Decommissioning of Nuclear Power Plants and Storage of Nuclear Waste

Experiences from Germany, France, and the U.K.

Ben Wealer, Jan Paul Seidel, and Christian von Hirschhausen[1]

Abstract

The decommissioning of nuclear power plants and the storage of nuclear waste are major challenges for all nuclear countries. Both processes are technologically and financially challenging. We provide an analysis of the status quo of both processes in three major nuclear countries: Germany, France, and the U.K. Germany was able to gain some decommissioning experiences but not one large-scale reactor has been released from regulatory control. EDF was forced to cancel its target to immediately dismantle all GCRs by 2036 due to underestimated technological challenges, while in the U.K., decommissioning of the legacy fleet lasts well into the 22nd century. Until now, no scale effects could be observed, if EDF can reap scale effects due to the standardization of its fleet remains to be seen. The search for a deep geological disposal facility is the most advanced in France, where the start date is fixed by law to 2025. There are many uncertainties related to estimated future costs. In the three countries, three different funding schemes are implemented: Germany switched from internal non-segregated funds to an external segregated fund for waste management. In the U.K. the decommissioning of the

1 Ben Wealer, TU Berlin, Germany, bw@wip.tu-berlin.de; Jan Paul Seidel, TU Berlin, Germany, janpaulseidel@gmail.com; Christian von Hirschhausen, TU Berlin, Germany, cvh@wip.tu-berlin.de

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legacy fleet will be paid by the taxpayer for the next 100 years while an external segregated fund was established for the current operational fleet. In France, an internal segregated fund finances the future liabilities of EDF.

1 Introduction

The decommissioning of nuclear power plants (NPP) and the long-term storage of nuclear waste are important elements of the life cycle of nuclear power plants, but both processes have been underestimated for a long time, both in terms of the technological challenges as well as the financial implications. Traditional economic analysis has discounted the future costs for decommissioning and storage so that these never appeared in the financial calculations. Furthermore, the little available experience leads to a high uncertainty about future pathways. In addition, technical and financial data are difficult to compare between countries.

In this chapter we provide an in-depth analysis of decommissioning and waste storage processes in three major European nuclear countries: Germany, France, and the United Kingdom. To do so, we are going to compare the different national strategies of organizing and financing the decommissioning of NPPs and the storing of high-level nuclear waste. We distinguish between the two main elements of the strategy: production and financing. First, someone has to manage and organize the decommissioning and storage process (the production): this can either be private or public companies, or a mixture of both. Second, both processes need to be financed: This can be done by the federal budget, an external segregated fund, or in-house financing by the companies, usually done in internal funds—segregated or non-segregated (OECD/NEA 2016a).[2]

The shutdown reactors in the three observed countries France, Germany, and the U.K. account for more than 77% of the reactors in shutdown state in the European Union (European Parliament 2013). In addition, these countries represent interesting features that reveal the different experiences and challenges. Germany is just exploring ways for large-scale decommissioning, having decided to phase out

2 External segregated fund: The operators pay their financial obligation in a publicly controlled fund managed by private or state owned external independent bodies. Internal non-segregated fund: The operator of a facility is obliged to form and manage funds autonomous, which are held within their accounts as reserves. Internal segregated fund: The operator feeds a self-administrated fund, which is separated from the other businesses.

nuclear power by 2022. Both, France and the U.K., are facing specific technological challenges with the graphite-moderated reactors of the 1960s. There are concerns in France that the financial challenges of the future decommissioning process—with 58 still operational reactors France will face the largest decommissioning project in Europe—are not yet well understood and underestimated. The case study of the U.K. reveals organizational and financial challenges of having to clean up after a few decades of operating the nuclear sector, and the long time frames to be expected.

The focus of this chapter is on the decommissioning of large-scale NPPs that were operated commercially for electricity production and the management of high-level radioactive waste (HLW). The two light water reactor (LWR) concepts—the pressurized water reactor (PWR) and the boiling water reactor (BWR)—are the most widely installed reactor designs in the world. However, in this case study, the only BWRs are located in Germany while France only operates PWRs. The concepts for gas-cooled and graphite-moderated reactors (GCR) were developed

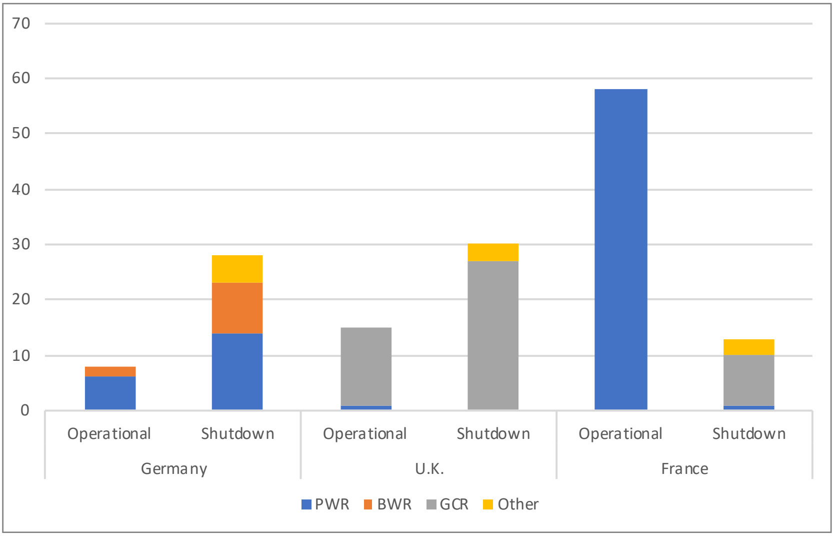

Fig. 1 Operational and shutdown reactors by reactor type in the observed countries, own depiction based on IAEA (2017).[3]

3 The cluster "other" comprises for France: two fast breeding reactors (FBR) and one heavy-water moderated gas-cooled reactor (HWGCR); for Germany: one high-tem-

and installed in France and the U.K. While France ceased operations of its entire GCR fleet, they are still operational in the U.K. The number of shutdown reactors in the United Kingdom and Germany outweigh the operational reactors by a large amount, as can be seen in Fig. 1.

