the NatLF, the NLF is committed to ESG[86] criteria and has completed the rollout of its “Long Term Sustainable Growth Portfolio”. The NLF provides information on investments in different subsidiaries and provides nondescriptive summaries of subsidiary activities. For example, Adams Steet UK Mid-Market Solutions LP, in which the NLF was invested with over 281 million GBP[87] in 2021, invests in “high growth equity investments in UK mid-market private companies” (Nuclear Liabilities Fund 2021,

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[83] Approx. 34.55 billion $EUR_{2020}$
[84] Approx. 6.2 to 8.27 billion $EUR_{2020}$
[85] Approx. 174.58 billion $EUR_{2020}$
[86] Environment, Sustainability, Governance
[87] Approx. 381 million $EUR_{2020}$

45). Other investments, including such in associates or joint ventures, focus on infrastructure, such as hospitals or highway projects or the UK mortgage sector (Nuclear Liabilities Fund 2021).

A 2022 report, issued by the Committee of Public Accounts of the House of Commons, criticizes the continuous underestimation of decommissioning costs and the subsequent additional costs for the British taxpayers. The report focusses on the to-be-decommissioned AGR fleet and highlights cost uncertainties resulting from defueling processes that can strongly impact decommissioning costs. For example, the early closure of Dungeness-B will result in additional costs of up to one billion GBP[88] for defueling only (House of Commons 2022). This practice of risk transfer from private liability to public, i.e., taxpayer liability, has been common practice in the British nuclear sector. For example, in 2004, the NAO heavily criticized the lack of risk monitoring for public funds during the privatization of British Energy (Thomas 2006; NAO 2004).

**Table 6-5: Actual returns of the NLF compared to target returns**

| Fiscal year | Total Fund Return (NatLF & MAP) | | MAP Return | |
|---|---|---|---|---|
| | Actual Return p.a. | Target p.a. | Actual Return p.a. | Target p.a. |
| **2018 – 2019** | 2.2 % | 5.7 % | 8.1 % | 7.9 % |
| **2019 – 2020** | 0.4 % | 5.7 % | 0.8 % | 7.5 % |
| **2020 – 2021** | 2.4 % | 4.9 % | 9.8 % | 7.3 % |
| **3 Year Period to March 2021** | 1.7 % | 5.4 % | 6.2 % | 7.6 % |

Source: Taken from Nuclear Liabilities Fund (2021)

It remains to be seen, whether the NLF can at some point achieve its targeted return or whether the government will have to inject further capital as was observed in 2021. As cost estimations for nuclear decommissioning, made by the NLF itself and the NDA, remain subject to high uncertainties, a risk remains that overachievement of investment targets will not generate sufficient capital and further taxpayer money will be spent.

## 6.5 Production

### 6.5.1 Overview

With its large legacy fleet of GCR MAGNOX reactors, the UK faces significant challenges in nuclear decommissioning. These challenges are of organizational nature, e.g., the reacquisition and reorganization of SLCs or incomplete documentation of nuclear inventories at legacy sites, and of technical nature, e.g., the structural nature of old NPPs, constructed during a time during which decommissioning was not taken into consideration during planning (MacKerron 2015; Laraia 2018;

[88] Approx. 1.13 billion $EUR_{2020}$

BEIS 2021; NDA 2021a). The decommissioning of the nuclear fleet (except Sizewell B) is managed by the NDA who is currently responsible for 17 sites across the UK, known as the legacy fleet, and has set the goal of completing the task by 2125. In time, EDF Energy's AGRs will be transferred into NDA ownership. Decommissioning work itself is carried out by NDA subsidiaries (SLCs) that will be discussed in Section 6.5.2. So far, no site has been fully decommissioned and retracted its nuclear license (NDA 2022; Schneider et al. 2021).

In accordance with the other country reports, UK reactors were classified into commercial and non-commercial following the classification scheme shown in Figure 1-7 in the appendix of Chapter 0. Following this, all UK reactors were classified to be commercial.

As of June 2022, two NPPs of the AGR type have been shut down, namely Hunterston B and Dungeness B. Initial decommissioning work will be conducted by the current owner, EDF Energy. This work includes defueling and is scheduled to commence in 2022 (EDF Energy Undated; 2021). Table 6-6 provides an overview of the status of NPP decommissioning in the UK.

**Table 6-6: Summary of decommissioning progress in UK as of June 2022**

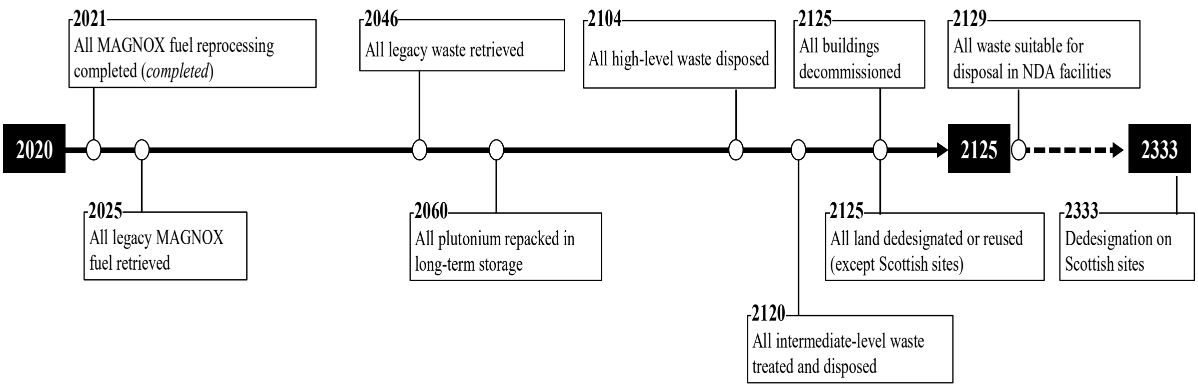
| UK | June 2022 |
|---|---|
| **"Warm-up-stage"** | 13 |
| ***of which defueled*** | *11* |
| **"Hot-zone-stage"** | 9 |
| **"Ease-off-stage"** | 0 |
| **LTE** | 8 |
| **Finished** | 0 |
| ***of which greenfield*** | *0* |
| **Shut-down reactors** | 34 |

Source: Own compilation of Sellafield Ltd. (2017) and NDA (2021a; 2022)

### 6.5.2 Progress

After the initial blanket approach of LTE of about 85 years applied to each Magnox reactor was deemed unsuitable, SLCs are currently establishing site-specific decommissioning strategies. These strategies are scheduled to be published in the course of 2022. In the meantime, the NDA has published a roadmap that outlines the milestones of the decommissioning process of the legacy fleet, mainly Magnox reactors, as shown in Figure 6-5 (NDA 2021a). In this section, the progress for each SLC shall be presented.

**Figure 6-5: Strategic roadmap of the NDA**




Source: Own depiction taken from NDA (2021a)

***Sellafield Ltd***

Of the NDA's sites, Sellafield is the largest, oldest and most complex (Foster et al. 2021). At Sellafield, electricity generation, reprocessing and fuel fabrication were conducted. Today, operations include interim storage of fuel and waste, waste treatment as well as decommissioning. Sellafield was the first SLC to be extracted from the PBO scheme and became an NDA subsidiary in 2016 (Sellafield Ltd 2017; NDA 2021a). This subsection on Sellafield highlights the tasks that are currently being worked on. This includes fuel transfer, retrieval, and processing, as well as demolition and deconstruction of old infrastructure.

All fuel from Magnox NPPs has been successfully transferred to Sellafield. This includes fuel from the four reactors at Calder Hall, located at the Sellafield site. Most of the legacy fuel, originally stored in the "First Generation Magnox Storage Pond" and the "Pule Fuel Storage Pond", is to be retrieved, reprocessed and placed into interim storage by 2025. Some of this fuel will be transferred to the modern Fuel Handling Plant as the fuel itself has degraded too heavily to allow reprocessing at existing plants. When this fuel can then be transferred to dry interim storage has not been determined. (NDA 2021c)

Milestones that are currently being worked on include the retrieval of bulk sludge and fuel from legacy ponds and silos, expected to be completed by the early 2030s. Legacy fuel retrieval had originally been planned to be completed by 2020, but due to the Covid-19 pandemic, delays occurred. Thus, whether the envisioned dates for milestone completion can be achieved, remains to be seen. First successful fuel removal of Magnox legacy fuel was achieved in June 2022. (Sellafield Ltd 2017; NDA 2021c; WNN 2022)

The NDA plans to have received, reprocessed and stored all oxide fuel from AGR plants operated by EDF Energy by 2035. Legacy oxide fuel was fully retrieved in 2016, including that of the Windscale AGR located at Sellafield and the Steam Generating Heavy Water Reactor at Winfrith. Exotic fuel consolidation at Sellafield, including fuel coming from the Dounreay site, is expected to be completed by 2028. Plutonium stocks have been fully consolidated, with repackaging estimated to be completed by 2060. (NDA 2021a; 2021c; 2022)

In terms of decommissioning, Sellafield Ltd plans to complete the demolition of the upper diffusion section of the Windscale Pile Chimney Number 1 and begin cleaning out the Magnox reprocessing plant. Both steps are to be completed by end-2023 with first successful work on the chimney already having been completed. (NDA 2022)

***Magnox Ltd***

Magnox Ltd became an NDA subsidiary in 2019 and is responsible for decommissioning at Berkeley, Bradwell, Chapelcross, Dungeness A, Harwell, Hinkley Point A, Hunterson A, Oldbury, Sizewell A, Trawsfynydd, Winfrith and Wylfa. The gross electrical capacity of these old Magnox reactors accumulates to over 4.7 GW. Three of these sites, Winfrith, Trawsfynydd, and Dounreay (operated by

UKAEA and DSRL), have been nominated as "lead and learn sites" to optimize the decommissioning strategy for the legacy fleet, which includes Calder Hall at Sellafield, and determine best practices for the upcoming decommissioning of the AGR fleet operated by EDF Energy. For Winfrith and Trawsfynydd, revisions of initial strategies concluded that some contaminated underground structures will remain in place. Land will therefore be suitable for its next planned use (brownfield). Each site operated by Magnox Ltd will in time receive a revised decommissioning plan with milestone dates. These have however not yet been published for each site. An overview of the current status of strategic goal achievement and planned dates, if available, is given in Table 6-8 in the annex. (NDA 2021a; 2022)

***Dounreay Site Restoration Ltd (DSRL)***

At the Dounreay site in northern Scotland, two reactors are to be decommissioned. Dounreay Fast Reactor (15 MW) was permanently shut down in 1977 and is to be fully dismantled by 2025. Dismantling of Dounreay Prototype Fast Reactor (250 MW) will be completed by 2027 after it was shut down in 1994. Defueling of both reactors is to be completed by 2025. As mentioned above, this fuel will be transferred to Sellafield for processing and interim storage. (NDA 2022)

***EDF Energy***

EDF Energy is the owner and operator of all remaining commercial NPPs in the UK. Of these, as of June 2022, two sites, Dungeness-B (2x 615 MW) and Hunterston-B (2x 644 MW), have been permanently shut down. Since September 2018, Dungeness-B had been in a long-term outage following several safety inspections that exposed faster than expected decay of relevant, irreplaceable components. Thus, in June 2021, it was decided to defuel both reactors at Dungeness-B (EDF Energy 2021).

After initially extending the lifetime of both reactors at the Hunterston-B site to 2023 with a +/- 2 year proviso in 2012, permanent shutdown was recorded in November 2021 for the first reactor and in January 2022 for the second reactor (IAEA 2022c). Defueling is to begin in the course of 2022 (EDF Energy Undated).

Hinkley Point B, an NPP consisting of two GCR reactors with a gross electrical capacity 655 MW each, is set to be permanently shut down by July 2022. (EDF Energy Undated)

To ensure that defueling of these AGR plants is conducted efficiently, an arrangement was made with the British government. This arrangement included the possibility of EDF Energy earning up to 100 million GBP for good performance – or the loss of the same amount if performance was deemed to be insufficient. Whether this amount will be able to incentivize efficient defueling and smooth transfer of sites into NDA custody, remains to be seen. The Commission of Public Accounts remains skeptical as to the positive impact of this incentive. (House of Commons 2022)

### 6.5.3 Actors involved

Following the UK's return from the privatized PBO scheme to full state ownership and responsibility, bundled at the NDA, major actors have since retreated from the decommissioning market in the UK. Nevertheless, this section will briefly list former PBOs. Further detail on the PBO scheme and its failure is provided in Section 6.5.4 below.

The first SLC to be removed from the PBO scheme was Sellafield Ltd after it was realized in 2015 that the clean-up task and corresponding technical uncertainties were too great to be placed into private responsibility. The private sector was therefore to "become a supplier to Sellafield Ltd rather than a parent of it" (NDA 2015, 3). Following this, Nuclear Management Partners, a consortium of Areva[89], URS (a subsidiary of AECOM Technologies) and Amec Foster Wheeler[90], were not allowed to continue the PBO contract first established in 2008 (NAO 2013a; NDA 2015; WNN 2015).

Until the award of the *Magnox Contract* to Cavendish Flour Partnership (CFP) in 2014, from which the NDA withdrew in 2017, the PBO of Magnox Ltd was EnergySolutions EU Ltd. The 2014 Magnox Contract not only handled Magnox Ltd, but also included PBO rights to Research Restoration Limited (RSRL), that was tasked with decommissioning at research facilities Harwell and Winfrith, now both assets of Magnox Ltd. Until 2014, Cavendish Nuclear, a member of CFP and subsidiary of defense company Babcock International Group, had been PBO of RSRL. Before Cavendish Nuclear, UKAEA Ltd., also a subsidiary of Babcock, had been responsible PBO. (NAO 2013a; Holliday, HM Government, and BEIS 2021)

Former PBOs at DSRL Ltd (Dounreay) and LLWR Ltd (Low-level waste repository) were Babcock Dounreay Partnership Ltd, a consortium of Babcock, CH2M Hill and URS, and UK Nuclear Waste Management Ltd, consisting of URS, Studsvik, Areva and Serco, respectively (NAO 2013a). The NDA decided to reassume control of both SLCs in 2021 (NDA 2022).

Depending on the site and contract volume, actual decommissioning work is still tendered to the best bidder. At Sellafield, several high-volume contracts, valued at several million GBP, have been awarded to former PBOs, e.g., Cavendish Nuclear. In total, more than 680 individual tasks have been contracted to approx. 430 individual companies. A further 131 tasks are still to be assigned. A similar contract approach can be seen at Magnox Ltd, however not as detailed. Here, more than 140 individual tasks have been or are to be awarded to individual contractors. Detailed information is provided at the procurement plan information websites of Magnox Ltd (2022), updated monthly, and Sellafield Ltd (2022), updated on a quarterly basis.

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[89] Areva was split into New NP (now Framatome, owned by EDF) and New Areva (now Orano) after filing for bankruptcy in 2016, see Areva (2017) for further details.

[90] Acquired by Wood Group in 2017, see Wood Group (2017) for further details.

