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Phasing Out Nuclear Power: The Economy and Policies of the Dismantling of Nuclear Power Plants in France and Germany

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Master in International Studies

Supervisor:

PhD. Nuno Luís Madureira, Full Professor

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Abstract

Humanity will no longer be able to depend on oil, gas and coal for its energy needs as crises and the threat of climate change rise. This statement pushes countries to rely more heavily on clean energy. Nuclear power is a carbon-free energy, operated in 32 countries and providing 10% of the worldwide electricity. As it can be a response to providing green energy, some countries are investing massively in the development of nuclear power. However, nuclear power can also refer to disasters. The accidents of Chernobyl and Fukushima, and the threat of a nuclear war have made some countries reconsider the use of atomic power and, in some cases, completely phase out nuclear power.

Costs and policies regarding nuclear and, more particularly, nuclear dismantling are not very well known by citizens. This increases the risk of misinformation to the public, leaving room for misinterpretation of the actual dangers and benefits of nuclear power.

This paper will compare the estimated costs of a nuclear phase-out of France and Germany. It will also state the policies put in place for nuclear dismantling, the role of supranational organisations, and how do French and German national policies compare in this regard.

Keywords: *Nuclear energy, Nuclear energy in France, Nuclear energy in Germany, Dismantling, Costs, Policy*

Resumo

A humanidade não poderá mais depender de petróleo, gás e carvão para as suas necessidades energéticas à medida que as crises e a ameaça das mudanças climáticas aumentam. Esta declaração leva os países a depender mais fortemente de energia limpa. A energia nuclear é uma energia livre de carbono, operada em 32 países e fornecendo 10% da electricidade mundial. Como pode ser uma resposta ao fornecimento de energia verde, alguns países estão investindo maciçamente no desenvolvimento da energia nuclear. No entanto, a energia nuclear também pode se referir a desastres. Os acidentes de Chernobil e Fukushima, e a ameaça de uma guerra nuclear fizeram alguns países reconsiderarem o uso da energia atómica e, em alguns casos, eliminarem completamente a energia nuclear.

Os custos e as políticas em matéria nuclear e, mais particularmente, ao desmantelamento nuclear não são muito conhecidos pelos cidadãos. Isso aumenta o risco de desinformação para o público, deixando espaço para interpretações erróneas dos perigos e benefícios reais da energia nuclear.

Este artigo irá comparar os custos estimados de uma eliminação nuclear da França e da Alemanha. Também indicará as políticas implementadas para o desmantelamento nuclear, o papel das organizações supranacionais e como as políticas nacionais francesas e alemãs se comparam a esse respeito.

Palavras-chave: *Energia nuclear, Energia nuclear na França, Energia nuclear na Alemanha, Desmantelamento, Custos, Política*

Index

List of acronyms and abbreviations

AEA	Atomic Energy Act
ANDRA	National agency for the management of radioactive waste (*French: Agence nationale pour la gestion des déchets radioactifs*)
ASN	Nuclear Safety Authority (*French: Autorité de sûreté nucléaire*)
BGZ	Company for Interim Storage (*German: Gesellschaft für Zwischelagerung*)
BWR	Boiling water reactor
CCGT	Combined-cycle gas turbine
CDS	Centre of Social Democrats (*French: Centre des démocrates sociaux)*
CDU	Christian Democratic Union of Germany (*German: Christlich Demokratische Union Deutschlands)*
CEA	Alternative Energies and Atomic Energy Commission (*French: Commissariat à l'énergie atomique et aux énergies alternatives*)
CIDEN	Centre ingénierie déconstruction et environnement
CIINB	Commission Interministérielle des Installations Nucléaires de Base
DSIN	Direction de la Sûreté des Installations Nucléaires
ECSC	European Coal and Steel Community
EDF	Electricité de France
EEC	European Economic Community
EIA	Environmental Impact Agreement
EPR	Evolutionary power reactor
EU	European Union
Euratom	European Atomic Energy Community
EWN	Entsorgungswerk für Nuklearanlagen
FBR	Fast breeder reactor
FDP	Free Democratic Party (*German: Freie Demokratische Partei)*
FNR	Fast-neutron reactor
GCR	Gas-cooled reactor
GDE	German Democratic Republic
GDP	Gross domestic product
GNS	Gesellschaft für Nuklearservice
HLW	High-level waste
HTGR	High-temperature gas reactor
HWGCR	Heavy water gas cooled reactor
IAEA	International Atomic Energy Agency
ISCD	International Structure for Decommissioning Costing
KW	Kraftwerk Union