The decommissioning and clean-up of the global civil nuclear legacy and the long-term storage of nuclear waste represents technological, safety and environmental challenges for all nuclear countries. During the period when nuclear energy was established, the focus of planners and operators was predominantly on designing, building and operating a safe plant and only limited on the eventual decommissioning of the facility and the management of resulting radioactive wastes (McIntyre 2012). In general, the decommissioning process of an NPP moves from the outer to the inner area of the reactor. Simultaneously, the degree of contamination of the handled parts increases. The eventual process of decommissioning of the nuclear power plant can be divided into five main stages.[4] A geological disposal facility for high-level waste is still missing worldwide. As spent nuclear fuel (SNF) has to be stored for 40–50 years in order to cool down, before it can be permanently stored in an underground disposal repository, the time was not that pressing to tackle this problem for the responsible actors, which led to the construction of interim storage facilities for high-level wastes.

As the goal of this chapter is an analysis of the technical, organizational and financial status quo of both processes in Germany, France, and the U.K., the different national strategies and approaches of organizing the production and the financing of the decommissioning process, and storing the nuclear waste will firstly be analysed and then compared; the final section concludes.

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perature gas-cooled reactor (HTGR), one FBR, two pressurized heavy-water reactors, one HWGCR, and one FBR; for the U.K.: two FBRs and one SGHWR

4 Stage 1: Dismantling of systems that are not needed for the decommissioning process and installation of the logistic in the hot zone. Stage 2: Dismantling of higher contaminated larger system parts. Stage 3: Dismantling in the hot zone, e.g. deconstruction of the activated reactor pressure vessel (RPV) and its internals (RVI) and of the biological shield. Stage 4: Deconstruction of contaminated system parts, removal of operating systems and decontamination of buildings. Stage 5: Demolition of the building or further nuclear or non-nuclear use (Wealer et al. 2015).

2 France

With a nuclear share in the net electricity production of 72.28% in 2016 (IAEA 2017) France still relies heavily on nuclear power. The Energy Transition for Green Growth bill, approved by the National Assembly in 2015, foresees a reduction of this share to 50% by 2025. In 2017, Electricité de France (EDF) operates 58 NPPs on 19 sites across the country with a total installed capacity of 63.2 GW. The oldest running reactors are the two Fessenheim units which became critical in 1978, and the most recently installed NPPs are the two Civeaux units, commissioned in 2002. The French nuclear fleet has an average age of around 30 years and has with its three PWR designs[5] the highest degree of standardization in the world (World Nuclear Association 2017). All the nuclear steam supply systems of the operational NPPs were designed by Framatome (IAEA 2017). In 2010, EDF announced that it was assessing the prospect of raising the 40-year lifetimes to 60 years for all its existing reactors. This strategy would involve replacement of all steam generators in the 900 and 1,300 MW reactors and other refurbishments costing 400–600 million EUR per unit.[6] As the focus of this chapter lies on the decommissioning and waste management of commercial NPPs, the activities of EDF will be the focus in the following.

2.1 Production

2.1.1 Decommissioning of nuclear power plants

Currently, there are 13 NPPs in a stage of permanent shutdown; of which nine NPPs are from the first-generation GCRs, similar to the U.K. Magnox reactors. Chooz-A is the only PWR currently being decommissioned by EDF. The decommissioning of the former military installations in Marcoule G-1, G-2, and G-3 is taken over by the public nuclear research agency Commissariat à l'énergie atomique et aux énergies alternatives (CEA). French regulation states that NPPs have to be immediately dismantled and the process has to be carried out as fast as possible; depending on the complexity of the plant this could mean several years up to several decades (Autorité de sûreté nucléaire 2016b). Initially EDF planned to decommission its shutdown NPPs in two waves within 25 years with an estimated end in 2036 (Au-

5 The three-loop 900 MW reactors (CP0, CP1, CP2), the four-loop 1,300 MW reactors (P4), and the four-loop 1,450 MW reactors (N4).

6 So far EDF has replaced the three steam generators in 22 of their 900 MW reactors, ordered 44 steam generators for eleven of the 1,300 MW class and will proceed with the other nine (World Nuclear Association 2017).

torité de sûreté nucléaire 2016a). The first wave consisted of the FBR Super-Phénix, the HWGCR Brennilis, the PWR Chooz-A and the GCR Bugey-1; in the second wave the last five GCRs Chinon A 1–3 and Saint Laurent A 1–2 were planned to be decommissioned. This ambitious plan was changed in 2016.

Chooz-A (operational from 1967 to 1991) was the first European commercial PWR and built under a Westinghouse license. By December 1995 the reactor was defueled and the SNF dispatched to the reprocessing centre in La Hague. The policy change in the French decommissioning strategy in 2011 from Long-Term Enclosure to Immediate Dismantling accelerated the decommissioning plans and reduced the enclosure period from 50 to only a few years (European Parliament 2013). Since 2014, the reactor pressure vessel of Chooz-A is being decommissioned under water. The work was contracted to a Westinghouse-Nuvia France consortium (Hitchin 2010). The experiences with the PWR dismantling are seen as an important feedback source for the further dismantling of the still operational PWR fleet, but this is questionable (Seidel and Wealer 2016) as Chooz-A is an early reactor design and quite unique with its embedment inside a bedrock of a hill in the Ardennes. Chooz-A is therefore not really comparable to the other PWRs. EDF missed the ambitious target of completing the decommissioning process by 2016, the process is now expected to be completed by 2020–2025 (Martelet 2016).

