University of Basel
Faculty of
Business and Economics

WWZ

January 2023

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

WWZ Working Paper 2023/04

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

A publication of the Center of Business and Economics (WWZ), University of Basel.

Universität Basel
Peter Merian-Weg 6
4052 Basel, Switzerland
wwz.unibas.ch

Corresponding Author:
Hannes Weigt
Tel.: +41 61 207 32 59
Mail: hannes.weigt@unibas.ch

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

January 2023

Rebekka Bärenbold[1], Muhammad Maladoh Bah[1], Rebecca Lordan-Perret[1], Björn Steigerwald[2], Christian von Hirschhausen[2,3], Ben Wealer[2], Hannes Weigt[1], Alexander Wimmers[2]

[1] University of Basel, Faculty of Business and Economics

[2] TU Berlin, Fachgebiet für Wirtschafts- und Infrastrukturpolitik

[3]DIW Berlin

Abstract

In this survey paper, we bring together the insights from six country case studies on decommissioning commercial nuclear power plants (NPPs). Nuclear decommissioning has often been overlooked in past literature but will gain relevance in future research as more and more NPPs reach the ends of their respective lifetimes. 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. Based on the cross comparison of countries and their approaches to decommissioning, we highlight a series of gaps in the existing research that we and other researchers should fill in order to derive best practices for the commercial decommissioning industry.

Keywords: nuclear decommissioning, survey, research gaps

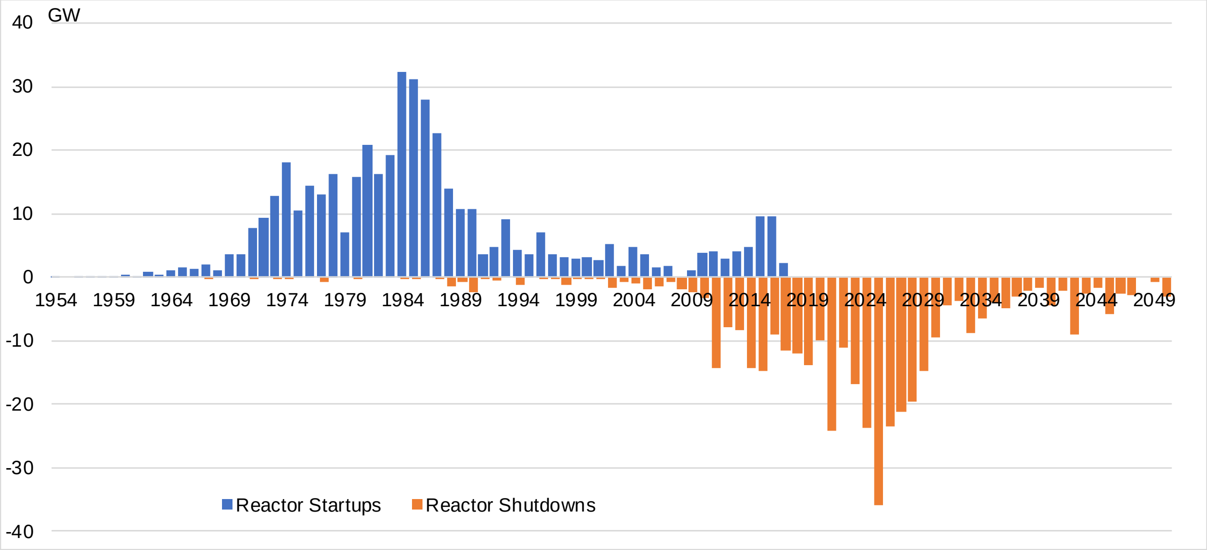
This survey is part of the joint research project of University Basel and TU Berlin *"Best Practices for Decommissioning of Nuclear Power Plants: How to ensure efficient plant decommissioning under different regulatory schemes"*. Details on the project and further reports are provided on the project webpage.

The research project was jointly financially supported by the Swiss National Science Foundation (SNSF), grant number 100018L 185154 and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), project number 423336886.

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 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).

Figure 1: Distribution of global nuclear reactor startups and shutdowns



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

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

---

[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).

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).

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.

2 Background

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 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

---

[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.

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). 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: 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, 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 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 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).

---

[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).

In Table 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 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 SAFSTOR = Deferred Dismantling ENTOMB = *in situ* disposal	Majority of licensees using DECON; approx. 10 in SAFESTOR; ENTOMB not seen as option for commercial reactors

2.2 Current status and outlook of nuclear decommissioning

The international NPP decommissioning industry is still nascent. Worldwide, eleven commercial nuclear power reactors over 100MW 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). We display this trend in plant retirements in our case study countries; Table 3 shows the progress of 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).

---

[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.

[6] Refer to Appendix A for the classification of a commercial nuclear reactor.

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

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 3.1-3.5, 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.

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 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 Nuclear Power Industry Decommissioning Profile" (Wimmers, Von Hirschhausen, and Steigerwald 2023).

Table 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 3 shutdown 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 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 "Germany Nuclear Power Industry Decommissioning Profile" (Wimmers et al. 2023).

Table 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 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 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 the "Swedish Nuclear Power Industry Decommissioning Profile" (Baerenbold, Rebekka 2023a).

Table 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, 5 decommissioning
3 PWR	852-1130	40-45	2 operating 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 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 a complete overview, see the "Swiss Nuclear Power Industry Decommissioning Profile" (Baerenbold, Rebekka 2023b).

Table 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 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 the "UK Nuclear Power Industry Profile" (Wimmers, Steigerwald, and Von Hirschhausen 2023).

Table 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 2 under construction
41 GCR	24 – 620	18 – 47	31 shutdown 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 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 "United States Nuclear Power Industry Decommissioning Profile" (Bah 2023).

---

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

Table 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 7 decommissioning 5 decommissioned
81 PWR	60-1314	1-54	61 operating 12 decommissioning 8 decommissioned
2 HTGR	40-330	8-13	1 decommissioning 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

3.2 Organization

Each country allows different ownership structures. In Figure 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 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 6 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 9 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

---

[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.

