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

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

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3 Germany

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

3.1 Introduction

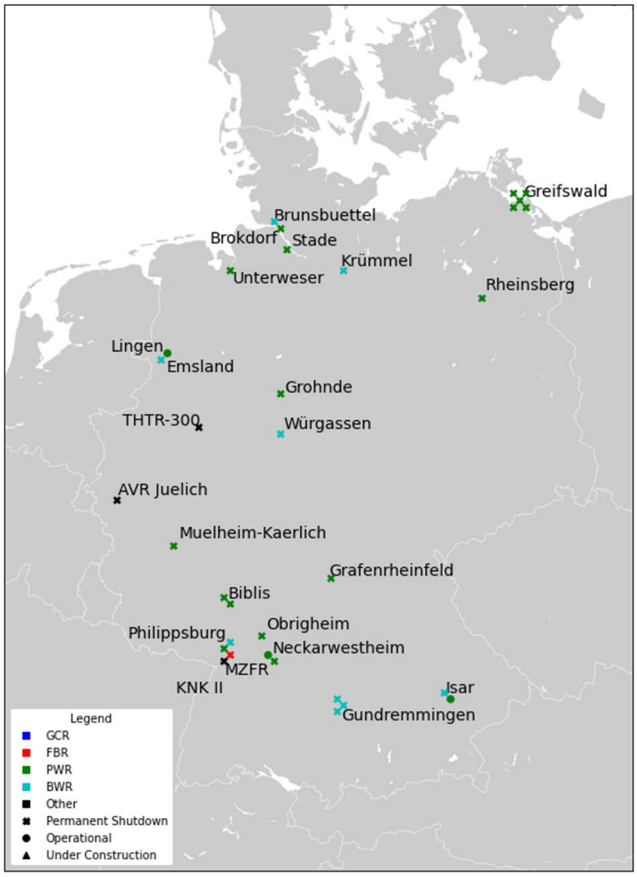
With the closure of three nuclear power plants in 2021, the number of closed nuclear reactors in Germany rose to 30, corresponding to 22.2 GW capacity. Three more reactors are still operational and will be permanently shut down in Spring 2023. Following the Fukushima disaster, the 13th amendment of the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

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

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

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

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



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

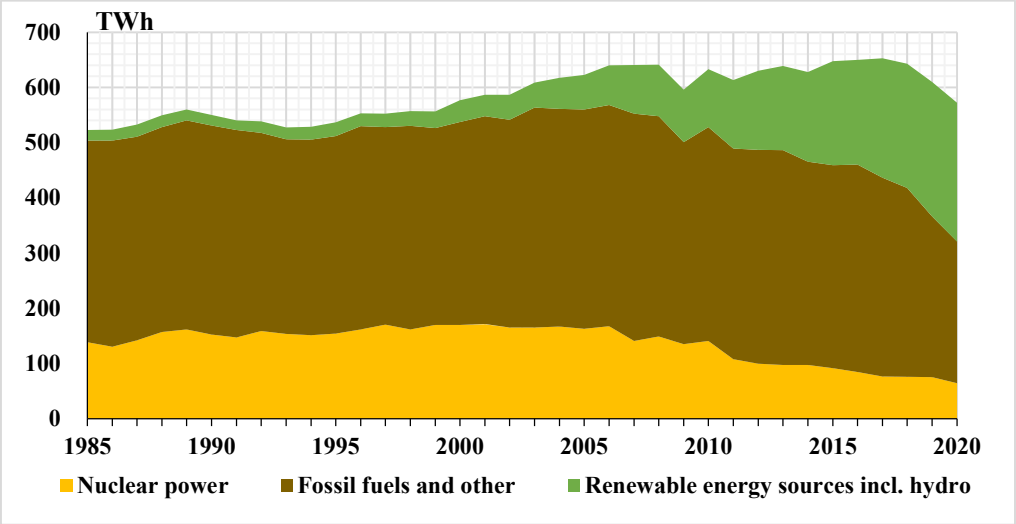
Over the last ten years, this political decision was widely accepted amongst the general public. With the Russian attack on Ukraine in early 2022 however, concerns about energy security slowly grew, until a debate about life-time extensions of Isar, Lingen and Neckarwestheim and the re-initialization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

[26] Inflation calculated to 2020 values based on inflationtool.com: 156.5 million EUR_{2020}
[27] 944.4 million and 1.5 billion EUR_{2020}.