As disposal routes for irradiated graphite waste are still missing, the Long-Term Enclosure of a GCR is the worldwide preferred decommissioning strategy. Nonetheless the change of EDF's strategy also affected its GCR decommissioning strategy, which was considered to be more global and interconnected as it had to cope with a considerable amount of irradiated graphite. To cope with this waste, EDF initially started with the construction of an interim storage facility on the Bugey site, but the construction was stopped in 2012. In 2016, EDF announced a change of its GCR strategy to the regulatory authority ASN (Autorité de sûreté nucléaire): the focus for the next 15 years would lie on dismantling nuclear installations except for the reactors and its buildings. The plans foresee that the first reactor (Chinon A-1) will start the dry dismantling in 2031; during the estimated dismantling duration of 25 years, the five remaining reactors will be enclosed. This new strategy will lead to a possible release of the GCRs from regulatory control in the beginning of the 22nd century. The major motivations for a switch to a dry dismantling strategy were constrains due to the long immersion times of the reactors, i.e. corrosion and leak tightness (Martelet 2016). The initial plan with the continuous flow of graphite waste and the very tight focus on the reactor core could not be implemented because the actual dismantling is technologically complex and needs more preliminary tests than expected.[7] ASN recognized the proposal and expects by the end of 2017 a detailed decommissioning plan for the next 15 years and EDF to take a position regarding this sudden change in strategy. In France, EDF officially uses the term "Safe Configuration" instead of Long-Term Enclosure (or Safe Storage), while in the U.K., where EDF Energy is responsible for the decommissioning of the operational GCR fleet, the company opts officially for the Long-Term Enclosure strategy. It is also unsure, if the new strategy is compatible with the implication of the French regulatory authority to carry out the decommissioning as fast as possible (Seidel and Wealer 2016).

2.1.2 Storage of high-level wastes

As France operates a closed fuel cycle, SNF is not declared as waste but as a resource and is reprocessed in La Hague by Areva. The glass canisters containing vitrified HLW are stored at the production sites Marcoule, Cadarache, and La Hague (Lehtonen 2015). The final forecasts for the generated waste of the operational nuclear fleet—assuming an average life of 50 years—is expected to be around 10,000 m^3 (OECD/NEA 2016b). The Waste Management Act established the way to treat radioactive waste and set the direction of research undertaken by the government agency ANDRA. Research for a final storage is mainly undertaken at the 500-metre deep underground rock laboratory Cigéo in Bure situated in clays. ANDRA expects to present its master plan to the government for operation and disposal at Cigéo site in 2017 and expects a construction permit in 2018. Construction should start in 2020 and the start of the pilot phase is set by law to 2025. Contrary to other countries, research is also undertaken in the field of partitioning and transmutation, and long-term surface storage of wastes following conditioning. A major part of the low-level long-lived waste is the graphite from the GCRs, which is probably going to be stored 200 meters underground in a layer of clay as ("Intact Cove Disposal") or going to be stored with the HLW in the Cigéo disposal (Ministry for Ecology, Sustainable Development and Energy 2014).

7 According to EDF's previous time schedule, the critical path of the former GCR initial decommissioning project consisted of the graphite removal from the reactor core and the decommissioning of the reactors was already well behind in schedule in 2011 (Laurent 2011).

2.2 Financing

Applying the polluter-pays-principle, the operators of nuclear power plants are responsible to bear all costs related to decommissioning and waste management. The financing scheme is based on two different kinds of funds. The first is characterized by a segregated internal fund set up by EDF and Areva[8] and managed under separate accountability. Besides that, there are two more internal restricted funds related to ANDRA: one for research for future storage facilities and one for the construction and operation of a future storage facility for medium and long lived high-level waste. The majority of future costs is related to the facilities of EDF. **Table 1** provides this cost estimation and the provisions set aside by EDF.

Tab. 1 Estimated costs of EDF end of 2016 in million EUR (EDF 2017).

Purpose	Estimated costs end of 2016 (Mio. EUR)	Provisions set aside end of 2016 (Mio. EUR)
Spent Fuel Management	18,460	10,658
Long-term Radioactive waste management	29,631	8,966
Nuclear plant decommissioning	26,616	14,122
Last cores	4,344	2,287
Total	79,051	36,033

In total, the estimated costs are more than 79 billion EUR, with the main parts being for the geological disposal facility Cigéo (~ 30 billion EUR) and decommissioning (~ 27 billion EUR). Critical reports about the cost estimations mention that, especially the decommissioning costs of 27 billion EUR for 58 reactors are underestimated. Extrapolations of costs estimations of other countries show that EDF is expecting comparatively low costs per unit (Cour des Comptes 2014). EDF argues that the costs will be lower due to the high standardization degree of their fleet and because multiple reactors are situated on the same site (Assemblée Nationale 2017). Nonetheless, the cost estimations are increasing continuously every year. In only three years, since the end of 2012, the estimated costs increased by nearly 10 billion EUR. The current provisions are discounted with an interest rate of 4.2% and an assumed inflation rate of 1.5%. As always, little changes of the estimated interest or inflation

8 Areva has no NPPs and operates nuclear facilities like the reprocessing center in La Hague.

rate for provisions and cost can have large influences on the calculations resulting in an underestimation of the needed financial resources. In its assessment of the EDF decommissioning and waste strategy, the French National Assembly could not the share "the excessive optimism" of EDF for its future decommissioning projects. The report concluded that the decommissioning and the clean-up will take more time, the technical feasibility is not fully assured, and will cost more money than EDF currently anticipates (Assemblée Nationale 2017).

The two funds set up by the waste management agency ANDRA are fed by payments from the operator's internal funds at the time they are needed. The only fund fed right now is the research fund, receiving payments through a tax paid by the operators. As there is not yet a construction license, the construction fund is currently not fed but the operators make payments from their internal funds to ANDRA's general budget to finance operations related to the storage facilities for short-lived, medium-level wastes. AREVA and EDF were forced to advance their back-end provisions and accountancy practice because of partial privatizations. Both have now set up restricted internal segregated funds for the financing of the nuclear back-end. EDF feeds its fund by a charge of 0.14 Eurocent/kWh included in the price of electricity. Due to the Waste Law of 2006, the assets in the funds of EDF and Areva have to be accounted separately and the market value has to be at least as high as the provisions to be covered. In cases of insolvency or bankruptcy of an operator, the state can claim right over the assets. The internal funds are supervised by an administrative authority, who is authorized to impose corrective measures. This also includes the right to impose payments to ANDRA's budget. A detailed report about the estimated costs, the timing and the value of the provisions has to be presented at least every three years (European Commission 2013).

