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Lessons for the Organization of Nuclear Decommissioning from the UK and the US: Risks, Challenges, and Opportunities

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Organizational Models for the Decommissioning of Nuclear Power Plants

Lessons from the United Kingdom and the United States

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Abstract

With nuclear reactor fleets continuously aging, the decommissioning of closed reactors is gaining increasing attention. In nuclear decommissioning, technical, organizational, and regulatory challenges lead to long project durations and cost escalations. This paper attempts a first examination of the organizational efficiencies in nuclear decommissioning by applying new institutional economics. It compares the UK's former parent-body-organization-model with current US approaches, highlighting potential gains and policy recommendations for private sector involvement in nuclear decommissioning.

UK inefficiencies include regulatory issues, private actors' opportunism, and information asymmetries. The US models show fewer such issues, but regulators must address profit-driven shortcuts and fund adequacy concerns.

Keywords

Nuclear power; nuclear decommissioning; organizational models;

JEL classification

Q48; L52; P18

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Table of contents

Abstract	i
Keywords	i
JEL classification	ii
Funding	ii
Disclosure Statement	ii
List of Figures	iv
List of Tables	v
1 Introduction	1
2 Theoretical Background	3
2.1 Framework Description	3
2.2 Introducing NEI to Nuclear Decommissioning	4
3 The System Good Nuclear Decommissioning	6
3.1 Technical System	6
3.1.1 Approaches to nuclear decommissioning	6
3.1.2 Processes and Assets	6
3.2 Tasks, Roles, and Relations	7
3.2.1 Production	7
3.2.2 Financing	8
3.3 Actors and Institutions	8
4 Organizational Models in Nuclear Decommissioning in the UK and the US10	
4.1 United Kingdom	10
4.1.1 Privatization of the British nuclear sector (t_3 & t_2)	11
4.1.2 Parent-Body Organizations and British Energy (t_1)	11
4.1.2.1 Production	12
4.1.2.1.1 Sellafield Ltd	12
4.1.2.1.2 Magnox Ltd	14
4.1.2.1.3 British Energy	15
4.1.2.2 Financing	15
4.1.3 Decommissioning in the UK today (t_0)	16
4.1.3.1 Production	16
4.1.3.2 Financing	16
4.1.4 Summary	16
4.2 United States	17
4.2.1 Nuclear power market structure (t_2 & t_1)	17
4.2.1.1 Production	18
4.2.1.2 Financing	18
4.2.2 Organizational models in nuclear decommissioning since the 2010s (t_0)	18
4.2.2.1 License Acquisition	19
4.2.2.2 License Stewardship	21
4.2.3 Summary	21
5 Discussion	22
6 Conclusion and Policy Recommendations	24
References	26

List of Figures

Figure 1: Key elements of the system good analysis, own translation adapted from Gizzi (2016, p. 10)	4
Figure 2: Stylized organization of decommissioning including actors and institutions.....	9
Figure 3: Timelines for nuclear decommissioning responsibilities in the UK	11
Figure 4: PBO model and adapted market-enhanced SLC model.....	12
Figure 5: Fees paid to NMP by the NDA for Sellafield performance.....	14
Figure 6: Timelines in US decommissioning responsibilities	17
Figure 7: Nuclear Decommissioning Organizational Models in the US for investor-owned utilities.....	19
Figure 8. Organizational Models for Nuclear Decommissioning in the UK and US for production (vertical) and financing (horizontal)	22

List of Tables

Table 4-1: Overview of recent decommissioning status.....	10
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1 Introduction ¹

Once a nuclear power plant (NPP) reaches the end of its operational lifetime, it must be decommissioned. However, other than the demolition of conventional industrial facilities, nuclear decommissioning poses significant risks from radiological contamination and activation (IAEA 2005; Laraia 2018). Historical negligence of the necessity of decommissioning in the early days of nuclear power has led to unexpected delays in thereof, which in turn might pose financial risks to financiers, be it the operator or the state (MacKerron 2015; Pasqualetti 2019; Wealer, Seidel, and von Hirschhausen 2019; Lordan-Perret, Sloan, and Rosner 2021). With world-wide reactor fleets continuously ageing, nuclear reactors will be coming offline at an increasing rate in the years to come. Additionally, ageing nuclear reactors are becoming increasingly expensive to operate and susceptible to early closure due to costly maintenance and replacement work (Schneider et al. 2023). Thus, given that closed NPP sites still pose risks of radiation, nuclear decommissioning will become increasingly relevant in the future (Foster et al. 2021; Hirose and McCauley 2022). Nuclear decommissioning in itself is not a new challenge – experience nevertheless remains limited as only eleven reactors with electrical capacities of over 100 MW have been fully decommissioned (Schneider et al. 2023). With the nuclear industry increasingly focusing on the nuclear back-end (including nuclear waste management), organizational models have emerged that will likely influence future decommissioning strategies in several countries and might deliver efficiency gains in an industry so long pained by economic inefficiency (Rothwell 2022; Wealer and von Hirschhausen 2020; Stenger, Roma, and Desai 2019).

In literature, nuclear decommissioning has mostly been analyzed from a technical viewpoint. While Laraia (2012; 2018; 2022) focuses on technical approaches to nuclear decommissioning at individual NPPs, others analyze risks and benefits of dismantling strategies (MacKerron 2012; Foster et al. 2021; Hirose and McCauley 2022). Financial issues arising from the organization of nuclear decommissioning have been raised (Cacuci 2010; MacKerron 2015; Schneider et al. 2018; Irrek 2019a; Stenger, Roma, and Desai 2019; Wealer, Seidel, and von Hirschhausen 2019; Lordan-Perret, Sloan, and Rosner 2021), social aspects of decommissioning remain of a secondary nature (Pasqualetti 2019) and discussions of shortcomings of individual current governance structures remain limited (MacKerron 2015; Wealer and von Hirschhausen 2020; Wimmers et al. 2023). Consequently, literature lacks a methodological comparison of organizational models for production and financing of nuclear decommissioning, especially focusing on the introduction of market-based competition of private industry actors, coinciding with the application of established economic theory.

¹ Abbreviations used in this manuscript: ADP = Accelerated Decommissioning Partners; AGR = Advanced gas-cooled reactor; BWR = Boiling water reactor; CEGM = Central Electricity Generating Board; DTF = Decommissioning Trust Fund; ES = EnergySolutions; HDI = Holtec Decommissioning International LTE = Long-term enclosure; NDA = Nuclear Decommissioning Authority; NLF = Nuclear Liabilities Fund; NPP = Nuclear Power Plant; NRC = United States Nuclear Regulation Commission; PBO = Parent Body Organization; PWR = Pressurized water reactor; SLC= Site License Company; TAC = Transaction Costs; UK = United Kingdom; US = United States of America

This paper provides insights into organizational models for the decommissioning of NPPs, e.g., for policy makers who might stand before the challenge of implementing new or adapting existing regulation. This paper first provides an analysis of the “system good” that is nuclear decommissioning (Beckers, Gizzi, and Jäkel 2012). The analysis allows for the scrutiny of two approaches that were observed in the United Kingdom (UK) and the United States of America (US), respectively. The development of the observed organizational models is described chronologically. Based on New Institutional Economic Theory (NIE), reasons for the failure of the UK’s past approach are extracted and possible success criteria for the currently applied organizational models observed in the US are identified.

The remainder of this paper is structured as follows. First, the methodology of system good analysis following Beckers et al. (2012) is introduced. Section 3 applies the methodology to nuclear decommissioning. From this, the organizational models in the UK and US are derived. For both countries, an overview of past and ongoing developments of the respective nuclear industry provides context. NIE analyses are conducted to understand the reasons for failure of the UK’s approach, and the US’ models possible future success. These findings are discussed in Section 5. The paper closes with a conclusion and policy recommendations.

2 Theoretical Background

Oftentimes, the provision of goods and services requires the supply of multiple activities, conducted successively or in parallel. As a consequence, coordination between involved actors becomes imminent (Beckers, Gizzi, and Jäkel 2012, 1). Following Beckers et al. (2012), we refer to these types of complex activities as “system goods” and introduce a framework for the analysis thereof. The second part of this section introduces NIE (Furubotn and Richter 2005).

2.1 Framework Description

The framework is structured around the analysis of three main components. The goal of the first, the so-called technical system, is the analysis of necessary goods, assets, and processes along the value chain to supply the system good, including interdependencies between different parts of the system. Continuing the analysis, one can identify roles in the technical system. These roles “contain a structured bundle of tasks to be performed relating to the supply of a defined good” (Beckers, Gizzi, and Jäkel 2012, 4). These roles are in varying relations to one another, and coordination needs arise once decisions made by roles impact other roles’ tasks. From these roles emerges the final component of the system good analysis: actors and institutions. In this framework, actors take on certain roles corresponding to their specific assets and resources.