### 6.5.4 Design, objectives, and results of the SLC-PBO competitive tendering scheme

In 2002, when the idea of creating a non-departmental governmental agency for nuclear waste and decommissioning management, then dubbed "Liabilities Management Authority", was first introduced, efficiency and cost-effectiveness of nuclear legacy clean-up were already major points of interest. Out of this original idea emerged the NDA and, consequentially, the PBO management scheme. (Department of Trade and Industry 2002; MacKerron 2015)

The NDA was set up as a strategic agency not directly involved in the day-to-day decommissioning operations of its nuclear sites. These operations were to be conducted by the site license companies (SLCs) who would hold the nuclear license and employ the workforce tasked with nuclear clean-up. Arrangements between the SLCs and the NDA would be made on a contractual basis to provide shared business risk and defined key performance indicators as well as to establish an incentive-driven framework to increase operational efficiency, safety and environmental standards and, most importantly, generate "the best value for money" (Department of Trade and Industry 2002, 25). A contract change, to be conducted every 5 to 10 years by competitive tender, would thus exchange upper management of SLCs, but keep the licensee itself operable. The SLC in turn may tender contracts to other subcontractors for specific tasks, as shown in Section 6.5.3. (Department of Trade and Industry 2002; MacKerron 2012)

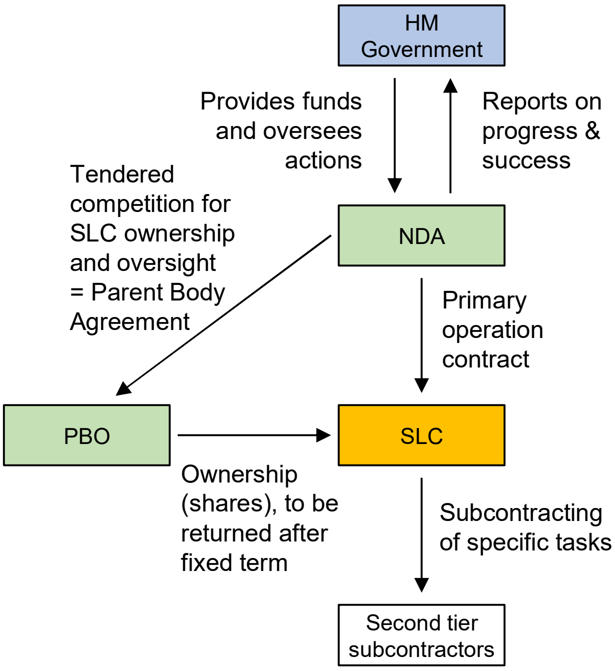
This upper management is organized in the so-called "Parent Body Organizations" (PBO) that own the shares of the SLC for which they won the competitive tender, and thus operation contract, for a pre-determined amount of time. The PBO provides strategic management and aims to improve efficiency. It can earn performance dependent fees. In this scheme, the NDA is still in full ownership of assets and liabilities, although some responsibility shift can occur. The PBO contracts were designed either as reimbursable contracts, that required the NDA to pay all costs generated by contractors, or as Target Cost (TCIF) model. In the TCIF model, a fixed target cost is agreed upon at the beginning of the contract. In this contract, the PBO is compensated with a fee that depends on achievement of the set target cost. If actual costs were higher than the target, the PBO would not be paid in full. If cost savings were achieved, the difference between actual cost and target cost could be shared between NDA and PBO, in addition to full fee payment. Figure 6-6 provides an overview of the PBO scheme. (MacKerron 2012; 2015; KPMG 2013; Holliday, HM Government, and BEIS 2021)

The PBO scheme was designed for increased efficiency and cost savings for the task of decommissioning the UK's extensive legacy fleet (esp. Magnox reactors) and the problematic Sellafield site. However, over the years it was active, the scheme failed to consequently deliver these goals and consequently, all SLCs have now been returned to full NDA ownership. (NDA 2022)

The PBO contract for Sellafield, awarded to Nuclear Management Partners (NMP) (see Section 6.5.3), was finally discontinued in 2015 after it was determined that the clean-up and resulting technical uncertainties at Sellafield were too complex to be placed into private responsibility (WNN 2015). Sellafield Ltd thus became the first SLC to be fully retransferred into NDA custody, effective from 2016

(Schneider et al. 2021; NDA 2021a). Before this decision, the NDA had initially decided to allow the PBO contract to continue, even after concerns about the adequacy of NMP to perform had been reported (KPMG 2013; MacKerron 2015).

**Figure 6-6: PBO scheme**




Source: Own depiction following MacKerron (2012) and KPMG (2013)

In 2013, the NDA conducted a tender competition for the *Magnox Contract*, a highly controversial 6.2 billion GBP[91] 14-year PBO contract for SLCs Magnox Ltd and RSRL. After having been awarded to the bidder Cavendish Fluor Partnership (CFP) by end March 2013, with work to commence in June 2014, the termination of the contract was initiated by the NDA in 2017, and it finally ended in 2019. The main reason for termination was the initial false estimation of the so-called baseline. This is the initial on-site situation in terms of remaining fuel, contamination, components, buildings and so on. It is used to determine the target that is to be achieved by the end of the contract, including the target cost. This initial false evaluation resulted in an increased cost assumption of over 1.8 billion GBP[92], giving the NDA a valid reason to terminate and resulting in negotiated termination costs of additional 20 million GBP[93] paid to CFP. (House of Commons 2020, 9–10; Holliday, HM Government, and BEIS 2021, 45–73, 102–16)

[91] Approx. 7.3 billion $EUR_{2020}$
[92] Approx. 2.12 billion $EUR_{2020}$
[93] Approx. 23.56 million $EUR_{2020}$

Furthermore, the tender itself had been overly complicated and falsely conducted, when the Magnox contract was awarded to CFP (Holliday, HM Government, and BEIS 2021, 18–19). EnergySolutions, the Magnox PBO before 2014 had competed in the tender in a consortium named Reactor Site Solutions (RSS) with Bechtel Management Company Ltd. EnergySolutions initially filed a claim against the tender at the High Court of England and Wales. Bechtel followed later on, once it had become clear that the claim was valid. Inquiries showed that the NDA had made mistakes in the calculations to determine the best bidder and had thus falsely awarded the contract to CFP instead of RSS, who had actually presented the better offer. This led to a settlement between RSS and the NDA, resulting in additional costs of 122 million GBP[94] in compensation and legal fees for the NDA. (House of Commons 2020; Holliday, HM Government, and BEIS 2021)

After the two largest PBO contracts for Sellafield and Magnox had been retracted, the NDA decided to also terminate remaining PBO contracts at DSRL and LLWR and to reinstate both SLCs as full NDA subsidiaries by 2021. This decision ended the NDA's PBO scheme and now the NDA aims to achieve efficiency, value for money and better performance, ironically the initial goals of the PBO scheme, from its new organizational design. (NDA 2021a)

The reasons for the failure of the PBO scheme can be summarized into four key points that are described below.

***Operation***

As was mentioned above, the Sellafield contract was terminated due to the overly complex nature of decommissioning a nuclear site whose legacy fuel had been neglected over several decades, especially with poor reporting and record keeping. For a PBO scheme to function and to fulfil its goals, the baseline status of the site must be determined. Due to lack of knowledge of waste amounts and contamination as well as poor oversight of what previous PBOs had achieved, an accurate determination of a baseline status and subsequent definition of necessary tasks to achieve the desired status by the end of contract, was not possible. (MacKerron 2012; Holliday, HM Government, and BEIS 2021; BEIS 2021)

Furthermore, operational challenges occurred when new PBOs implemented process and management changes. This lead to wasted time that could have been more effectively used for actual decommissioning work. (Holliday, HM Government, and BEIS 2021)

***Organization***

BEIS, the department charged with overseeing the NDA, concluded in their most recent report on the NDA, that two main organizational issues impacted PBO performance. First, SLC employees, often former employees of restructured public companies UKAEA and BNFL[95], still considered themselves as to belonging to the public sector and were discontent with PBO management style that aimed at

[94] Approx. 143.72 million $EUR_{2020}$

[95] British Nuclear Fuels Limited, see MacKerron (2012) for further details.

increasing private value. This discontent was further increased by the second issue: it was virtually impossible for SLC employees to advance through the management structure imposed by the PBOs and thus resulted in low morale and loss of qualified personnel. (BEIS 2021)

***NDA Management***

When the NDA was created, little experience, especially commercial, existed in the agency. This lack of skilled staff and knowledge resulted in the inability to provide adequate oversight over the PBOs. For example, after having awarded the Magnox Contract to CFL, NDA oversight staff consisted of only 20 members, as opposed to 3,500 staff at CFL. Only since deeper inquiries into the NDA's shortcomings have been made, has the NDA increased its recruiting efforts. (House of Commons 2020; BEIS 2021; Holliday, HM Government, and BEIS 2021)

***Trust***

In-depth inquiries into the NDA's shortcomings have led to an increase in governmental oversight of the NDA and several critical reviews (NAO 2013b; House of Commons 2020; BEIS 2021). Failure to produce accurate cost estimates, mistakes made during the Magnox competition and resulting litigation, as well as costs resulting from the retraction of all PBO contracts, have led Parliament to place the NDA under increased scrutiny over the years to come. However, BEIS is also heavily criticized for its lack of oversight in the past. Thus, due to the perceived incompetence of the NDA, the agency will have to restore governmental and public trust in its capabilities by delivering on its set decommissioning targets. With all SLCs in governmental ownership, oversight can be guaranteed in a more efficient and effective manner (House of Commons 2020; BEIS 2021; NDA 2021a).

## 6.6 Country specific nuclear and decommissioning developments

Decommissioning in the UK highlights three important issues: Firstly, as one of the leading countries of the post WWII nuclear expansion, the UK did not consider the long-term issues of decommissioning and waste management. Secondly, the time horizons now envisaged by the NDA, after some decades without significant progress in decommissioning must be further stressed: The NDA is now planning a process stretching over the next century and more, well into the 22$^{nd}$ century. And finally, an interesting feature of the UK approach is to include competitive elements, mainly competitive tendering and some incentive contracts. Although the PBO approach has since failed in achieving its goals, incentives are still included in contracts with EDF Energy, see Section 6.5.2 – a development that must be closely monitored.

### 6.6.1 Neglection of long-term nuclear responsibilities in the early days

As one of the first countries to adopt nuclear power, and as a global nuclear superpower after 1945, the UK's authorities gave only little consideration to longer-term issues such as decommissioning of nuclear installations, and nuclear waste management. Starting with the first reactors, the Calder Hall series, problems of decommissioning started to accumulate, both having to do with the complex technical structure (graphite moderation), but also the absence of technical considerations of the post-operational period. A similar trend is observed vis-à-vis waste management, which was not considered an issue at all in the early nuclear period: Until today, all sorts of waste are stored at seemingly random locations, and in various technical states (liquid, solid), which is both dangerous and costly. Sellafield, where most of these fuel ponds and storage sites are located today, has since become one of the most complex and dangerous nuclear sites to face decommissioning, as was described in Section 6.5.2.

### 6.6.2 Extensive time horizons

The Sellafield site also represents the long time horizons and high technical and economic uncertainties related to nuclear decommissioning in the UK. According to current planning, the retrieval of the legacy wastes from the reactors will last until the late 2040s, whereas the dedesignation of the lands used for the nuclear sites is planned to have occurred by 2125, while Scottish sites will be reusable only in the year 2333. Waste treatment for disposal in final storage facilities is currently planned for 2129. Not all technological steps are known at this point, in particular the treatment of the graphite. The vast timeframe also implies major economic and financial risks, as highlighted by the low returns of the NLF and the variation in stated provisions made on behalf of the NDA, shown in Section 6.4.2. Given the divestment of the legacy companies of decommissioning and waste risks observed in other countries, full nationalization of economic and financial risks might be likely within the next decades in the UK, too.

### 6.6.3 Competitive tendering gone wrong

Perhaps the most interesting lesson from the UK is the failure of the real-world experiment of competitive tendering in the presence of high asset specificity and, thus, incomplete and asymmetric information about the technical and economic challenges of decommissioning. Awarding the control of site licence companies (SLCs) to parent body organizations (PBOs) and thus create temporary monopoly rights in the decommissioning sector was a bold idea, which was hoped to accelerate the process and make it more cost-effective. However, difficulties of establishing appropriate incentives for the agents, in terms of timing and remunerate and other issues, discussed in Section 6.5.4, have led to longer decommissioning times, and lower cost-efficiency. This was particularly salient in the case of the Magnox legacy reactors. The fact that the NDA had to regain control of all sites, and withdraw from the experiment, highlights the challenges and most likely pushed the UK's decommissioning efforts back by several years.

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## Appendix

**Table 6-7: Ownership of shut down UK NPPs**

| Nuclear reactor | Type | Model | Owner | Operator | Gross El. Capa. [MW] | Constr. Start Date | Com. Op. Date | Perm. Shut-down Date |
|---|---|---|---|---|---|---|---|---|
| **Berkeley-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 166 | 01.01.1957 | 12.06.1962 | 31.03.1989 |
| **Berkeley-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 166 | 01.01.1957 | 20.10.1962 | 26.10.1988 |
| **Bradwell-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 150 | 01.01.1957 | 01.07.1962 | 31.03.2002 |
| **Bradwell-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 150 | 01.01.1957 | 12.11.1962 | 30.03.2002 |
| **Calder Hall-1** | GCR | MAGNOX | NDA | Sellafield Ltd. | 60 | 01.08.1953 | 01.10.1956 | 31.03.2003 |
| **Calder Hall-2** | GCR | MAGNOX | NDA | Sellafield Ltd. | 60 | 01.08.1953 | 01.02.1957 | 31.03.2003 |
| **Calder Hall-3** | GCR | MAGNOX | NDA | Sellafield Ltd. | 60 | 01.08.1955 | 01.05.1958 | 31.03.2003 |
| **Calder Hall-4** | GCR | MAGNOX | NDA | Sellafield Ltd. | 60 | 01.08.1955 | 01.04.1959 | 31.03.2003 |
| **Chapelcross-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 60 | 01.10.1995 | 01.03.1959 | 29.06.2004 |
| **Chapelcross-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 60 | 01.10.1995 | 01.08.1959 | 29.06.2004 |
| **Chapelcross-3** | GCR | MAGNOX | NDA | Magnox Ltd. | 60 | 01.10.1995 | 01.12.1959 | 29.06.2004 |
| **Chapelcross-4** | GCR | MAGNOX | NDA | Magnox Ltd. | 60 | 01.10.1995 | 01.03.1960 | 29.06.2004 |
| **Dounreay DFR** | FBR | | NDA | UKAEA | 15 | 01.03.1955 | 01.10.1962 | 01.03.1977 |
| **Dounreay PFR** | FBR | | NDA | UKAEA | 250 | 01.10.1966 | 01.07.1976 | 31.03.1994 |
| **Dungeness A-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 230 | 01.07.1960 | 28.10.1965 | 31.12.2006 |
| **Dungeness A-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 230 | 01.07.1960 | 30.12.1965 | 31.12.2006 |
| **Dungeness B-1** | GCR | AGR | EDF Energy | EDF Energy | 615 | 01.10.1965 | 01.04.1985 | 07.06.2021 |
| **Dungeness B-2** | GCR | AGR | EDF Energy | EDF Energy | 615 | 01.10.1965 | 01.04.1989 | 07.06.2021 |
| **Hinkley Point A-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 267 | 16.02.1965 | 30.03.1965 | 23.05.2000 |
| **Hinkley Point A-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 267 | 01.11.1957 | 05.05.1965 | 23.05.2000 |
| **Hunterston A-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 173 | 01.10.1957 | 05.02.1964 | 30.03.1990 |

| Nuclear reactor | Type | Model | Owner | Operator | Gross El. Capa. [MW] | Constr. Start Date | Com. Op. Date | Perm. Shut-down Date |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Hunterston A-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 173 | 01.10.1957 | 01.07.1964 | 31.12.1989 |
| **Hunterston B-1** | GCR | AGR | EDF Energy | EDF Energy | 644 | 01.11.1967 | 07.02.1976 | 26.11.2021 |
| **Hunterston B-2** | GCR | AGR | EDF Energy | EDF Energy | 644 | 01.11.1967 | 01.04.1977 | 07.01.2022 |
| **Oldbury A-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 230 | 01.05.1962 | 31.12.1967 | 29.02.2012 |
| **Oldbury A-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 230 | 01.05.1962 | 30.09.1968 | 30.06.2011 |
| **Sizewell A-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 245 | 01.04.1961 | 25.05.1966 | 31.12.2006 |
| **Sizewell A-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 245 | 01.04.1961 | 15.09.1966 | 31.12.2006 |
| **Trawsfynydd-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 235 | 01.07.1959 | 24.03.1965 | 06.02.1991 |
| **Trawsfynydd-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 235 | 01.07.1959 | 24.03.1965 | 04.02.1991 |
| **Windscale AGR** | GCR | AGR | UKAEA | UKAEA | 36 | 01.11.1958 | 01.03.1963 | 03.04.1981 |
| **Winfrith SGHWR** | SGHWR | | UKAEA | UKAEA | 100 | 01.05.1963 | 01.01.1968 | 11.09.1990 |
| **WYLFA-1** | GCR | MAGNOX | NDA | Magnox Ltd. | 530 | 01.09.1963 | 01.11.1971 | 30.12.2015 |
| **WYLFA-2** | GCR | MAGNOX | NDA | Magnox Ltd. | 540 | 01.09.1963 | 03.01.1972 | 25.04.2012 |

Source: Own compilation based on IAEAs Operating Experience with Nuclear Power Plants (IAEA 2022b)

**Table 6-8: Overview of strategic goals and achievements at UK MAGNOX NPPs.** Dedesignated land (in hectares, ha) has been released from nuclear licensing. The entry TBD is used when no date has been set.

| Site | Area dedesignated | Free from Spent Fuel | Free from Nuclear Materials | All Radioactive Waste Disposed | All Buildings Decommissioned or Relicenced | All Land Suitable for Reuse | All Land Dedesignated or Reused |
|---|---|---|---|---|---|---|---|
| **Berkeley** | 11 of 27 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Bradwell** | 0 of 20 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Sellafield** | 0 of 276 ha | - | - | - | TBD | 2125 | 2125 |
| **Chapelcross** | 0 of 96 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Dungeness A** | 0 of 20 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Dounreay** | 0 of 60 ha | 2025 | TBD | TBD | TBD | TBD | TBD |
| **Harwell** | 23 of 107 ha | Achieved | Achieved | 2025 | TBD | TBD | TBD |
| **Hinkley Point A** | 0 of 19 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Hunterston A** | 0 of 15 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Oldbury** | 32 of 47 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Sizewell A** | 0 of 14 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Trawsfynydd** | 0 of 15 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Winfrith** | 10 of 81 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |
| **Wylfa** | 0 of 21 ha | Achieved | Achieved | TBD | TBD | TBD | TBD |

Source: Compiled from NDA (2022, 36–52).