2.3 Conclusion for France

The operators EDF and CEA are responsible for the decommissioning of their power plants. While the latter is clearly a public agency, this classification is not so clear for EDF. The major shareholder of the private company is the French state (over 85%), making EDF de facto a public enterprise. The gained decommissioning experiences are not sufficient and the strategic impact of Chooz-A for the future decommissioning of the operational PWRs is questionable. If Chooz-A finishes in 2025, the process will have taken 34 years to complete. The decommissioning process of the GCRs has not really started yet and an end is not in sight. A long time frame is to be expected, reaching well into the 22nd century. The management of high-level radioactive waste is in the hands of the public agency ANDRA. The anticipated start of operations of the HLW disposal facility to begin in 2025 is ambitious. The financial aspects of the nuclear back-end in France are dominated by questionable cost estimations and hence set aside financial resources which are likely to be too low. The internal segregated funds are managed by the operators and subject to an administrative control and oversight by national authorities. If this control will be able to prevent a shortfall of financial resources in the future is uncertain.

3 United Kingdom

The U.K. currently operates 15 NPPs on 8 sites—all operated by EDF Energy, a subsidiary of EDF—and has an installed nuclear capacity of 8.8 GW representing a nuclear share of 20.4% of the British electricity production in 2016 (IAEA 2017). The latest shutdown was Wylfa-1 in 2015. A particularity of the British nuclear feet is that, with the exception of Sizewell B (PWR) only GCRs are operational. At the moment, EDF Energy is considering lifetime extensions for its nuclear fleet until 2023[9], and is therefore investing about 600 Mio. GBP in plant upgrades (EDF 2017). Currently, there is a controversial discussion about plans to commission new reactors with a total capacity of 16 GW starting in 2030, including the well discussed NPP Hinkley Point C.

3.1 Production

3.1.1 Decommissioning of nuclear power plants

The first generation of British NPPs—the so-called Magnox line—was operated by the publically owned British Nuclear Fuels Limited and U.K. Atomic Energy Authority (UKAE) and is in a state of shutdown now. The public body Nuclear Decommissioning Authority (NDA) is responsible for the decommissioning of this legacy fleet. The NDA estate comprises besides the Magnox NPPs, research centres, fuel-related facilities, and Sellafield, the most hazardous site in Europe. Here the site operations include fuel reprocessing, fuel fabrication, and storage of nuclear materials and radioactive wastes. With the exception of the latter, all sites are managed through private-sector consortia, while Sellafield is managed by the NDA itself. The NDA has employed more than 3,500 contractors all over the U.K.

9 Sizewell B will probably be extended until 2055.

and already spent around 12 billion GBP; contracting is critical to the NDA, as 95% of the NDA's funding is spent externally (NDA 2016c).

The 17 sites of the estate are grouped into 6 Site Licence Companies (SLC). The NDA owns these sites and takes the role as the supervising and contracting authority and is turning the management over to the contractors, the so-called SLCs under European public procurement law. The latter are the long-term shareholders of the sites but the management is periodically open to competition. The winner of these contracts acts as the Parent Body Organization (PBO). The PBO receives the shares of the SLC and organizes the strategic management for the duration of the contract. This mechanism was introduced with the idea to increase the efficiency of the procedure by opening the work to private contractors (MacKerron 2015). The NDA is responsible for defining both the target and the timing of decommissioning and remediation, allowing the SLCs to determine how best to deliver this outcome. The current plans of the NDA indicate that it will take around 110 years to complete the core-mission of nuclear clean-up and waste management (NDA 2016c).

With the exception of Calder Hall 1–4, part of the Sellafield complex, all the sites with Magnox reactors are operated by Magnox Limited. Since 2014 Cavendish Fluor Partnership[10] is the current PBO and hence the long-term owner of Magnox Ltd. and supplier of the strategic management and additional resources. The Sellafield complex is operated by the SLC Sellafield Limited. The organization of this site was changed in April 2016 and Sellafield Ltd is now a wholly owned subsidiary of the NDA. A detailed review concluded that the complex, technical uncertainties at the Sellafield site were less suited to the PBO model (NDA 2016a). Its mission to retrieve nuclear waste from some of the world's oldest nuclear facilities extends well into the 22nd century and the sums of money involved are much greater than on other NDA sites.

Since 1977, 30 reactors were shut down and 26 of these are currently in the dismantling process. The current strategy for the Magnox fleet is the Long-Term Enclosure approach. With the exception of the Wylfa reactors, the reactors are defueled and most of the systems external to the biological shield have been removed. According to NDA's strategy, the biological shield, the reactor pressure vessel, the external pressure circuit, and steam generators would be sealed and stored. The dismantling of the reactors will begin 85 years after the shutdown of the plant. However, the NDA and Magnox Ltd are currently reviewing their strategy as there have been advances in remote decommissioning techniques and considerable experience gained in remote handling, packaging, and storage of highly activated waste at Magnox sites. In addition, an improved understanding of

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10 A consortium of Cavendish Nuclear—a subsidiary of Babcock International—and Fluor.

the implications of radioactive decay has shown that after the long period of Long-Term Enclosure, the larger amount of the reactor waste will still not be suitable for management as low-level waste. A last development is the realization that the reduction in decommissioning costs with the increase in deferral time is largely offset by the increased cost of preparing and managing the Long-Term Enclosure of the reactor. The waste has been conditioned on-site and interim storages have been built to store the waste until the final disposal route is available. Some site decommissioning and remediation work has been undertaken at most sites with a major focus on the preparation of the ponds for the Long-Term Enclosure state. Since 2011 the focus has been on the plants in Bradwell and Trawsfynydd. Magnox is working towards a target of placing all the reactors into the Long-Term Enclosure state by 2028. The ultimate goal for NDA's mission is to achieve the end state of all sites by 2125 (NDA 2016c).