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

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

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



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

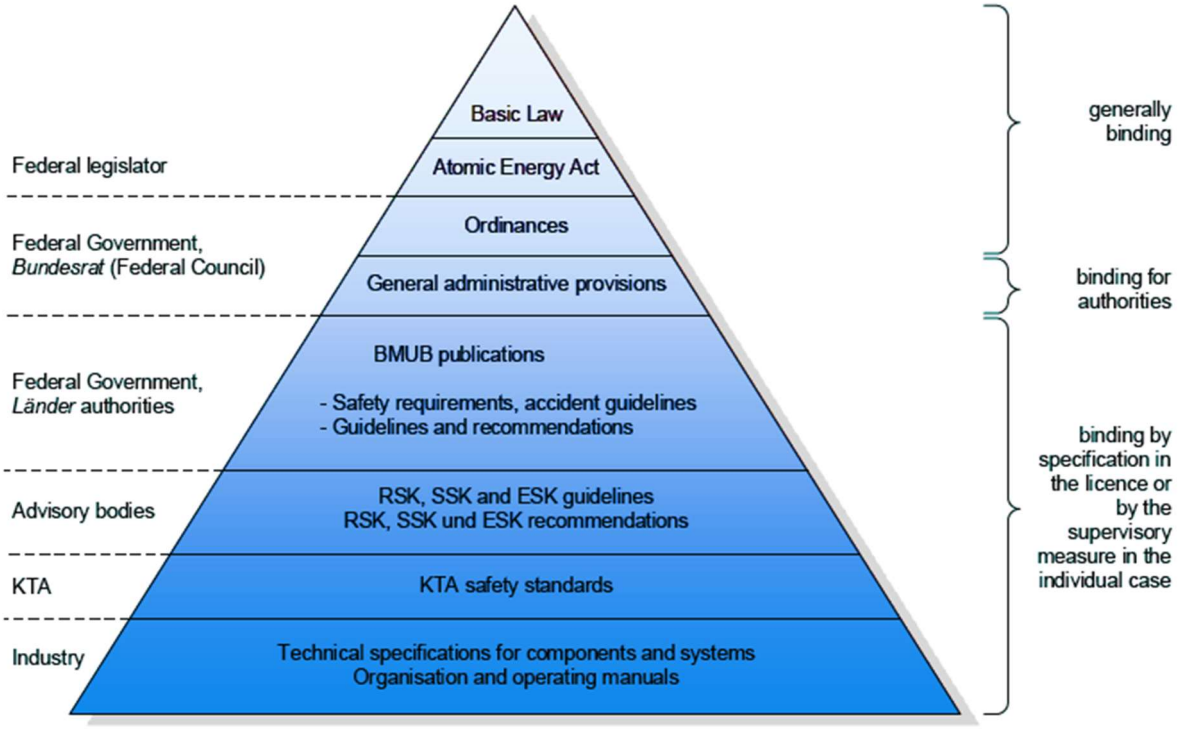
With Germany phasing-out electricity generation from NPPs by spring of 2023, dismantling and decommissioning of the nuclear fleet will be a major undertaking for governmental regulators, involved utilities, operators and other involved stakeholders. This report will provide an overview of the legal framework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