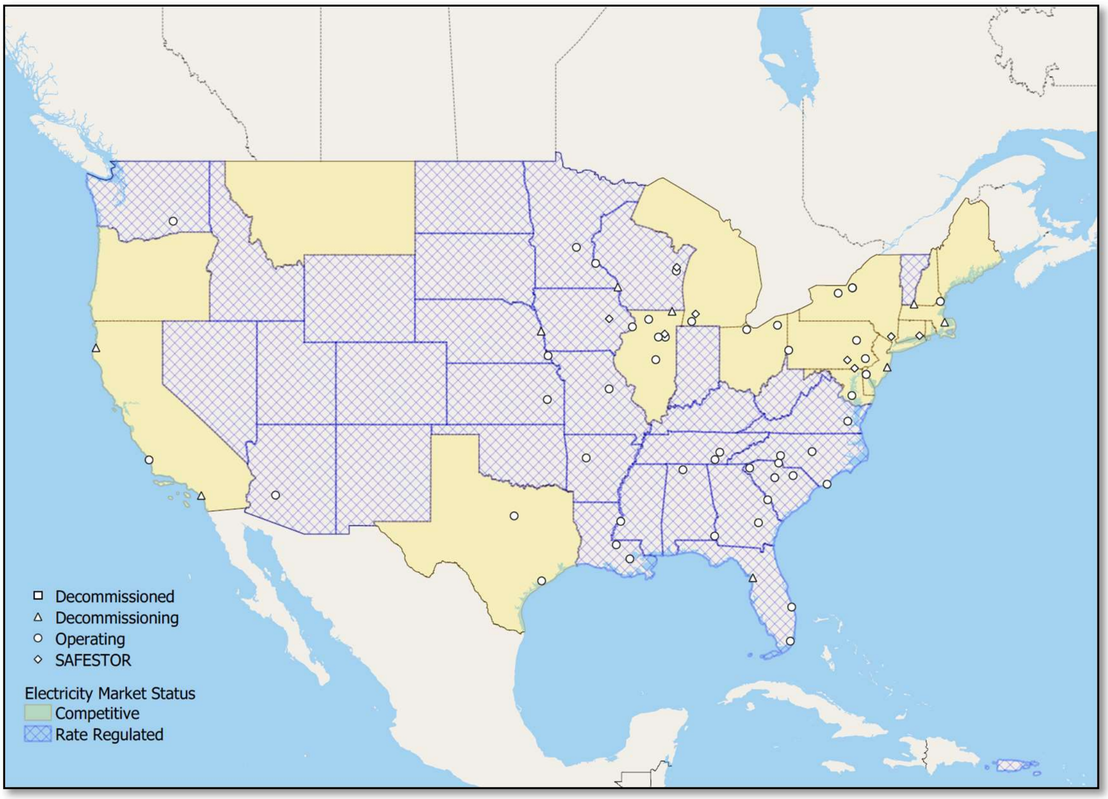
# 7 United States

Muhammad Maladoh Bah

## 7.1 Introduction

Development of the commercial nuclear industry in the United States began in earnest during the early 1960s after the passage of the Atomic Energy Act (1954). The introduction of the turnkey contract in the mid-1960s spurred the momentum to construct nuclear reactors. The first commercial nuclear reactors (Shippingport, Dresden-1, Indian Point-1, and Yankee NPS) were commissioned and constructed during mid-1950s and early 1960s. By 1967, U.S. utilities ordered more than 50 nuclear power reactors and by 1973, 40 reactors were operating (Scurlock 2007; Squassoni 2012). At its peak in 1990, the U.S. nuclear industry operated 112 nuclear reactors (Lordan-Perret, Sloan, and Rosner 2021). Today the U.S. commands the largest commercial fleet globally with 92 operating reactors spread across 28 states and accounting for 94.7 GW (see Table 7-6 in the appendix of this chapter). The current nuclear fleet is also the oldest in world with an average age of 41.6 years (Schneider et al. 2022). In terms of new reactor builds, only one reactor has started over the past two decades (i.e., Watts Bar in 2016). Construction is ongoing the Vogtle units 3 and 4 reactors, and they are expected to commence operations in 2023 (WNN 2022). Figure 7-1 shows the location of all operating commercial reactors and the status of shutdown reactors (decommissioned or decommissioning).

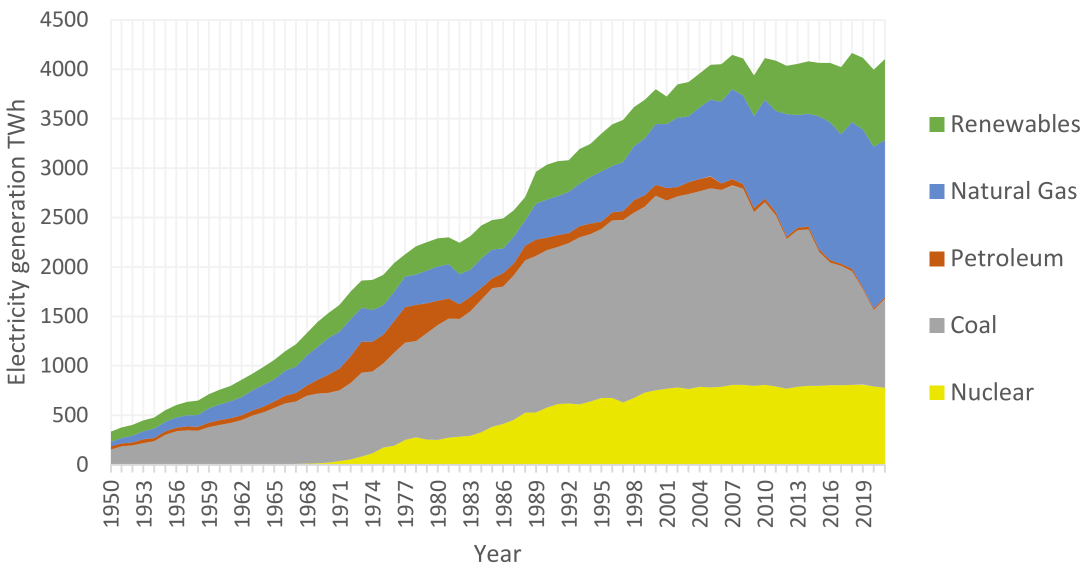
**Figure 7-1: Map of operating commercial nuclear reactors in the U.S.**




Source: (Lordan-Perret, Sloan, and Rosner 2021).

Nuclear power currently commands a 19% share of the total electricity generation mix (EIA 2022). Although nuclear power generation has increased markedly from the 1980s, in the past decade, its share in the electricity mix has stagnated in comparison to other sources of energy such as natural gas and renewables as depicted in Figure 7-2. For example, between 2000 and 2020, the share of natural gas in the electricity mix increased from 16% to 39%, while renewables share[96] expanded from 9% to 20%. Over the same period, the share of nuclear generation contracted marginally from 20% to 19%.

**Figure 7-2: U.S. electricity generation by energy source**




Source: own depiction based on (EIA 2022).

The U.S. electricity market has undergone substantial regulatory reforms in the 1990s when energy markets in many states were deregulated. Traditional vertically integrated utilities were split up into distinct activities: generation, transmission, distribution and retailing (Borenstein and Bushnell 2015; Chen 2019). In doing so, many state-owned nuclear plants were sold off to independent power producers, leading to a consolidation of plants into a few large holding companies (see Section 2.2). Today, nuclear power plants (NPP) operate in both regulated and deregulated electricity markets, with approximately 54 GW of generating capacity in regulated markets and 45 GW in deregulated markets (World Nuclear Association 2020). Nuclear plants in regulated markets are compensated based on cost-of-service, while plants in deregulated markets rely on the wholesale market and capacity market as their primary revenue sources. However, nuclear plants may receive additional out-of-market revenues through state subsidy schemes.

From 2017 to as recently as 2020, low wholesale market prices prompted nuclear licensees to seek out-of-market payments to remain competitive in deregulated markets. State support schemes are

[96] Renewable generation comprises of solar, wind, geothermal, biomass and hydropower.

presently active in five U.S. states (New York, Illinois, New Jersey, Connecticut, New Hampshire) covering 19 reactors with a combined capacity of 19.4 GW. The schemes vary considerably in terms of length and financial provisions. At the federal level, two new schemes were rapidly introduced in late 2021 to counter the threat of early nuclear retirements (Schneider et al. 2022). In November 2021, the Civil Nuclear Credit Program (CNC) was introduced as part of the Infrastructure and Investments Jobs Act (IIJA) with the goal of providing out-of-market payments to NPPs in imminent risk of shutting down in wholesale electricity markets. The Department of Energy (DOE) was tasked with overseeing the $6 billion program over a five-year period from 2022-2027, with the possibility of extending it up to 2031 (DOE 2022b; NIRS 2022). In August 2022, the Inflation Reduction Act (IRA) was signed into law, incorporating provisions for a second federal-level support scheme known as the zero-emission Nuclear Power Production Credit (NPPC). Operating reactors that meet the prevailing wage requirement stand to receive a maximum credit value of $15/MWh for a nine-year period starting in 2024 until 2032 (Schneider et al. 2022). Reactors that do not meet the criteria would still receive credits valued at $3/MWh. This development is also part of an effort of the current administration to reduce emissions and achieve a clean electric grid (Schneider et al. 2021).

Over the coming decades, a wave of reactors in the U.S. will be reaching the end of their operating lifespan and will need to be decommissioned. By 2040 alone, approximately half of the U.S. nuclear fleet will be reaching the end of their operating licenses. The closure of the Palisades reactor in May 2022 brings the total number of shutdown reactors in the U.S. to 41, amounting to approximately 20 GW of capacity. The U.S. nuclear industry has accumulated some decommissioning experience with 17 reactors fully decommissioned (the most of any country). Nevertheless, it stands that the U.S. nuclear industry is just beginning an unprecedented undertaking to decommission the world's largest fleet. Supporting and shaping this effort are many stakeholders, including public agencies, private firms, regulators, financial institutions.

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

## 7.2 Legal and Regulatory Framework

### 7.2.1 Governmental and regulatory framework

The primary law governing the entire nuclear industry is the Atomic Energy Act of 1954. The Act established the Atomic Energy Commission (AEC) in 1946, which then later split into the Nuclear Regulatory Commission (NRC) and the DOE (formerly the Energy Research and Development Administration, ERDA). Apart from the Atomic Energy Act, other key statues were introduced to regulate specific areas of the nuclear industry (see Box 8-1).

The **NRC** is the federal agency responsible for regulating the civilian use of radioactive materials for the protection of public health. It has a broad range of regulatory responsibilities covering commercial nuclear plants (with jurisdiction over licensing, operation, and decommissioning), research and test reactors[97], and nuclear fuel cycle facilities. The NRC's regulatory oversight also extends to the transport, storage, and disposal of radioactive materials and waste. The NRC adopts a broad array of mechanisms to exert its regulatory authority such as rule making, technical reviews, inspections and investigations, issuance of licenses and evaluating operating experience. Inspections are a major component of the NRC's regulatory authority to ensure that nuclear plants operations and activities meet the NRC regulations.

The **Department of Energy (DOE)** is responsible for policy formulation and funding programs on nuclear energy, fossil fuel and renewable energy. On the nuclear energy front,

**Box 8-1: Legal framework of the U.S. nuclear industry**

**Atomic Energy Act of 1954, as Amended:** Permits the use of atomic energy for peaceful applications. It transformed the atomic energy program with a key goal of expanding the growth of the commercial nuclear industry.

**Energy Reorganization Act of 1974:** This Act divided the functions of the Atomic Energy Commission (AEC) into two separate agencies. The DOE (formerly ERDA) became responsible for the development of nuclear weapons and promotion of nuclear energy. The NRC assumed the overall nuclear regulatory responsibility.

**Nuclear Waste Policy Act of 1982:** Sets out the government's responsibility for the identification and development of a suitable geological site for the disposal of civilian and defense spent nuclear fuel, high-level waste and nuclear licensee's responsibility for bearing the cost. The Act also established the Nuclear Waste Fund (NWF) to finance the management and disposal of spent nuclear fuel.

**Low-Level Radioactive Waste Policy Amendments Act of 1985:** Established the policy for the disposal of low-level radioactive waste. The act grants states the authority to establish and operate facilities for the disposal of low-level waste generated within their borders.

**Price-Anderson Act of 1957**: Established to address nuclear liabilities and sets a limit on total liabilities each licensee faces in the event of an incident.

**Uranium Mill Tailings Control Act of 1978:** Established a program to stabilize and control mill tailings at uranium- and thorium-ore processing mill sites.

**Nuclear Non-Proliferation Act of 1978:** The act seeks to provide effective control over the proliferation of nuclear weapons.