LTE	Long-term enclosure
LWR	Light-water reactor
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
OECD	Organisation for Economic Co-operation and Development
PCF	French Communist Party (*French: Parti Communiste Français)*
PHWR	Pressurised heavy water react
PNGMDR	National plan for the management of radioactive waste and materials (*French: Plan national de gestion des matières et des déchets radioactifs*)
PR	Republican Party (*French: Parti Républicain)*
PWR	Pressurised water reactor
RPR	Rally for the Republic (*French: Rassemblement pour la République*)
RTE	Electricity Transmission Network (*French: Réseau de transport d'électricité*)
SDP	Social Democratic Party (*German: Sozialdemokratische Partei Deutschlands)*
SNF	Spent nuclear fuel
TFEU	Treaty on the Functioning of the European Union
UN	United Nations
UNGG	Natural Uranium Graphite Gas (*French: Uranium naturel graphite gaz*)
We	Watt electrical

Chapter 1 — Introduction

1.1. Definitions

For a better understanding of this research, the following key concepts are defined.

Nuclear energy (or nuclear power, or atomic power) corresponds to the civil and military usage of energy provided by nuclear fission, fusion or decay reactions within nuclear reactors. Most electricity from nuclear power is produced by the nuclear fission of uranium, plutonium or thorium in nuclear power plants. For the purpose of this research, the focus will be on the production of nuclear energy for civil purposes.

Nuclear energy policy corresponds to international and national policies, strategies and programs concerning all aspects of nuclear energy and the nuclear fuel cycle. This paper will focus on policies targeted at nuclear decommissioning and nuclear waste.

Nuclear decommissioning is the process in which a nuclear facility is dismantled to the point that it no longer requires measures for radioactive protection; thus, it does not create any risk for the environment or populations.

1.2. Nuclear energy technology

Nuclear power production is based on a self-sustaining chain reaction, in which three water conducts work separately. In a nuclear reactor, the fission of atoms of uranium 235 produces a large quantity of heat, warming up to 320°C water circulating in the reactor. However, water remains under pressure so that it does not boil. This closed conduct is called primary conduct. This conduct is related to another conduct, called secondary conduct, in which warm water from the primary conduct is transformed into steam through a steam generator. Pressure from the steam turns turbines, which itself turns an alternator that eventually produces electricity. The remaining conduct is the cooling system, in which steam from the secondary conduct is converted back into the water thanks to a condenser in which water from rivers or the sea circulates. This technology is used by pressurised water reactors (PWR), which is the most frequent type of nuclear reactor. However, it is worth pointing out that

France started its civil nuclear development with Graphite-moderated CO_2 cooling reactors, which use carbon as a neutron moderator, allowing natural uranium to be used as nuclear fuel.

1.3. Background

France and Germany started their nuclear activity in the 1950s during a period of growing demand for energy and in the context of the creation of the European Coal and Steel Community (ECSC). As a result, both countries cooperated to support their industries that could contribute to energy production.