3.2 Legal Framework

3.2.1 Governmental and regulatory framework

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

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



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

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

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

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

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

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

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

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

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

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

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

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

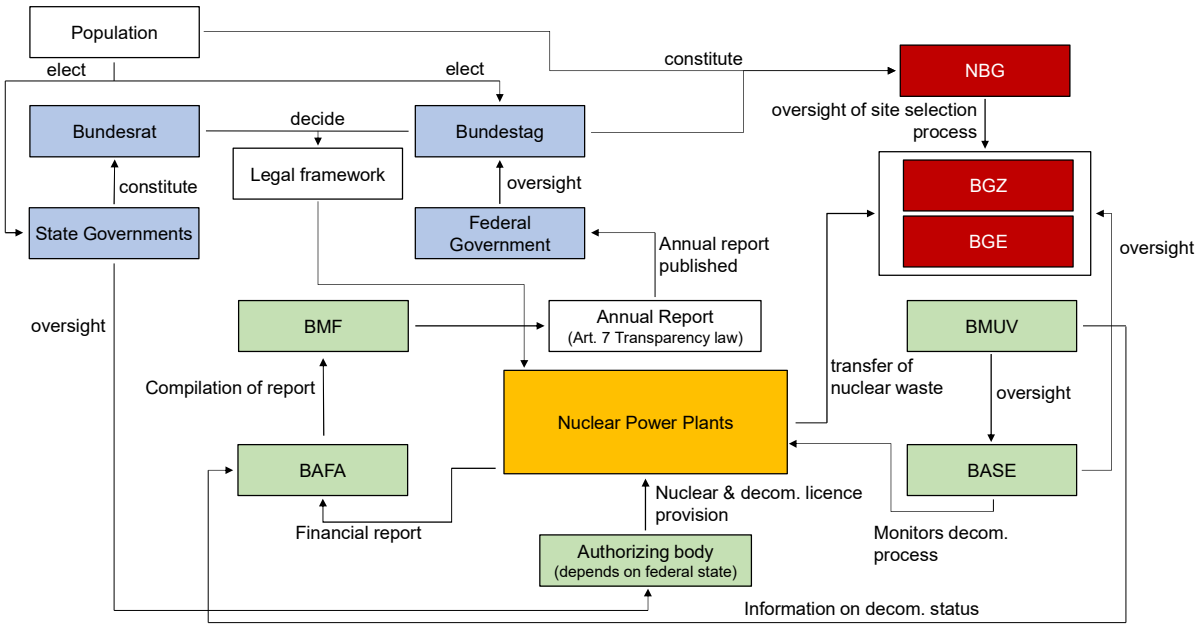
In terms of financial regulation, the "Act on Transparency for Costs of Decommissioning of Nuclear Power Plants and Waste Packaging" (Transparency Act) introduces BAFA (Bundesamt für Wirtschaft und Ausfuhrkontrolle) as the responsible oversight agency. Each year, BAFA reports to the German government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

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

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

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

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



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

Source: Own depiction.

3.2.2 Ownership

3.2.2.1 Overview

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

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

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

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

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

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

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

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

3.2.2.2 Detailed ownership description for utilities

EnBW AG

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

[32] 0.05% are held by Kernkraft Obrigheim GmbH (100% EnBW AG), 0.2% by Deutsche Bahn AG, and 1.3% by ZEAG Energie AG (100% EnBW AG).

[33] These municipalities are Alb-Donau-Kreis, Biberach, Bodenseekreis, Freudenstadt, Ravensburg, Reutlingen, Rottweil, Sigmaringen, Zollernalbkreis (OEW Undated).

