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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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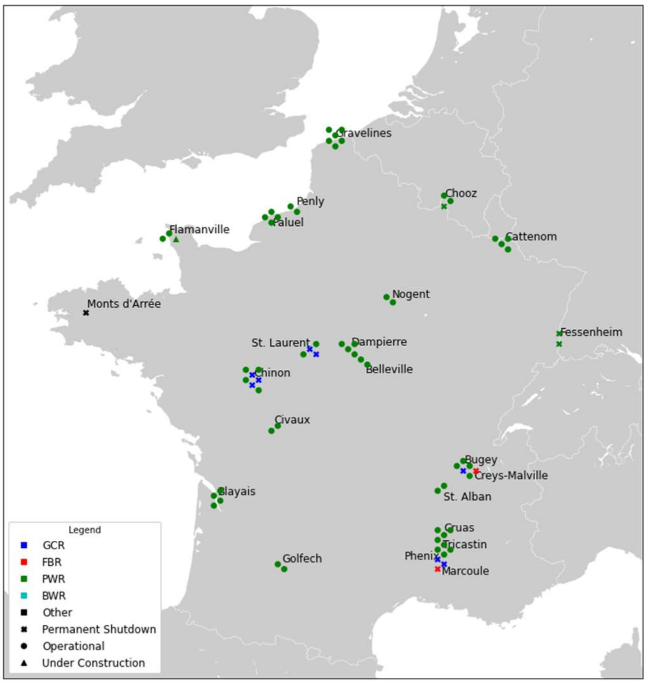
2 France

Alexander Wimmers, Christian von Hirschhausen, Björn Steigerwald

2.1 Introduction

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

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



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

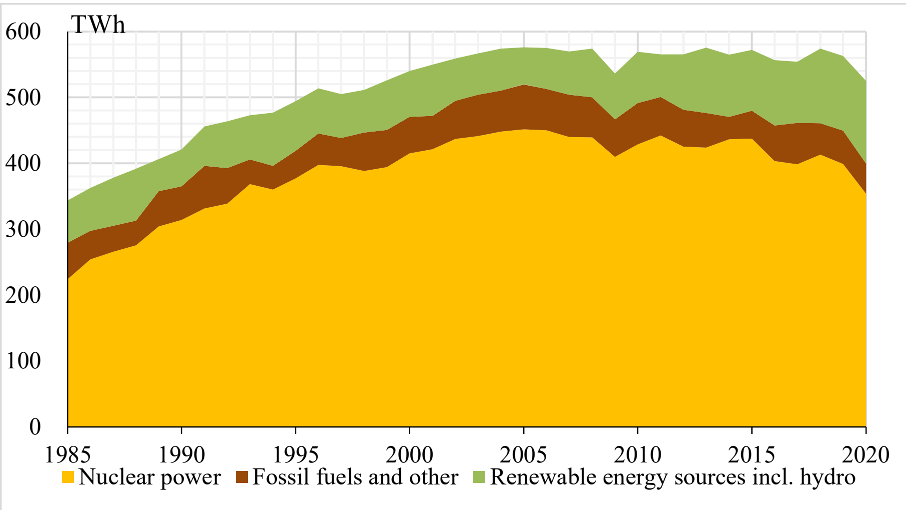
After World War II, the French electricity sector was nationalized by regrouping private utilities to one single state-owned utility, Électricité de France (EDF), in April 1946 (EDF 2022). Around the same time, Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) was founded and entrusted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

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

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

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

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



Source: Own depiction compiled from BP (2021)