The French nuclear industry became significant after the military nuclear agenda in the 1960s and continued to develop over the next decades. In 2016, 72% of the French electricity production and 27% of the final energy production in the country were provided by nuclear energy (Ministère de la Transition écologique et solidaire, 2018). Today, France has 56 pressurised water reactors (PWR) in 18 nuclear power plants, totalising a production of about 61.3 GWe. It includes 34 CP0, CP1, and CP2 reactors of about 900 MWe each, 20 P4 and P'4 reactors of about 1,300 MWe each, and four N4 reactors of about 1,450 MWe each. All reactors are operated by EDF (Électricité de France). Fifteen reactors are permanently shut down or are currently being dismantled, such as the two PWR reactors of Chooz (1962-1991) and Fessenheim (1978-2020), the Brennilis heavy water gas-cooled reactor (HWGCR) (1967-1985), nine uranium natural graphite gas (UNGG) reactors, and two fast-neutron reactors (FNR). In addition, one evolutionary power reactor (EPR) is being built in Flamanville with an expected production capacity of 1,650 MWe. In 2010, EDF[1] announced that it was assessing the prospect of raising the 40-years lifetime to 60 years for all remaining reactors, replacing all steam generators in the 900 and 1,300 MW reactors. The expected refurbishment cost for each unit was about 480-720 million $€_{2022}$. The lifetime of nuclear reactors tends to last longer since it was realised that they were lasting longer than their design

[1] EDF is the French company responsible for the production and supply of electricity in France. Privatised in 2004, it is, nevertheless, owned by the French state at 83.8%.

lifetime[2]. Moreover, long-life nuclear reactors come with economic advantages. Indeed, the total production cost of nuclear power diminishes when the original debt is paid off (Weinberg, 2004).

The nuclear fleet in Germany has been less developed than France's, but it used to be more diverse and with multiple operators. Germany constructed a total of 38 nuclear reactors, including three that are still operational as of October 2022, two that never entered into service, and 33 shut down or are in the process of dismantlement. It includes 11 boiling water reactors (BWR), of which the last was dismantled in December 2021, two fast breeder reactors (BFR), including one that has never entered into service, 22 high-temperature gas reactors (HWGCR), one pressurised heavy water reactor (PHWR), and 25 PWR, including one that never entered into service, four unfinished or never built, and three that are still in use: the ones of Emplaned, Isar-2, and Neckarwestheim-2. Four operators were in charge of the nuclear power plants: E. ON Kernkraft GmbH, EnbH AG, RWE Power AG, and Vattenfall Europe Nuclear Energy GmbH.

The difference regarding the number of shutdown nuclear power plants in Germany stands in how France and Germany reacted to the use of nuclear power within the last two decades. After the Fukushima disaster in 2011 and a shift in public opinion on the use of nuclear power, the German government adopted in 2011 the Atomic Law, aiming to shut down its nuclear fleet by the end of 2022. As a result, the part of nuclear power in Germany's total energy production decreased from 22.2% in 2010 to 11.8% in 2018. After the adoption of the law of energetic transition in 2015, France aimed to reduce the part of nuclear in the production of electric to 50% by 2025, which the government delayed by 2035 in 2017. Facing the longevity of its nuclear fleet, French President Emmanuel Macron announced in February 2022 its wish to see the construction of six new EPR2 reactors by 2050, which will largely depend on thorium, as well as modular nuclear reactors with fewer energy production capacities. Later this year, Prime Minister Elisabeth Borne announced the nationalisation of EDF, a way to more efficiently conduct the construction of these new nuclear reactors (Ouest France, 2022).

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[2] The present generations of reactors usually have a 40-year operating licence. Forty years was the projected lifetime of fossil plants, therefore became by default the licensing period for nuclear power plants. The current proposed reactors are now designed to last 50 to 60 years (Weinberg, 2004).

The differences between France and Germany regarding nuclear power leave the question of which resources to rely on in the future as crises and geopolitical tensions arise. In addition, the threat of climate change imposes debates over which energies to develop and to phase out. An increase in the use of renewable energies is expected in France and Germany, as it made up 23% of the total energy needs in France and 42% in Germany in 2020. France wants to double its share by 2030, and Germany aims to get 100% of its energy from renewable resources by 2035. Even though the goal regarding the use of renewable resources is different in those countries, Germany, due to the rapid phasing-out of its nuclear energy without the necessary compensation in renewable energies, saw an increase in its greenhouse gas emissions by 4.5% more between 2020 and 2021. It is due to the reopening of coal-fired plants, as well as the imports of natural gas, making respectively 29.7% and 10.4% of the country's electricity production in 2021.