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.

Ownership Changes

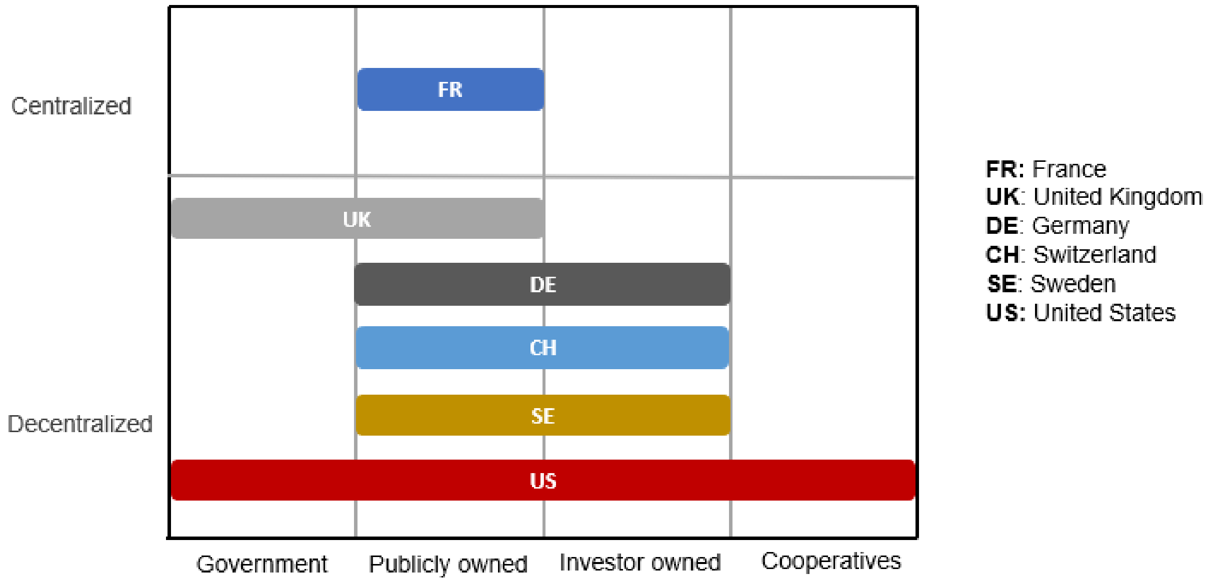
Ownership of nuclear plants in some countries is subject to change before or during the decommissioning process. In some countries, NPPs have changed ownership during operations. These ownership changes may affect decommissioning if the new owners decide to alter the existing decommissioning schedule (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 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 (Wimmers, Steigerwald, and Von Hirschhausen 2023).

---

[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 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.

3.3 Regulation

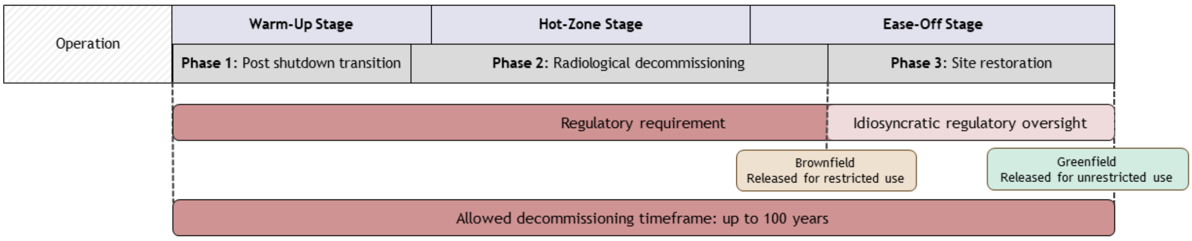
In every country, the nuclear industry is highly regulated. In some countries, the regulators are centralized in one agency overseeing the entirety of the industry from granting licenses to environmental protection to safety inspections (e.g., France with ASN or the U.S. with the NRC). However, in other 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 (see (Baerenbold, Rebekka 2023b) 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 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 2.1. 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 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 3: A generalized depiction of the lifetime of a nuclear power plant and some important regulatory junctures

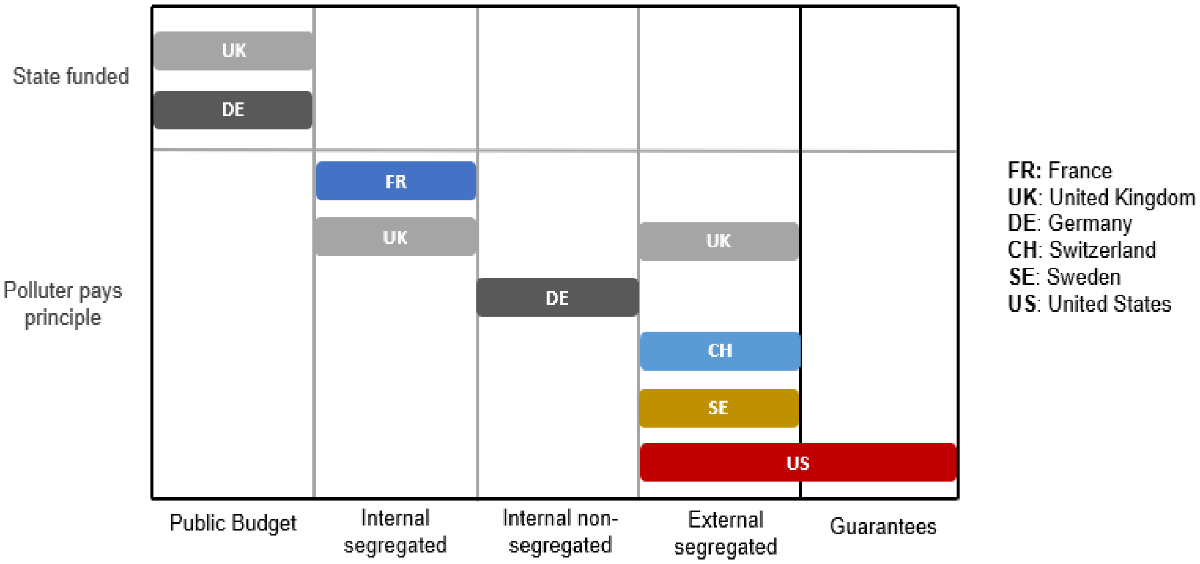


3.4 Financing

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 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.