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

2.2 Legal Framework

2.2.1 Governmental and regulatory framework

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

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

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

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

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

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

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

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

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

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

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

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

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

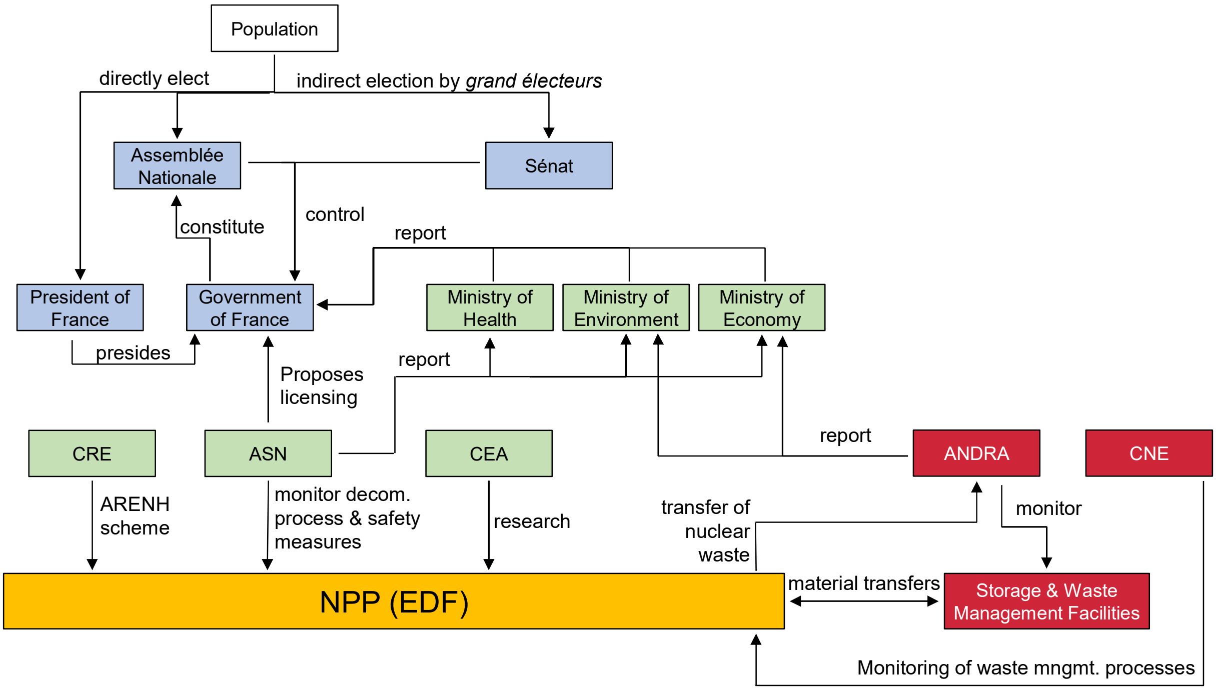
The waste act also instructed the Commission National d'Évaluation (CNE2) with the evaluation of various programs concerning waste management. The abbreviation CNE2 is used to distinguish the current commission from the first commission of the same name that was originally introduced in 1991. CNE2 consists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

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

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

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

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



Source: Own depiction.

2.2.2 Ownership

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

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

2.2.3 License provision and extension

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

2.2.4 Oversight

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

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

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

2.3 Decommissioning Regulation

2.3.1 Decommissioning policy

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

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

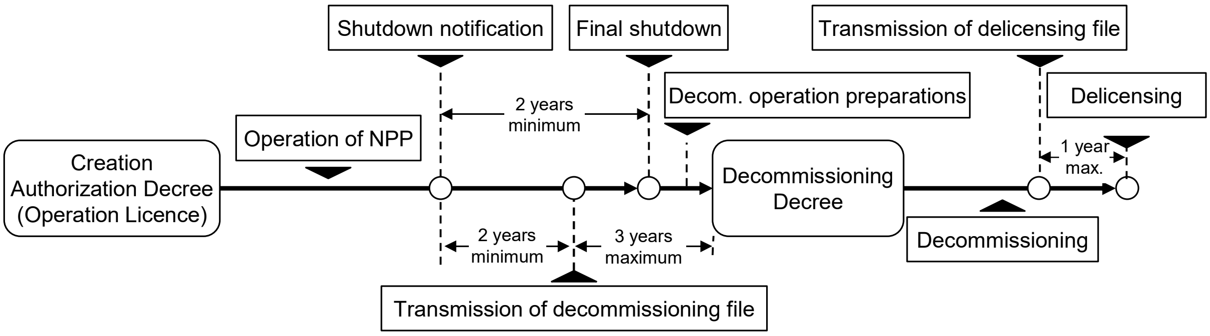
The principle of complete clean-out aims at the complete removal of any hazardous, mainly radioactive, substances from buildings, structures, or soil – in essence the goal of radiological decommissioning world-wide. To achieve this, licensees must utilize economically viable state-of-the-art techniques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

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

2.3.2 Regulatory and legal process

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

Figure 2-4: Decommissioning process



Source: Own depiction based on ASN (2021)

2.3.3 Oversight

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

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

2.3.4 Liability

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

2.4 Financial Regulation

2.4.1 The funding of decommissioning

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

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

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

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

2.4.2 Current balance in funds

Électricité de France (EDF)