Institutions define the field of action for actors. For example, coordination is guided by contracts or laws, while actors might be restricted from taking on certain roles by licensing requirements. The complete description of all activities to supply a system good is referred to as an organizational model. The optimal design of such an organizational model, consisting of actors and institutions, is a main consideration of NEI, that aims at “getting the institutions right” to achieve functional and efficient markets (Radulovic 2005, 1886).

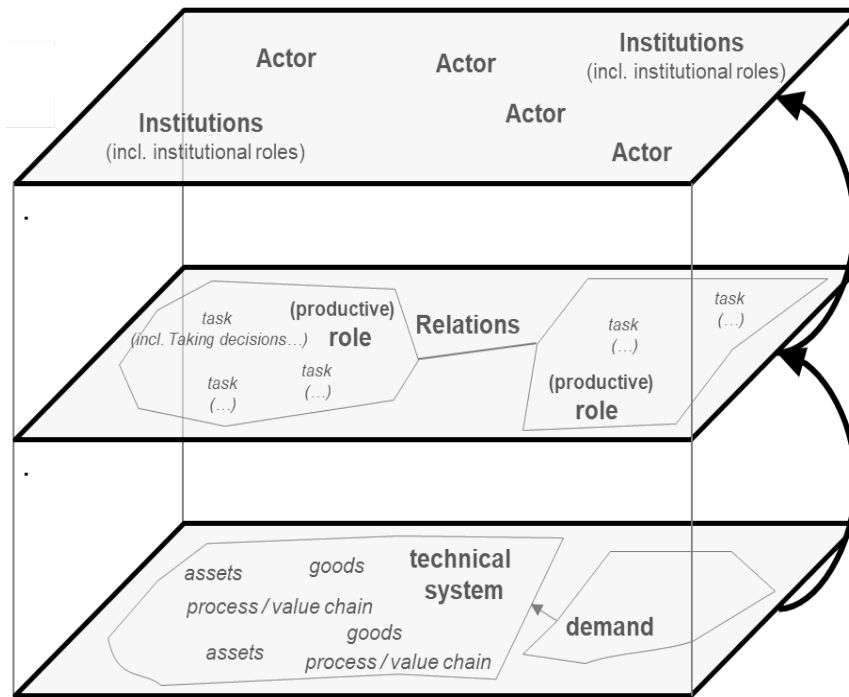


Figure 1: Key elements of the system good analysis, own translation adapted from Gizzi (2016, 10)

To define an organizational model, Gizzi (2016) suggests a three-step iterative approach. In a first step, the system good itself must be described (Figure 1). This includes the central properties of assets, goods, and processes as well as technical aspects and possibly necessary quantities required in the value chain. The second step constitutes the three-stage mapping of the system good in the analysis framework. Initially, a stylized description of the system good is mapped onto the technical system by identifying all relevant assets, processes, and goods as well as their interdependencies. Following this, the model of roles can be defined. In this step, roles and their relations are described in a way that minimizes the required number of roles, meaning that some roles may be able to take on several processes or tasks. This is the basis for the later analysis of organizational models. Moving on, needs for coordination and associated coordination areas can be defined. This allows the third and final step to be conducted: the creation of organizational models. These organizational models include assumptions about which actors are involved in taking on certain roles. From this, actor models, such as monopolistic structures, can be derived. Further assumptions are made on the effect institutions have on actor behavior.

2.2 Introducing NEI to Nuclear Decommissioning

Once organizational models have been described, measuring their efficiency in delivering desired outcomes becomes necessary. A major component of NEI theory is the inclusion of transaction costs (TAC) that arise from coordination between actors, e.g., communication, or information gathering (Coase 1937; Williamson 1979). TAC are not directly associated with value creation and are influenced by the frequency of a transaction, the specificity of an asset, and uncertainty (Williamson 1979; 1985).

The frequency of a transaction refers to how often it is performed. If identical or similar transactions are performed regularly, costs can be reduced through learning (Furubotn and Richter 2005). In the case of nuclear decommissioning, the possibility to repeat tasks or apply proven techniques at different sites depends on the specificity of NPPs. However, the adaptability of standardized techniques is limited due to certain variations among plants or the limited reusability of specialized or contaminated tools and machinery (Weinand 2022).

Asset specificity refers to the dependence of actors on each other. When an asset has low specificity, it can be used for other production factors, while high specificity results in dependence on a limited number of actors or specified investments. Different types of asset specificity exist, such as site specificity and physical specificity (Joskow 1985; Furubotn and Richter 2005). While similarities in nuclear fleets exist, even seemingly small design differences can cause significant TAC when it comes to decommissioning (Wimmers et al. 2023). Due to the high physical specificity, institutional knowledge is highly relevant in the nuclear industry and more so in nuclear decommissioning (IAEA 2005). On-site personnel is familiar with the specifications of the to-be-decommissioned plant and is therefore invaluable for safe, secure and fast decommissioning (Suh, Hornibrook, and Yim 2018).

Incomplete information influences TAC by adding uncertainty. This uncertainty is either parametric, where the future environmental circumstances are unknown, or behavioral, which arises from opportunistic behavior of actors (Williamson 1985). In nuclear decommissioning, parametric uncertainties can result from unknown levels of radiological contamination and activation, necessitating careful measurement and decontamination efforts (NDA 2021a), or from unknown structural integrity of sites in “long-term enclosure” (LTE) (Borchardt 2019). Information asymmetry amongst actors leads to behavioral uncertainty, where specialist agents may possess information advantages compared to principals. This may to risks of adverse selection and moral hazard, requiring principals to monitor agents' behaviors (Williamson 1985; Gauld 2007).

Overall, TAC and uncertainties play a significant role in determining the efficiency of organizational models in delivering desired outcomes. These factors highlight the importance of considering the frequency of transactions, asset specificity, and information asymmetry in evaluating the efficiency of different organizational approaches.

3 The System Good Nuclear Decommissioning

Nuclear decommissioning is an important step in the lifetime of a NPP that merits the provision of various complex tasks and oftentimes the interaction of a large number of individual actors. The complexity of this system good “nuclear decommissioning” shall be derived in the following section.

3.1 Technical System

3.1.1 Approaches to nuclear decommissioning

Nuclear decommissioning is a task that must be completed safely and swiftly to minimize radiological risks to the environment and the public (Hirose and McCauley 2022). Further, the removal and safe storage of radioactive material increases security by reducing the risks of proliferation and intentional targeting of the sites (Lévêque 2015). Decommissioned nuclear facilities can be released from regulatory oversight and then be reused or sold (NRC 2017).

There are three strategies to decommission an NPP. The first, immediate or direct dismantling, is the fastest option. Here, decommissioning begins directly after plant closure. While radiation remains at relatively high levels, remaining institutional knowledge allows for more efficient decommissioning, potentially reducing overall cost (Suh, Hornibrook, and Yim 2018; Irrek 2019b; Park et al. 2022). Delayed or deferred dismantling involves the placement of the reactor in LTE for years to decades to allow for short-lived radioisotopes to decay, which reduces health risks for workers, and allows decommissioning funds to accumulate (OECD/NEA 2006; Blowers 2019). This strategy might be chosen at sites with gradual closure of reactors to allow for parallel decommissioning. Disadvantages include the loss of institutional knowledge and possible loss of structural integrity of buildings (OECD/NEA 2006; Suh, Hornibrook, and Yim 2018). The third strategy, entombment, can be applied to sites that have experienced an accident. Here, the site is sealed as dismantling poses too large a risk to workers (Blowers 2019).

Regardless of the chosen strategy, once dismantling begins, operations tend to follow a similar pattern. In the first stage, the „warm-up“-stage, which includes the post-operational phase, the reactor is defueled, and first components are removed to allow access to the reactor core. In the subsequent “hot-zone“-stage, dismantling of highly contaminated parts, such as the reactor pressure vessel, is conducted. In the final “ease-off“-stage, remaining internal components and buildings are decontaminated. Depending on the target state of the site, buildings are demolished (“greenfield”) or decontaminated to a degree as to be eligible for other (non-nuclear) purposes (“brownfield”) (Schneider et al. 2018).

3.1.2 Processes and Assets

Nuclear decommissioning involves various interconnected processes that are dependent on one another (Wealer and von Hirschhausen 2020). While some fleets are somewhat homogeneous, standardized techniques may not apply to all plants, requiring the development of specialized tools with

limited reusability.² The availability of skilled personnel, particularly with institutional knowledge, is crucial for successful decommissioning (Suh, Hornibrook, and Yim 2018). Site-specific conditions and opposition from local populations can further affect progress (Schabel 2020). Uncertainty regarding radiological contamination and activation arises during the dismantling of remaining buildings and components (Wimmers et al. 2023). Consequentially, the need for coordination amongst actors arises to ensure safety, security, and efficiency to decommissioning projects.