Figure 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 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).

---

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

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"?

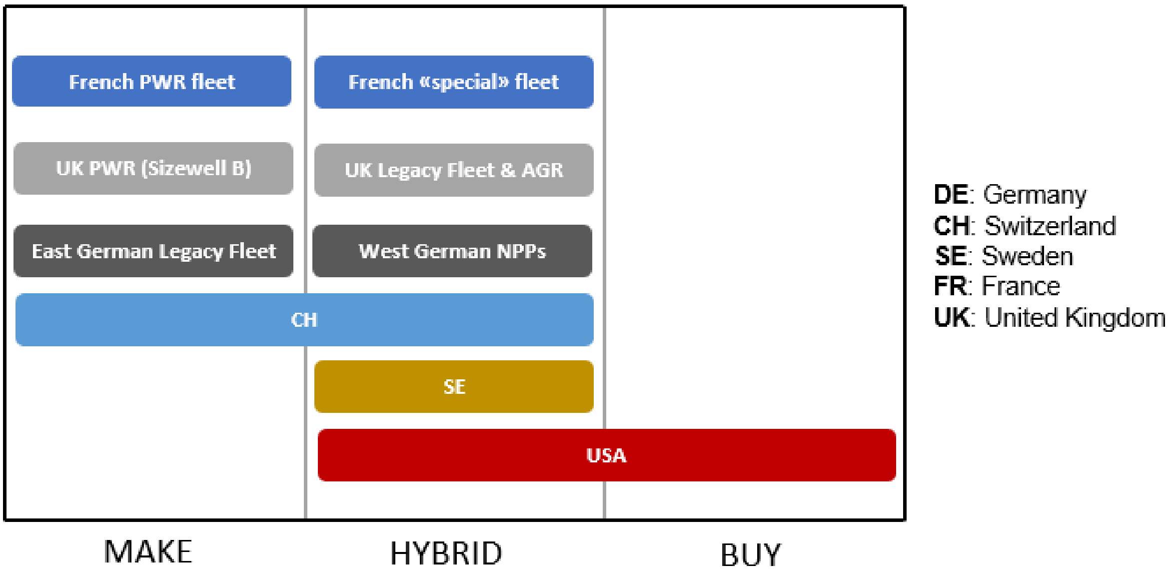
In the case of nuclear decommissioning, this question is particularly relevant for the most complex and risky tasks of decommissioning, which occur during the hot-zone phase. This phase is characterized by a high degree of asset specificity. Licensees/operators must ask themselves whether it will be 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 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 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.

3.6 Nuclear waste management

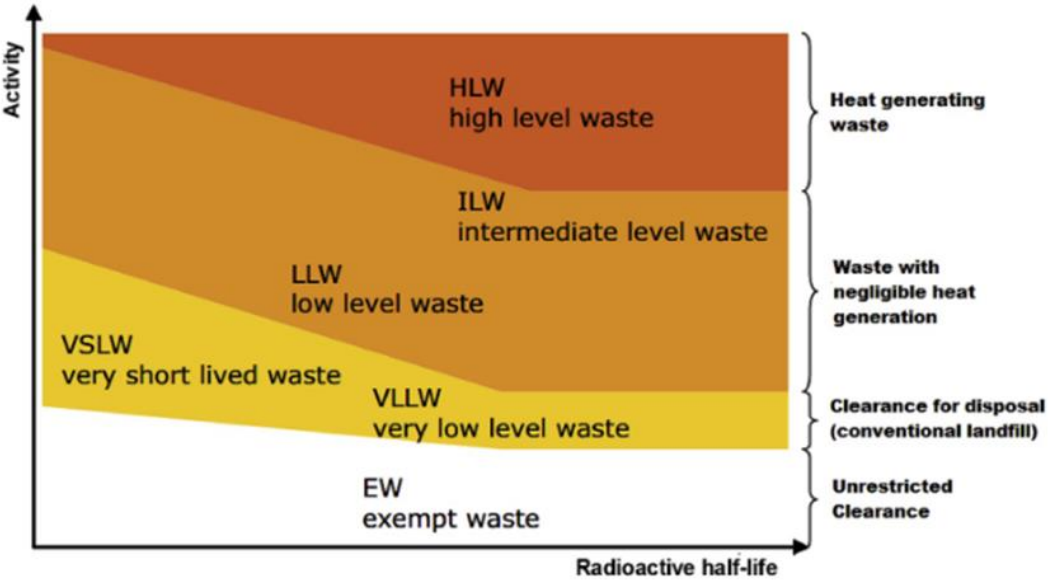
When a licensee decommissions its NPP, there are multiple radioactive waste streams. These waste streams vary in terms of their radioactivity, thus they must be disposed of with different regulatory controls and technologies. While the details of waste disposal worldwide are both interesting and important, 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 6) (IAEA 2009) and is typically the waste that people think of associated with nuclear power.

In Table 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.”

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



Source: Thierfeldt and Schartmann (2009)

Table 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.

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.

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).

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.

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).

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).