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

Orano

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

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

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

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

Table 2-2: Provisions made by Orano for its nuclear operations (in million EUR_{2020})

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

Source: Compilation taken from Orano (2022)

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

ANDRA

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

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

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

Source: Own compilation taken from ANDRA (2021)

CEA

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

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

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

Source: Own compilation of CEA (2019; 2021)

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

2.4.3 Cost assessments

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

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

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

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

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

2.4.4 Cost experience and accuracy of assessments

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

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

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

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

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

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

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

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

2.5 Production

2.5.1 Overview

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

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

Table 2-7: Status of decommissioning NPPs in France

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

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

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

2.5.2 Progress

EDF

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

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

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

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

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

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

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

CEA

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

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

2.5.3 Actors involved

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

2.6 Country specific nuclear and decommissioning developments

2.6.1 Hopes for economies of scale and ageing nuclear fleet

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

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

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

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

2.6.2 Financial burdens

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

2.6.3 Legacy fleet

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

[24] Approx. 575.1 EUR_{2020}

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

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

References

Alderman, Liz. 2022. "French Nuclear Power Crisis Frustrates Europe's Push to Quit Russian Energy." *New York Times*, June 18, 2022. https://www.nytimes.com/2022/06/18/business/france-nuclear-power-russia.html.

ANDRA. 2019. "All You Need to Know about Radioactive Waste Management." 337 M. Chêtenay-Malabry: Agence Nationale Pour La Gestion Des Déchets Radioactifs. https://international.andra.fr/sites/international/files/2021-11/Andra-MAJ_Plaquette_institutionnelle-19_08Aout_EN_LQP.pdf.

———. 2021. "Rapport Financier 2020." Financial Report DDP/DICOM/21-0030. Châtenay-Malabry: Agence Nationale Pour La Gestion Des Déchets Radioactifs. https://www.andra.fr/sites/default/files/2021-05/Rapport%20financier%202020.pdf.

———. 2022. "French Legal Framework." About ANDRA. 2022. https://international.andra.fr/about-andra/french-legal-framework.

Areva. 2017. "2017, a Pivotal Year." Areva Group. 2017. https://www.sa.areva.com/EN/group-4369/2017-a-pivotal-year.html.

ASN. 2006a. "The Law on Sustainable Management of Radioactive Materials and Waste." Montrouge, France: Autorité de Sûreté Nucléaire. https://www.asn.fr/annual_report/2006/PDF/radioactive-waste-management-act.pdf.

———. 2006b. *ACT No. 2006-686 of 13 June 2006 on Transparency and Security in the Nuclear Field. 2006-686*. https://www.french-nuclear-safety.fr/asn-regulates/regulations/act-no.-2006-686-of-13-june-2006.

———. 2009. "ASN Policy Concerning the Decommissioning and Delicensing of Basic Nuclear Installations (BNIs) in France." Revision 0.v3. Montrouge, France: Autorité de Sûreté Nucléaire. https://www.french-nuclear-safety.fr/content/download/54408/file/ASN%20policy%20concerning%20the%20decommissioning.pdf.

———. 2018. "ASN Report on the State of Nuclear Safety and Radiation Protection in France in 2017." Montrouge, France: Autorité de Sûreté Nucléaire. https://www.french-nuclear-safety.fr/asn-informs/publications/asn-s-annual-reports/asn-report-on-the-state-of-nuclear-safety-and-radiation-protection-in-france-in-2017.

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

Assemblée Nationale. 2017. "Rapport d'Information déposé en application de l'article 145 du règlement par la mission d'Information relative à la faisabilité technique et financière du démantèlement des installations nucléaires de base." Paris: Commission du développement durable et de l'aménagement du territoire. http://www.assemblee-nationale.fr/14/pdf/rap-info/i4428.pdf.

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

CEA. 2015a. “Dossier de presse - Démentèlement.” Paris: Commissariat à l’énergie atomique et aux énergies alternatives (CEA). https://www.francetnp.gouv.fr/IMG/pdf/dossier_de_presse_demantelement_-_2015_v2.pdf.

———. 2015b. “Advances in Research on Partitioning-Transmutation and Plutonium Multi-Recycling in Fast Neutron Reactors - Summary of Results.” Paris: Commissariat à l’énergie atomique et aux énergies alternatives (CEA). https://www.cea.fr/english/Documents/corporate-publications/advances-research-on-partitioning-transmutation-and-plutonium-multi-recycling-in-fast-neutron-reactors.pdf.