Further, access to waste disposal routes and facilities is crucial for successful decommissioning (Wealer and von Hirschhausen 2020). Radiological waste must be disposed of at specialized facilities, the availability of which depends on the type of waste (Thierfeldt and Schartmann 2009). Interim storage facilities for high-level waste, mostly spent fuel, are often located on-site and remain operational after technical decommissioning of the plant itself is completed (Blowers 2019; Scherwath, Wealer, and Mendelevitch 2020). The release a site from regulatory oversight requires the removal of all waste from the premises, either to a consolidated interim storage facility, or to (currently unavailable) final repositories (Wimmers et al. 2023).

3.2 Tasks, Roles, and Relations

Put simply, “a firm [has] [...] a role to play in the economic system if it [is] possible for a transaction to be organized within the firm at less cost than would be incurred if the same transaction were carried out through the market” (Coase 1988, 19). This decision marks the degree of vertical integration. A high level of vertical integration supposes that a firm conducts a transaction using its own resources and capabilities. The opposite would be to use market participants for efficiency. This strongly depends on the product or service as with an increasing level of TAC through, e.g., high specificity of a product and resulting lengthy communications and negotiations with market participants, vertical integration might become increasingly favorable (Tirole 1988). Another interpretation of this concept is the “make-or-buy” question, with “make” referring to a high degree of vertical integration (Klein 2005).

Previous research established that the organization surrounding nuclear decommissioning strongly differs between countries and sometimes even within a single country (Wimmers et al. 2023). To allow for the comparison of organizational models in our case studies, we distinguish between organization of the “production”, i.e., the provision of goods and services necessary for nuclear decommissioning, and the organization of “financing”, i.e., the provision of required funding.

3.2.1 Production

Following Cacuci (2010, 3007), we analyze two theoretical organizational models that could occur in different countries, depending on their regulatory setting and domestic nuclear decommissioning industry. The later discussed organizational models in the UK and the US lie somewhere in between. The first model is vertical integration, where a single state-owned utility owns and operates all NPPs.

² For example, at the German nuclear power plant Stade, most tools used in the hot-zone stage had to be specially designed (Loeb 2011), and activated and contaminated tools might not be reusable at other sites (Weinand 2022).

Decommissioning is financed by state funds (see Section 3.2.2), and there is limited private industry involvement. Possible benefits may include the utility's incentivization to provide a better service to reduce radiation risks and minimize public expenditure resulting from secure funding and organizational proximity to the overseeing state. Efficiency gains are possible due to knowledge concentration, reduced risks from external agents, and limited unforeseen events. However, as often discussed in literature, a publicly owned utility may not prioritize efficiency (Borenstein and Bushnell 2015; Chen 2019). The second model is market competition, with multiple entities owning or operating NPPs. The state acts solely as an overseeing agency, and decommissioning is financed via external segregated funds. There is a market consisting of multiple profit-maximizing decommissioning companies. Learning effects and fund owners keeping surplus cash could lead to faster and cheaper decommissioning if asset specificity and uncertainty remain limited. For highly asset specific plants, the risk of stranding in final state liability remains. In reality, hybrid solutions were also observed in which individual tasks were contracted to different agents (Scherwath, Wealer, and Mendelevitch 2020).

3.2.2 Financing

Five options to finance nuclear decommissioning projects exist. These depend mostly on respective national legislation. However, regulations might also differ in a single country for individual reactors. For some decommissioning projects, funds come directly from the state budget. The option of internal segregated funds allows for licensees to self-administer funds, but these are ear-marked in balance sheets and may not be used otherwise. Internal non-segregated funds however must not necessarily be separated from other assets or business interests. If decommissioning is organized via external segregated funds, licensees or electricity consumers make payments to funds that are managed by independent fund operators. These funds are completely separated from other assets. Finally, although only practiced in the US, licensees may use a combination of financial instruments such as surety bonds, letters of credit or other forms of guarantees to provide surety methods to the regulator. (Wimmers et al. 2023)

Lordan-Perret et al. (2021) discuss the challenges of liability in nuclear decommissioning. For example, with high decommissioning costs come risks of fund shortfalls, which might result in bankruptcy of nuclear licensees and require state interventions.

3.3 Actors and Institutions

Having established the technical system of nuclear decommissioning, the related tasks, roles and relations, a stylized description of involved actors and institutions can be derived. Previous research provides analyses of country-specific regulation and organization of nuclear decommissioning (Wealer and von Hirschhausen 2020; Wimmers et al. 2023) from which we derive this stylized organigram, shown in Figure 2.

For most countries, the organization of nuclear decommissioning follows a pattern: The government, represented by responsible ministries, defines the relevant laws and regulations, e.g., mandates regarding decommissioning strategies, and provides agency and funds to the overseeing departmental agencies. The number of involved agencies differs amongst countries as responsibilities for oversight

can be split up, e.g., regarding radiation safety or financial oversight. These agencies are involved either directly or indirectly with the NPP licensee and can, in some cases, even be owners. A given NPP has one licensee. The number of required licenses over the lifetime of a power plant can vary but oftentimes the licensee itself remains the same. In the case studies described below, the license itself changes hands over the plant's lifetime. A licensee may be owned by one or several entities who can themselves be subject to scrutiny by agencies. The nuclear licensee can outsource individual decommissioning tasks or the whole process to third party-contractors who in turn interact with on-site staff at the NPP itself. Generated wastes are transferred to waste disposal, potentially on site. The organization thereof is country specific.

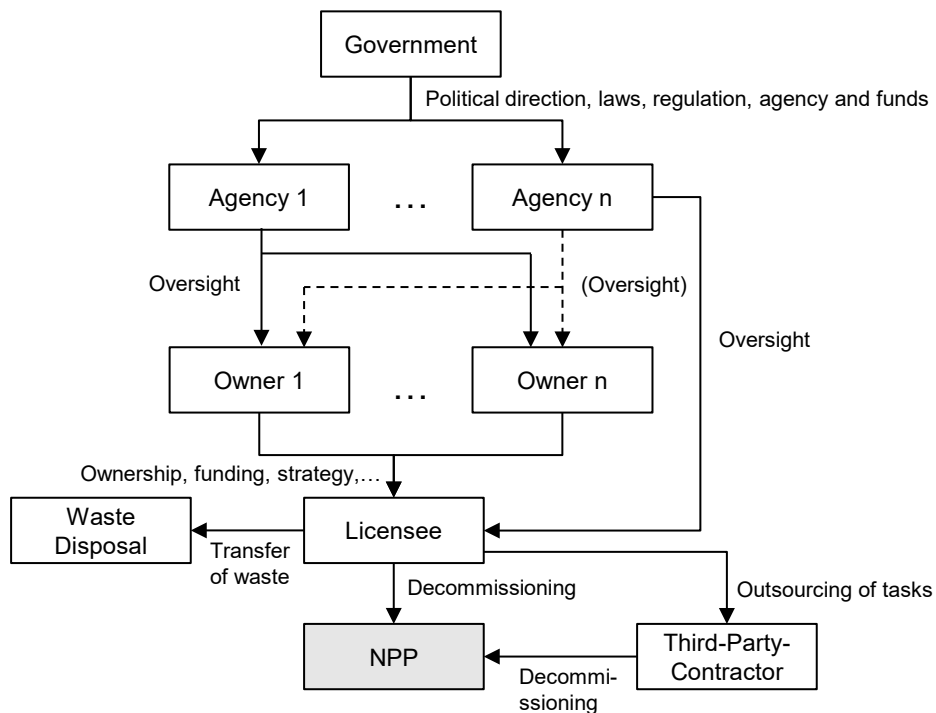


Figure 2: Stylized organization of decommissioning including actors and institutions.

4 Organizational Models in Nuclear Decommissioning in the UK and the US

This paper analyzes two organizational models that aim or aimed at involving market-based approaches in the nuclear decommissioning industry in the UK and US, respectively. It focuses on interactions between the licensee and third-party contractors, as well as ownership changes. Both countries experienced waves of privatization of public assets and industries from the 1980s to early 2000s (S. Thomas 2006; Prentis 2014). However, the UK's nuclear industry, particularly its legacy fleet of Magnox reactors, remained mostly state-owned, while ownership in the US is more diversified (Wimmers et al. 2023). Both countries tried bringing in private decommissioning specialists with varying success. The UK returned to state-run operations, while the US industry is adapting to emerging organizational models. The current state of NPP decommissioning is shown in Table 4-1.