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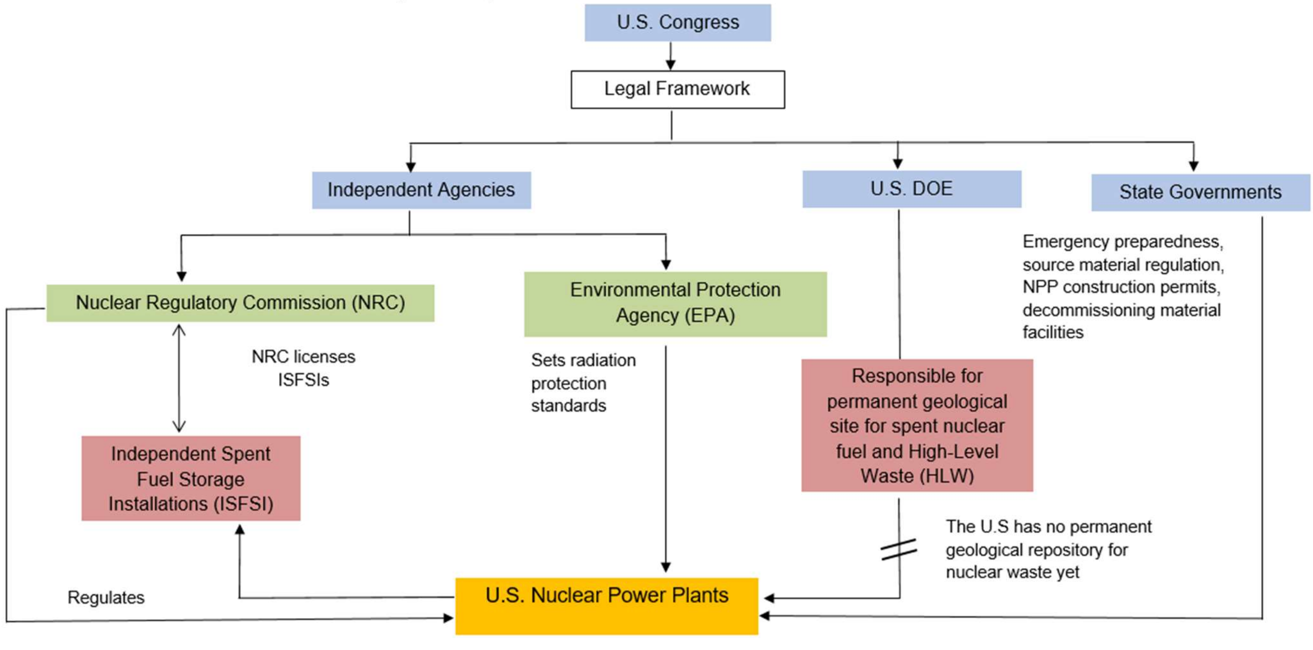
[97] The NRC regulates 31 operating research reactors and three shutdown reactors (NRC 2021a).

the DOE conducts a range of activities such as research and development of next generation nuclear plants, funding construction of new nuclear plants, nuclear security and development of advanced fuel cycle technology. The DOE is responsible for the management of high-level nuclear waste and spent nuclear fuel as directed in the Nuclear Waste Policy Act of 1982 (OECD/NEA 2016b). The DOE also oversees and regulates its own fleet of research and test reactors, which do not fall under the jurisdiction of the NRC.

The **Environmental Protection Agency (EPA)** is responsible for setting public health and radiation protection standards as outlined in federal regulation 40 CFR Part 190. The **Department of Transport (DOT)** coordinates with the NRC for the transportation of hazardous radioactive materials and regulates shipments while on transit. The **Department of Defense (DOD)** is primarily responsible for the safety of nuclear materials including nuclear weapons.

**State and local governments** exercise regulatory control over certain aspects of nuclear energy. For example, under the Atomic Energy Act of 1954, states are permitted to exercise independent authority to license and regulate by-product materials, source materials and selective quantities of special nuclear material as part of the Agreement State Program (Squassoni et al. 2014). Presently, 39 states have signed up to the program. In terms of emergency preparedness, core responsibilities are shared between the NRC and the Federal Emergency Management Agency (FEMA). However, state governments are responsible for implementing public protection protocols during nuclear emergencies. State governments also play a role in the issuance of nuclear construction permits. Figure 7-3 provides an overview of the various governmental and regulatory bodies and their association with NPPs in the U.S.

**Figure 7-3: Governmental and regulatory actors and their connection to U.S. NPPs**




Source: own depiction based on (IAEA 2002; OECD/NEA 2016b).

### 7.2.2 Ownership

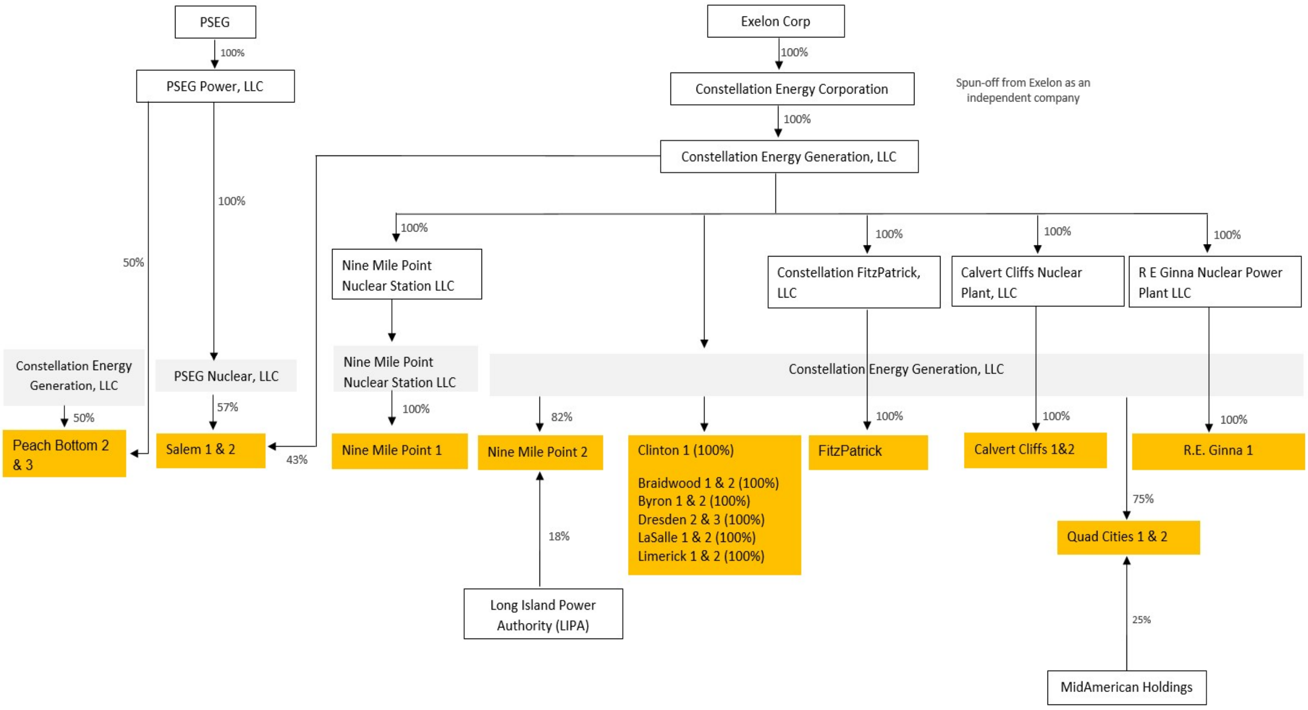
NPP ownership in the U.S. is fragmented across several ownership structures[98] such as the federal government, publicly owned entities, investor-owned companies and cooperatives. In some cases, NPPs can be owned by several ownership types. NRC regulation (10 CFR 50.38) prohibits foreign ownership or operation of domestic NPPs.

In the case of the federal government, ownership of the reactor falls under the control of a federal agency. For example, the Tennessee Valley Authority (TVA) is a federally owned agency that fully owns the Browns Ferry, Sequoyah and Watts Bar NPPs. Publicly owned NPPs are owned or partly owned by a state utility company or municipality entity. For example, the Municipal Electric Authority of Georgia (MEAG Power) has a 17.7% share in the Edwin Hatch NPP and a 22.7% share in the Vogtle NPP as illustrated in Figure 7-4.

Turning to investor-owned corporations, following the restructuring of the U.S. energy sector, a considerable number of nuclear reactors were consolidated into a few large private holding energy companies such as Constellation Energy Corporation, Duke Corporation, NextEra and Entergy. These major holding companies are diversified across the energy value chain, with several energy sources in their portfolio. Investor-owned companies own majority of operating commercial reactors. The investor-owned plant ownership structure is comprised of several layers between the holding company and the nuclear power plant. Most holding companies do not directly own nuclear plants, but instead ownership is held by a subsidiary company in the form of a Limited Liability Company (LLC). LLCs are generally the preferred vehicle of ownership amongst multi-tiered nuclear holding companies in the U.S., as they provide a flexible means of transferring funds from subsidiaries and avoiding tax (Schlissel, Peterson, and Biewald 2002). Parent company liabilities are only restricted to the initial investment made in setting up the LLC. This ensures that parent companies are financially shielded from any liabilities (i.e., accident or decommissioning risks) emerging from its subsidiaries (Schlissel, Peterson, and Biewald 2002). An example of investor-owned nuclear reactor ownership is Constellation Energy Corporation, a spin-off from its former parent company Exelon Corporation. Constellation through its chain of subsidiary LLC's, fully owns 16 reactors, apart from Peach Bottom (50% ownership), Quad Cities (75% ownership) and Salem nuclear plant (43%). MidAmerican holdings owns 25% of both Quad Cities reactors while Long Island Power Authority (LIPA) owns 18% of Nine Mile Point 2. Figure 7-4provides a graphical representation of Constellation Energy Corporation ownership structure for its nuclear reactor fleet.

[98] Refer to NEI (2022) for data on reactor ownership shares.

**Figure 7-4: Investor-owned nuclear plant ownership structure**




*Light grey boxes depict reactor operator. Solid black lines signify ownership.*

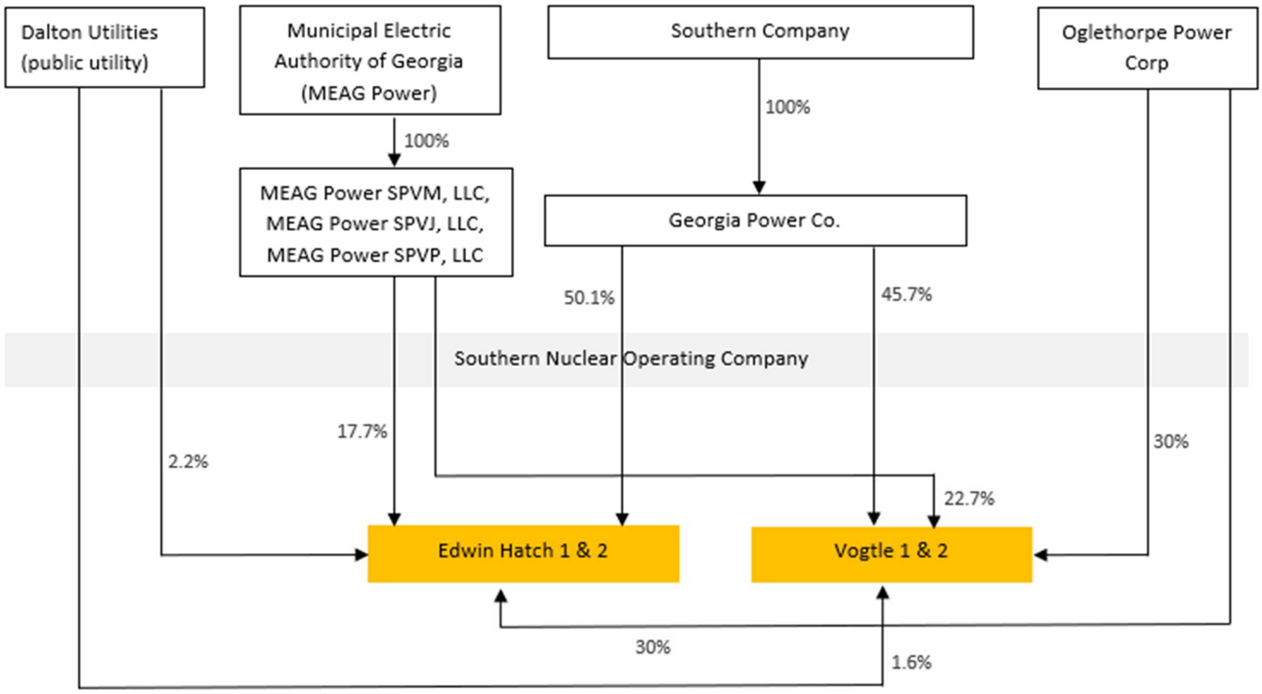
Source: own depiction based on (Constellation Energy Corporation 2021).

Cooperatives are independent not-for-profit member-owned utilities. In the case of nuclear reactors, the members of the cooperative have ownership interest in the reactors and they are also its customers (Sunshine 2020). An example of a Cooperative is Oglethorpe Power Cooperative that owns 30% of the Vogtle 1 & 2 reactors.

In some cases, nuclear reactors are owned by a combination of ownership structures. For example, ownership of the Edwin Hatch and Vogtle NPPs are shared between an investor-owned utility (Georgia Power), publicly owned utilities (Municipal authority of Georgia[99] and Dalton utilities), and a cooperative (Oglethorpe Power Corp). Figure 7-5 depicts the mixed nuclear plant ownership structure.

[99] In June 2015, MEAG Power divided its ownership interest (22.7%) in Vogtle 1 and 2 reactors into three separate limited liability companies. In particular, 41.175% of the Vogtle ownership share was transferred to MEAG Power SPVJ, LLC, 33.87% to MEAG Power SPVM, LLC, and 24.95% to MEAG Power SPVP, LLC (MEAG 2017).

**Figure 7-5: Mixed nuclear plant ownership structure**




*Investor owned: Georgia Power Corporation. Public utilities: MEAG Power and Dalton utilities. Cooperative: Oglethorpe Power Corp. Light grey boxes depict reactor operator.*

Source: Own depiction based on (NEI 2022; Southern Company 2021).

### 7.2.3 License provision and extension

The NRC oversees licensing regulations for commercial nuclear plants. All the 92 currently operating commercial reactors were licensed under a two-step licensing framework governed by 10 CFR Part 50 regulations. Under the two-step process, the applicant applies for a construction permit first before applying for an operating license once the plant was nearing completion. NRC regulations limits the initial license period for commercial nuclear plants to 40 years. Nuclear plant licenses can be renewed for additional 20-year periods. The decision to apply for a license extension rests with the licensee and often depends on economic considerations and whether a plant can continue to meet the NRC's stringent standards. As of July 2022, 84 currently operating reactors have received a 20-year license extension (Schneider et al. 2022).

Though still a valid way of seeking a license, the two-step process was criticized, and the NRC modified the licensing regulation by introducing a streamlined combined license (COL) process under the 10 CFR Part 52(C) regulations. Unlike the two-step process, the COL authorizes the applicant to construct and operate a reactor at a specific site with one unified application. A prospective licensee applies for a COL by referencing either an early site permit or a standard design certification or both

(NRC 2009).[100] The early site permit is granted for a period of 10 to 20 years and allows the holder to address site safety issues, environmental protection concerns, and emergency plans under the 10 CFR Part 52(A) regulations. Alternatively, a standard design certification[101] is issued to certify a reactor design under 10 CFR Part 52(B) regulations and is valid for 15 years. If the applicant decides not to reference either of the two frameworks, it should provide equivalent information for both certifications. The COL application should also include a preliminary safety analysis report, environmental review and financial and antitrust statements (NRC 2009).

Upon receiving the COL application, the NRC conducts a preliminary review to assess the suitability of the application. Once accepted, the licensing review starts and the NRC organizes public meetings at the proposed reactor site to brief the public about safety and environmental elements of the application (NRC 2020). The NRC publishes its staff review findings in a safety evaluation report and environmental impact statement (NRC 2009). Following the NRC staff review, the independent Advisory Committee on Reactor Safeguards (ACRS) is convened to review each COL application in a mandatory public hearing. At this stage, the public can submit written or oral statements on record or apply to participate in the hearing. Once the review is completed and the application is approved, the NRC issues a COL to the applicant. An overview of the COL process is depicted in Figure 7-6. Like the two-step process, a COL is issued for 40 years and can be renewed for an additional 20 years. Since 2007, the NRC has received 18 COL applications for 28 reactors and approved eight of the applications covering 14 reactors[102] (NRC 2021a). Six of the issued COL's were terminated[103] at the behest of the licensee.

Moving forward, The NRC has also developed a standard review plan for subsequent license renewals that would extend the operating life of nuclear reactors beyond 60 years and up to 80 years. So far, six reactors Turkey Point 3 & 4, Peach Bottom 2 & 3 and Surrey units 1, 2 & 3 have been issued subsequent license renewals and the NRC is reviewing applications for nine operating reactors[104] (NRC 2022d).