5 Conclusion

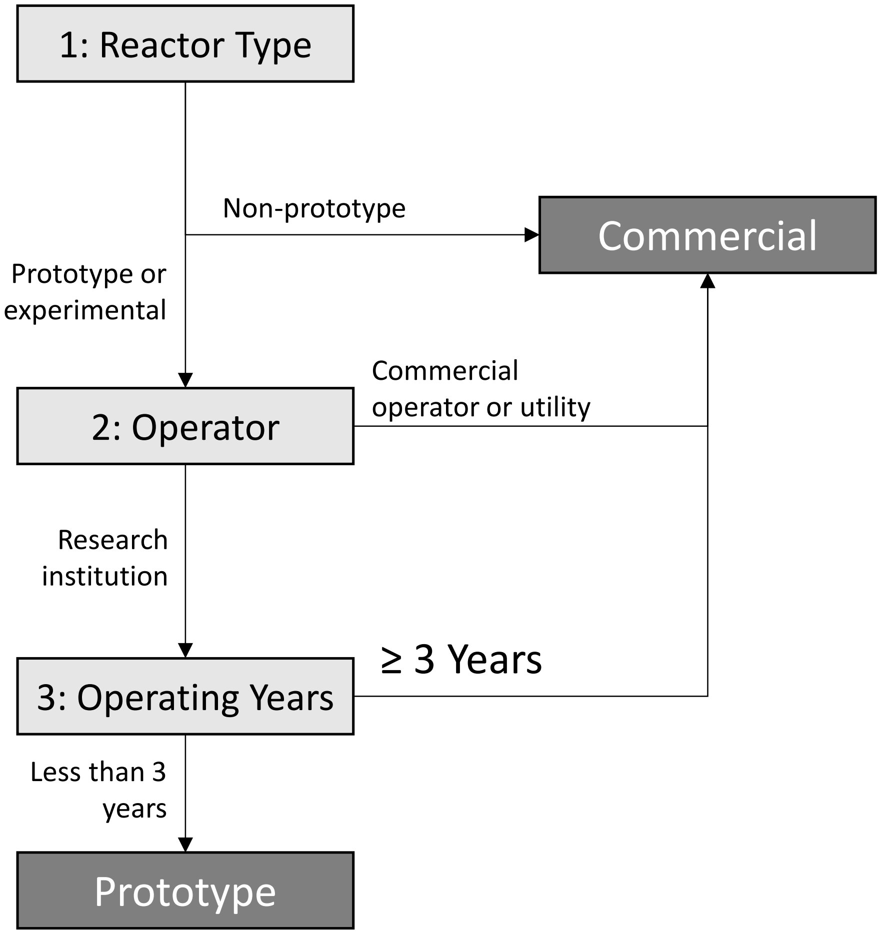
In this survey paper, we bring together the insights from six country case studies on decommissioning commercial NPPs. The six countries we selected for our research have commercial nuclear industries that span a wide spectrum in terms of organization, regulation, financial provisions, and production 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?

Appendix

Appendix A: Reactor classification

Figure 7: Commercial nuclear reactor classification



Appendix B: 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

References

Ahiaga-Dagbui, Dominic D., and Simon D. Smith. 2014. “Dealing with Construction Cost Overruns Using Data Mining.” *Construction Management and Economics* 32 (7–8): 682–94. https://doi.org/10.1080/01446193.2014.933854.

AlKaabi, Hamad. 2022. “Nuclear Newcomer Countries-The Path of the United Arab Emirates.” In *Nuclear Law: The Global Debate*, 299–318. The Hague, The Netherlands: ASSER PRESS.

ASN. 2021. “ASN Report on the State of Nuclear Safety and Radiation Protection in France in 2020.” Montrouge, France: Autorité de Sûreté Nucléaire. https://www.french-nuclear-safety.fr/asn-informs/publications/asn-s-annual-reports/asn-report-on-the-state-of-nuclear-safety-and-radiation-protection-in-france-in-2020.

Assemblée Nationale. 2017. “Rapport d’Information Déposé En Application de l’article 145 Du Règlement Par La Mission d’Information Relative à La Faisabilité Technique et Financière Du Démantèlement de Installations Nucléaires de Base.” Paris.

Axpo. 2020. “Lernen Sie Uns Besser Kennen.” 2020. https://www.axpo.com/ch/de/ueber-uns/portraet.html.

Baerenbold, Rebekka. 2023a. “Swedish Nuclear Power Industry Decommissioning Profile.” University of Basel. https://forschdb2.unibas.ch/inf2/rm_projects/object_view.php?r=4660186&type=4.

———. 2023b. “Swiss Nuclear Power Industry Decommissioning Profile.” University of Basel. https://forschdb2.unibas.ch/inf2/rm_projects/object_view.php?r=4660184&type=4.

Bah, Muhammad Maladoh. 2023. “The United States Nuclear Power Industry Decommissioning Profile.” University of Basel.

BEIS. 2021. “Departmental Review - Nuclear Decommissioning Agency.” London: Department for Business, Energy & Industrial Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/995177/nda-departmental-review-2021.pdf.

Besnard, Manon, Marcos Buser, Ian Fairlie, Gordon MacKerron, Allison Macfarlane, Eszter Matyas, Yves Marignac, Edvard Sequens, Johan Swahn, and Ben Wealer. 2019. “The World Nuclear Waste Report. Focus Europe.” Berlin, Brussels.

BFE. 2021. “76 Prozent Des Stroms Aus Schweizer Steckdosen Stammten 2020 Aus Erneuerbaren Energien.” 2021. https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-84908.html.

BKW. 2020. “Stilllegung Kernkraftwerk Mühleberg ‘Kompetenz.’”

Bloomberg. 2022. “Nuclear Decommissioning Services Market Size Worth $9.43 Billion, Globally, by 2027 at 6.3% CAGR.” 2022. https://www.bloomberg.com/press-releases/2022-01-24/nuclear-decommissioning-services-market-size-worth-9-43-billion-globally-by-2027-at-6-3-cagr-exclusive-report-by-the.

BMUV. 2015. “Nationales Entsorgungsprogramm.”

———. 2022. *Entwurf eines Neunzehnten Gesetzes zur Änderung des Atomgesetzes. AtGÄndG.* https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Glaeserne_Gesetze/20._Lp/19_atg_aendg/Entwurf/19_atg_aendg__refe_bf.pdf.