Table 4-1: Overview of recent decommissioning status

	June 2022		June 2023	
	UK	US	UK	US
Closed reactors (total)	34	41	36	41
Warm-up stage (of which defueled)	13 (11)	7 (7)	21 (13)	5 (5)
Hot-zone-stage	9	3	9	5
Ease-off stage	0	1	0	2
LTE	8	13	6	11
Completed (of which greenfield)	0	17 (6)	0	17 (7)

Sources: Own compilation of (Schneider et al. 2023; Wimmers et al. 2023)

4.1 United Kingdom

Over the last 40 years, the UK's nuclear power sector has undergone several restructurings following the initial attempt at privatization in 1990. With every restructuring, the question of liability and responsibility for nuclear decommissioning re-emerged. Figure 3 shows the timeline of these restructurings from the 1990s (t_{-3} & t_{-2}) over the 2000-2010s (t_{-1}) to the situation today (t_0). The following sections will provide a detailed account of these events.

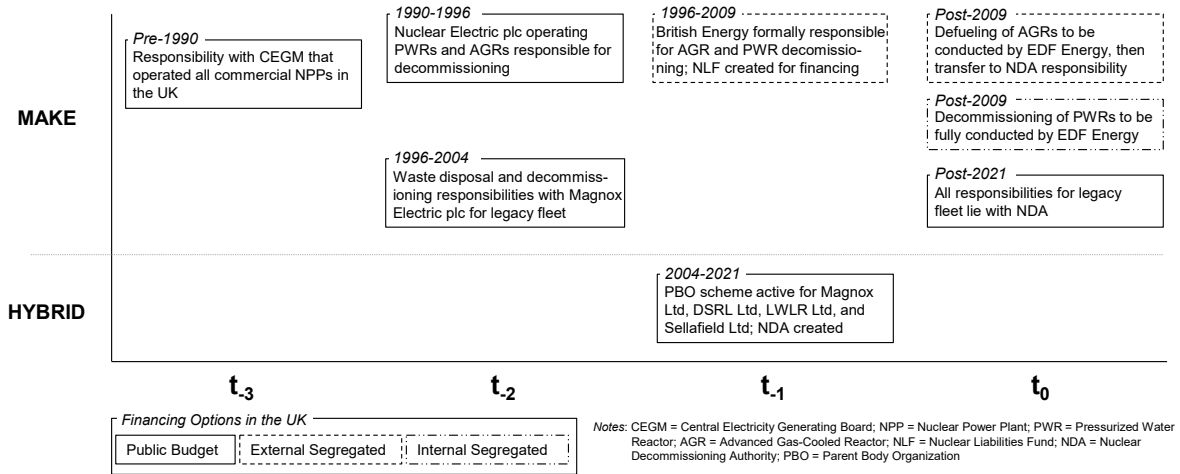


Figure 3: Timelines for nuclear decommissioning responsibilities in the UK

4.1.1 Privatization of the British nuclear sector (t_3 & t_2)

From the 1980s to the early 2000s, the British state sold public assets until there was nothing left to be sold or, as was the case with the nuclear legacy fleet, consisting today of 26 Magnox gas-cooled reactors built in the 1950s and 1960s, no one would buy (Hood 1995; Rhodes, Hough, and Butcher 2014). In 1990, the Central Electricity Generating Board (CEGB) was split into several state-owned and to-be-privatized entity. By 1996, further reorganization had resulted in the UK's NPP ownership having been divided between British Energy and Magnox Electric plc, the latter taking over the legacy fleet (Rhodes, Hough, and Butcher 2014). Magnox Electric was later taken over by state-owned British Nuclear Fuels Limited (BNFL), that had been established in 1971 to operate nuclear fuel production and reprocessing facilities formerly run by the UK Atomic Energy Authority (Rhodes, Hough, and Butcher 2014). With BNFL beginning to face internal and external pressures, considerations to establish a public private partnership for the legacy fleet were scrapped due to safety concerns (Morgan 2000; Haraldsen 2018). This led to the publication of the 2002 White Paper "Managing the Nuclear Legacy" that defines the UK's current legislation and led to the creation of the Nuclear Decommissioning Authority (NDA) in 2004 (Department of Trade and Industry 2002; Foster et al. 2021).

4.1.2 Parent-Body Organizations and British Energy (t_1)

The NDA was established as an agency not directly involved in day-to-day nuclear decommissioning activities, but rather for oversight. Actual tasks were to be carried out by so-called "site license companies" (SLC) that to this day act as license holders for individual nuclear sites. Assets and liability however mostly remained in NDA ownership (MacKerron 2015). NDA and SLCs would make arrangements regarding shared business risks and the establishment of incentive-driven frameworks to increase operational efficiency as well as ensure safety and environmental standards. Most importantly however, the NDA's task was to generate "the best value for money" (Department of Trade and Industry 2002, 25). This section is divided into an analysis of the organization of first production, and then financing.

4.1.2.1 Production

The prospect of privatization bringing efficiency resulted in the creation of an incentive-based model based on three main goals: “efficiency savings, performance in meeting project milestones and identifying work that can be removed from the program without affecting overall progress on the site” (NAO 2015, 18). Given particular national regulations requiring the operator of decommissioning activities to also be the license holder, rather than involving license transfers as observed in the US (see Section 4.2), private organizations bid for the ownership of SLCs via share transfers to be returned after a fixed term. This private organization would be dubbed “parent body organization” (PBO), giving the model its name. PBOs would acquire the role of “upper management” of the SLC (Tier 1) and provide strategic management to achieve the earlier identified goals, as shown in Figure 4. SLC employees remained at their positions. The state would take on risks as ownership remained with the NDA and would, depending on the contract design, also be responsible for financing (Haraldsen 2018).

Over the years it was active, the PBO scheme failed to deliver its three main goals and thus, all SLCs have now been returned to full NDA ownership that now operates decommissioning in a so-called “market-enhanced SLC” model, as shown in Figure 4 and described in Section 4.1.3. (NDA 2022)

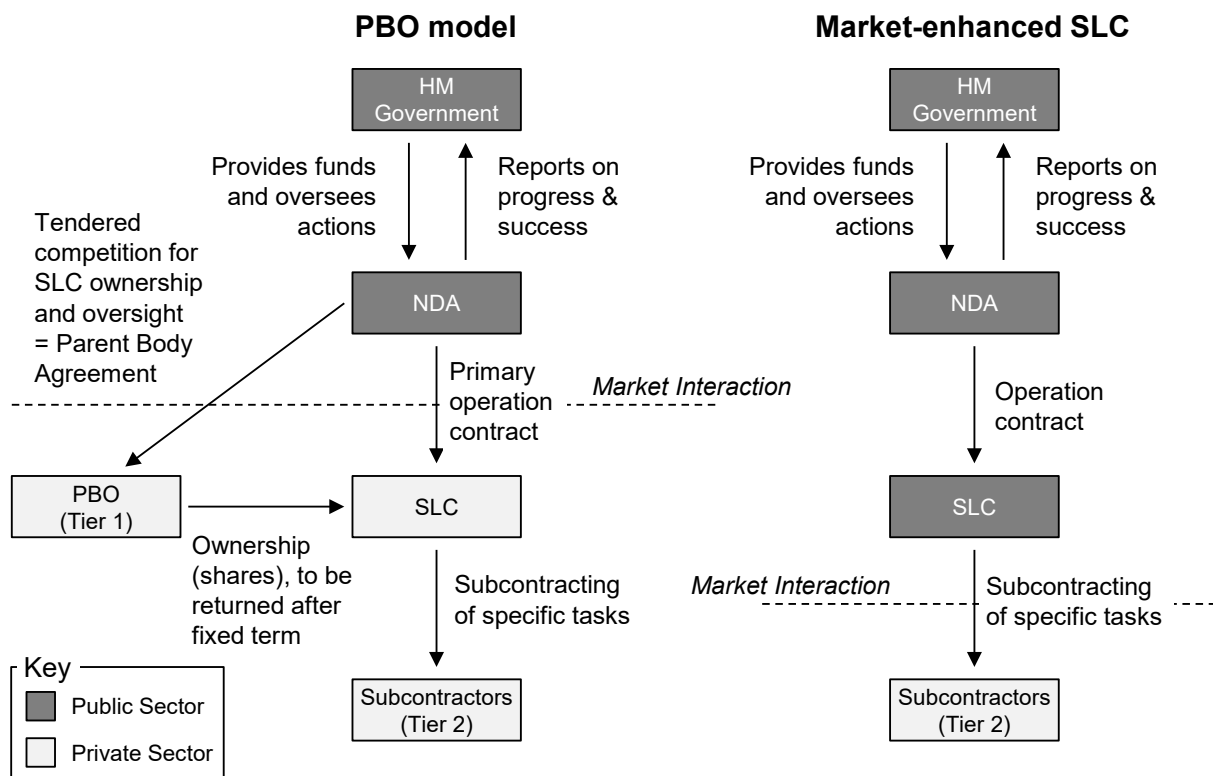


Figure 4: PBO model and adapted market-enhanced SLC model

Source: Own depiction following MacKerron (2012) and NDA (2014).