———. 2019. “Rapport Financier 2018.” Financial Report. Gif-sur-Yvette: Commissariat à l’énergie atomique et aux énergies alternatives (CEA). https://www.cea.fr/multimedia/Lists/StaticFiles/rapports/financier/rapport-financier-2018.pdf.

———. 2021. “Rapport Financier 2020.” Financial Report. Gif-sur-Yvette: Commissariat à l’énergie atomique et aux énergies alternatives (CEA). https://www.cea.fr/multimedia/Lists/StaticFiles/rapports/annuel/pdf/rapport-financier-2020-fr.pdf.

CNE2. 2021. “Rapport d’évaluation no. 15.” 15. Paris: Commission National d’Èvaluation. https://cne2.fr/telechargements/RAPPORT_CNE2_15_2021.pdf.

Cour des comptes. 2012. “The Costs of the Nuclear Power Sector.” Thematic public report. Paris: Cour des comptes. https://www.ccomptes.fr/sites/default/files/EzPublish/thematic_public_report_costs_nuclear_%20power_sector_012012.pdf.

CRE. 2022. “Volumes d’ARENH supplémentaires pour limiter la hausse des prix de l’électricité.” Commission de Régulation de l’Énérgie. March 29, 2022. https://www.cre.fr/Actualites/volumes-d-arenh-supplementaires-pour-limiter-la-hausse-des-prix-de-l-electricite.

Cyclife. 2020. “Waste-Led Decommissioning Approach.” Paris: Cyclife. https://www.cyclife-edf.com/sites/default/files/Cyclife/pdfs/brochures-fiches-techniques/cyclife-brochure_waste-led-decommissioning-approach-en.pdf.

Diekmann, Florian. 2022. “Atomreaktor in Flamaville läuft noch später an.” *SPIEGEL ONLINE*, January 12, 2022. https://www.spiegel.de/wirtschaft/unternehmen/flamanville-atomreaktor-inbetriebnahme-verzoegert-sich-erneut-a-e5565145-0f6c-4b09-8764-167931e55530.

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

EDF. 2018. “Consolidated Financial Statements at 31 December 2017.” Financial Report. Paris. https://www.edf.fr/sites/groupe/files/contrib/groupe-edf/espaces-dedies/espace-finance-en/financial-information/publications/financial-results/2017-annual-results/pdf/fy-results-2017-consolidated-financial-statements-20180216.pdf.

———. 2020. “Consolidated Financial Statement at 31 December 2019.” Financial Report. Paris. https://www.edf.fr/sites/groupe/files/contrib/groupe-edf/espaces-dedies/espace-finance-en/financial-information/publications/financial-results/2019-annual-results/pdf/fy-results-2019-consolidated-financial-statements-20200214.pdf.

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

———. Undated. “Shaping the Future of Nuclear.” Nuclear Energy. Undated. https://www.edf.fr/en/the-edf-group/producing-a-climate-friendly-energy/nuclear-energy/shaping-the-future-of-nuclear.

European Commission. 2013. “EU Decommissioning Funding Data - Commission Staff Working Document.” SWD(2013) 59. Brussels: European Commission. http://aei.pitt.edu/42990/.

Felix, Bate. 2019. “France Sets 2050 Carbon-Neutral Target with New Law.” *Reuters*, June 27, 2019. https://www.reuters.com/article/us-france-energy-idUSKCN1TS30B.

Fitch. Undated. “Electricite de France (EDF).” Fitch Ratings. Undated. https://www.fitchratings.com/entity/electricite-de-france-edf-80464183.

Gouvernement Francais. 2014. “La transition énergétique.” 2014. https://www.gouvernement.fr/la-transition-energetique.

Graphitech. 2020. “EDF and VEOLIA Announce the Creation of Graphitech.” Press Release. June 15, 2020. https://www.graphitech-nuclear.com/en/edf-and-veolia-announce-creation-graphitech.

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

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

IAEA. 2022a. *Nuclear Power Reactors in the World*. IAEA-RDS-2/42. Vienna: International Atomic Energy Agency. https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-2-42_web.pdf.

———. 2022b. *Operating Experience with Nuclear Power Stations in Member States*. Operating Experience with Nuclear Power Stations in Member States. Vienna: International Atomic Energy Agency. https://www.iaea.org/publications/15212/operating-experience-with-nuclear-power-stations-in-member-states.