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[100] The NRC introduced the early site permit and standard design certification in 1989 under 10 CFR Part 52 regulations, which contribute to the COL process (NRC 2009).

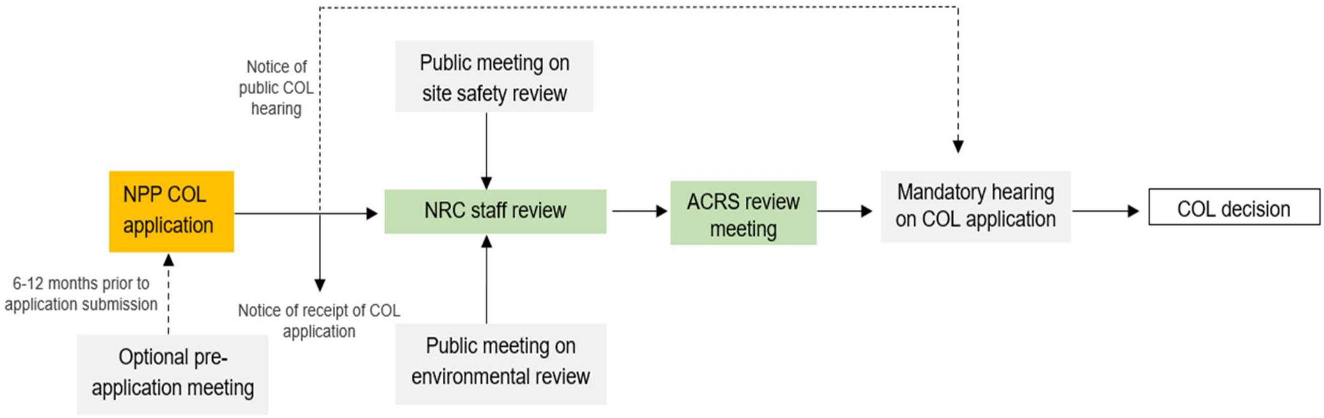
[101] The NRC has thus far issued standard deign certifications for seven Generation III+ reactor designs (NRC 2021a).

[102] Fermi 3, Levy units 1 & 2, North Anna 3, South Texas Project units 3 & 4, Turkey Point units 6 & 7, Virgil Summer Units 2 & 3, Vogtle units 3 & 4 and William States Lee units 1 & 2 . All the approved reactors were Generation III+ large light water reactor designs.

[103] Levy Country units 1 & 2 (terminated April 2018), South Texas Project units 3 & 4 (terminated July 2018) and V.C. Summer units 3 & 4 (terminated March 2019) (NRC 2021a).

[104] Reactor applications under review: St. Lucie units 1 and 2, Oconee units 1, 2 and 3, Peach Bottom units 1 and 2, and North Anna units 1 and 2.

**Figure 7-6: COL licensing process**




*Light grey boxes represent opportunities for public involvement in the licensing process.*

Source: Own depiction based on (NRC 2009).

### 7.2.4 Oversight

The NRC is primarily responsible for oversight responsibilities. Within the NRC structures, the Office of Nuclear Reactor Regulation (NRR), Office of New Reactors (NRO) and the Office of Nuclear Material Safety and Safeguards (NMSS) are the three major statutory program offices (OECD/NEA 2016b). The NRR oversees all licensing, oversight, rule-making and incident response for commercial nuclear reactors and research and test reactors. The NRO is responsible for regulating new commercial nuclear plants. Finally, the NMSS maintains regulatory oversight of activities associated with nuclear fuel for commercial reactors, transportation of radioactive materials and high-level nuclear waste. The NMSS is also responsible for decommissioning of nuclear reactors and material sites.

### 7.2.5 Liability

Extensive financial regulations are in place that cover financial assurances for decommissioning nuclear reactors (10 CFR 50.33(k), 10 CFR 50.75, 10 CFR 50.82). Before commencing operation, nuclear power plant owners are required to provide financial assurances (i.e., trust fund, government fund, sinking fund) to ensure that sufficient resources are available to ultimately decommission the facility.[105] There has been considerable speculation about the adequacy of the funds, who would be required to finance any potential shortfalls in funds, and how well funds are insulated from, for example, bankruptcy proceedings. In their research article, Lordan-Perret, Sloan, and Rosner (2021) outline four plausible scenarios in which funds might be inadequate and determine who would bear financial responsibility: decommissioning cost overrun, a radiological accident, bankruptcy, decommissioning funds investment downturn.

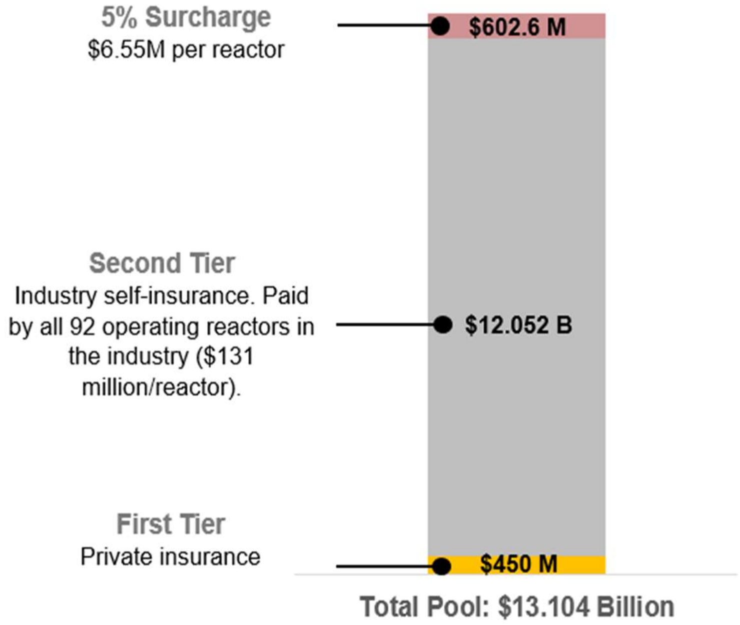
[105] Refer to Section 4.1 and 4.2 for a detailed description of the decommissioning financial regulation.

In the case of inadequate funds and company bankruptcy, the authors discuss two potential routes for a host state to reclaim outstanding decommissioning funds from a licensee. First, assuming an investor-owned corporate structure, the host state could file a lawsuit against the parent company of the licensee (i.e., piercing the corporate veil). However, chance of success is slim since the basic principle of corporate liability ensures that parent companies are not held responsible for decommissioning liabilities of its subsidiary (Barrett et al. 2017). The second route to reclaim decommissioning funds is for a federal body (e.g., EPA) to activate the liability provisions of the Comprehensive Environmental Compensation Liability Act (CERCLA)[106]. Through the CERCLA, a designated body such as the EPA could reclaim outstanding decommissioning funds from all past and current owners of the reactor. Under certain conditions, however, accessing outstanding funds from previous owners may be challenging in certain cases such as a dissolved former owner or a public utility former owner (Lordan-Perret, Sloan, and Rosner 2021). In this case, financial resources from a taxpayer funded trust fund known as the Hazardous Substance Superfund Trust Fund (or Superfund), would be used to pay for decommissioning and site cleanup costs.

In the event of a nuclear accident (e.g., Fukushima), even during decommissioning, the Price-Anderson Act (PAA) passed in 1957, would provide the legal basis to cover liability claims made against nuclear power plant owners for personal injury and property damage (Lordan-Perret, Sloan, and Rosner 2021). The Act sets a cap on the total liability each nuclear plant owner is required to pay in the event of a nuclear accident (Barrett et al. 2017). Nuclear plant owners currently pay an annual insurance premium for off-site liability coverage (see Figure 7-7). As of 2019, the average annual premium for a NPP site is $1.3 million. If nuclear accident liabilities exceed the first-tier amount ($450 million), a proportional share of the excess, up to $131 million per reactor is allocated to each nuclear plant owner. This leads to a secondary insurance pool with approximately $12 billion in total. Any payout that exceeds 15% of the second tier requires a prioritization plan that is ratified by the federal district court. If the liability is approved to exceed the first and second insurance tiers, each nuclear plant owner is again assigned a proportional share of the increment not exceeding 5% of the maximum deferred premium ($131 million), equating to approximately $6.55 million per reactor (NRC 2019b). Finally, as a backstop, Congress will determine if additional disaster relief fund is needed once the second tier is depleted. The Price-Anderson Act therefore provides substantial insurance coverage for nuclear incidents that is funded entirely by commercial nuclear plants. If nuclear related incident costs exceed the insurance pool, the NRC commits to indemnify the licensee from "public liability...which is in excess of the level of financial protection required of the licensee" (42 U.S. Code § 2210(c)).

[106] CERCLA was passed into law in 1980 and grants powers to the federal government to clean up contaminated sites and hold parties financially responsible for liabilities associated with cleaning up contaminated sites (Bearden 2012).

**Figure 7-7: Nuclear insurance under the Price-Anderson Act**




Source: Own depiction based on NRC (2019b).

## 7.3 Decommissioning Regulation

### 7.3.1 Decommissioning policy

The NRC recognizes three decommissioning strategies- Decontamination (DECON), Safe Storage (SAFSTOR) and Entombment (ENTOMB). Briefly;

**DECON:** Immediately following the permanent shutdown of the nuclear facility, radioactive structures, equipment and materials are either removed or decontaminated to a level that allows the facility to be released from regulatory controls and its license terminated (NRC 2022a).

**SAFSTOR:** Decommissioning is put on hold for a period allowing radioactivity to decay (NRC 2022a). However, the reactor is defueled and radioactive liquids are drained from the systems. Following the ‘holding period’, which may take up to 50 years, the plant is decontaminated and dismantled (NRC 2022a). This approach is also known as “Deferred Dismantling”.

**ENTOMB:** Under entomb, radioactive plant structures, systems and components are entombed in situ in concrete (NRC 2022a). The facility is monitored until radioactivity decays to safe levels which permits the termination of the license. So far, in the U.S., only three reactors have been entombed: Hallam Nuclear Power Facility (HNPF), Piqua Nuclear Power Facility and Boiling Nuclear Superheating Power Station (BONUS). All three reactors were commissioned under the Atomic Energy Commission (AEC) Power Demonstration Reactor Program (PDRP)[107] and entombed within a year between 1969 and 1970 (Vernon, Birk, and Hanson 2000). The ENTOMB option is deployed for

[107] The demonstration program commenced in 1955 soon after the passage of the Atomic Energy Act of 1954 with the goal of spurring private investment into the construction and operation of experimental reactors (Allen 1977).

exceptional situations, such as a critical nuclear accident (e.g., Chernobyl), which would require the facility to be sealed in-situ (OECD/NEA 2016a; Borys 2017).

For nuclear licensees, the optimal choice of decommissioning strategy depends on various factors such as the site-specific cost of each decommissioning strategy (DECOM/SAFSTOR), availability of an interim spent fuel storage facility, radiation exposure, and public concerns (Gallagher 2019). The licensee can adopt a combination of the first two options. For instance, adopting DECON for certain portions of the plant whilst leaving the remaining portions in SAFSTOR (NRC 2022a). NRC regulations stipulate that decommissioning must be completed within a 60-year timeframe following shutdown (10 CFR 50.82(a)(3)). Decommissioning activities that extend beyond the 60-year timeframe are considered under certain conditions to protect public health and safety (NRC 2022a).

### 7.3.2 Regulatory and legal process

The procedures governing nuclear plant decommissioning are outlined in several federal regulations[108]. The NRC has also compiled decommissioning guidance documents[109] to assist both licensees in complying with decommissioning regulations and NRC staff in reviewing submitted documents.

The decommissioning regulatory process in the United States is segregated into three distinct stages; transition activities, major decommissioning activities, and license termination activities (Simeone 2016; NRC 2022a). Once a licensee decides to permanently shut down a NPP, a written notice must be submitted to the NRC within 30 days. The licensee is required to submit another written notice after the reactor has been defueled. Within two years following shutdown, the licensee submits a Post Shutdown Decommissioning Activities Report (PSDAR). The PSDAR details the scheduled decommissioning activities, time schedules, site-specific decommissioning cost estimate (DCE) and estimation of spent fuel management costs. The licensee can start major decommissioning activities 90 days after the submission of the PSDAR without specific approval from the NRC. Major decommissioning activities include dismantlement of major components such as the reactor vessel, steam generators, large piping systems, pumps, and valves (NRC 2022a).

Two years prior to the license termination date, the licensee applies for license termination and includes a License Termination Plan (LTP). The LTP incorporates details such as site characterization, remaining dismantling activities, site remediation plans, site end use, updated site-specific cost estimate, and a supplement to the environmental report. Upon receipt of the LTP, the NRC makes it publicly available and schedules a public meeting near the facility. The LTP is subject to approval by the NRC based on the review plan for license termination (i.e., NUREG-1700) (NRC 2018b). Once decommissioning activities have been completed, the licensee submits a Final Status Survey Report (FSSR) that provides information on the radiological conditions of the site and requests that the NRC

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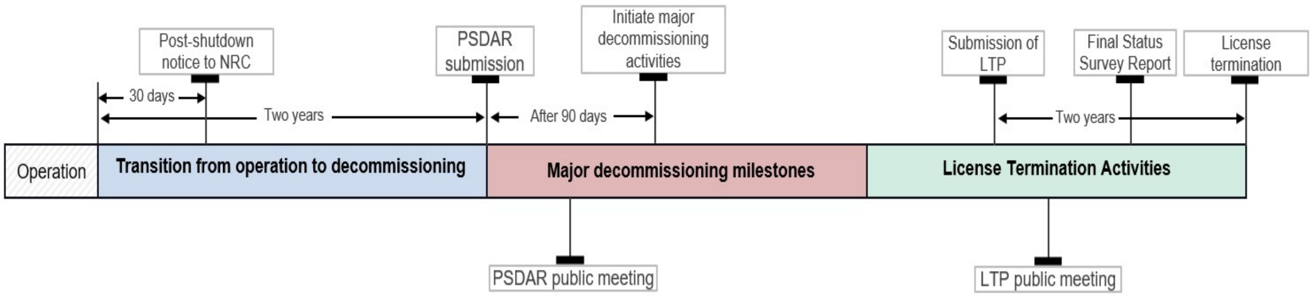
[108] 10 CFR Parts 20(E), 40.42, 50, 51, 70.38, 72.54 and 73 (NRC 2022b).

[109] Consolidated Decommissioning Guidance (NUREG-1757) and the Standard Review Plan for Evaluating Nuclear Power Reactor License Termination Plan (NUREG-1757).

either terminates the 10 CFR Part 50 license or reduces the geographical boundaries of the license to the Independent Spent Fuel Storage Installation (ISFSI) site (Simeone 2016). The NRC terminates the operating license if the licensee shows that the remaining dismantling activities complied with the approved LTP and the final radiation survey (10 CFR 50.82). Licensees that store spent fuel on site maintain a general license limited only to the ISFSI under the 10 CFR 50.72(K) regulation. [110] Figure 7-8 illustrates the decommissioning regulatory process in the U.S.

**Figure 7-8: U.S: decommissioning regulatory process**




Source: own depiction based on (NRC 2019a).

### 7.3.3 Oversight

The NRC is primarily responsible for decommissioning regulatory oversight of all commercial nuclear power reactors, materials and fuel cycle facilities, research reactors, and uranium mining facilities. When a plant begins the transition from operating to decommissioning, regulatory oversight responsibilities are transferred from the office of NRR to the office of NMSS. The transition of responsibilities begins when a nuclear plant licensee announces plans to cease operations and submits the required notices (shutdown & defueling) to the NRC (Baker 2019).

For plants undergoing decommissioning, the NRC has established a decommissioning power reactor inspection program. Following a permanent shutdown of operations, one resident inspector will provide initial short-term oversight. The decommissioning inspection program commences once the reactor is defueled and extends until license termination. NRC inspectors may be present at the facility two or three times a month and during significant decommissioning activities. For plants in SAFSTOR, the intensity of inspections reduces to several times a year (NRC 2003; 2017).