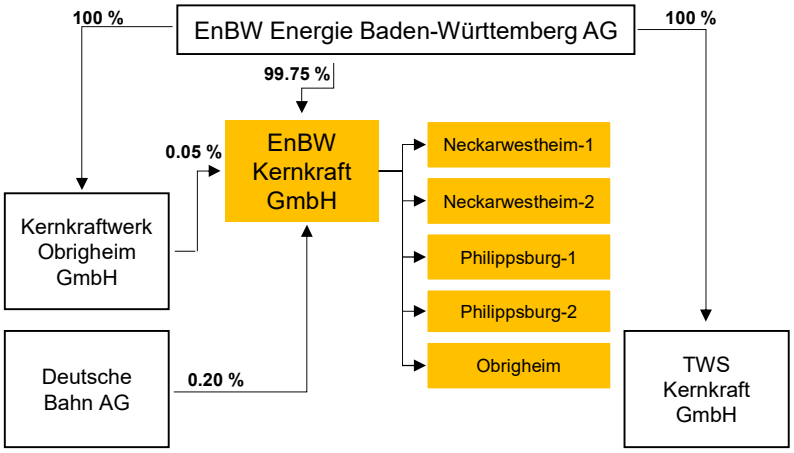
EnKK operates the five reactors Neckarwestheim-1/2 (GKN), Obrigheim (KWO), and Philippsburg-1/2 (KKP) on behalf of the owners of the plants. EnBW AG is the sole shareholder of the two Philippsburg reactors and holds 48.4% of the shares of Neckarwestheim-1 and 62.4% of Neckarwestheim-2. Kernkraftwerk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

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

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

Source: Own compilation based on EnBW AG (Undated)

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



Source: Own depiction following Deutscher Bundestag (2021)

E.ON / PreussenElektra

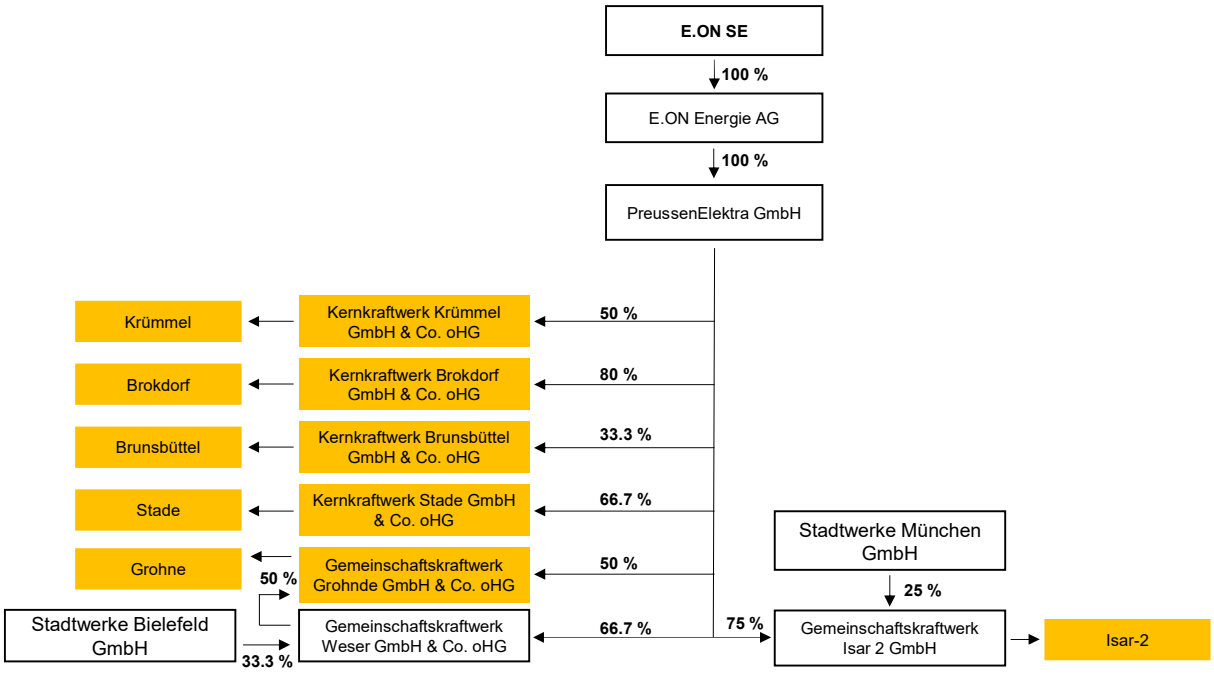
Within the E.ON Group, the nuclear energy business (operation and decommissioning) is managed by the operating unit PreussenElektra GmbH (PEL), of which E.ON SE is the sole owner.[34] PEL is included in the consolidated financial statements of E.ON SE. PEL is the sole nuclear operator of the four shut-