Kirong, Nephele. 2020. “S&P Downgrades EDF to BBB+ on Nuclear Operation Risks, Lower Output.” S&P Global Market Intelligence. June 22, 2020. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/s-p-downgrades-edf-to-bbb-on-nuclear-operation-risks-lower-output-59132743.

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

Koomey, Jonathan, Nathan E. Hultman, and Arnulf Grubler. 2017. “A Reply to ‘Historical Construction Costs of Global Nuclear Power Reactors.’” *Energy Policy* 102 (March): 640–43. https://doi.org/10.1016/j.enpol.2016.03.052.

Légifrance. 2016a. *Code de l’environnement*. https://www.legifrance.gouv.fr/codes/texte_lc/LEGITEXT000006074220/2022-04-27.

———. 2016b. *Code de la santé publique*. https://www.legifrance.gouv.fr/codes/id/LEGISCTA000032044833/.

Louet, Sophie, Sarah White, and David Evans. 2018. “France to Cut Nuclear Energy Reliance by 2035: Minister.” *Reuters*, November 18, 2018. https://www.reuters.com/article/us-france-nuclearpower-idUSKCN1NN0OK.

Martin, C, A Portelli, and F Guarnieri. 2014. “Myths and Representations in French Nuclear History: The Impact on Decommissioning Safety.” In *Safety, Reliability and Risk Analysis: Beyond the Horizon: Proceedings of the European Safety and Reliability Conference, ESREL 2013, Amsterdam, The Netherlands, 29 September-2 October 2013*, 393–400. Boca Raton London New York Leiden: CRC Press, a Balkema book.

Moody’s. 2022. “Rating Action: Moody’s Downgrades EDF’s Issuer Rating to Baa1; Negative Outlook.” Press release. Paris: Moody’s Investors Service. https://www.edf.fr/sites/groupe/files/2022-02/moodys-press-release-2022-02-21.pdf.

NEI. 2021. “French Regulator Approves 10 More Years of Operation for Oldest Reactos.” *Nuclear Engineering International Magazine*, March 2, 2021. https://www.neimagazine.com/news/newsfrench-regulator-approves-10-more-years-of-operation-for-oldest-reactors-8561158.

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

Orano. 2022. “2021 Annual Activity Report.” Châtillon. https://www.orano.group/docs/default-source/orano-doc/finance/publications-financieres-et-reglementees/2021/orano-annual-activity-report-2021-online.pdf?sfvrsn=dd0d6b85_20.

Pelleterat de Borde, M, C Martin, and F Guarnieri. 2014. “Nuclear Decommissioning: From Case-Studies to a Proposed Typology of Risk.” In *Safety, Reliability and Risk Analysis: Beyond the Horizon: Proceedings of the European Safety and Reliability Conference, ESREL 2013, Amsterdam, The Netherlands, 29 September-2 October 2013*, 571–78. Boca Raton London New York Leiden: CRC Press, a Balkema book.

Reuters Events. 2018. “EDF Ramps up Nuclear Decommissioning Efficiency with Eyes on Europe.” *Reuters*, June 6, 2018. https://www.reutersevents.com/nuclear/edf-ramps-nuclear-decommissioning-efficiency-eyes-europe.

Rodriguez, G., R. Frith, and M. Berte. 2004. "General Review of the Decommissioning of Liquid Metal Fast Reactors (LMFRs) in France." In *Operational and Decommissioning Experience With Fast Reactors: Proceedings of a Technical Meeting Held in Cadarache, France, 11-15 March 2002*, 159–83. Cadarache, France: International Atomic Energy Agency. https://www-pub.iaea.org/MTCD/publications/PDF/te_1405_web.pdf.

Rose, Michel, and Tassilo Hummel. 2022. "France Plans Full Nationalisation of Power Utility EDF." *Reuters*, July 6, 2022. https://www.reuters.com/world/europe/frances-edf-be-fully-nationalised-borne-2022-07-06/.

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

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

Schneider, Mycle, Antony Froggatt, Julie Hazemann, Christian von Hirschhausen, M.V. Ramana, Alexander James Wimmers, Michael Sailer, et al. 2022. "World Nuclear Industry Status Report 2022." Paris: Mycle Schneider Consulting. https://www.worldnuclearreport.org/IMG/pdf/wnisr2022-hr.pdf.