[110] Refer to Section 4.1 and 6 for additional insights into nuclear waste management.

## 7.4 Financial Regulation

### 7.4.1 The funding of decommissioning

The NRC mandates all licensees to preserve decommissioning funds using a variety of financial mechanisms such as prepayment, external sinking fund, statement of intent, surety method or a combination of methods as outlined in 10 CFR 50.75(e). The main reason for the funds, collectively referred to as Decommissioning Trust Funds (DTF), is to provide reasonable assurances that sufficient funds are available for decommissioning activities once a reactor shuts down (OIG 2021). Funding assurances are based on a minimum decommissioning amount calculated using precise equations (Table 1). The equations specifically estimate costs for radiological decommissioning[111] that would be sufficient to terminate the reactor's operating license (see Section 7.4.2). Alternatively, licensees can provide funding assurances based on a Site-Specific Cost Estimate (SSCE), as long as the estimate is not less than the value obtained from the minimum fund formula (NRC 1999).

Traditional rate-regulated utilities accumulate decommissioning funds by charging customers a fee (0.1 to 0.2 cents/kWh) which is then deposited into the DTF. About 70% of rate-regulated or indirectly regulated licensees are authorized to accumulate decommissioning funds over the lifetime of the plant (NRC 2022a). The remaining licensees must provide financial assurances via alternative approaches such as prepaid decommissioning funds, surety method or parent company guarantee (Simeone 2016; Moriarty 2020). Licensees are required to submit DTF status reports biennially to the NRC, and annually once the plant approaches within five years of expected shutdown (10 CFR 50.75(f)(2)). NRC staff review the DTF reports to ensure decommissioning funds meets the minimum decommissioning funding requirements. If funding shortfalls are identified in the biennial DTF reports for operating reactors, the NRC considers it to be a 'temporary lapse' that can be corrected by providing evidence of a parent company guarantee, trust fund growth, or trust fund contributions (Lubinski 2021). The licensee should ensure that the shortfall is rectified by the subsequent biennial fund status report. Likewise, if a shortfall is identified in the funds for reactors undergoing decommissioning, the licensee is mandated to provide additional financial guarantee to cover the estimated costs of decommissioning (10 CFR 50.82(a)(8)(vi)). If a reactor shuts down prematurely, the NRC will determine the schedule for collection of outstanding funds on a case-by-case basis.

Strict regulations govern how licensees should spend the accumulated DTF amount. Funds should only be used for the purpose of decommissioning the facility (10 CFR 50.82(a)(8)). Licensees are required to submit written request to the NRC for DTF withdrawals that are not for decommissioning. During the planning stages of decommissioning, licensees are permitted to use 3% of the DTF amount. An additional 20% of the funds become available 90 days after the NRC receives

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[111] According to the NRC regulations, *"Decommission* means to remove a facility or site safely from service and reduce residual radioactivity to a level that permits (1) release of the property for unrestricted use and termination of the license; or (2) release of the property under restricted conditions and termination of the license" (10 CFR 50.2).

the PSDAR. The remainder (77%) can be withdrawn once the licensee submits the site-specific decommissioning cost estimate, which is typically provided in the PSDAR (10 CFR 50.82(a)(8)(ii)).

***Funding of nuclear waste storage***

Turning to nuclear waste funding, the Nuclear Waste Policy Act of 1982 established the Nuclear Waste Fund (NWF) to finance the management and disposal of spent nuclear fuel at a permanent geological repository. Presently, the U.S. does not have a permanent geological repository for nuclear waste. Yucca Mountain was selected by Congress as the ideal location for a geological repository in 1987, but the program was disbanded by the DOE in 2009 (Rusco 2013). Initially, nuclear plant operators deposited a one-tenth of a cent per-kWh fee (known at the "millage fee") into the fund amounting to $750 million annually. As of 2019, the waste fund has accumulated a total of $43.5 billion (DOE 2019). However, following the disbandment of the protracted Yucca Mountain program by the DOE, the U.S. Court of Appeals ordered the federal government to suspend the collection of fees in 2013 (Hurley 2013). Hence, nuclear licensees are storing nuclear waste on-site in cooling pools and then in dry cask storage systems. In order to recuperate the costs of this long-term storage, nuclear plant owners are suing the federal government for breaching its contractual obligations to accept the fuel for final disposal (for further details and analysis on the situation, see Rosner and Lordan 2014). As of 2020, the federal government has spent approximately $9 billion compensating nuclear power plant owners for the costs of storing fuel on site[112] (GAO 2021). The DOE estimated that the federal government's outstanding spent fuel litigation liability stands at $30.9 billion (DOE 2021a). The funds in the NWF are restricted and accessed through Congressional appropriation process, and since legal settlements are not subject to appropriations, settling lawsuits are a way "around" the appropriations process. In December 2020, Congress signed into law the Consolidated Act of 2021 that included $7.5 million appropriation[113] for NWF oversight activities and $20 million appropriation to the DOE to pursue a consolidated interim storage facility program (DOE 2021b).

### 7.4.2 Cost assessments

Decommissioning cost assessments for nuclear plants in the U.S. are derived from the minimum decommissioning fund formula (Table 1). Some nuclear power plant operators have also opted to have a Site-specific Cost Estimate (SSCE) done; however, these estimates incorporate costs for managing spent fuel and site restoration, which is excluded from the decommissioning costs defined in the federal regulations. Although, both estimates often appear at utility hearings on decommissioning costs, SSCE's are the preferred approach for cost estimations and there are incentives for conducting such SSCE in the financial assurance regulations (10 CFR 50.75(b)(1)).

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[112] About 86,000 metric tons of commercial spent nuclear fuel is stored at 75 sites across the U.S. The U.S. has also accumulated 14,000 metric tons of high-level waste and spent nuclear fuel from the defense sector (GAO 2021).
[113] The $7.5 million appropriation is drawn out of the NWF balance.

***Minimum decommissioning cost estimate***

The minimum standard cost estimates, are produced with a financial model developed for reference PWR and BWR reactors in the late 1970s (Smith 1991; Short et al. 2011). These models are for radiological decommissioning and therefore should not be used to estimate the costs of returning a site to "greenfield" status. Power plant licensees are required to adjust the baseline decommissioning costs (Table 7-1) to current year dollars based on the escalation factors that consider three important and regionally variable cost components:

(1) Labor, materials and services.

(2) Energy and waste transportation.

(3) Radioactive waste burial.

The decommissioning fund formula only considers decommissioning costs that are consistent with the definition of decommissioning in the NRC regulations. Costs that fall outside the definition such as on-site spent fuel management costs and costs associated with the dismantlement of non-radiological structures and components are considered 'non-NRC decommissioning costs' and hence not factored into the decommissioning fund formulas (NRC 1999). The NRC minimum decommissioning cost estimate ranges between \$393 million to \$1 billion with an average of \$522 million per reactor (Holian 2018).

**Table 7-1: Minimum decommissioning fund formula**

| Reactor type | Thermal Capacity (TC) | Cost (millions USD 2020) |
|---|---|---|
| **Pressurized Water Reactor (PWR)** | $\geq$ 3400 $MW_t$ | \$247.9 million |
| | 1200 $MW_t \leq$ TC < 3400 $MW_t$<br>TC = 1200 $MW_t$ if TC < 1200 $MW_t$ | \$(177.1+0.02*TC*) million |
| **Boiling Water Reactor (BWR)** | $\geq$ 3400 $MW_t$ | \$318.8 million |
| | 1200 $MW_t \leq$ TC < 3400 $MW_t$<br>TC = 1200 $MW_t$ if TC < 1200 $MW_t$ | \$( 245.6 +0.02*TC*) million |
| **Adjustment equation** | 0.65L+0.13E+0.22B<br>Where L, E and B refer to escalation factors for labor, energy and low-level waste (LLW) burial. | |

Notes: $MW_t$ = Megawatt thermal
Source: 10 CFR 50.75(C).

## Site specific cost estimate (SSCE)

SSCE are detailed cost estimates developed by licensees in fulfillment of two key regulatory requirements[114]. Typically, SSCE are either developed by the licensee themselves or outsourced to a decommissioning planning company. Most licensees opt to outsource the development of

[114] (1) A preliminary decommissioning cost estimate is required as the nuclear plant approaches within five years of shutdown (10 CFR Part 50.75(F)(3)). (2) The licensee is required to submit a site-specific decommissioning cost estimate prior to or within two years following plant shutdown (10 CFR Part 50.82(a)(4)(i)).

decommissioning cost assessments to a specialized company (Short et al. 2011). Two companies are engaged in this field. TLG Services, Inc is arguably the largest and most experienced provider of decommissioning cost estimates. The Entergy-owned company has developed decommissioning cost estimates for approximately 85-90% of U.S. commercial nuclear reactors (Goff 2000). Energy*Solutions*, a decommissioning specialist company, developed a smaller fraction of decommissioning cost estimates. SSCE elements are classified into three cost categories;

(1) **License Termination/Radiological decommissioning:** Comprised of activities required to dismantle and dispose of all contaminated structures. These costs are sufficient to terminate the plant's 10 CFR Part 50 license.

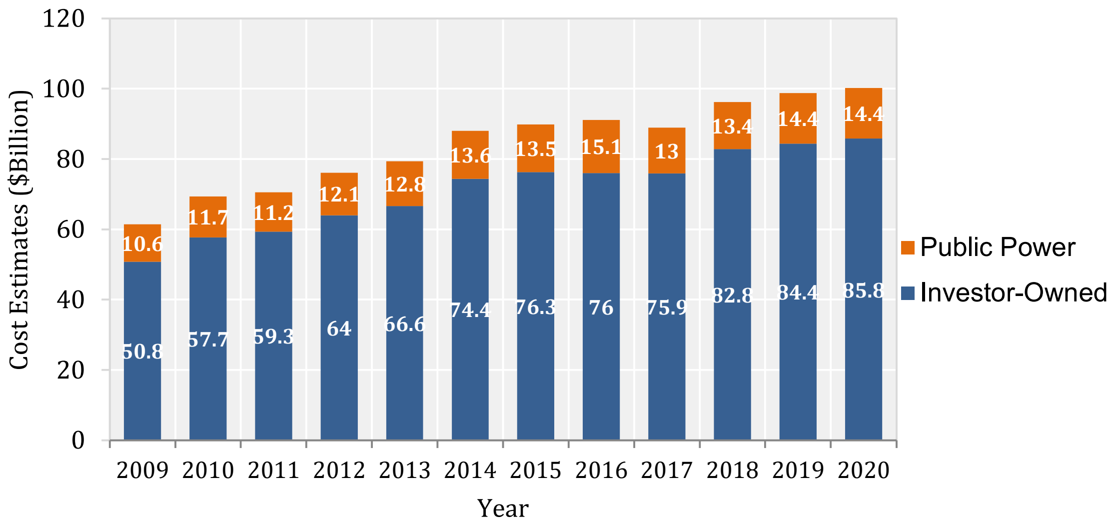
(2) **Spent fuel management:** Comprised of costs associated with the transfer of spent fuel from the spent fuel pool to an ISFSI and from the ISFSI to a DOE permanent geological repository. Costs associated with the temporary management of the ISFSI until eventual handover to the DOE are also factored into the management costs.

(3) **Site restoration:** Constitutes costs that are associated with the dismantling and demolition of structures and buildings not exposed to radiological contamination.

Table 7-2 provides a breakdown of the SSCE costs elements developed by TLG Services.

Figure 7-9 illustrates historical SSCE for investor-owned and publicly owned NPPs in the U.S. Over the past decade, decommissioning cost estimates have risen by approximately 60% from $61.5 billion in 2009 to approximately $100 billion in 2020 (Moriarty 2021). Investor-owned estimates have accounted for an average of 84% of total decommissioning estimates over the past decade. The rise in decommissioning cost estimates over time can be attributed to Low-Level Waste (LLW) and spent fuel management costs (Short et al. 2011; Laraia 2012).

**Figure 7-9: Nuclear reactor decommissioning cost estimates**




Source: own depiction based on data from (Moriarty 2021).

**Table 7-2: TLG Services site specific decommissioning cost estimate breakdown**

| Core activity | Cost element | Cost category |
|---|---|---|
| **(1) License Termination /Radiological Decommissioning** 10 CFR 50.75 | Decontamination<br>Removal<br>Packaging<br>Transportation<br>Waste Disposal<br>Waste processing<br>Spent fuel pool isolation<br>Miscellaneous equipment | **Direct Costs** |
| | Program management<br>Spent fuel management (non 10 CFR 50.54(bb) activities)<br>Site operations and management | **Management Costs** |
| | Insurance and regulatory<br>Energy<br>Characterization and licensing<br>Property taxes | **Other costs** |
| **(2) Spent Fuel Management** 10 CFR 50.54(bb) | Spent fuel storage and management<br>Insurance and regulatory<br>Property tax<br>Program management | |
| **(3) Site Restoration** | Decontamination<br>Program management<br>Insurance and regulatory<br>Site remediation/restoration | |

Source: (Short et al. 2011).

### 7.4.3 Cost experience and accuracy of assessments

A total of 17 nuclear reactors[115] have completed decommissioning in the U.S. The final decommissioning costs, however, vary across the plants, and the estimated costs for these plants have generally underestimated the actual decommissioning costs to various degrees. Table 3 compares the minimum decommissioning cost estimate to actual decommissioning costs for five decommissioned reactors. Four of the five reactors experienced decommissioning cost overruns to various degrees, signifying that the NRC minimum decommissioning cost formula is underestimating true decommissioning costs (Short et al. 2011).

Decommissioning costs for the Trojan reactor remained closely aligned to estimated decommissioning costs. This is because decommissioning completed without any major radiological remediation issues which allowed the licensee, Portland General Electric (PGE) to keep decommissioning costs low (Short et al. 2011). Another reason for the low decommissioning costs was the decision to remove the reactor vessel and internal components in one-piece. Total estimated waste volumes from the one-price removal were within the Class C waste category, which permitted PGE to classify the vessel as a low-level waste and dispose it in a low-level waste facility. The one-piece removal option was estimated to cost $23.8 million in 1996 dollars ($39.3 million in 2020 dollars), approximately $15 million less than the segmented approach (Wallis 2000). In contrast, decommissioning costs of the Haddam Neck reactor far exceeded estimated costs. Several factors contributed to the cost overruns including, reverting from a decommissioning contractor to self-management[116], costs of constructing an ISFSI and the complexity of segmenting the reactor vessel internals (Short et al. 2011). The Humboldt Bay reactor took 12 years to decommission and experienced significant cost overruns, primarily due to complicated remediation works and unplanned removal of the entire reactor caisson[117] (CPUC 2014). Note that the estimates in Table 7-3 are based on costs estimates for radiological decommissioning as defined in the NRC regulations. Other researchers incorporate estimates from the SSCE and therefore arrive at different decommissioning cost overruns (Lordan-Perret et al. 2022).

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[115] Out of the 17 decommissioned reactors, 14 were commercial reactors, two reactors were experimental reactors (CVTR, Pathfinder) and Saxton was a research and training facility. Refer to Table 7-8 in the appenidx for additional details on decommissioned reactors.

[116] Initially, Connecticut Yankee Atomic Power Company (CYAPCO) planned to oversee the decommissioning of Haddam Neck following shutdown in 1996. In 1999, CYAPCO contracted Bechtel Power Corporation to oversee the decommissioning operations on a fixed price contract (Short et al. 2011). Four years later, in 2003, CYAPCO decided to terminate the contract and oversee the remaining decommissioning activities.

[117] The Humboldt Bay reactor was encased in concrete and buried 80 feet underground. The owner PG&E initially planned to leave the reactor in place, but the discovery of contamination on the reactor bioshield wall forced PG&E to remove the caisson structure costing $191.6 million in 2012 dollars ($216 million in 2020 dollars) (CPUC 2014).