4.1.2.1.1 Sellafeld Ltd

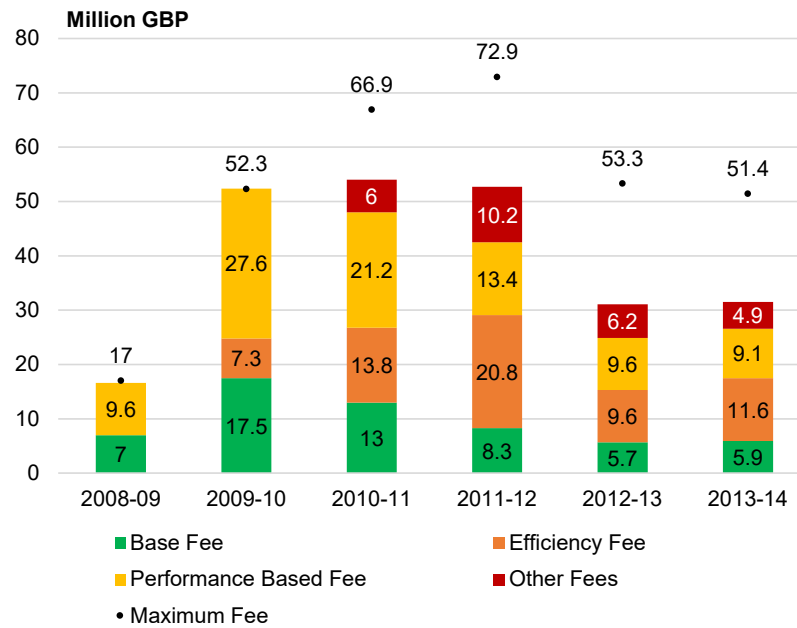
Sellafeld is one of Europe’s most complex nuclear facilities, consisting of the UK’s first nuclear power reactors as well as reprocessing facilities to generate plutonium. NPPs located on the premises include Calder Hall and the Windscale reactor. Today, Sellafeld also incorporates several used nuclear fuel

ponds of unknown composition and is used as a storage site for nuclear waste. (Foster et al. 2021; Haraldsen 2018; Sellafield Ltd 2017; NDA 2021a)

Initially, decommissioning at Sellafield was to be contracted from 2012 onwards. However, following the break-up of BNFL, the PBO competition was brought forward to 2007. Nuclear Management Partners (NMP)³, was awarded the 17-year contract in 2008, to be reviewed after five years (Haraldsen 2018). Until 2013, efficiency savings of 715 million GBP had been achieved, resulting in fee payments of 237 million GBP to Sellafield Ltd, from which NMP earned profits via dividends, see Figure 5 (NAO 2015). However, as NMP had focused primarily on short-term efficiencies, motivation had shifted away from longer-term investments, incurring cost increases that cannibalized efficiency gains. Consequently, performance based fees were reduced (NAO 2015). Doubts emerged on whether NMP was able achieve efficiency gains. Further incidents, while less severe, such as significantly higher wages being paid to NMP staff compared to local wage rates and reimbursed expenses for PBO executives, such as a trip to a golf tournament, added to the impression (Haraldsen 2018).

Despite these developments, the NDA in 2013 initially extended the contract with NMP for a second five-year period. Two years later, however, the contract was discontinued in favor of a “market-enhanced model” (NDA 2014; 2021a; NAO 2015). Reports on motivational challenges of SLC employees that hit a “glass ceiling” likely contributed to inefficiencies (BEIS 2021). While stating that the PBO model was adequate at other sites, NDA officials admitted that “many interacting [...] uncertainties and complexities on a very high interdependent site” reduced the effectiveness of the PBO model at Sellafield (Clarke 2014, 2).

³ A consortium of US company URS (a subsidiary of AECOM), British company Amec Foster Wheeler and French company Areva.



Note: The Base Fee was paid regardless of performance and is predetermined. The efficiency fee was earned upon outperformance of the contract baseline. Performance based fees were earned for achieving certain project milestones. Other fees were paid, e.g., for identifying work that could be removed from the plan without hindering other targets.

Figure 5: Fees paid to NMP by the NDA for Sellafield performance.

Source: Own depiction based on (NAO 2015, 19)

4.1.2.1.2 Magnox Ltd

Magnox Electric was initially run by PBO EnergySolutions (ES) from 2007 (Macalister 2007). By 2008, the NDA had announced that following the then perceived successful PBO competitions at Sellafield and Drigg⁴, plans to conduct further PBO competitions for the Magnox reactors and the Dounreay site were to begin by 2011 and 2009, respectively (WNN 2008b). So, in 2012, the NDA launched a competitive tender for the so-called Magnox Contract, valued at 6.2 billion GBP over 14 years, for Magnox Ltd and RSRL⁵ (House of Commons 2020). Competitors were CAS Restoration Partnership, a consortium of CH2M Hill International Nuclear Services, Areva and Serco, Cavendish Fluor Partnership (CFP), consisting of Cavendish Nuclear Services and Fluor Enterprises, United Kingdom Nuclear Restoration Limited, comprised of AMEC Nuclear, Atkins and Rolls Royce Power Engineering, and Reactor Site Solutions (RSS), a consortium of Bechtel and ES (Holliday 2021).

The Magnox Contract was designed as a target cost model. Competitors had made their bids on a baseline resulting from the assumptions made in the so-called Lifetime Performance Plan (LTP)⁶ 48 of

⁴ A low-level waste repository in Cumbria, see WNN (2008a).

⁵ SLC for nuclear sites Harwell and Winfrith (House of Commons 2020).

⁶ An LTP comprises of a programme of work and tasks (completed or planned) for one or more of the NDA's to-be-decommissioned sites, see Holliday (2021, 156).

the Magnox sites that had forecast the condition of the sites to September 2014, when work was supposed to begin after ownership change. For any mismatch from LTP 48 and the actual state of the sites, the NDA assumed liability. Deviations from the LTP 48 could result from inaccuracies in reporting or a lack of knowledge of the actual sites' state, and the performance of the then still operational PBO ES between April 2013 and September 2014 (Holliday 2021). In March 2014, the Magnox contract was awarded to CFP for 3.8 billion GBP, resulting in ES, member of RSS, suing the NDA for wrongful award of the contract, that led to a total of 122 million GBP in settlement and legal fees being paid to RSS by the NDA (WNN 2014; House of Commons 2018; 2020). Nevertheless, the consolidation period to set the baseline of the Magnox Contract with CFP began. By Spring 2017, CFP had submitted around 100 change requests, increasing the planned cost from 3.8 to 6 billion GBP (House of Commons 2018). Holliday (2021, 102–16) provides a detailed report on the procedures during this consolidation process. This cost increase was viewed as contract material variation risk, and thus, in March 2017, the decision was made to terminate the contract with CFP by September 2019. Termination fees paid to CFP amounted to 20 million GBP (House of Commons 2020). During the process, a team of only 20 was assigned to oversee CFL's evaluation, while CFL had 300 staff members dedicated to the job (House of Commons 2018; 2020).

4.1.2.1.3 British Energy

British Energy had been established to operate as a profitable business and expected to fund its nuclear liabilities using the Nuclear Liabilities Fund (NLF) (NAO 2004). In 2002 however, British Energy received its first government bail-out and required government support from thereon (S. Thomas 2006). British Energy in 2009 filed for bankruptcy and was purchased by French utility EDF, see below (to).

4.1.2.2 Financing

Initial contract designs of the PBO scheme, all financed via state budget (Wimmers et al. 2023), had been designed as cost reimbursable contracts, until the Sellafield contract in 2007 introduced a target-cost based approach. Here, costs were still reimbursed by the employer, but the contractor could earn fees based on achieved savings. The higher the savings, the higher the fees. However, if costs increased over a threshold, fees were reduced. The contracts were designed for durations of up to a decade and with a broad scope to allow the PBO to exert a high level of influence on the SLC and ensure enough flexibility to deliver the goals (Lal 2013; Haraldsen 2018; Holliday 2021). But the target cost approach required a high degree of knowledge of the sites to estimate to-be conducted tasks and resulting costs. This proved to be one of the main issues that caused the PBO scheme to fail.