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

Sfen. 2017. "Chooz A : Vitrine de La Déconstruction Des Réacteurs à Eau Pressurisée." Société Francaise d'énergie Nucléaire. May 5, 2017. https://www.sfen.org/rgn/chooz-vitrine-deconstruction-reacteurs-eau-pressurisee/.

S&P Global. 2022. "Electricite de France Downgraded To 'BBB' From 'BBB+' On Strong Debt Increase In 2022-2023; Outlook Negative." Research Update. Paris: S&P Global Ratings. https://www.edf.fr/sites/groupe/files/2022-02/sp-edf-ratings-direct-2022-02-21.pdf.

Topçu, Sezin. 2007. "Les Physiciens Dans Le Mouvement Antinucléaire : Entre Science, Expertise et Politique." *Cahiers d'histoire. Revue d'histoire Critique*, no. 102 (October): 89–108. https://doi.org/10.4000/chrhc.214.

Veolia. Undated. "A Strategic Partnership with the Franch Atom Energy Agency (Commissariat à l'énergie Atompqie et Aus Énergies Alterantices Francais - CEA)." Veolia Nuclear Solutions - Our Expertise. Undated. https://www.nuclearsolutions.veolia.com/en/our-expertise/case-studies/strategic-partnership-french-atomic-energy-agency-commissariat-lenergie.

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

WNN. 2010. "Westinghouse the Choice for Chooz." *World Nuclear News*, April 27, 2010. https://www.world-nuclear-news.org/Articles/Westinghouse-the-choice-for-Chooz.

———. 2015. "Areva to Remove Superphénix Internals." *World Nuclear News*, December 1, 2015. https://www.world-nuclear-news.org/Articles/Areva-to-remove-Superphenix-internals.

———. 2021. "Dismantling of Marcoule Reprocessing Cell Approaching." *World Nuclear News*, December 23, 2021. https://www.world-nuclear-news.org/Articles/Dismantling-of-Marcoule-reprocessing-cell-approach.

———. 2022a. "EDF Revises up Cost of Nuclear Power Plant Outages." *World Nuclear News*, May 19, 2022. https://www.world-nuclear-news.org/Articles/EDF-revises-up-cost-of-nuclear-plant-outages.

———. 2022b. "Olkiluoto 3 Test Production to Continue until December." *World Nuclear News*, June 16, 2022. https://www.world-nuclear-news.org/Articles/Olkiluoto-3-test-production-to-continue-until-Dece.

Appendix

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

NPP	Type	Model	Owner	Operator	Gross El. Capa. [MW]	Constr. Start Date	Commercial Operation Date	Perm. Shut-down Date
Bugey-1	GCR	UNGG	EDF	EDF	555	01.12. 1965	01.07. 1972	27.05. 1994
Chinon A-1	GCR	UNGG	EDF	EDF	80	01.02. 1957	01.02. 1964	16.04. 1973
Chinon A-2	GCR	UNGG	EDF	EDF	230	01.08. 1959	24.02. 1965	14.06. 1985
Chinon A-3	GCR	UNGG	EDF	EDF	480	01.03. 1961	04.08. 1966	15.06. 1990
Chooz-A	PWR	CHOOZ-A	EDF	SENA	320	01.01. 1962	15.04. 1967	30.10. 1991
EL-4 (Monts d'Arrée)	HWGCR	MONTS-D'ARREE	EDF	EDF	75	01.07. 1962	01.06. 1968	31.07. 1985
Fessenheim-1	PWR	CP0	EDF	EDF	920	01.09. 1971	01.01. 1978	22.02. 2020
Fessenheim-2	PWR	CP0	EDF	EDF	920	01.02. 1972	01.04. 1978	30.06. 2020
G-2 (Marcoule)	GCR		CEA (80%), EDF (20%)	C.G.M.N..	43	01.03. 1955	22.04. 1959	02.02. 1980
G-3 (Marcoule)	GCR		CEA	C.G.M.N.	43	01.03. 1956	04.04. 1960	20.06. 1984
Phenix	FBR	PH-250	CEA	CEA (80%); EDF (20%)	142	01.11. 1968	14.07. 1974	01.02. 2010
Saint-Laurent-A-1	GCR	UNGG	EDF	EDF	500	01.10. 1963	01.06. 1969	18.04. 1990
Saint-Laurent-A-2	GCR	UNGG	EDF	EDF	530	01.01. 1966	01.11. 1971	27.03. 1993
Super-Phenix	FBR	Na-1200	EDF	EDF	1242	13.12. 1976	01.12. 1986	31.12. 1998

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