3.1.2 Storage of high-level wastes

The NDA advocates an approach where wastes are managed according to the radiological, physical, and chemical properties and divides its strategy of radioactive waste management in two topics: Higher Activity Waste (HAW) and Lower Activity Waste (LAW).[11] According to the NDA (2015), the radioactive waste stocks and future arising sum up to around 4,720,000 m^3 in terms of final packaged volume. About 90% of this volume can be attributed to LAW and about 10% consists of HAW. 75% of the NDA-owned HAW is from the Sellafield Site and about 22% from Magnox sites (NDA 2015). Within the U.K., there are large quantities of graphite present with approximately 60,000 tonnes on the Magnox sites alone (NDA 2016b). As the dismantling of the reactors is deferred, the biggest amount of graphite will arise from 2070 onwards. High-level vitrified waste stemming from reprocessing SNF is stored in stainless steel canisters in silos at Sellafield. In 2016, a dry cask storage facility for SNF was commissioned at the Sizewell B station. U.K. policy states that SNF management is a matter for the commercial judgement of its owners, subject to meeting the necessary regulatory requirements. SNF is not considered as waste and the U.K. has a closed fuel cycle in place, i.e. used fuel was reprocessed. If the U.K. government gives up reprocessing and declares SNF as a waste, SNF would be

11 The term HAW refers to all radioactive material that has no further use and is either LLW, ILW or HLW and deemed not suitable for the disposal at the LLW repository in Cumbria or the LLW repository in Dounreay. The strategy of the NDA consists in converting HAW into a form that can be safely stored and managed for many decades awaiting the opening of the geological disposal facility (NDA 2016b).

consigned to a geological disposal facility. The aim of the NDA is to reprocess at least all of the Magnox fuel, which should be achieved by the year 2020 (NDA 2016c).

The long-term management policy for HAW is to package and store wastes in interim storages until they can be transferred to a geological disposal facility. The inventory to be disposed of is currently being stored by the waste owners.[12] In 2014, the Department of Energy and Climate Change (DECC) published a White Paper on implementing a geological facility and the Radioactive Waste Management Limited (RMW) was established as an NDA subsidiary. As a legal entity, RWM will be able to apply for and hold the regulatory permits and licenses required for the siting, construction and operation of a geological disposal facility (DECC 2014). A public agency is therefore responsible for the preparatory work to plan the geological disposal of HAW and delivering the disposal facility. Until today no possible suitable sites have been identified. The detailed layout and design of the facility will depend on the waste inventory and the specific geological characteristics of the site. The underground facilities are expected to comprise a system of vaults for the disposal of ILW, and an array of engineered tunnels, for the disposal of HLW and SNF (DECC 2014). During the construction and operational stage, which will last around 100 years, wastes that have been placed in the facility could be retrieved, which is not an option after the closing of the facility. The siting is still based on a voluntarist approach, i.e. the willingness of local communities to participate in the process, although this approach has already failed once. Current plans predict the deep geological facility being available around 2060 (NDA 2016c).

3.2 Financing

Following the reorganization of the nuclear sector in the United Kingdom there, are three different financing systems for the nuclear back-end in place: one for the NDA facilities, one for the reactors owned by EDF Energy, and one for possible newbuild power plants—the decommissioning costs for the nuclear facilities in the U.K. have to be considered separately for the NDA and the EDF Energy sites. The NDA expects in their annual report for 2016/17 discounted costs of 116 billion GBP for more than 120 years; the majority (around 75%) of the costs are attributed to the Sellafield site alone (NDA 2017).[13]

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12 NDA and its SLCs, EDF Energy, Urenco U.K. Ltd, Ministry of Defence, GE Healthcare and other non-nuclear users of radioactive material.

13 The uncertainty of this estimation was mentioned in the NDA annual of 2012/13 report as follows: "*Given the very long timescale involved and the complexity of the plants and*

The decommissioning process is managed by the NDA and undertaken by contractors, which are primarily financed through public funds. The annual budget for the NDA is set by the U.K. Department for Energy and Climate and HM Treasury (OECD/NEA 2016a). In addition to the governmental funding, the NDA generates income with commercial activities. In the commercial year 2016/17, the NDA earned around 1 billion GBP, with 612 million GBP coming from reprocessing and waste management activities (NDA 2017). With the shutdown of Wylfa, income through selling of electricity production, which used to decrease the payments from the taxpayers, came to an end. So the funding of the NDA will become even more dependent on the British taxpayers in the future.

The decommissioning of the EDF Energy NPPs will be primarily payed by the Nuclear Liabilities Fund (NLF), an external segregated fund established by the U.K. government in 1996. The only function of the fund is to provide funding to meet specific waste management costs and the decommissioning liabilities for the NPPs originally owned by public utility British Energy (OECD/NEA 2016a). The NLF had assets with a market value of around 8,935 million GBP at the end of the financial year 2015 (NLF 2015). In 2005, when British Energy was restructured and became EDF Energy, the U.K. government announced that it would fund the qualifying liabilities for the case that they exceed all the assets of the fund (OECD/NEA 2016a). The owner of the NLF is the Nuclear Trust, a public trust established under Scottish law.[14] When the NLF was established it received an initial endowment of 228 million GBP from the U.K. government. Today, the fund is fed by two sources: one source is a small quarterly payment by EDF Energy, the second and predominant sources are the revenues of the investments of the fund (OECD/NEA 2016a). In the financial year 2014/15, EDF Energy made contributions of around 26.5 million GBP to the fund and the operating profit before tax was around 155 million GBP (NLF 2015). If EDF Energy wants to receive payments from the fund to meet liabilities, it has to apply to the NDA, which acts as an agent of the U.K. government. The NDA as the administrator of the Liabilities Management Agreements approves the NLF payments for decommissioning and waste management. Table 2 provides the cost estimations and the provisions set aside by EDF Energy. The provisions for the eight operational NPPs of EDF Energy are calculated with a discount rate of 2.7% and an implicit inflation rate based on long-term forecast of adjusted retail prices.

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material being handled, considerable uncertainty remains in the cost estimate particularly in later years."

14 The five trustees—three are appointed by the U.K. government and two by EDF Energy—also act as the directors of the NLF.

Tab. 2 Estimated costs and related provisions for EDF Energy nuclear backend in million GBP (EDF 2017).