Another major issue in the European Union regarding energy is the importance of energy sovereignty. As member states still heavily rely on foreign powers for their imports of natural gas and oil, countries are subject to geopolitical situations and tensions. For example, the Russian war on Ukraine cut short the NordStream2 project between the Russian Federation and Germany, which aimed to increase the inflows of natural gas in Europe, after a decision of German Chancellor Olaf Scholz in February 2022. This put member states to envisage solutions against the dependency on such resources, leaving the question about the use of nuclear energy open, even in Germany. Indeed, two of the three remaining nuclear reactors in Germany are expected to remain active until Spring 2023 (Der Spiegel, 2022). On the European level, it has also been debated whether the use of nuclear energy —among other energy sources— was ecological or not. Many countries have decided to phase out their nuclear fleet, such as Switzerland, Belgium and Italy, and oppose the construction of new nuclear reactors for environmental or security reasons. In contrast, others like France and Finland have declared their wish to build new nuclear infrastructure and make their existing fleet last longer. The European Parliament has adopted through a vote of 328 in favour to 278 against a green label for nuclear energy as well as natural gas in July 2022, allowing European funds to countries that desire to develop these industries.

Nuclear phase-out in Germany led to the increase of electricity prices in order to finance the construction of renewable energies, subsiding the shutdown of nuclear reactors. In

2012, the Federal Ministry of Economy announced that prices would have increased by between three and five euro cents per kilowatt hour by 2013 (Der Spiegel, 2012); for reference, the average price for electricity in Germany at that time was 0.26 € per kilowatt, and reached 0.30 € per kilowatt in 2013, a year after. As of 2022, it costs 0.32 € per kilowatt on average. For comparison, electricity prices in France cost an average of 0.10 € per kilowatt in 2012, and 0.15 €[3] per kilowatt in 2022 (Insee, 2019; Statistisches Bundesamt, 2022). The electricity prices in France are low due to the predominance of nuclear energy which is considered to be a low-cost energy source; yet, their increase is due to the maintenance costs of grid connection as well as tax increases due to the construction of new renewable energies.

In France, the 50 or 60-year lifetime of nuclear reactors allowed the country to rely on atomic power for a longer time despite its ageing fleet. However, this lifetime extension brings other issues, and more importantly, safety issues. Corrosion is the main concern for ageing reactors; if it remains undetected, it can lead eventually to a serious reduction in design safety margins or in the effectiveness of the installed safety systems. Other ageing effects include changes in physical properties (e.g., electric conductivity), irradiation embrittlement and wear (e.g., fretting and cracking assisted by wear, such as fretting fatigue) (IAEA, 1987).

At this date, nearly 600 nuclear installations —including 17 reactors— have already been dismantled worldwide. About 450 other nuclear installations —including reactors, fuel cycle installations and research structures— have been shut down and are being dismantled.

1.4. Problem statement

In a period of rising crises, from climate change to socio-economic crises, doubts increase about countries' capacity to respond adequately to the growing demand for energy and the difficulty of providing sufficient green energy. The use of atomic power and the question of its security and capacity to provide GHG-free energy divides public opinion and governments. As a result, several countries have declared their wish to phase out their nuclear fleet.

Thus, it is relevant to describe policies that are implemented to dismantle nuclear en-

[3] These prices include national taxes.

ergy and to analyse and compare the economic costs of a phase-out in countries where the importance of nuclear in the energy mix is drastically different.

1.5. Research objective

The objective of this research is to widen the information base for European policy-making based on two countries with different energy strategies (France and Germany) through the analysis and comparison of economic and political aspects of dismantling nuclear energy.

The arguments for each country will give a better comprehension of the role of international organisations, the implication of national institutions in the current policies regarding nuclear dismantlement and its financing, and how the estimated costs compare between the two countries.

1.6. Research questions

The main research question of this paper is:

How do France and Germany compare economically and politically regarding their position on a possible nuclear phase-out?