BMWI. 2016. “Act Reorganising Responsibility for Nuclear Waste Management – Facts and Additional Information.” Berlin: Bundesministerium für Wirtschaft. https://www.bmwk.de/Redaktion/EN/Downloads/gesetz-zur-neuordnung-der-verantwortung-der-kerntechnischen-entsorgung-fakten-und-ergaenzende-informationen.pdf?__blob=publicationFile&v=4.

BP. 2021. “Statistical Review of World Energy 2021.” 70. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

Deutscher Bundestag. 2021. “Bericht nach § 7 des Transparenzgesetzes - Rückbau von Kernkraftwerken.” Drucksache 20/42. Berlin: Deutscher Bundestag 20. Wahlperiode. https://dserver.bundestag.de/btd/20/000/2000042.pdf.

Dorfman, Paul. 2017. “How Much Will It Really Cost to Decommission the Aging French Nuclear Fleet?” *Nuclear Monitor*, no. 839: 4–5.

Downey, A., and D.M Timmons. 2005. “Study into the Applicability of Thermochemical Conversion Technology to Legacy Asbestos Wastes in the U.K.” In .

EDF. 2022. “Universal Registration Document 2021 - Including the Annual Financial Report.” Paris. https://www.edf.fr/sites/groupe/files/2022-03/edf-2021-universal-registration-document.pdf.

Electric Power Research Institute. 2008. “San Onofre Nuclear Generating Station – Unit 1 Decommissioning Experience Report.” 1016773. Palo Alto, CA: EPRI.

Endlagerkommission. 2016. “Abschlussberich der Kommission Lagerung hoch radioaktiver Abfallstoffe.” Abschlussbericht K-Drs. 268. Berlin: Kommission Lagerung hoch radioaktiver Abfallstoffe. https://www.bundestag.de/endlager-archiv/blob/434430/bb37b21b8e1e7e049ace5db6b2f949b2/drs_268-data.pdf.

EWN. 2021. “Kernkraftwerk Rheinsberg - Geschichte, Stilllegung und Rückbau.” Rheinsberg: Entsorgungswerk für Nuklearanlagen. https://www.ewn-gmbh.de/fileadmin/user_upload/EWN/Projekte/Rueckbau_des_KKW_Rheinsberg/Brosch%C3%BCre_R%C3%BCckbau_KKR_10_2021.pdf.

Flyvbjerg, Bent, Mette K. Skamris Holm, and Søren L. Buhl. 2004. “What Causes Cost Overrun in Transport Infrastructure Projects?” *Transport Reviews* 24 (1): 3–18. https://doi.org/10.1080/0144164032000080494a.

Foster, Richard I., June Kyung Park, Keunyoung Lee, and Bum-Kyoung Seo. 2021. “UK Civil Nuclear Decommissioning, a Blueprint for Korea’s Nuclear Decommissioning Future?: Part I - Nuclear Legacy, Strategies, and the NDA.” *Journal of Nuclear Fuel Cycle and Waste Technology(JNFCWT)* 19 (3): 387–419. https://doi.org/10.7733/jnfcwt.2021.19.3.387.

Furubotn, Eirik Grundtvig, and Rudolf Richter. 2005. *Institutions and Economic Theory: The Contribution of the New Institutional Economics*. 2nd ed. Economics, Cognition, and Society. Ann Arbor: University of Michigan Press.

Grubler, Arnulf. 2010. “The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing.” *Energy Policy* 38 (9): 5174–88. https://doi.org/10.1016/j.enpol.2010.05.003.

Gusterson, Hugh. 2017. “A Predictable Nuclear Accident at Hanford.” Bulletin of the Atomic Scientists. 2017. http://thebulletin.org/predictable-nuclear-accident-hanford10774.

Hägler, Fabian. 2022. “FDP Aargau Setzt Sich Für Neue Atomkraftwerke Ein: Parteitag Fordert Eine Aufhebung Des Geltenden Bauverbots.” *Aargauer Zeitung*, 2022. https://www.aargauerzeitung.ch/aargau/kanton-aargau/stromzukunft-fdp-aargau-setzt-sich-fuer-neue-atomkraftwerke-ein-parteitag-fordert-eine-aufhebung-des-neubauverbots-ld.2240124?reduced=true.

Harribin, R. 2017. “Offshore Wind Power Cheaper than New Nuclear.” BBC News. 2017. http://www.bbc.co.uk/news/business-41220948.

Hecht, Gabrielle. 2009. *The Radiance of France: Nuclear Power and National Identity after World War II*. Inside Technology. Cambridge, Mass: MIT Press.

Hippel, Frank N. von. 2021. “Biden Can Rescue the Nuclear Regulatory Commission from Industry Capture.” 2021. https://thebulletin.org/2021/01/biden-can-rescue-the-nuclear-regulatory-commission-from-industry-capture/.

Hirose, Rika, and Darren McCauley. 2022. “The Risks and Impacts of Nuclear Decommissioning: Stakeholder Reflections on the UK Nuclear Industry.” *Energy Policy* 164 (May): 112862. https://doi.org/10.1016/j.enpol.2022.112862.

HM Government. 2022. “British Energy Security Strategy.” London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067835/british-energy-security-strategy-web.pdf.

Holliday, Steve, HM Government, and Energy & Industrial Strategy Department for Business. 2021. *Report of the Holliday Inquiry: Inquiry into Award of the Magnox Decommissioning Contract by the Nuclear Decommissioning Authority, Related Litigation and Its Subsequent Termination*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/966572/The_Holliday_Inquiry.pdf.

House of Commons. 2020. “The Nuclear Decommissioning Authority’s Management of the Magnox Contract.” HC 653. London: House of Commons, Committee of Public Accounts. https://publications.parliament.uk/pa/cm5801/cmselect/cmpubacc/653/653.pdf.

———. 2022. “The Future of the Advanced Gas-Cooled Reactors - Third Report of Session 2022-23.” HC 118. London: House of Commons, Committee of Public Accounts. https://committees.parliament.uk/publications/22301/documents/164944/default/.