Purpose	Costs based on year-end economic conditions of 2016 (Mio. GBP)	Amounts in provisions at present value in 2016 (Mio. GBP)
Spent Fuel Management	3,101	1.771
Long-term Radioactive waste management	5,326	888
Nuclear plant decommissioning	15,808	6,190
Last cores		1,373
Total	24,230	10,222

According to EDF's financial statement, the provisions for decommissioning and waste management are reported in the assets as "receivables" (EDF 2017, 93). The current value of the fund exceeds the discounted cost estimates of EDF Energy. But already in 2012, the NLF expressed the view, that the fund may not be large enough in the end. In addition, the U.K. government insists that the fund is deposited almost entirely in the National Loans Fund to earn an annual rate of interest used to reduce the overall U.K.'s public debt (MacKerron 2015). EDF Energy is responsible for all operational aspects of the decommissioning of the existing NPPs, but the U.K. government has the power to decide to transfer the decommissioning responsibility to the NDA at any point after the electricity generation at the power stations ended (OECD/NEA 2016a).

According to the Energy Act of 2008 operators that want to construct new nuclear power plants have to establish secure financing arrangements and exact plans for decommissioning and disposal before they get the application to build a new plant. The financing has to be realized by an independent external fund that will be fed during the operational time of the plant with levy of a certain amount per generated kWh.

3.3 Conclusion for the U.K.

The public agency NDA is responsible for the decommissioning of the legacy fleet. The licenses remain with the NDA, but the work is tendered to a PBO, a consortium of private enterprises. This was a changed in 2016 for the Sellafield site, where a public organizational model is seen as more suitable for the complex and long-lasting clean-up of the site. Nearly all the shutdown reactors have been defueled and are currently being prepared for the Long-Term Enclosure. A long time frame is to be expected, reaching well into the 22nd century. For the current operational NPPs the operator EDF Energy—a private enterprise and subsidiary of EDF—is responsible for the decommissioning. Concerning the high-level waste management, the construction of a disposal facility is the scope of a NDA subsidiary and thus a public matter. Up to now all site selection activities failed and have to restart again. The financing of decommissioning and waste management will be challenging too, especially for Sellafield. The costly decommissioning and site remediation of the legacy fleet have to be financed by the taxpayers over more than 100 years. The lessons learned from the shortfall of former provisions led to the establishment of an external segregated fund for the operational NPP fleet, which should prevent public payments in the future but it remains questionable if the financial resources set aside in the fund will cover these costs.

4 Germany

With a nuclear share of 13.1 percent (80.07 TWh) in 2016 (IAEA 2017), Germany has the smallest share of nuclear energy among the observed countries, but the 28 shutdown NPPs (in 2017) constitute the most diverse NPP fleet to dismantle of the observed countries (see Fig. 1). The 13th amendment of the Atomic Energy Act in August 2011 withdrew the operating licenses of the seven oldest NPPs and Krümmel. The remaining eight operational plants will be gradually shutdown by the year 2022. The current fleet is operated by the German utilities EnBW, PreussenElektra (E.ON subsidiary) and RWE as well as the Swedish utility Vattenfall Europe Nuclear Energy. Siemens Kraftwerke Union AG (KWU), later to be dissolved with the French firm Framatome into Areva NP, built all the nuclear steam supply systems—the reactor and the reactor coolant pumps and associated piping in an NPP—in the operational power plants. The operational Pre-Convoi PWRs (Vor-Konvois) will be shut down in 2021. The Convoi reactors (Konvoi)—the latest PWR-design commissioned in the late 1980s—are the last NPPs to be shut down in 2022.

4.1 Production

4.1.1 Decommissioning of nuclear power plants

The different shutdown reactors are in different stages of their decommissioning process: two are in a stage of Long-Term Enclosure (LTE), three plants have been successfully dismantled and released from regulatory control, two plants have been dismantled but await regulatory release, while the remaining NPPs are currently in different phases of the decommissioning process.

The BWR Lingen was put into Long-Term Enclosure[15] in 1998, the request for decommissioning was submitted to the regulatory authority by RWE in 2008 and approved in 2016. The three NPPs—two BWRs and one HWGCR—that have been successfully decommissioned and released from regulatory control were rather small prototype reactors. Of the three, VAK Kahl (BWR, 25 MW), was the only reactor that operated for a longer period of time (24 years) and was after its shutdown immediately dismantled and released as a greenfield in 1998.[16] The BWR Würgassen was the first larger commercial NPP to be dismantled. The reactor was of the first generation BWRs and had a capacity of 640 MW. After 19 years of operating time, the NPP was shut down in 1994 and de facto decommissioned by 2014. During the dismantling in the hot zone (stage three) PreussenElektra tendered the dismantling and conditioning of the reactor vessel internals to Areva NP GmbH. The site has not yet been released as a greenfield as parts of the buildings are used as an interim storage for low and medium level wastes awaiting the opening of the disposal site Konrad. Decommissioning of Gundremmingen-A, another first generation BWR (237 MW), started in 1983 and in 2016 the majority shareholder RWE finished the actual decommissioning process with the decontamination of the buildings (Bredberg et al. 2017), but as it is the case with Würgassen the site cannot be released from regulatory control as parts of the building are used for future decommissioning works for the still operational units B and C.

There are currently 12 power plants in the process of being dismantled, the major part of them are PWRs.[17] The NPP Stade has nearly finished decommissioning, here PreussenElektra again tendered the removal and conditioning of the reactor vessel

15 The other NPP in Long-term Enclosure is the pebble bed HTGR THTR-300.

16 HDR Großwelzheim (Superheated BWR, 25 MW, 1969–1971) was decommissioned from 1988 until 1998. Niederaichbach (HWGCR, 100 MW, 1973–1974) was decommissioned from 1987 until 1995.