**Table 7-3: Comparison of decommissioning cost estimates for selected NPPs (million USD, 2020)**

| Plant | Reactor type [Net capacity MW] | Operational years | Decommissioning duration (years) | Minimum decommissioning cost estimate | Actual decommissioning cost | Cost difference % |
|---|---|---|---|---|---|---|
| Haddam Neck | PWR [560] | 1967-1996 | 1997-2007 (10) | 491.38 | 1,090.17 | 121.86% |
| Maine Yankee | PWR [860] | 1972-1997 | 1997-2005 (8) | 532.92 | 618.61 | 16% |
| Rancho Seco | PWR [873] | 1974-1989 | 1997-2009 (12) | 533.6 | 608.17 | 14% |
| Trojan | PWR [1,095] | 1975-1992 | 1993-2005 (12) | 349.4 | 334.76 | -5% |
| Humboldt Bay | BWR [63] | 1963-1976 | 2009-2021 (12) | 470.13 | 797.32 | 70% |

Notes: Decommissioning duration recorded from the year actual decommissioning works started. Values for minimum decommissioning cost and actual decommissioning cost represents only radiological decommissioning and does not include spent fuel management cost. All values were adjusted to 2020 dollars.
Source: (Short et al. 2011; PG&E 2019).

Several studies have reviewed the NRC's minimum decommissioning funding formula and recommended that the formula needs to be revised, yet it remains unchanged. An audit conducted by the U.S. Office of the Inspector General (OIG) in 2016 recommended that the minimum decommissioning cost estimate be reevaluated given that the formula was based on outdated values and most licensees rely on site-specific cost estimates (OIG 2016). The report further claimed that the current unchanged formula may not provide a realistic estimate of decommissioning costs. Another audit report found that site-specific decommissioning costs were typically higher than the NRC formula and recommended an update of the formula taking into account the relationship between formula based and site-specific estimates (OIG 2006).

### 7.4.4 Current balance in individual decommissioning funds

The latest review of the Decommissioning Fund Status (DFS) reports published by the NRC in December 2021 covers a total of 95 operating reactors[118] and 24 reactors undergoing decommissioning. The total Decommissioning Trust Fund (DTF) balance accumulated for operating nuclear reactors stands at $71.1 billion, an increase of approximately $14.6 billion from the 2019 DFS review (Lubinski 2021). All operating reactors met the minimum decommissioning funding requirements and no shortfalls were identified. For plants undergoing decommissioning, total accumulated decommissioning funds from 22 reactors stands at $12.3 billion (Lubinski 2021) and is documented in Table 7-4. Likewise, all

[118] Three reactors have retired since then.

reactors undergoing decommissioning met the decommissioning financial requirements by either having sufficient funds or providing additional financial provisions (Lubinski 2021).

**Table 7-4: Decommissioning fund balance for reactors undergoing decommissioning (million USD, 2020)**

| Plant Name | Operational duration | Estimated year of completion of decommissioning | DTF Balance (as of 2020) | Estimated remaining cost to complete decommissioning |
|---|---|---|---|---|
| Crystal River-3 | 1977-2013 | 2026 | 635.90 | 450.17 |
| Dresden-1 | 1960-1978 | 2036 | 421.08 | 458.96 |
| Duarne Arnold | 1974-2020 | 2036 | 632,82 | 705.44 |
| Fermi-1 | 1966-1972 | 2032 | 38.00 | 24.00 |
| Fort Calhoun | 1973-2016 | 2026 | 542.09 | 590.96 |
| Humboldt Bay-3 | 1963-1976 | 2021 | 170.10 | 4.00 |
| Indian Point-1 | 1962-1974 | 2026 | 631.25 | 606.15 |
| Kewaunee | 1974-2013 | 2073 | 780.40 | 561.30 |
| LaCrosse | 1968-1987 | 2022 | 60,000 | 60,000 |
| Millstone-1 | 1970-1998 | 2056 | 697.50 | 370.70 |
| Oyster Creek | 1969-2018 | 2025 | 713.00 | 615.00 |
| Peach Bottom-1 | 1967-1974 | 2034 | 148.82 | 276.85 |
| Pilgrim | 1972-2019 | 2025 | 881.00 | 824.00 |
| San Onofre-1 | 1967-1992 | 2028 | 468.50 | 184.30 |
| San Onofre -2 | 1982-2013 | 2028 | 1,596.10 | 1,402.60 |
| San Onofre-3 | 1983-2013 | 2028 | 1,894.10 | 1,641.20 |
| Three Mile Island-1 | 1974-2019 | 2079 | 742.50 | 955.10 |
| Three Mile Island-2 | 1978-1979 | 2037 | 862.55 | 1,044.36 |
| GE Vallecitos | 1957-1963 | 2025 | 15.58 | 15.58 |
| Vermont Yankee | 1972-2014 | 2030 | 388.03 | 348.32 |
| Zion-1 | 1973-1998 | 2022 | | |
| Zion-2 | 1973-1998 | 2022 | 3.20 (both units) | 3.00 (both units) |
| **Total** | | | **$12,262.57** | **$11,082.06** |

Note: Zion 1 and 2 units completed decommissioning in 2020 and are awaiting final release from regulatory controls. Nuclear Savannah Ship and General Electric ESADA Vallecitos Experimental Superheat Reactor (GE EVESR) are omitted from the list.

Source: (Lubinski 2021).

## 7.5 Production

### 7.5.1 Overview

On a global scale, the U.S. has the largest operating reactor fleet (92), closed reactors (41) and the most decommissioning experience with 17 reactors fully decommissioned (9 PWR, 6 BWR, 1 HTGR & 1 PHWR). Out of the 17 decommissioned reactors, two were experimental reactors (CVTR, Pathfinder) and one was a research and training facility (Saxton). The remaining 14 were commercial reactors. Active decommissioning is currently ongoing at 11 reactors and 13 reactors are in long-term enclosure (i.e. SAFSTOR). Table 7-5 provides an overview of the current decommissioning status of nuclear plants in the U.S. Refer Table 7-7 and Table 7-8 in the appendix of this chapter for information on reactors undergoing decommissioning and decommissioned reactors, respectively. The following section provides an overview on the current progress in decommissioning and companies engaged in decommissioning. In accordance with other country reports, US-american reactors were classified into commercial and non-commercial reactors following Figure 1-7 in the appendix of Chapter 1.

### 7.5.2 Progress

As of 2022, the most recent reactors to complete decommissioning are the Zion 1 and 2 reactors. Official decommissioning works began in September 2010, approximately 13 and 14 years after official shutdown respectively. In 2015, all spent nuclear fuel were transferred from the spent fuel pool to 61 dry cask storage containers on site. The decommissioning operator, Zion*Solutions* opted to segment the reactor vessel internals underwater and subsequently section the reactor vessel (Hylko 2014). The reactor vessel components were then shipped to the Clive disposal facility in Utah. Physical cleanup works were completed in 2020, eight years behind the original plan. In August 2021, the NRC issued an order approving a one-year extension to transfer the operating license of both units back to Exelon Generation, the original license holder, thereby delaying the full release of the reactors from regulatory control (Nuclear Engineering 2021).

The completion of the Zion reactors closely follows the decommissioning of Humboldt Bay, a one-reactor unit 63 MW BWR plant located in Eureka, California. The plant officially shut down in 1976 after 13 years of service and was subsequently placed in SAFSTOR by its owner Pacific Gas and Electric Company (PG&E). Decommissioning activities commenced in June 2009 and concluded 12 years later in in July 2021. In November 2021, the NRC terminated the operating license of Humboldt Bay and released the site for unrestricted use (NRC 2021d). The ISFSI site was licensed separately and therefore remains active until the spent fuel is removed and the site decommissioned. Total cost for radiological decommissioning is estimated to be $797 million (PG&E 2019).

Decommissioning experience varies significantly across the decommissioned reactors in terms of both time horizons and cost. The plant with the shortest decommissioning period so far was a relatively small reactor, Shippingport (60 MW), which took 4 years to decommission at an estimated cost[119] of $28.7 million in 1990 dollars ($56.83 million in 2020 dollars) (GAO 1990). In contrast, the LaCrosse reactor was placed in SAFSTOR for an extended duration following shutdown in 1987 and completed decommissioning in 2019. Total cost for radiological decommissioning was estimated to be $83.3 million in 2020 dollars (LaCrosseSolutions 2021). These dramatic differences—and those anticipated in the future—could result from any host of sources, for example: technology difference; plant operations and record keeping; project management; essential equipment and resource bottlenecks.

In May 2022, Entergy permanently closed Palisades, a single reactor unit located in Michigan. The operator decided to bring forward the closure date due to deterioration of a control rod drive seal. Shortly following the closure of the plant, in June 2022, Entergy finalized the transaction[120] to transfer both the operating and general ISFSI license of Palisades unit to Holtec Decommissioning International (HDI) for the purpose of decommissioning the facility (Holtec International 2022). Holtec proposed an expedited 20-year timeframe to complete the decommissioning project once the reactor fuel has been transferred from the spent fuel pool to ISFSI. The closure of the Palisades reactor closely follows the retirement of Entergy owned Indian Point 3 reactor in April 2021. In May 2021, Entergy finalized the sale of all three shutdown Indian Point units to Holtec for decommissioning. The sale agreement includes the transfer of operating licenses, spent fuel, liabilities and the DTF's (Entergy 2019; 2021). Over the past years, Entergy has gradually sold off or retired its merchant nuclear plant fleet as part of a strategy to withdraw from the merchant nuclear generation sector. The closure of Palisades and Indian Point completes Entergy's complete exit from the commercial nuclear market. Entergy now fully owns and operates four reactors (Arkansas 1 & 2, River Bend 1 and Waterford 3) and is a majority owner of the Grand Gulf 1 reactor. These remaining reactors are all rate regulated.

**Table 7-5: Current status of decommissioning in the United States as of June 2022**

| United States | June 2022 |
|---|---|
| **Warm-up-stage** | 7 |
| *of which defueled* | *7* |
| **Hot-zone-stage** | 3 |
| **Ease-off-stage** | 1 |
| **LTE** | 13 |
| **Completed** | 17 |
| *of which released from regulatory control* | *6* |
| **Total Closed Reactors** | **41** |

Notes: LTE: Long term enclosure

Source: (Schneider et al. 2022)

[119] Only for radiological decommissioning.

[120] The NRC ratified the agreement in December 2021. The agreement also includes the transfer of the decommissioned Big Rock Point's ISFSI to Holtec (NRC 2021b).

### 7.5.3 Actors involved in the decommissioning process

In the U.S., nuclear licensees are increasingly gravitating towards an asset sale decommissioning model, whereby the licensee engages with a specialized decommissioning company to take over the facility and complete the decommissioning of the plant. Currently, there are three variations on outsourcing decommissioning: License Stewardship, License Acquisition, and Fleet Models.[121]

License Stewardship involves a license transfer from the licensee holder to the decommissioning firm. Under this arrangement, the decommissioning firm undertakes all the responsibility for decommissioning such that the original licensee can be released from its 10 CFR part 50 license—at least that the license would be reduced to an ISFSI. The firm also gains full access to the DTF and assumes all liability for cost overruns. Once the decommissioning work is completed, the decommissioning firm returns the remaining assets to the original licensee. The decommissioning firm never takes possession of the fuel or the site.

License Acquisition enables the decommissioning firm to take ownership of all the plant assets (e.g., DTF and land) and liabilities—including the spent nuclear fuel. Thus, the original licensee effectively discharges its decommissioning liability in total, though some legal instruments may, in some aberrant circumstances, still require the original licensee to bear some responsibility in case of unfunded decommissioning liability (Lordan-Perret, Sloan, and Rosner 2021).

Finally, Fleet Models[122] are a financial arrangement whereby a financial company manages the DTFs of a fleet of plants. The idea is that through prudent investments and economies of scale, such a company stands to gain a lot from pooling the risk of shortfalls and cost savings over multiple plants. In such a model, this financial company would also be liable for unfunded decommissioning liabilities.

In theory, by outsourcing with one of these models, licensees can be rid of a large liability and decommissioning can be accomplished much faster and more cost-effectively that if it were undertaken by the owner itself. A brief overview of a few major decommissioning specialist companies and their current decommissioning activities is provided below.

**Energy*Solutions*** is arguably one of the largest specialized nuclear services company operating both domestically and internationally. The Utah-based firm provides a wide range of services spanning the entire decommissioning spectrum, from transition activities to major decommissioning activities and license termination services. Energy*Solutions* leverages its extensive physical assets and facilities for waste transfer, processing and disposal. The company owns the Clive disposal facility in Utah and operates the Barnwell disposal facility in South Carolina. The company follows the license stewardship decommissioning model. Energy*Solutions* has provided support for decommissioning projects at Fort St Vrain, Trojan, Haddam Neck, Maine Yankee and Yankee Rowe (Schneider et al. 2020). The company through its subsidiary LaCrosse*Solutions* has recently decommissioned the 50 MW LaCrosse reactor

[121] It is important to note that individual contracts will vary.
[122] The NRC has not approved this model yet.

located in Genoa, Wisconsin. Energy*Solutions* undertook the decommissioning project in May 2016 under a license stewardship structure from Dairlyland Power Cooperative (DPC) and announced the completion of physical dismantling works in November 2019. In addition, the company also completed decommissioning works at Zion 1 and 2 reactors as elaborated above. In March 2022, the NRC approved the transfer of the 566 MW single reactor Kewaunee nuclear plant's license from its current owner Dominion Energy to Energy*Solutions* for decommissioning (NRC 2022c). The license transfer also includes the ISFSI site. The company is currently overseeing decommissioning projects at the Three Mile Island (TMI) unit 2 reactor and the Fort Calhoun nuclear plant in Nebraska. The company is also providing technical support for the ongoing decommissioning of Fort Calhoun reactor as a decommissioning contractor (WNN 2019).

Another company actively engaged in the decommissioning scene is **Holtec International** and its wholly owned subsidiary company **Holtec Decommissioning International (HDI)**. Holtec is a versatile energy technology company that manufactures and sells wet and dry storage technologies to nuclear plants domestically as well as globally. On the decommissioning front, Comprehensive Decommissioning International (CDI), a joint venture between Holtec and SNC-Lavelin is the general decommissioning contractor for Holtec. The company has not completed any decommissioning projects to date, but it is involved in four ongoing decommissioning projects at several NPPs such as Oyster Creek, Pilgrim, Indian Point and recently Palisades. For its decommissioning portfolio, Holtec is relying on a fleet model[123], whereby standardized processes and procedures are adopted at both the corporate level and decommissioning sites (Reuters 2019). In March 2017, Holtec and Eddy-Lea Energy Alliance (ELEA) submitted a license application to the NRC for an autonomous consolidated interim storage facility (CISF) in Southeast New Mexico. The facility known as HI-STORE CIS will accommodate 500 Holtec manufactured underground dry cask storage casks and operate for a 40-year duration (Holtec International 2017). The license application remains under review and a final decision is expected in January 2023.

A relatively new entrant into the decommissioning domain is the New York based **NorthStar Group Services (NorthStar)**. To date, the company's nuclear decommissioning experience is only limited to research reactors. In February 2017, the company submitted a joint license transfer application with Entergy to the NRC for expedited decommissioning of the Vermont Yankee Nuclear Power Station. The transfer included the nuclear DTF and spent fuel storage installation and was approved by the NRC in October 2018 (NRC 2019c). As part of the agreement, decommissioning activities should be completed by 2030. The company has also acquired the Crystal River-3 plant as a licensed decommissioning operator through its joint venture subsidiary (Accelerated Decommissioning Partners) in April 2020. The reactor is currently in the warm-up stage and Accelerated Decommissioning aims to

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[123] This approach merely describes Holtec's organizational approach to decommission the fleet and differs from the outsourcing fleet model described earlier. Holtec is closely aligned with the license acquisition decommissioning strategy.

complete decommissioning by 2027, 50 years earlier than the original decommissioning plan (WNN 2020).

In total, out of the 24 reactors currently undergoing decommissioning, 10 units were transferred to specialized decommissioning companies (see Table 7-7).