IAEA. 2005. “Selection of Decommissioning Strategies: Issues and Factors.”

———. 2007a. “Categorizing Operational Radioactive Wastes.” IAEA-TECDOC 1538. Vienna, Austria: International Atomic Energy Agency. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1538_web.pdf.

———. 2007b. “IAEA Safety Glossary - Terminology Used in Nuclear Safety and Radiation Protection.” Vienna, Austria: International Atomic Energy Agency. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf.

———. 2009. “Classification of Radioactive Waste.” GSG-1. Vienna: IAEA.

———. 2021. “Experiences of Member States in Building a Regulatory Framework for the Oversight of New Nuclear Plants: Country Case Studies.” IAEA-TECDOC-1948. Vienna, Austria: International Atomic Energy Agency. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1948web.pdf.

———. 2022. “Country Nuclear Power Profiles: Sweden.” 2022. https://cnpp.iaea.org/countryprofiles/Sweden/Sweden.htm.

Invernizzi, Diletta Colette, Akira Asahara, Giorgio Locatelli, and Satoshi Yanagihara. 2019. “Regulatory Challenges of Nuclear Decommissioning Projects and Programmes from the Viewpoint of Project Management.” In .

Invernizzi, Diletta Colette, Giorgio Locatelli, and Naomi J. Brookes. 2017. “Managing Social Challenges in the Nuclear Decommissioning Industry: A Responsible Approach towards Better Performance.” *International Journal of Project Management* 35 (7): 1350–64. https://doi.org/10.1016/j.ijproman.2016.12.002.

Irrek, Wolfgang. 2019. “Financing Nuclear Decommissioning.” In *The Technological and Economic Future of Nuclear Power*, edited by Reinhard Haas, Lutz Mez, and Amela Ajanovic, 139–68. Energiepolitik Und Klimaschutz. Energy Policy and Climate Protection. Wiesbaden: Springer VS. https://doi.org/10.1007/978-3-658-25987-7_12.

Irrek, Wolfgang, Lars Kirchner, and Lutz Jarczynski. 2007. “Comparison among Different Decommissioning Funds Methodologies for Nuclear Installations - Final Country Report (WP 1/ WP 3) Italy.” TREN/05/NUCL/S07.55436. Wuppertal: Wuppertal Institut for Climate, Environment and Energy.

Islam, Md. Shafiqul, Shafiqul Islam Faisal, and Sadia Khan. 2021. “Development and Strengthening of the Nuclear and Radiation Safety Infrastructure for Nuclear Power Program in Bangladesh.” *Nuclear Engineering and Technology* 53: 1705–16. https://doi.org/10.1016/j.net.2020.11.020.

Kärnavfallsfonden. 2020. “About the Nuclear Waste Fund.” 2020. http://www.karnavfallsfonden.se/informationinenglish/aboutthenuclearwastefund.4.697303b91648b46fd8d22a3.html.

Kernkraftwerk Gösgen. 2020. “Die Schweizer Kernkraftwerke.” 2020. https://www.kkg.ch/de/i/die-schweizer-kernkraftwerke-_content---1--1240.html.

Klein, Peter G. 2005. “The Make-or-Buy Decision: Lessons from Empirical Studies.” In *Handbook of New Institutional Economics*, edited by Claude Menard and Mary M. Shirley, 435–64. Berlin/Heidelberg: Springer-Verlag. https://doi.org/10.1007/0-387-25092-1_18.

Koomey, Jonathan, and Nathan E. Hultman. 2007. “A Reactor-Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005.” *Energy Policy* 35 (11): 5630–42. https://doi.org/10.1016/j.enpol.2007.06.005.

Laraia, Michele, ed. 2012. *Nuclear Decommissioning: Planning, Execution and International Experience*. Oxford, Cambridge, Philadelphia, New Dehli: Woodhead Publishing.

———. 2018. *Nuclear Decommissioning*. Vol. 66. Lecture Notes in Energy. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-75916-6.

Lazard. 2021. “Lazard’s Levelized Cost of Energy Analysis.” Analysis 15.0. Lazard’s Levelized Costs of Energy Analysis. New York: LAZARD. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Lordan-Perret, Rebecca, Robert D. Sloan, and Robert Rosner. 2021. “Decommissioning the U.S. Nuclear Fleet: Financial Assurance, Corporate Structures, and Bankruptcy.” *Energy Policy* 154 (July): 112280. https://doi.org/10.1016/j.enpol.2021.112280.

Lovins, Amory B. 2022. “US Nuclear Power: Status, Prospects, and Climate Implications.” *The Electricity Journal* 35. https://doi.org/10.1016/j.tej.2022.107122.

MacKerron, Gordon. 1989. “The Decommissioning of Nuclear Plant.” *Energy Policy*, Energy and Environment, 17 (2): 103–8. https://doi.org/10.1016/0301-4215(89)90088-8.

———. 2015. “Multiple Challenges.” In *Nuclear Waste Governance*, edited by Achim Brunnengräber, Maria Rosaria Di Nucci, Ana Maria Isidoro Losada, Lutz Mez, and Miranda A. Schreurs, 101–16. Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-08962-7_4.

Mallet, Benjamin, and Leigh Thomas. 2022. “France Starts Process to Fully Nationalise Power Group EDF.” 2022. https://www.reuters.com/business/energy/france-keeps-edf-buyout-offer-12-euros-per-share-filing-2022-10-04/.

McIntyre, P.J. 2012. “Nuclear Decommissioning - Planning, Execution and International Experience.” In *Nuclear Decommissioning - Planning, Execution and International Experience*, edited by Michele Laraia, 33–48. Oxford, Cambridge, Philadelphia, New Dehli: Woodhead Publishing.

Moriarty, Julia A. 2021. “2021 Nuclear Decommissioning Funding Study.” Callan Institute. https://www.callan.com/blog-archive/2021-nuclear-decommissioning-funding/.