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

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

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

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



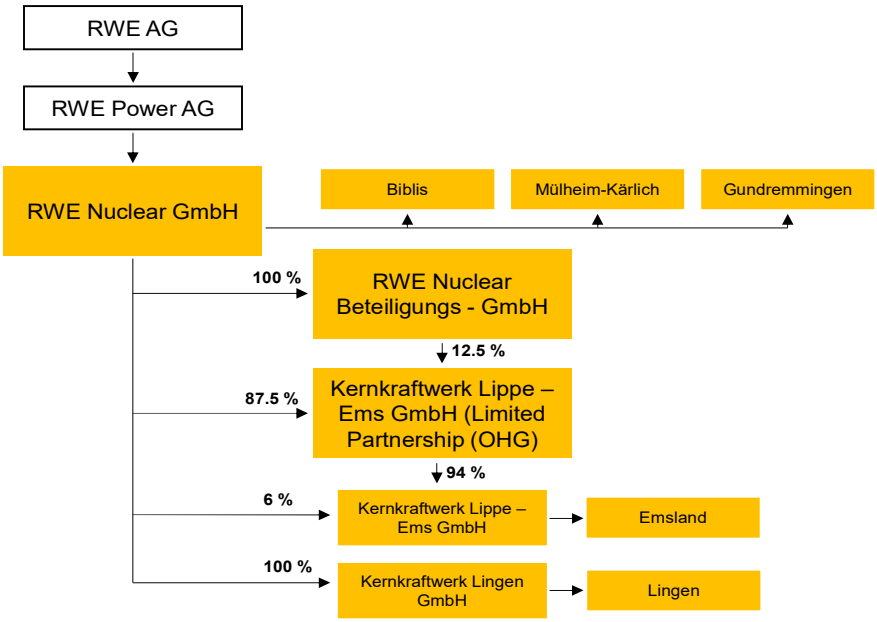
Source: Own depiction following Deutscher Bundestag (2021)

RWE

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

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

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

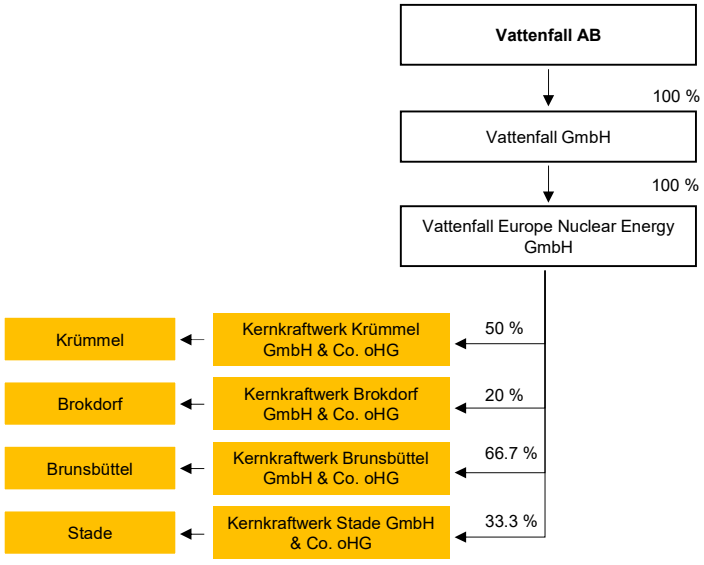


Source: Own depiction following Deutscher Bundestag (2021)

Vattenfall

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

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



Source: Own depiction following Deutscher Bundestag (2021)