In 1996, the NLF was set up in 1996 with an initial endowment of 223 million GBP to cover financial liabilities for waste management and decommissioning for all AGRs, as well as some spent fuel management liabilities for Sizewell B. The plan was to accumulate funds over several decades to limit the need for state funding (Nuclear Liabilities Fund 2021).

4.1.3 Decommissioning in the UK today (to)

4.1.3.1 Production

Sellafield Ltd is now a direct NDA subsidiary under the new “market enhanced model”. Since 2016, work is thus being carried out by Sellafield Ltd under direct governance of the NDA. Sellafield is to become the central interim fuel storage facility for the UK’s nuclear waste. All Magnox fuel has been transferred to the site. The Sellafield site is planned to be viable for reuse in 2125, a century from now. (NDA 2021a; 2022)

Since the termination of the Magnox Contract, full ownership of Magnox Ltd has been returned to the NDA. Decommissioning strategy changes have been conducted at certain “lead and learn sites” in an attempt to optimize the decommissioning approach for the legacy fleet and evaluate strategies for the soon-to-be closed AGRs in EDF Energy’s ownership. Most Magnox sites have since been defueled, while detailed plans on decommissioning completion dates remain unpublished. (Wimmers et al. 2023)

With its strategy change, the NDA has regained control of most nuclear sites in the UK. In parallel came the transfer of Dounreay Site Restoration Ltd, responsible for the fast breeder reactor clean-up in Scotland, into NDA custody. LLWR Ltd and Radioactive Waste Management Ltd, tasked with building a deep geological disposal facility, are to be merged as the NDA’s Nuclear Waste Services Ltd which is responsible for the transport of radioactive waste and other hazardous materials since 2021. (Wimmers et al. 2023)

British Energy was purchased by French state-owned utility EDF in 2009 (EDF 2022). Decommissioning obligations for British AGRs and PWRs now lie with subsidiary EDF Energy but, for the AGRs, will transfer to the NDA after defueling (House of Commons 2022).

4.1.3.2 Financing

The NDA is fully financed via the public budget. The government makes provisions for nuclear decommissioning that by 2021 had amounted to 135.8 billion GBP (NDA 2021b). Considering the decade-to-century long duration of UK decommissioning efforts, it remains uncertain whether these provisions will suffice (and will have to be further increased on taxpayers’ expense) (NAO 2016). The NDA’s annual budget lies at around 4 billion GBP and will likely increase as sites advance further towards hot-zone decommissioning (Wimmers et al. 2023).

AGR and PWR financing is to be covered by the NLF that has been underperforming for years and thus from 2020 to 2021 received tax-funded cash injections totaling 10 billion GBP. Financial responsibilities for Sizewell B and the PWR at Hinkley Point C, currently under construction, lie with EDF that has earmarked funds in its balance sheet for this purpose (Wimmers et al. 2023).

4.1.4 Summary

To summarize, the lack of NDA oversight and competence strengthened the PBOs’ informational advantages. Combined with the high complexity and uncertainty regarding the British legacy fleet, this poised a breeding ground for exploitive opportunistic behavior. Consequently, as of today, the NDA has resumed full ownership, control, and responsibility for the decommissioning of the legacy fleet, the

Sellafield site, and, in the future, the AGRs. The decommissioning strategy has been switched from a “blanket strategy” to a site-specific approach, and pooling information at a centralized organization (NDA) could benefit the UK’s decommissioning efforts. Whether decommissioning costs can be reduced, remains uncertain. The public budget will continue to finance legacy fleet decommissioning, while financing of AGR decommissioning is closely tied to the performance of the NLF, another point of uncertainty that merits a separate discussion.

4.2 United States

At its peak in 1990, the US nuclear power industry had 112 nuclear reactors in operation (Lordan-Perret, Sloan, and Rosner 2021). This number has subsided to 93. This not only makes the US operational nuclear fleet the largest, but also one of the oldest worldwide, with an average age of around 42 years⁷ (Schneider et al. 2023). The nuclear fleet’s ownership is characterized by a diverse array of organizational structures, reflected by heterogeneous organization in the nuclear decommissioning sector. Figure 6 provides a timeline for the organization thereof, from the early 1990s to today.

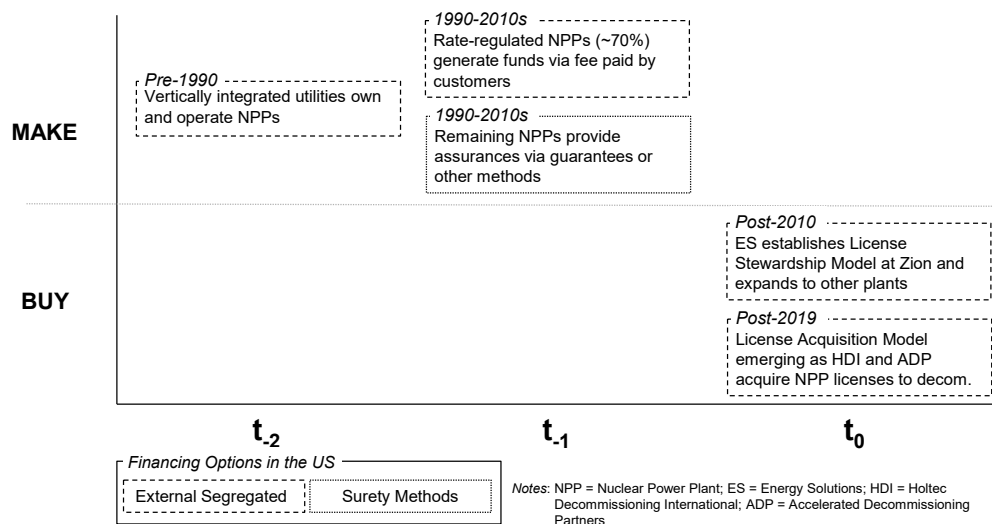


Figure 6: Timelines in US decommissioning responsibilities

4.2.1 Nuclear power market structure (t₂ & t₁)

Established monopolistic vertically integrated electricity generation structures were restructured in many states in the 1990s (Borenstein and Bushnell 2015). For the nuclear industry sector in these deregulated markets, this led to the recommercialization of their NPPs that, having been considered as stranded assets before the turn of the millennium, were now generating substantial profits due to high retail prices (Davis and Wolfram 2012). By the mid-2010s however, retail prices had dropped, leading to the implementation of support schemes for NPPs to keep them operational (Woo et al. 2014; Bah 2023a).

⁷ Superseded only by the Netherlands (50 years), Switzerland (47 years), Armenia (44 years) and Belgium (44 years).

Some plants have nevertheless closed early despite existing operational licenses (Schneider et al. 2023).

4.2.1.1 Production

Regarding power plant ownership, the US offers more diversity than the UK. While some plants are in federal ownership, e.g., via the Tennessee Valley Authority, others are (partly) owned by state utilities. Investor-owned power plants make up the bulk of US ownership structures. Following the above mentioned restructuring of the US energy sector, corporate NPP ownership is now consolidated to several large utilities such as Exelon or Duke (Bah 2023b). Direct plant ownership is held via limited liability companies that reduce the financial risk for the overarching corporations, but prompt uncertainties related to final liability (Lordan-Perret, Sloan, and Rosner 2021). Some plants are owned by not-for-profit member-owned utilities, so-called cooperatives. Other plants may be owned by a variety of owners (Bah 2023b). Following this diverse ownership structure, the approaches followed by owners and operators regarding first-tier-decommissioning are similarly diverse, ranging from vertically integrated approaches to more hybrid approaches (Wimmers et al. 2023). The analysis in the remainder of this paper focusses on NPPs in investor-owned structures where previously unknown organizational models have emerged.

4.2.1.2 Financing

In the US, decommissioning responsibilities lie with the nuclear licensee that can provide a range of financial instruments to ensure the availability of necessary finances. These may consist of forms of prepayment, externally managed funds, or surety methods. In the following, we refer to these collectively as “Decommissioning Trust Funds” (DTF). Funds are accumulated in various ways. For example, rate-regulated utilities charge a fee from customers which is then deposited to the DTF. Most utilities are authorized to accumulate funds throughout the plants’ lifetimes. When and how funds in a DTF can be spent, is regulated by the Nuclear Regulatory Commission (NRC). (Bah 2023b)

4.2.2 Organizational models in nuclear decommissioning since the 2010s (t₀)

Over the last few years, the decommissioning industry in the US has been experiencing some noteworthy developments, limited to the production side of decommissioning. The organization of financing (external segregated) remains unchanged. We thus refrain from separating the models in this section.