Nagra. 2022a. “Nagra Schlägt ‘Nördlich Lägern’ Als Standort Vor.” 2022. https://nagra.ch/nagra-schlaegt-noerdlich-laegern-als-standort-vor-3/.

———. 2022b. “Unser Auftrag Und Wer Uns Finanziert.” 2022. https://nagra.ch/wissensforum/auftrag-finanzierung/.

NDA. 2021a. “Strategy - Effective from March 2021.” Cumbria: Nuclear Decommissioning Authority.

———. 2021b. “Annual Report and Accounts 2020/21.” SG/2021/145. Moor Row: Nuclear Decommissioning Authority. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1004159/NDA_Annual_Report_and_Accounts_2020_to_2021.pdf.

———. 2022. “Business Plan - 1 April 2022 to 31 March 2025.” SG/2022/39. Nuclear Decommissioning Authority. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062302/Business_Plan_2022-2025_220322.pdf.

NRC. 2017. “Backgrounder on Decommissioning Nuclear Power Plants.” United States Nuclear Regulatory Commission - Office of Public Affairs. https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html.

———. 2021. “Power Reactor Decommissioning Status.” 2021. https://www.nrc.gov/images/reading-rm/doc-collections/maps/power-reactors-decommissioning-sites.png.

———. 2022. “Backgrounder on Decommissioning Nuclear Power Plants.” United States Nuclear Regulatory Commission - Office of Public Affairs. https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html.

Nuclear Liabilities Fund. 2021. “Fulfilling Our Purpose.” Annual Report and Accounts. Edinburgh. https://www.nlf.uk.net/media/1088/2021-nlf-annual-report-and-accounts.pdf.

Nussbaum, Ania, and Francois De Beaupuy. 2022. “Macron Pledges New Nuclear Reactors - If He’s Re-Elected.” *Bloomberg*, October 2, 2022. https://www.bloomberg.com/news/articles/2022-02-10/macron-pledges-new-nuclear-reactors-if-he-s-re-elected.

OECD, and Nuclear Energy Agency. 2006. “Selecting Strategies for the Decommissioning of Nuclear Facilities.” 6038. Radioactive Waste Management. Paris.

OECD/NEA. 2006. “Decommissioning Funding: Ethics, Implementation, Uncertainties.”

———. 2016. “Costs of Decommissioning Nuclear Power Plants.” Paris: Nuclear Energy Agency / Organisation for Economic Co-operation and Development.

Ökmen, Önder, and Ahmet Öztaş. 2010. “Construction Cost Analysis under Uncertainty with Correlated Cost Risk Analysis Model.” *Construction Management and Economics* 28 (2): 203–12. https://doi.org/10.1080/01446190903468923.

OPC. 2021. “Form 10-K Annual Report.” Oglethorpe Power Corporation. https://opc.com/wp-content/uploads/2022/03/2021-Form-10-K.pdf.

Park, Kwangheon, Seunghyun Son, Jinhyuk Oh, and Sunkuk Kim. 2022. “Sustainable Decommissioning Strategies for Nuclear Power Plants: A Systematic Literature Review.” *Sustainability* 14 (10): 5947. https://doi.org/10.3390/su14105947.

Pearce, Fred. 2017. “Industry Meltdown: Is the Era of Nuclear Power Coming to an End?” Yale Environment 360. 2017. http://e360.yale.edu/features/industry-meltdown-is-era-of-nuclear-power-coming-to-an-end.

Rosner, Robert, and Rebecca Lordan. 2014. “Why America Should Move towards Dry Cask Consolidated Interim Storage of Used Nuclear Fuel.” *Bulletin of the Atomic Scientists* 70 (6): 48–62. https://doi.org/10.1177/0096340214555107.

Rothwell, Geoffrey. 2022. “Projected Electricity Costs in International Nuclear Power Markets.” *Energy Policy* 164 (May): 112905. https://doi.org/10.1016/j.enpol.2022.112905.

Scherwath, Tim, Ben Wealer, and Roman Mendelevitch. 2019. “Nuclear Decommissioning after the German Nuclear Phase-Out An. Integrated View on New Regulations and Nuclear Logistics.” DIW Discussion Paper 1779. Berlin: DIW Berlin.

Schlissel, David, Paul Peterson, Bruce Biewald, and Synapse Energy Economics. 2002. *FINANCIAL INSECURITY : The Increasing Use of Limited Liability Companies and Multi- Tiered Holding Companies to Own Nuclear Power Plants*.

Schneider, Mycle, Antony Froggatt, Julie Hazemann, Ali Ahmad, Mariana Budjeryn, Yuichi Kaido, Naoto Kan, et al. 2021. “World Nuclear Industry Status Report 2021.” Paris: Mycle Schneider Consulting. https://www.worldnuclearreport.org/IMG/pdf/wnisr2021-hr.pdf.

Schneider, Mycle, Antony Froggatt, Julie Hazemann, M. V. Ramana, Michael Sailer, Tatsujiro Suzuki, Christian von Hirschhausen, et al. 2022. “World Nuclear Industry Status Report 2022.” Paris: Mycle Schneider Consulting.

Schneider, Mycle, Antony Froggatt, Phil Johnstone, Andy Stirling, Tadahiro Katsuta, M. V. Ramana, Christian von Hirschhausen, Ben Wealer, Agnès Stienne, and Julie Hazemann. 2018. “World Nuclear Industry Status Report 2018.” Paris, London: Mycle Schneider Consulting.

Short, S. M, M. C. Bierschbach, R.F. Layton, and B.E. Greenfield. 2011. “Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula.” U.S. Nuclear Regulatory Commission.

SKB. 2021. “Our Task.” 2021. https://www.skb.com/about-skb/our-task/.

Sovacool, Benjamin K., Alex Gilbert, and Daniel Nugent. 2014. “An International Comparative Assessment of Construction Cost Overruns for Electricity Infrastructure.” *Energy Research & Social Science* 3 (September): 152–60. https://doi.org/10.1016/j.erss.2014.07.016.