Stadtwerke München

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

3.2.3 License provision and extension

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

3.2.4 Oversight

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

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

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

[35] Already in EUR_{2020}

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

3.3 Decommissioning Regulation

3.3.1 Decommissioning policy

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

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

3.3.2 Regulatory and legal process

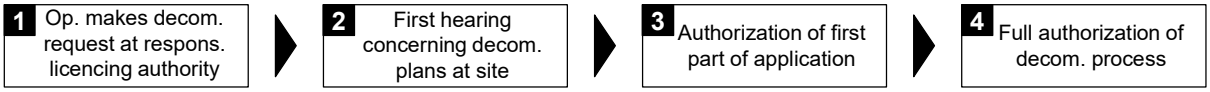
Once the operating life of an NPP ends, the plant enters the POP. According to Article 7 Section 3 AtG, an approval from the regulatory authority is needed for the closure and the actual dismantling of a reactor or parts of the facility. The course of the licensing procedure is regulated in the above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

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

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

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

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



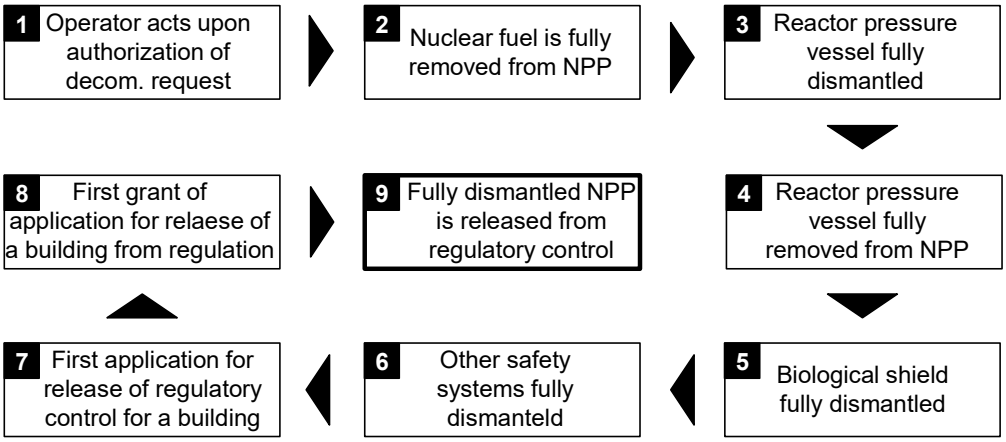
Source: One depiction following Deutscher Bundestag (2021)

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

from nuclear regulatory oversight and control, it can be used for other purposes, as was done at the FBR Kalkar, see Section 3.2.2, or it may be "conventionally" demolished (Scheuten 2012; BMUV 2021).

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

Figure 3-10: Milestones of decommissioning process



Source: Own depiction following Deutscher Bundestag (2021)