The sub-research questions are:

What role do supranational organisations play regarding nuclear dismantlement, and what political power is left to nation-states?

What are the economic costs of a total phase-out of nuclear energy, and how do France and Germany compare?

1.7. Table of contents

With the complementary table of contents provided with the titles of each chapter and sub-chapter, here is a short description of each chapter and its role in this paper.

Chapter 2 describes the methodology used to answer the research questions.

Chapter 3 gives an overview of the historical context of the nuclear industry in France and Germany and what led Germany to decide on its nuclear phase-out while France is expected to develop this industry. It will also provide researchers' stances on the choice of nuclear energy and the dismantlement process.

Chapters 4 and 5 answer the first sub-research question by giving an overview of the international and national policies on nuclear dismantlement, fuel cycle and waste.

Chapter 6 answers the second sub-research question, firstly by stating the policies on financing nuclear dismantlement and then by analysing and comparing the costs for a total nuclear phase-out of France and Germany.

Chapter 7 answers the main research question.

Chapter 2 — Research methods

This chapter describes the methodological processes that will be used for this research.

2.1. Research framework and strategy

2.1.1. Research framework

This paper is a comparative study aiming to analyse and compare two countries, France and Germany, regarding a possible phase-out of their nuclear fleet and, more particularly, the policies and costs of nuclear decommissioning.

2.1.2. Selection of research unit

The choice of France and Germany for this research is based on the two countries' similar nuclear development, which started as soon as the 1960s, as well as their similar political, geographical, economic and technical status. France and Germany are member states of the European Union and are, respectively, the seventh and fourth biggest powers in the world by their GDP (IMF, 2022).

Nuclear energy is under the spotlight as European countries decide whether to phase out or to develop atomic energy, in order to develop affordable and clean energy as part of a climate action curriculum and through the development of their nuclear industry.

2.1.3. Research boundary and limitations

In order to focus the research on political and economic aspects, this research will provide an analysis neither on social and technological aspects nor on the political choice of choosing or not nuclear energy. Furthermore, this research's notion of nuclear phase-out is purely hypothetical and at a defined time. Thus, it does not consider any outcomes concerning the future of atomic energy in the studies countries. Also, the purpose of this research is to analyse the estimated costs of a nuclear phase-out. It will only consider the dismantlement of nuclear power plants without taking into account other facilities such as research facilities. Finally, the outcomes of this research will be general and will not answer the specific features of nuclear power plants.

2.2. Research material and assessment method

Information and data are extracted from various primary and secondary sources. Primary sources are composed of official documents such as policy documents and reports, as well as company reports. Secondary sources are composed of the use of media and academic literature. Media data is used to get a broader overview of the countries' plans for using atomic energy, as this matter has recently been of great interest. Academic literature involves scientific papers on nuclear energy regarding its comprehensive history and analyses regarding its political and economic aspects.

2.3. Data analysis

The research uses quantitative, qualitative and mixed methods to answer sub-research and the main research questions. Data on the specific topics are produced by public authorities or companies under the public authorities (primary sources), media and academics (secondary sources). Documents from official sources will be confronted with relevant scientific literature. Finally, the data will be analysed and interpreted to make a conclusive comparison.

Chapter 3 — Literature review

Extensive academic literature has existed regarding nuclear power and its development since the 1950s. Germany and France are often compared as similar events marked their history. Nevertheless, as part of the *Energiewende*[4] agenda, Germany decided on the phasing-out policy of its nuclear plants; academics have written a lot about the economic, social and environmental costs of this decision. France decided on other policies, and literature about a French nuclear phase-out resembles fiction, even though many scenarios have been studied to give the most accurate approaches.

3.1. Historical context

3.1.1. Early beginning and the oil crisis

As Wiliarty (2013) observes, it can be thought that France and Germany would follow the same path concerning the use of nuclear energy. Both countries are industrialised democracies in high demand for energy, lacking many natural sources that could provide alternative energy sources. Both countries have cooperated to support the industry sector that could contribute to energy production, notably with the foundation in 1952 of the European Coal and Steel Community (ECSC).