17 Other NPPs being decommissioned are AVR Jülich (HTGR, 15 MW), KNK II (FBR, 17 MW), and MZFR Karlsruhe (PHWR, 1,219 MW); all three reactors are decommissioned by the public company EWN respectively EWN subsidiaries.

internals to Areva. The legacy fleet of the former German Democratic Republic (GDR) Rheinsberg and the five units of Greifswald are being decommissioned by EWN Entsorgungswerk für Nuklearanlagen (EWN), a public company under control of the Federal Ministry of Finances. For both sites, the deferred dismantling strategy was chosen. The Rheinsberg reactor pressure vessel was transported to the centralized on-site interim storage facility (Zwischenlager Nord), also operated by EWN. In Greifswald the reactor vessel internals of reactor one and two were immediately dismantled and conditioned. For the internals of reactor three and four as well as all the reactor pressure vessels of the five reactors deferred dismantling was the strategic choice; also in storage and planned to be dismantled later on are the 17 steam generators and parts of the primary cooling system. Decommissioning of Obrigheim, operated by EnBW, should be completed sometime between 2020 and 2025. Mülheim-Kärlich, the only RWE power plant and the only Konvoi reactor currently being dismantled, is entering the reactor decommissioning phase and is planned to be released from regulatory control in 2021.

All NPPs shut down in 2011 and Grafenrheinfeld shut down in 2015 have submitted their decommissioning proposal at the regulatory authority; the proposal was also submitted for Gundremmingen B, which shut down in December 2017. Of these, Brunsbüttel, Isar 1, Biblis A and B as well as Neckarwestheim 1 have been granted their decommissioning requests in 2017. The major part of the NPPs are still in the post-operational phase or are just starting with the decommissioning process. The German operators currently face several obstacles in order to be able to conclude the decommissioning process in a timely manner without escalating costs. At the moment there is still not a sufficient number of transport and storage casks being produced in order to defuel the reactors. The quick shutdown of the NPPs after the Fukushima incident caused a high number of special fuel rods—not completely burnt-down fuel—in the reactor cores. For these fuel rods no casks for the safe storage have been approved by the regulatory authority at this point. The defueling of the reactors cores and subsequently storing in an interim storage cannot be achieved until the required casks are available.

4.1.2 Storage of high-level wastes

The high-level radioactive waste consists of SNF and vitrified structures from the reprocessing process. The political decision to stop German reprocessing was final in 1989, after this the German operators invested in the French reprocessing facility in La Hague. Until 2005, nearly half of all the SNF was sent to France and the U.K. for reprocessing. From 2005 on, the policy was direct geological disposal—which meant interim storage of SNF and no more reprocessing (Hocke and

Kallenbach-Herbert 2015). For this, the utilities operated through Gesellschaft für Nuklearservice (GNS) two centralized interim storage facilities in Gorleben and Ahaus; a third facility is Zwischenlager Nord operated by the public company EWN. But the major part of the SNF is currently still stored in the storage pools or in one of the twelve de-centralized on-site storage facilities.

In 2016, the institutional framework of the waste management process was changed with the introduction of the law aimed to restructure the responsibilities in the nuclear waste management process.[18] The ownership of the centralized interim storage facilities was transferred to the newly created public company Gesellschaft für Zwischenlagerung (BGZ, "company for interim storage"), which will also take over the decentralized interim-storage facilities and the low-level waste repositories. According to the final report[19] of the high-level waste management commission set up by the Repository Site Selection Act in July 2013 –the site for the deep geological facility with "the best safety" for the 30,000 m^3 of high-level waste[20] is to be found in a three-phase process, accompanied by extensive public participation. For the up 200,000 m^3 of low- and intermediate waste and salt mixture to be retrieved from the Asse II geological facility currently no disposal solution exists. The goal of the Repository Site Selection act is a "deep geological repository with reversibility" in either clay, salt or granite. The plans foresee a start of operation of the disposal site after 2050, but more realistic estimates expect the start after 2080 (Thomauske 2015). After 50 years of operation time the disposal facility is planned to be sealed off.

4.2 Financing

The funding system in Germany differs between purely public-owned facilities, facilities with mixed-ownership and the facilities in private ownership. The costs for the decommissioning of the former owned nuclear facilities are financed from the current public budget; the Federal Government covers the majority of the costs, while some are covered by State Governments. The most common examples for public funding are the former GDR NPPs Greifswald and Rheinsberg, the decommissioning of which is totally funded by the Ministry of Finance. For the facilities in mixed-ownership, there is a proportional split of the costs between the public and the private utilities clarified by special arrangements (European Commission

18 Gesetz zur Neuordnung der Verantwortung in der kerntechnischen Entsorgung (BT 768/16).

19 See Kommission Lagerung hoch radioaktiver Abfallstoffe (2016).

20 This includes the high-level waste until the shut-down of the last power plant on 31.12.2022.

2013). However, the majority of the costs are related to the nuclear back-end of the privately-owned NPPs. In 2015, the auditing company Warth & Klein Grant Thornton AG provided on behalf of the German government an estimation of the whole costs for the nuclear back-end of 23 commercial NPPs: 47.5 billion in 2014 Euros. The several undiscounted cost categories are presented in Table 3.

Tab. 3 Estimated Nuclear Back-End Costs in Germany (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015).

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

In addition, there are costs the for the public funded decommissioning of Greifswald and Rheinsberg and for research facilities: The initial decommissioning costs for Greifswald were estimated to be about 4 billion EUR and for Rheinsberg 600 million EUR; the latest cost estimate in 2016 was around 6.5 billion for both facilities. As always, all cost estimations are subject to many uncertainties related to expectations about future inflation rates, cost increases, and time delays. The estimation of Warth & Klein Grant Thornton AG considered this by a computation of the estimated costs with a nuclear specific inflation rate of 1.97% until 2099, which resulted in total discounted costs of around 169.8 billion EUR. The audit concluded that the effect of changing the estimated nuclear-specific inflation rate on future costs is strong and causes the most uncertainties.