Recently, organizational models involving nuclear license transfers to and from specialized nuclear decommissioning companies have emerged (Maag 2019; Schneider et al. 2023). The US nuclear regulatory and energy systems pose a unique combination of requirements that allow for such organizational models to develop. First, the Nuclear Regulatory Commission (NRC) allows for a flexible license transfer process, and due to past restructuring in the nuclear sector, the NRC is experienced in this regard. Further, DTFs are linked to individual NPPs and are segregated from licensee balance sheets, also allowing for DTF ownership to be easily transferred. Thirdly, following the Federal Government’s failure in procuring a long-term waste repository and consequentially taking financial

responsibility for nuclear waste management, the risk of decommissioning companies having to finance waste management has been minimized (Stenger, Roma, and Desai 2019; Bell and Macfarlane 2022).

In general, three organizational models were identified: license stewardship, license acquisition, and fleet models (Bah 2023b; Stenger, Roma, and Desai 2019). While for the first two actual applications were identified, the third could not be verified as this type of model is still pending approval by the NRC (Bah 2023b). Thus, the subsequent analysis is limited to license stewardship and license acquisition.

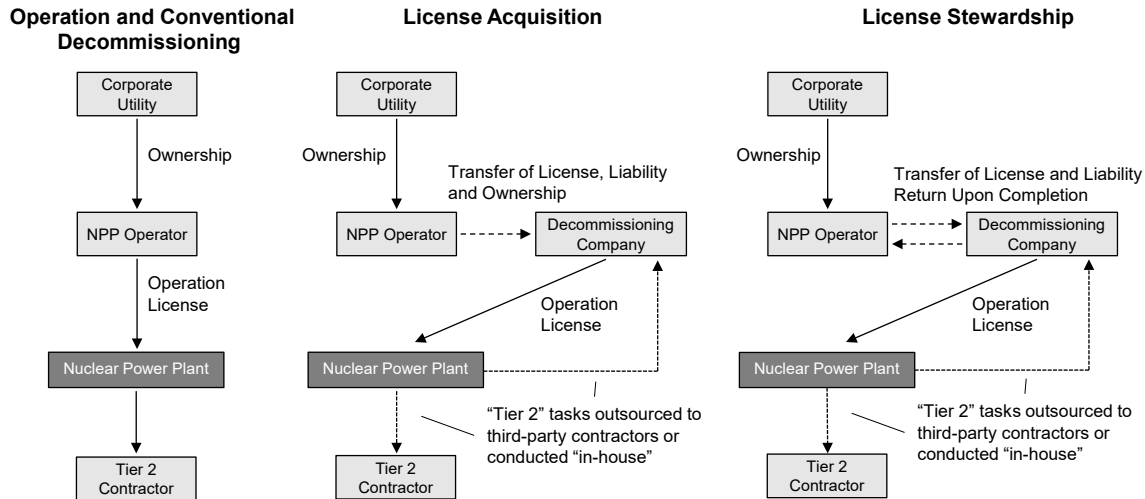


Figure 7: Nuclear Decommissioning Organizational Models in the US for investor-owned utilities

Source: Own depiction following (Wimmers et al. 2023)

4.2.2.1 License Acquisition

In the license acquisition model, decommissioning companies take over the ownership of the NPP, including all assets, liabilities, and the DTF. These companies typically purchase homogeneous NPPs to profit from supposed standardization and learning effects, to potentially achieve faster and cheaper decommissioning. Tasks on the Tier 2 are either contracted to third-party specialists or conducted vertically integrated.

The most prominent example for this is Holtec Decommissioning International (HDI), a wholly owned subsidiary of Holtec International, a company most known for its nuclear waste container products (HDI 2023). HDI is applying its decommissioning strategy to three NPPs: Oyster Creek and Pilgrim-1 (acquired in 2019), and Indian Point (acquired in 2021). Palisades was acquired in 2022, and while the plant has been defueled, HDI is currently seeking to restart commercial operations (Flesher and Associated Press 2023). Unlike the PBO approach, employees at acquired NPPs become employees at HDI (Radwaste Solutions 2021).

HDI follows a specific strategy for decommissioning that involves defueling the plants and then moving spent fuel from wet storage to dry cask storage at Independent Spent Fuel Storage Installations (ISFSI). HDI, as cask manufacturer, supposedly has the experience to safely operate ISFSI. The goal is to swiftly release the plant sites themselves from regulatory oversight (Schneider et al. 2020). The spent fuel is planned to be transferred to a consolidated interim storage facility that is currently being planned to be

operated by HDI, albeit facing opposition from the New Mexican government (Russell 2018; Moore 2023). With the federal government's failure to pursue the Yucca mountain repository, liability for long-term storage has moved to the taxpayer (Wegel et al. 2019; Bell and Macfarlane 2022).

Nonetheless, HDI is making progress. Oyster Creek adopted an immediate dismantling strategy and was defueled two years earlier than originally planned. Indian Point and Pilgrim-1 also now follow the same strategy (Schneider et al. 2023; 2018). HDI's inhouse knowledge and standardized decommissioning approach are claimed as main reasons for this (Radwaste Solutions 2021). Pilgrim-1 and Oyster Creek are both BWRs, while all three Indian Point reactors and Palisades are PWRs. Both BWRs are of the same model, the PWR designs differ (Wimmers et al. 2023).

Regulatory changes have also supported HDI's initial success. For instance, the NRC has amended regulations on safety and security at NPPs that are undergoing decommissioning, regarding, for example, emergency preparedness regulations (NRC 2021c). HDI itself is granted a further, rather substantial exception from current legislation and may use funds in the DTF for ISFSI management without prior NRC consultation or approval (NRC 2019). This might be one major incentive for HDI to follow their license acquisition approach.

Another incentive might lie in the DTFs themselves. According to the U.S. Code of Federal Regulation, "fund balances [that] exceed the amount expended for decommissioning [...] [shall be returned] to ratepayers" (U.S. Congress 2004, para. 35.32 (a) (7)). At Indian Point however, HDI claims that due to New York ratepayers not bearing the financial risk, surplus funds would remain with the owner of the DTF, i.e., HDI (MacMillan 2022; HDI 2023). Prospects were dampened in 2023, when, blaming unfavorable economic conditions, the completion date for Oyster Creek was pushed back by four years (Oglesby 2023).

Accelerated Decommissioning Partners (ADP), a consortium of US construction company NorthStar and French state-owned company Orano⁸, is HDI's main competitor (ADP 2017). Orano has conducted decommissioning operations in several European countries (Wimmers et al. 2023). NorthStar has experience in nuclear decommissioning in the US and UK (NorthStar Undated).

The Vermont Yankee plant had originally been following a deferred dismantling strategy that was changed to a direct dismantling approach by ADP after takeover (NRC 2021a). ADP also operates the Crystal River-3 plant in Florida, pulling the decommissioning date forward by several decades. Here, utility Duke Energy remains as owner and licensee of the reactor, and ADP acting as the operator while being compensated through the DTF. ADP has become the owner of the onsite ISFSI (ADP n.d.). This approach can be identified as a more conventional decommissioning in which tasks are outsourced by the utility to a third-party contractor.

⁸ As of end-2021, the French State held 89.99% of Orano's shares (Orano 2022).

4.2.2.2 License Stewardship

Two substantial differences separate license stewardship from license acquisition. First, the operating license is transferred to the contractor, but ownership of the site and spent fuel or other assets remain with the original licensee. With the operational license however come access to the DTF and, consequentially, financial liabilities and obligations. Secondly, the license is returned to the original owner upon completion of decommissioning tasks.

As of today, Utah-based EnergySolutions (ES) is the only known decommissioning operator practicing this approach. ES was active as the PBO for the UK's Magnox fleet until 2014 and conducted dismantling work at several power plants in the US, e.g. Three Mile Island-2 (Schneider et al. 2020). ES has been following the license stewardship approach through specially created subsidiaries.

ZionSolutions was founded in 2010 to take over the license of the Zion NPP in Illinois. This initiated actual decommissioning work, although the plant had been closed in 1998 (Hylko 2014). Reactor vessel parts and other contaminated parts were shipped to ES' disposal facility in Clive, Utah, where they were further dismantled (Bah 2023b). While physical decommissioning was completed in 2020, ZionSolutions has been awaiting approval for unrestricted release by the NRC to retransfer the license back to utility Entergy (NEI Magazine 2021). In 2016, the license for the LaCrosse reactor that had been in LTE since 1987 was transferred to LaCrosseSolutions (NEI Magazine 2021; K. Thomas 2016). In 2023, the site was released by the NRC for unrestricted use and the license is to be returned to local utility Dairyland Power (Radwaste Solutions 2023). ES' most recent project involves the Kewaunee NPP that was closed for economic reasons in 2013. In May 2022, the license was transferred to KewauneeSolutions (Dalton 2022). Following this license transfer, the decommissioning date is to be moved from 2073 to 2031 (NRC 2021b).