France and Germany started to develop their civilian nuclear program in the 1950s. The French state became mainly involved in developing nuclear power economically and technologically. Two government agencies played an important role in overseeing the development of this industry, the Commissariat à l'énergie atomique et aux énergies alternatives (CEA), established in 1945 as an agency for nuclear research and development, and the Électricité de France (EDF). In the 1960s, France began to generate enough power to sell, and EDF started to exert control over the nuclear power industry. Nelkin & Pollak (1980) indicate that the French civilian program was based on independent graphite design in the late 1950s but was changed to a light-water reactor (LWR) design in 1969, with the ambition to expand

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[4] The Energiewende (German for "energy turnaround") refers to the ongoing transition in Germany to rely on low carbon and affordable energy supply, aiming to increase the share of renewable energies and phase out nuclear power.

its nuclear program to produce 8,000 MW in 1976. The nuclear capacity drastically increased after the oil crisis of 1973 and 1974.

The development of the French civil nuclear program is a result of the military nuclear program. France did its first nuclear bomb test in 1960, eight years after the United Kingdom. Through its nuclear programs, France wanted to remain an independent nation and a world's strong military force (Fouquet, 2019). In France, public discourse linked nuclear power to nationalism and the power of the French state and its idea of *grandeur*[5], legitimising the suppression of protesters and the expropriation of properties. This discourse is largely different from Germany's memory of National Socialism (Wiliarty, 2013).

The German nuclear power industry began later, at the end 1950s, as the Allies initially banned the development of German nuclear technology (Wiliarty, 2013; Nelkin & Pollak, 1980). However, contrary to France, Germany never seriously considered developing nuclear weapons and focused on developing its civilian nuclear industry, immediately favouring the LWR design. Also, this industry was more linked to profits than France's; private companies worked together, but the German state remained a major shareholder in private utilities and therefore had a significant role in developing this industry (Wiliarty, 2013). As Nelkin & Pollak (1980) explain, the development of nuclear power was slow at first. Growing pressure from the chemical and electronic industries converged with the increasing oil price due to the oil crisis pushing the nuclear program. European countries had planned in the early 1970s to increase their capacity, projecting that in 1985, 33% of the total consumed electricity in the European Economic Community (EEC) would originate from nuclear (from 5,000 MW in 1972 to 100,000 MW in 1985).

France pursued this wish to push for nuclear power since EDF built 58 reactors, with a total gross installed capacity of 66 GWe, from the early 1970s to the late 1990s using the PWR design developed by Westinghouse Corporation (Komanoff, 2010). Grubler (2010) praises the success of the construction of nuclear power plants in France by quoting the analogy made by Jasper (1992) in comparison to Greek mythology. The main groups of actors of this success can be categorised as "gods" (governments), "titans" (large industries and institu-

[5] After the end of World War II, Charles de Gaulle defined two priorities: to make France independent of foreign influences and to conduct a foreign policy on a global scale. This mindset inspired many policies throughout the following decades in France.

tional actors) and “mortals” (the general public). By this analogy, Jasper says that “mortals”, the general public, never played a decisive role in the technocratic decision-making, allowing the rapid construction of NPPs. Senior actors were extremely well coordinated by state engineers from the *Corps des Mines* and the *Corps des Ponts*. Finally, “god”, the government, and the two “titans”, EDF and the CEA, acted in cooperation as the two entities were state-owned, overcoming divergent opinions and rivalries. The development of nuclear energy was accompanied by European treaties such as the Euratom. Established on January 1st, 1958, Fouquet (2019) points out that its original objective was to promote and guarantee nuclear energy development, but that it never was a harmonising treaty for a joint common approach and objective.

3.1.2. Opposition in 1977

Though public opinion agreed with the decision to favour the use of nuclear power (74% of the French people and 60% of the German people in 1975), their views changed in 1978 (47% of the French people, 53% of the German people in favour of nuclear energy) (Wiliarty, 2013). As Nelkin & Pollak (1980) point out, local opposition and actions in the early 1970s against “nuclear society” rather than the construction of nuclear power plants (NPPs) led to massive demonstrations in the late 1970s, and more particularly in 1977. These anti-nuclear movements increased globally and became transnational, so this is no surprise that both France and Germany were impacted by these demonstrations. However, the national governments reacted differently, leading to a different faith between the two countries.