SRF. 2019. “In 10 Jahren Ist Auch in Beznau Schluss,” 2019. https://www.srf.ch/news/regional/aargau-solothurn/ende-der-kernenergie-in-10-jahren-ist-auch-in-beznau-schluss#:~:text=Ende%20der%20Kernenergie%20In%2010%20Jahren%20ist%20auch%20in%20Beznau%20Schluss&text=Am%20Freitag%20ging%20mit%20M%C3%BChleberg,Mitte%20des%20Jahrhunderts%20abgeschaltet%20werden.

STENFO. 2021a. “Faktenblatt Nr. 1 - Allgemeine Informationen.” Bern: Stilllegungsfonds für Kernanlagen / Entsorgungsfonds für Kernkraftwerke.

———. 2021b. “Faktenblatt Nr. 2 - Kosten Und Beiträge.”

Stenger, Daniel F., Amy C. Roma, and Sachin S. Desai. 2019. “Innovations in Decommissioning and Their Application Abroad.” *Nuclear News*, July.

Strahlenschutzgesetz. 2017. “Strahlenschutzgesetz Vom 22. März 1991 (StSG).” 2017. https://www.admin.ch/opc/de/classified-compilation/19910045/index.html.

Stralsakerhetsmyndigheten. 2015. “Safe and Responsible Management of Spent Nuclear Fuel and Radioactive Waste in Sweden.” 2015:32.

Suh, Young A, Carol Hornibrook, and Man-Sung Yim. 2018. “Decisions on Nuclear Decommissioning Strategies: Historical Review.” *Progress in Nuclear Energy* 106 (July): 34–43. https://doi.org/10.1016/j.pnucene.2018.02.001.

Swedish Energy Agency. 2021. “Energy in Sweden 2021.” Excel Sheet 6.2. http://www.energimyndigheten.se/en/facts-and-figures/statistics/.

Swedish National Debt Office. 2022. “How Is Nuclear Waste Management to Be Financed?” 2022. https://www.riksgalden.se/en/our-operations/financing-of-nuclear-waste-management/how-is-nuclear-waste-management-to-be-financed/.

swissinfo. 2016. “Ein Halbes Jahrhundert Atomenergie in Der Schweiz.” November 16, 2016. https://www.swissinfo.ch/ger/zwischen-konsens-und-opposition_ein-halbes-jahrhundert-atomenergie-in-der-schweiz/42590926.

The New York Times. 2016. “Giant Arch, a Feat of Engineering, Now Covers Chernobyl Site in Ukraine,” 2016. https://www.nytimes.com/2016/11/29/world/europe/chernobyl-disaster-cover.html.

Thomas, Stephen. 2006. “UK Decommissioning Funds: A Cautionary Tale.” *Platts -Power in Europe*, no. Issue 477 (May): 9–12.

UVEK. 2019. “Bundesrat Beschliesst Revision Der Stilllegungs- Und Entsorgungsverordnung.” 2019. https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-76943.html.

———. 2020. “Energiestrategie 2050.” 2020. https://www.uvek.admin.ch/uvek/de/home/energie/energiestrategie-2050.html.

Wealer, Ben, Simon Bauer, Nicolas Landry, Hannah Seiß, and Christian von Hirschhausen. 2018. “Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017).” Data Documentation 93. Berlin: DIW Berlin, TU Berlin.

Wealer, Ben, Jan Paul Seidel, and Christian von Hirschhausen. 2019. “Decommissioning of Nuclear Power Plants and Storage of Nuclear Waste: Experiences from Germany, France, and the U.K.” In *The Technological and Economic Future of Nuclear Power*, edited by Reinhard Haas, Lutz Mez, and Amela Ajanovic, 261–86. Energiepolitik Und Klimaschutz. Energy Policy and Climate Protection. Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-25987-7_12.

Wimmers, Alexander, Björn Steigerwald, and Christian Von Hirschhausen. 2023. “United Kingdom Nuclear Power Industry Decommissioning Profile.” DIW Berlin - Deutsches Institut für Wirtschaftsforschung. https://www.diw.de/documents/publikationen/73/diw_01.c.864222.de/diw_datadoc_2023-104.pdf.

Wimmers, Alexander, Christian Von Hirschhausen, and Björn Steigerwald. 2023. “French Nuclear Power Industry Decommissioning Profile.” DIW Berlin - Deutsches Institut für Wirtschaftsforschung. https://www.diw.de/documents/publikationen/73/diw_01.c.864222.de/diw_datadoc_2023-104.pdf.

Wimmers, Alexander, Ben Wealer, Björn Steigerwald, and Christian Von Hirschhausen. 2023. “Germany Nuclear Power Industry Decommissioning Profile.” DIW Berlin - Deutsches Institut für Wirtschaftsforschung. https://www.diw.de/documents/publikationen/73/diw_01.c.864222.de/diw_datadoc_2023-104.pdf.

World Nuclear Association. 2017. “Emerging Nuclear Energy Countries.” 2017. http://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx.

———. 2022a. “Nuclear Power in Finland.” 2022. https://world-nuclear.org/information-library/country-profiles/countries-a-f/finland.aspx.

———. 2022b. “Nuclear Power in Sweden.” 2022. https://world-nuclear.org/information-library/country-profiles/countries-o-s/sweden.aspx.

———. 2022c. “Nuclear Power in the World Today.” 2022. https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

World Nuclear News. 2019. “Swedish Support for Nuclear Continues to Grow, Poll Shows.” 2019. https://world-nuclear-news.org/Articles/Swedish-support-for-nuclear-continues-to-grow,-pol#:~:text=As%20many%20as%2078%25%20of,and%20published%20by%20Analysgruppen%20shows.

———. 2020. “Swedish Municipality Gives Approval for Fuel Repository.” 2020. https://www.world-nuclear-news.org/Articles/Swedish-municipality-gives-approval-for-fuel-repos.