Similar to HDI, information on ES' incentives is ambivalent. Reports suggest that ES will be able to pocket surplus cash from DTFs if decommissioning is conducted for less money than planned (McDevitt 2023).

4.2.3 Summary

From today's point of view, license acquisition and stewardship could bring substantial efficiency gains as monitoring and tender efforts are reduced for the original licensee. However, costs of discovery, especially regarding DTF balance and the physical conditions on site remain, although these are borne by the potential steward or acquirer. Additionally, assuming that a decommissioning specialist fails in completing the task and another firm steps in, multiple license transfers could increase regulatory oversight needs to ensure that profit-maximizing entities remain committed to safety and security principles of nuclear decommissioning.

5 Discussion

Following the discussion of organizational models in Section 3.2, we classify the described organizational models in the UK and US. We find that the NDA, as principal, outsourced management tasks to the PBO (agent), while actual work was still conducted by the SLCs, officially state-owned companies. Today, with the NDA having taken full responsibility of decommissioning and waste management, these tasks are fully vertically integrated and thus fit the “MAKE” category. The PBO scheme is a “HYBRID” approach due to the interrelations of actors. The same goes for the UK’s AGRs currently in EDF Energy ownership, while the PWRs will be decommissioned by EDF in a “MAKE” approach. In the US, license stewardship is an example of a “BUY” strategy. The same goes for the license acquisition scheme where the whole task (and responsibility) is sold off. Figure 8 shows the classification for all schemes. In the following, we discuss differences regarding the efficiency of the UK and US approaches.

	Public Budget	Internal Segregated	Internal Non-Segregated	External Segregated	Guarantees
MAKE	UK Legacy Today	UK PWRs		UK AGRs	
HYBRID	UK PBO				US Others
BUY				US Stewardship US Acquisition	

Note: PWR = Pressurized Water Reactors; AGR = Advanced Gas-Cooled Reactors; PBO = Parent Body Organizations

Figure 8. Organizational Models for Nuclear Decommissioning in the UK and US for production (vertical) and financing (horizontal)

The PBO scheme demonstrates the influence of asset specificity and information asymmetry exploitation by opportunistic actors on nuclear decommissioning. The NDA was unable to monitor progress due to lack of information and heterogeneous sites, but their main disadvantage was the lack of qualified personnel compared to well-equipped PBO staff. In the initial reimbursement contracts, work could not be accurately monitored, and for the target cost contracts, baseline determination became impossible, leading to the termination of all PBO contracts.

As the US companies’ approach focuses on selected individual rather than several plants, allowing for more accurate assessments of DTF adequacy and site status. As utilities can rid themselves from future liability, monitoring costs on their side remain limited – and because they were operating the plants themselves, they likely have better insight of the state of the plants than the UK’s NDA; information that can be passed on to the decommissioning company.

Merging private and public employment in the PBO reduced employee motivation and efficiencies. The US companies address this issue by directly employing on-site workers. As the US nuclear industry is

organized more privately than publicly, the differences between public and private sectors might be less prevalent.

US actors actively search for closed NPPs that fit their portfolio and monitor them until they can acquire a license or make a stewardship contract. In contrast, with the NDA having to first design an overly complicated tender and then compare bids, delays and mistakes led to inefficiencies and cost increases.

Nuclear decommissioning is a process that can take several years, even decades, to complete. In the PBO scheme, contracts were designed for around 5 years, with possible extensions. This led to PBOs focusing on short term efficiency gains to earn fees rather than long-term investments. Now, having regained full control, the NDA applies a more long-term view that might lead to faster decommissioning in the long run. In the US, the agent has certainty regarding the decommissioning process. In license acquisition, the agent knows that the burden of having to complete decommissioning has moved to themselves, while in license stewardship, ultimate liability remains with the principal.

Financial liability differs substantial between the UK and US cases. The PBO scheme was designed to involve private companies in decommissioning without nuclear waste obligation and liability transfers that remained with the state. For the US, the situation is more diverse due to the heterogeneous ownership structure. While with the license acquisition model all financial liability for decommissioning is transferred to the new licensee, and in the stewardship model, liabilities remain with the principal, while waste management liability and responsibility lie with the federal government.

The US model relies on certain prerequisites to function, such as pre-existing expertise in the decommissioning field and (potential) access to centralized interim waste storage facilities. Other requirements, include plant specific DTFs and flexible license transfers.

The US outsourcing approaches have led to faster decommissioning as direct dismantling strategies are being applied. As US actors gain experience and extend their fleets, costs might be reduced through economies of learning. However, asset specificity and the limitation to certain power plants raise the question of whether this approach is suitable for all decommissioning projects. Some plants may pose more challenges and require specific approaches. Competition limited to a subset of plants could lead to overall inefficiencies as highly specific plants might be neglected.

Further, profit-maximizing decommissioning companies might feel additional pressure to swiftly decommission to ensure DTF fund sufficiency. This could incentivize actors to cut corners in terms of security and safety measures, potentially endangering local communities and on-site workers, or leading to project termination through regulators. While this has not yet been observed, the early stage of the nuclear decommissioning industry, and the uncertainty regarding NPP contamination and consequentially cost warrant caution.

6 Conclusion

The relevance of nuclear decommissioning in industry and policy will only increase over time as more and more NPPs inevitably close and face demolition. As NPPs pose safety and security risks even after closure, timely decommissioning is of utmost importance. However, historically, decommissioning was neglected in a nuclear industry that now faces substantial challenges in terms of project cost and duration overruns.

To allow for safe, swift, and cost-efficient decommissioning, regulators have implemented a degree of legislation that resulted in the emergence of various organizational models of which two were analyzed in this paper. Both models attempted at bringing private industry actors into nuclear decommissioning, although with underlying differences in terms of plant ownership and history. The findings of this analysis however are limited to Tier-1 organization and might not apply to the organization of Tier-2-tasks for individual part demolition by specialized contractors. Further, the unique regulatory and market settings in both the UK and US could limit the transferability of these models to other countries.

The UK's attempt at bringing private expertise to nuclear decommissioning faced the major challenge of finding private actors that would take on waste management liabilities. This led to the construction of the PBO scheme which failed due to organizational challenges experienced by the NDA, such as lacking monitoring capacity, and uncertainty regarding contamination at British NPPs.

Following this experience, we recommend countries that rely on state-funded actors to own and operate NPPs to note the high level of TAC that the British privatization attempt incurred. Consequently, it might be beneficial to leave or transfer decommissioning responsibilities with state actors as this is most likely where site specific institutional and technical knowledge will be kept. Further, questions of liability need not be addressed. However, this poses risks of inefficiencies and the possible nationalization of previously private liabilities and places the (financial) burden on future generations.

Uncertainty can also be observed in the US where, historically, utilities placed NPPs into LTE to allow for radiation levels to decrease. Newly emerged market-based organizational models have led to several NPPs being decommissioned much sooner. However, given that involved actors limit their activity to homogeneous NPPs, questions arise whether this model could be applied to the whole US reactor fleet and elsewhere. NPPs with unknown levels of radiation, a high degree of asset specificity or insufficient DTF volumes might not be attractive to be decommissioned by profit-maximizing private actors. This calls for regulation to clarify liability issues regarding finance, and the obligation to actively decommission and not place reactors into LTE for uncertain durations.

Liability clarification and financial transparency are also necessary if competition in the nuclear decommissioning industry is to be encouraged. Costs of discovery can be reduced when information on fund volumes is publicly available. This of course does not reduce uncertainty regarding the plant itself, and as cost estimations for nuclear decommissioning remain unpublished or uncertain and outdated at best, the assessment of fund adequacy should be addressed in future research.

We established that lacking willingness of private actors to take on liabilities for nuclear decommissioning and waste management resulted in the construction of the PBO scheme. In the US, the federal government has taken over final responsibility for interim and long-term waste storage.

Consequentially, private actors are exempt from liabilities and may profit from government inaction by providing waste management and storage services. Therefore, to allow for privatization of nuclear decommissioning, responsibilities and liabilities must be clarified, and repositories made available soon. However, we suppose that if decommissioning contractors were forced to take on liability and consequential (financial) risks, competition in this field would be limited.

While there is no general lesson, we can state that attempts to increase the productivity in the decommissioning process seem to be worth the while, provided they are backed by solid regulation. This also applies to their countries follow different approaches than those discussed above. Germany, for example, has each utility decommissioning itself, with second-tier contractors conducting specialized tasks. Here, around 30 reactors are being decommissioned in parallel. In France, state-utility EDF plans to decommission the somewhat standardized PWR fleet on its own (Wimmers et al. 2023). Both countries could benefit from higher productivity incentives for the current monopolistic incumbents and consider some changes in the organizational structure to this end.

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