In the old financing system, the financial resources to cover decommissioning and waste disposal were managed by the private companies in internal non-segregated funds with no public authority controlling them. The companies set up the provisions according to international accounting standards and were free to choose where to invest it. The OECD/NEA (2016a) highlighted the unregulated and uncontrolled system of internal non-segregated funds itself as the most critical aspect of the German system. In the case of a bankruptcy of the operator, the financial resources to cover future costs would probably have been lost. The financial situation of the utilities was and still is not secured to exclude the risk of bankruptcy in the future. In the case of the loss of the funded provisions, the public budget would have been obliged to cover the costs. Table 4 presents the provisions of the companies as mentioned in their annual financial statements at the end of 2014. The calculations of the private companies were based on an average interest rate of 4.58% and the before mentioned nuclear specific inflation rate of 1.97%; both are highly uncertain. A lower real interest rate on the provisions set aside would have had a crucial effect. With an average interest rate of 2.03 %, the present value of the set provisions would have to be today around 77 billion EUR to cover the future costs (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015).

Tab. 4 Provisions of German Operators end of 2014 (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015)

Company	**Provisions end of 2014 (Mio. EUR)**	**Interest rate for the calculations (%)**
E.ON	16,567	4.7
RWE	10,367	4.6
EnBW	8,071	4.8
Vattenfall	3,014	4.0
Stadtwerke München	564	4.38
Total	38,288	Average 4.58

On behalf of the government, an expert commission reviewed the financing system and provided reform proposals to meet the actual risk related to the system of internal non-segregated funds.[21] Their recommendations and the new law published in December 2016 (BT 768/16) led to a fundamental change of the German funding system. This change was also motivated by concerns that the private utilities would not be able to cover all future liabilities with their internal non-segregated financial resources due to the experiences with high cost increases in former decommissioning and waste disposal projects. There were annually cost increases between 2.9 and 6 percent, which is much higher than the general inflation rate or the assumed

21 See KFK – Kommission zur Überprüfung der Finanzierung des Kernenergieausstiegs (2016).

nuclear-specific inflation rate (Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015). Based on the reform proposals, an external segregated fund was implemented in 2016, which will have to finance all aspects related to waste disposal, i.e. interim and final storage. The fund was fed by the former provisions for these tasks totalling 23 billion EUR, including a risk premium. The utilities are still responsible for decommissioning and for the conditioning of the wastes, but all tasks as well as the operation of the interim storage facilities will be done by public companies and paid from the fund. The responsibility as well as risks, including the financial ones in the case of insufficient set-aside money, will have to borne by the public, which infringes the polluter-pays-principle (Jänsch et al. 2017).

4.3 Conclusions for Germany

Germany was able to gain some experience in the decommissioning of NPPs. The four private utilities have chosen the Immediate Dismantling strategy in nearly all cases. The public enterprise EWN chose the deferred dismantling strategy for the reactor pressure vessels. The private operators carry out themselves the dismantling process, although specialized private companies carry out some part of the work; this is especially true for the technologically challenging dismantling of the reactor pressure vessel and its internals. All NPPs currently in the post-operational stage still face several obstacles in order to be able to conclude the decommissioning process in a timely manner without escalating costs, e.g., still not a sufficient number of transport and storage casks being produced in order to defuel the reactors. The future disposal path for HLW is still highly uncertain—this also applies for the disposal of low- and medium-level wastes—and has retroactive effects on the timing, progress, and costs of the decommissioning process. Additionally, all estimated future costs are underlying many uncertainties due to cost increases and interest rates. This is especially true for all future costs related to the management for both low-and intermediate, and high-level waste. It is questionable if the financial resources set aside in the fund will cover these costs.

5 Conclusions

Overall, the three case studies show that the biggest challenges concerning the decommissioning and storing still wait for solutions. Decommissioning was in most cases neglected, only Germany has gained some experiences in decommissioning NPPs but no large-scale reactor (over 1 GW) has successfully been decommissioned. It can be stated that overall the experience is still lacking, considering the high need for decommissioning in the coming years in all of the observed countries. Until now, no scale effects could be observed, if EDF can reap scale effects due to the standardization of its fleet remains to be seen. The preferred strategy for light water reactors is Immediate Dismantling, while in some cases the radiological decay was used and the deferred dismantling strategy was applied to highly activated components. In contrast, the worldwide preferred strategy for GCRs is the Long-Term Enclosure. EDF is now also considering this strategy for its French GCR fleet due to underestimated technological challenges and missing graphite disposal routes. This postpones the end of the decommissioning of the legacy fleets in the U.K. and France well into the 22nd century. In all three cases, the decommissioning of the NPPs is critical due to the missing disposal facilities, which led to the construction of interim storage facilities.

Considering the production of the decommissioning process in the observed countries, we have two public companies EWN and Magnox Ltd. organizing the decommissioning of the legacy fleets, while the latter tenders the work to a private consortium. In Germany and France, the operators are responsible for the decommissioning of their NPPs. Some part of the work, especially the most challenging work—the dismantling of the reactor pressure vessel and its internals—has been tendered to specialized nuclear companies. In the U.K., the decommissioning of the operational NPPs has to be done by the operator, but the NDA has a "take-over" option and can decide to transfer the decommissioning responsibility to the public body. On the other hand, the high-level disposal facility is in the three countries the scope of the government. If the construction permit for Cigéo is granted, France will have the most advanced process of implementing a deep geological disposal facility while Germany and the U.K. are still in the site selection process.

The financing of decommissioning and radioactive waste management will be a long-term challenge in all three countries. All cost estimations are underlying uncertainties due to long time-scales, cost increases, and estimated interest and inflation rates. This could lead to an underestimation of future costs. Of all the observed financial systems, the old German system of internal non segregated funds seemed to be the most uncontrolled and unsecured. This led to a change in the financial system and the implementation of an external segregated waste fund. In France, the financial resources are held in internal segregated funds with administrative control and oversight by national authorities. However, this does not prevent comparatively optimistic cost estimations and due to this, likely inadequate set aside financial resources. In the U.K., the costliest aim will be the decommissioning and site remediation of the legacy fleet and Sellafield payed by the taxpayers over the next 100 years. To prevent a repetition of a shortfall of funded provisions, a system with an external segregated fund for the operational nuclear fleet was introduced. This approach seems to be the most suitable to finance the future cost of the nuclear back-end, even if it also could not overcome the problem of too low cost estimations.

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