3.3.3 Oversight

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

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

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

3.3.4 Liability

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

3.4 Financial Regulation

3.4.1 The funding of decommissioning

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

3.4.1.1 … before the reform

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

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

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

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

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

3.4.1.2 … after the reform

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

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

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

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

3.4.2 Current balance in funds

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

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

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

[39] 24.3 billion EUR_{2020}

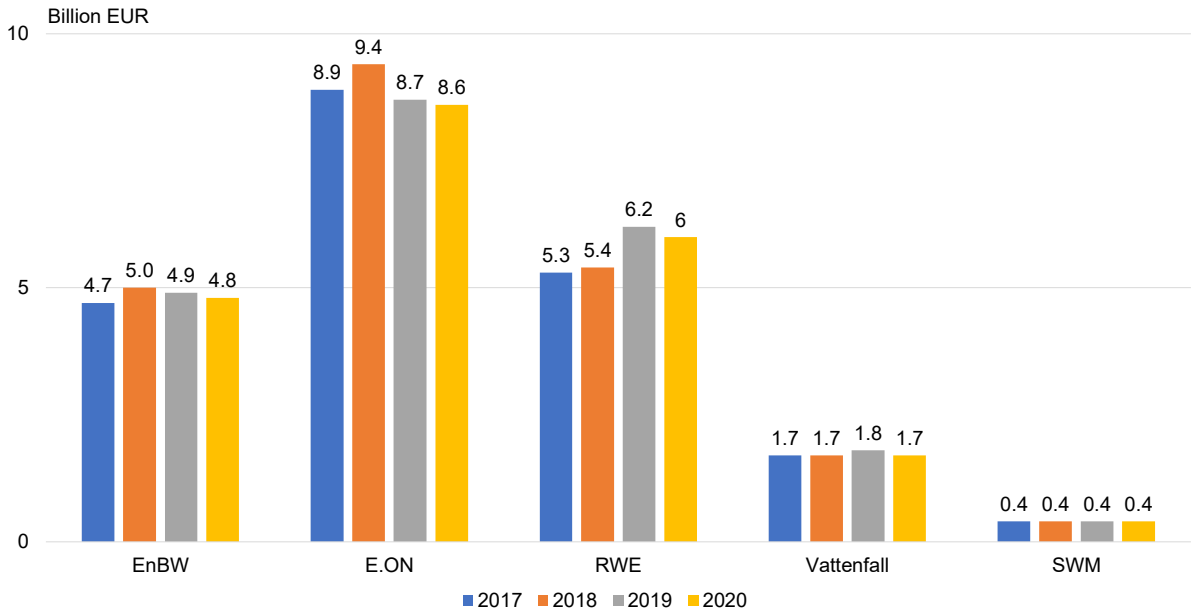
As of December 2020, total provisions made by RWE amounted to 6 billion EUR, distributed amongst RWE Nuclear GmbH, KKE GmbH and KWL GmbH

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

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

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

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



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

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

[40] 24.3 billion EUR_{2020}

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

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

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

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

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

3.4.3 Cost assessments

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

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

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

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

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

[41] Also, on behalf of the utilities, the private and utilities-owned GNS estimates the costs for waste management based on schedules and cost estimates produced by the German Federal Office for Radiation Protections (BfS, now BASE) for the disposal facilities.
[42] Inflation calculated with information taken from inflationtool.com.
[43] 50 billion EUR_{2020} of which 20.7 billion for decommissioning.
[44] 6.8 billion EUR_{2020}

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

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

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

3.4.4 Cost experience and accuracy of assessments

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

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

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

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

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

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

3.5 Production

3.5.1 Overview

By the end of 2021, Germany had a total of 30 closed commercial nuclear reactors corresponding to the second largest fleet of closed reactors worldwide. Including prototype and research reactors, it also has the second highest number of fully decommissioned units. The latest closures were Brokdorf, Grohnde (both operated by Preussen Elektra) and Gundremmingen-C (operated by RWE) on 31 December 2021 after an average time of operation of 36 years. In this and the accompanying country reports, reactors were classified as commercial and non-commercial following the classification scheme

depicted in Figure 1-7 in the annex of Chapter 1. German reactors have all been classified as "commercial" – even reactors originally designed as research reactors supplied electricity to the grid for many years, e.g., AVR Jülich. An overview of the current decommissioning status of German NPPs is provided in Table 3-8 in the annex. All reactors were determined to be commercial reactors due to long lasting connections to the grid. (Wealer et al. 2015; Kunz et al. 2018; Wealer, Seidel, and von Hirschhausen 2019; Besnard et al. 2019; Schneider et al. 2018; 2019; 2020; 2021; 2022; WNN 2021)

3.5.2 Progress

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

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

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

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

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

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

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

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

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

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

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

3.5.3 Actors involved in the decommissioning process

Experiences from past and ongoing decommissioning projects show that specialized companies are especially active in the hot-zone stage, where the reactor pressure vessel and the vessel internals are

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

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

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

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

3.5.4 Focus on decommissioning in the hot zone

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

are aiming to reap economies of scale by awarding hot-zone-decommissioning tasks to few large consortia, as shown below in Table 3-6 (Schneider et al. 2021; 2022).

Table 3-6: Hot-zone contractors & consortia

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

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

3.6 Country specific nuclear and decommissioning developments

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

3.6.1 Lack of incentives for timely decommissioning

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

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

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

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

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

3.6.3 Upcoming challenges

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

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

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

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Appendix

Table 3-7 Ownership of German Nuclear Power Plants

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

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

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

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

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

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