## 7.6 Country specific nuclear and decommissioning developments

As more nuclear plants are expected to shut down over the coming years, the focus inevitably turns towards the management of nuclear waste and spent nuclear fuel. Presently, spent nuclear fuel is stored on site at ISFSI facilities since the US has no permanent geological repository for nuclear waste. In 2019, the House and Senate put forward the Nuclear Waste Policy Amendments Act of 2019 (H.R. 2699) which directs the DOE to commence a consolidated interim nuclear waste storage program alongside the development of a permanent repository (Larson 2020). However, plans to revive the Yucca mountain permanent geological repository has stalled and is unlikely to continue given recent developments. In particular, the Biden administration has signaled its opposition to the Yucca mountain plan and is instead pursuing the idea a consent-based citing of a federal CISF (Fettus and McKinzie 2021; DOE 2022a). In September 2022, the DOE launched a $16 million fund to spur community interest in nuclear waste management and consent-based siting of a federal CISF. Furthermore, in the same month, the State of Nevada formally requested the NRC to lift the Yucca Mountain license review suspension[124] with the aim of permanently blocking the project (Sanchez 2022).

In parallel to developments at the federal level, two private companies have submitted license applications to develop commercial CISF's. In 2016, Interim Storage Partners (ISP) LLC[125] submitted a license application for a CISF at Andrews County in Texas. The facility will be built in stages and initially store up to 5,000 metric tons of spent fuel and 231.3 metric tons of Greater than Class C (GTCC) low-level radioactive waste (NRC 2021c). In September 2021, the NRC approved ISP's application and granted a 40-years license to the proposed facility. The company expects to begin receiving the first batch of spent nuclear waste by July 2023 (ISP 2020). As elaborated earlier, as recently as 2017, Holtec International also applied for a license for a CISF in Lea County in New Mexico. The application remains under review (NRC 2018a).

124 The NRC suspended the Yucca mountain license review process in September 2011, roughly three years after initiating it in October 2008.
125 Interim Storage Partners, LLC is a joint venture between Waste Control Specialists (WCS) and Orano CIS, LLC. Orano CIS is the majority owner of Interim Storage Partners (51%) and is wholly owned by Orano USA LLC.

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**Appendix**

**Table 7-6: Commercial operating reactors in the U.S. as of July 2022**

| Reactor Name | Type | Capacity (MWe) | Grid Connection | Age (2022) | License expiry |
|---|---|---|---|---|---|
| Arkansas Nuclear One-1 | PWR | 836 | 1974 | 48 | 2034 |
| Arkansas Nuclear One- 2 | PWR | 988 | 1978 | 44 | 2038 |
| Beaver Valley-1 | PWR | 908 | 1976 | 46 | 2036 |
| Beaver Valley-2 | PWR | 905 | 1987 | 35 | 2047 |
| Braidwood-1 | PWR | 1194 | 1987 | 35 | 2046 |
| Braidwood-2 | PWR | 1160 | 1988 | 34 | 2047 |
| Browns Ferry-1 | BWR | 1200 | 1973 | 49 | 2033 |
| Browns Ferry-2 | BWR | 1200 | 1974 | 48 | 2034 |
| Browns Ferry-3 | BWR | 1210 | 1976 | 46 | 2036 |
| Brunswick-1 | BWR | 938 | 1976 | 46 | 2036 |
| Brunswick-2 | BWR | 932 | 1975 | 47 | 2034 |
| Byron-1 | PWR | 1164 | 1985 | 37 | 2044 |
| Byron-2 | PWR | 1136 | 1987 | 35 | 2046 |
| Callaway-1 | PWR | 1215 | 1984 | 38 | 2044 |
| Calvert Cliffs-1 | PWR | 877 | 1975 | 47 | 2034 |
| Calvert Cliffs-2 | PWR | 855 | 1976 | 46 | 2036 |
| Catawba-1 | PWR | 1160 | 1985 | 37 | 2043 |
| Catawba-2 | PWR | 1150 | 1986 | 36 | 2043 |
| Clinton-1 | BWR | 1062 | 1987 | 35 | 2026 |
| Columbia | BWR | 1131 | 1984 | 38 | 2043 |
| Commanche-Peak-1 | PWR | 1205 | 1990 | 32 | 2030 |
| Commanche-Peak-2 | PWR | 1195 | 1993 | 29 | 2033 |
| Cook-1 | PWR | 1030 | 1975 | 47 | 2034 |
| Cook-2 | PWR | 1168 | 1978 | 44 | 2037 |
| Cooper | BWR | 769 | 1974 | 48 | 2034 |
| Davis-Besse-1 | PWR | 894 | 1977 | 45 | 2037 |
| Diablo Canyon-1 | PWR | 1138 | 1984 | 38 | 2024 |
| Diablo Canyon-2 | PWR | 1118 | 1985 | 37 | 2025 |
| Dresden-2 | BWR | 894 | 1970 | 52 | 2029 |
| Dresden-3 | BWR | 879 | 1971 | 51 | 2031 |
| Farley-1 | PWR | 874 | 1977 | 45 | 2037 |
| Farley-2 | PWR | 883 | 1981 | 41 | 2041 |
| Fermi-2 | BWR | 1115 | 1986 | 36 | 2045 |
| Fitzpatrick | BWR | 813 | 1975 | 47 | 2034 |
| Ginna | PWR | 560 | 1969 | 53 | 2029 |
| Grand Gulf-1 | BWR | 1401 | 1984 | 38 | 2044 |
| Harris-1 | PWR | 964 | 1987 | 35 | 2046 |
| Hatch-1 | BWR | 876 | 1974 | 48 | 2034 |
| Hatch-2 | BWR | 883 | 1978 | 44 | 2038 |
| Hope Creek-1 | BWR | 1172 | 1986 | 36 | 2046 |
| Lasalle-1 | BWR | 1137 | 1982 | 40 | 2042 |
| Lasalle-2 | BWR | 1140 | 1984 | 38 | 2043 |
| Limerick-1 | BWR | 1134 | 1985 | 37 | 2044 |
| Limerick-2 | BWR | 1134 | 1989 | 33 | 2049 |

| Reactor Name | Type | Capacity (MWe) | Grid Connection | Age (2022) | License expiry |
|---|---|---|---|---|---|
| Mcguire-1 | PWR | 1158 | 1981 | 41 | 2041 |
| Mcguire-2 | PWR | 1158 | 1983 | 39 | 2043 |
| Millstone-2 | PWR | 869 | 1975 | 47 | 2035 |
| Millstone-3 | PWR | 1210 | 1986 | 36 | 2045 |
| Nine Mile Point-1 | BWR | 613 | 1969 | 53 | 2029 |
| Nine Mile Point-2 | BWR | 1277 | 1987 | 35 | 2046 |
| Monticello | BWR | 628 | 1971 | 51 | 2030 |
| North Anna-1 | PWR | 948 | 1978 | 44 | 2038 |
| North Anna-2 | PWR | 944 | 1980 | 42 | 2040 |
| Oconee-1 | PWR | 847 | 1973 | 49 | 2033 |
| Oconee-2 | PWR | 848 | 1973 | 49 | 2033 |
| Oconee-3 | PWR | 859 | 1974 | 48 | 2034 |
| Palo Verde-1 | PWR | 1311 | 1985 | 37 | 2045 |
| Palo Verde-2 | PWR | 1314 | 1986 | 36 | 2046 |
| Palo Verde-3 | PWR | 1312 | 1987 | 35 | 2047 |
| Peach Bottom-2 | BWR | 1300 | 1974 | 48 | 2053 |
| Peach Bottom-3 | BWR | 1331 | 1974 | 48 | 2054 |
| Perry-1 | BWR | 1240 | 1986 | 36 | 2026 |
| Point Beach-1 | PWR | 591 | 1970 | 52 | 2030 |
| Point Beach-2 | PWR | 591 | 1972 | 50 | 2033 |
| Prairie Island-1 | PWR | 522 | 1973 | 49 | 2033 |
| Prairie Island-2 | PWR | 519 | 1974 | 48 | 2034 |
| Quad Cities-1 | BWR | 908 | 1972 | 50 | 2032 |
| Quad Cities-2 | BWR | 911 | 1972 | 50 | 2032 |
| River Bend-1 | BWR | 967 | 1985 | 37 | 2045 |
| Robinson-2 | PWR | 741 | 1970 | 52 | 2030 |
| Salem-1 | PWR | 1169 | 1976 | 46 | 2036 |
| Salem-2 | PWR | 1158 | 1981 | 41 | 2040 |
| Seabrook-1 | PWR | 1246 | 1990 | 32 | 2050 |
| Sequoyah-1 | PWR | 1152 | 1980 | 42 | 2040 |
| Sequoyah-2 | PWR | 1139 | 1981 | 41 | 2041 |
| South-Texas-1 | PWR | 1280 | 1988 | 34 | 2047 |
| South-Texas-2 | PWR | 1280 | 1989 | 33 | 2048 |
| St. Lucie-1 | PWR | 981 | 1976 | 46 | 2036 |
| St. Lucie-2 | PWR | 987 | 1983 | 39 | 2043 |
| Summer-1 | PWR | 973 | 1982 | 40 | 2042 |
| Surrey-1 | PWR | 838 | 1972 | 50 | 2052 |
| Surrey-2 | PWR | 838 | 1973 | 49 | 2053 |
| Susquehanna-1 | BWR | 1257 | 1982 | 40 | 2042 |
| Susquehanna-2 | BWR | 1257 | 1984 | 38 | 2044 |
| Turkey Point-3 | PWR | 837 | 1972 | 50 | 2052 |
| Turkey Point-4 | PWR | 821 | 1973 | 49 | 2053 |
| Vogtle-1 | PWR | 1150 | 1987 | 35 | 2047 |
| Vogtle-2 | PWR | 1152 | 1989 | 33 | 2049 |
| Waterford-3 | PWR | 1168 | 1985 | 37 | 2044 |
| Watts Bar-1 | PWR | 1157 | 1996 | 26 | 2035 |
| Watts Bar-2 | PWR | 1164 | 2016 | 6 | 2055 |
| Wolf Creek | PWR | 1200 | 1985 | 37 | 2045 |
| | | **Total**: 94,718 (94.72 GW) | | **Average**: 41.6 | |

Source: (NRC 2021a; IAEA 2022).

**Table 7-7: Reactors undergoing decommissioning as of June 2022**

Notes: HDI: Holtec Decommissioning International; NEDA, NextEra Energy Duarne Arnold, LLC

| Reactor | Net Capacity in MW | Reactor Type | Grid Connection Year | Shutdown year | Operating Years | Defueled | Decommissioning licensee |
|---|---|---|---|---|---|---|---|
| | | | ***Warm-up stage*** | | | | |
| Crystal River-3 | 860 | PWR | 1977 | 2009 | 32 | yes | Northstar/Orano |
| San Onofre-2 | 1,070 | PWR | 1982 | 2012 | 30 | yes | Southern California Edison Co. |
| San Onofre-3 | 1,080 | PWR | 1983 | 2012 | 29 | yes | Southern California Edison Co. |
| Kewaunee | 566 | PWR | 1974 | 2013 | 39 | yes | Energy*Solutions* |
| Vermont Yankee | 605 | BWR | 1972 | 2014 | 42 | yes | NorthStar/Orano |
| Indian Point-2 | 998 | PWR | 1973 | 2020 | 47 | yes | Holtec (HDI) |
| Indian Point-3 | 1030 | PWR | 1976 | 2021 | 45 | yes | Holtec (HDI) |
| | | | ***Hot zone stage*** | | | | |
| Fort Calhoun-1 | 482 | PWR | 1973 | 2016 | 43 | yes | Omaha Public Power District |
| Oyster Creek | 619 | BWR | 1969 | 2018 | 49 | yes | Holtec (HDI) |
| Pilgrim-1 | 677 | BWR | 1972 | 2019 | 47 | yes | Holtec (HDI) |
| | | | ***Ease-off stage*** | | | | |
| San Onofre-1 | 436 | PWR | 1967 | 1992 | 25 | yes | Southern California Edison Co. |
| | | | ***Long Term Enclosure*** | | | | |
| GE Vallecitos | 24 | BWR | 1957 | 1963 | 6 | yes | GE-Hitachi Nuclear Energy Americas, LLC |
| Hallam | 75 | Other | 1963 | 1964 | 1 | yes | Department of Energy (DOE) |
| Piqua | 12 | Other | 1963 | 1966 | 3 | yes | DOE |
| Bonus | 17 | BWR | 1964 | 1968 | 4 | yes | Puerto Rico Water Resources Authority |
| Fermi-1 | 61 | FBR | 1966 | 1972 | 6 | yes | DTE Electric Company |
| Indian Point-1 | 257 | PWR | 1962 | 1974 | 12 | yes | Holtec (HDI) |
| Peach Bottom-1 | 40 | HTGR | 1967 | 1974 | 7 | yes | Exelon |
| Dresden-1 | 197 | BWR | 1960 | 1978 | 18 | yes | Constellation Energy Generation, LLC |
| Three Mile Island-2 | 880 | PWR | 1978 | 1979 | 1 | yes | TMI-2 *Solutions* (Energy*Solutions*) |
| Millstone-1 | 641 | BWR | 1970 | 1995 | 25 | yes | Dominion Energy Nuclear Connecticut, Inc |
| Three Mile Island-1 | 819 | PWR | 1974 | 2019 | 45 | yes | Constellation Energy Generation, LLC |
| Daurne Arnold | 601 | BWR | 1974 | 2020 | 46 | yes | NEDA |
| Palisades | 805 | PWR | 1971 | 2022 | 51 | yes | Holtec (HDI) |

Source: (NRC 2021a; Schneider et al. 2022)

**Table 7-8: Decommissioned nuclear reactors as of July 2022**

| Reactor | Net Capacity in MW | Reactor type | Operational duration | Decommissioning duration (years) | License Status |
|---|---|---|---|---|---|
| CVTR | 17 | PHWR | 1963-1967 | 1967-2009 (42) | Terminated |
| Pathfinder | 59 | BWR | 1966-1967 | 1968-1993 (25) | Terminated |
| Elk River | 22 | BWR | 1963-1968 | 1971-1974 (3) | Terminated |
| Saxton | 3 | PWR | 1967-1972 | 1996-2005 (9) | Terminated |
| Shippingport | 60 | PWR | 1957-1982 | 1985-1989 (4) | Terminated* |
| Shoreham | 820 | BWR | 1986-1989 | 1992-1994 (2) | Terminated |
| Fort St. Vrain | 330 | HTGR | 1976-1989 | 1989-1997 (8) | ISFSI only |
| Rancho Seco-1 | 873 | PWR | 1974-1989 | 1997-2009 (12) | ISFSI only |
| Yankee NPS (Yankee Rowe) | 167 | PWR | 1960-1991 | 1993-2007 (14) | ISFSI only |
| Trojan | 1,095 | PWR | 1975-1992 | 1993-2005 (12) | ISFSI only |
| Maine Yankee | 860 | PWR | 1972-1997 | 1997-2005 (8) | ISFSI only |
| Haddam Neck | 560 | PWR | 1967-1996 | 1996-2007 (11) | ISFSI only |
| Big Rock Point | 67 | BWR | 1962-1997 | 1997-2006 (9) | ISFSI only |
| LaCrosse | 48 | BWR | 1968-1987 | 1994-2019 (25) | Pending |
| Humboldt Bay | 63 | BWR | 1963-1976 | 2009-2021 (12) | ISFSI only |
| Zion 1 | 1,040 | PWR | 1973-1998 | 2007-2020 (13) | Pending |
| Zion 2 | 1,040 | PWR | 1974-1998 | 2007-2020 (13) | Pending |
| | **Total:** 7,124 (7.12 GW) | | | | |

Notes: *DOE regulatory jurisdiction. Decommissioning duration recorded from the year actual decommissioning works started.
Source: (OECD/NEA 2016a; Wealer and Hirschhausen 2020; NRC 2021a).