Kirchhof & Meyer (2014) explain in their paper the importance of transitional exchange during the global protests against nuclear power in the 1970s and 1980s. The transnational impact of these demonstrations stands in how the issue of nuclear power transcends national borders. The first reason for that is the transnational diffusion of knowledge and ideas communicated by experts, through travels and scientific exchange and cooperation. Secondly, the importance of nuclear power transcends the nation-state due to global trade, industry and banks. During the 1970s, multinational cooperations (e.g., Westinghouse, General Electrics, Siemens) sold their expertise and technology in the nuclear sector worldwide. Thirdly, the consequences of nuclear power, such as the natural environment and radiation are not limited to national borders. Thus, protests against the risks of nuclear weapons also crossed borders. Those protests were the consequence of different factors. Firstly, the rise of environmentalism in the early 1970s contributed to a more critical view of nuclear power, highlighting the polluting impact and the dangers of nuclear waste. This was emphasised by new controversial scientific evidence of the dangers of low-level radiation. Secondly, these protests were influenced by the 1968 student movements. This led to a more politicised younger generation. Lastly, the increasing number of citizens confronted with the presence of new nuclear facilities gathered larger, national and even transnational protesters; French and German people protested together against the construction of new nuclear reactors, despite the long-time rivalry between the two countries (Kirchhof & Meyer, 2014; Milder, 2014).

In Germany, massive and violent demonstrations took place in the nuclear sites of Wyhl, Brokdorf and Grohnde, but also in Gorleben, where a giant nuclear reprocessing and waste disposal centre was supposed to be created. The construction of this centre was strongly opposed by the local farming community and was supported by anti-nuclear groups from all over the country (Jahn & Korolczuk, 2012).

A violent demonstration in Creys-Malville, France, took place in 1977. Creys-Malville was the intended location for the construction of a breeder reactor called Superphoenix. As the demonstration turned violent, 100 of the 60,000 demonstrators were injured, and one was killed (Nelkin & Pollak, 1980; Wiliarty, 2013). This demonstration led to the success the same year of the ecological parties in municipal elections, sometimes gaining more than 20% of the votes (Nelkin & Pollak, 1980). However, as Wiliarty (2013) mentions, the French authorities intimidated the protesters, resulting in much smaller subsequent demonstrations. Movements followed conventional channels such as political parties, but they were largely unsuccessful in the subsequent elections, totalising 2.14% of the votes during the parliamentary elections of 1978.

In Germany, however, ecological parties were more successful in the parliamentary elections of 1978, especially in Hamburg, Berlin and Lower Saxony. German anti-nuclear movements mixed protests and court activities and managed to gain strong electoral successes, and succeeded in slowing the development of the nuclear power program.

French and German opposition parties did not attempt to pressure their deputies on the nuclear question, as political behaviour was less determined by nuclear issues rather than the opportunity to criticise the opposing party responsible for decisions. As a result, only radical left parties participated in anti-nuclear activities, which fragmented the left on this issue (Nelkin & Pollak, 1980).

3.1.3. Political parties

After the demonstrations of 1977, political parties in France and Germany became divided on the issue of nuclear power.

In France, Nelkin & Pollak (1980) state that the Gaullist party (RPR) was the only major party advocating for the expansion of nuclear power, alongside the Radicals and the Republican Party (PR). The Radicals, however, criticised the centralisation of decision-making. Among the left-wing parties, the Centre of Social Democrats (CDS) was critical of using nuclear power and favoured a minimum programme. The Communist Party (PCF) was in favour of nuclear technology. However, it was critical of the fact that it demonstrates that France is dependent on the United States of America and Germany.

During the 1970s, Germany's main parties mostly favoured the development of nuclear power. The social democrats were in favour of more state control of energy development, whereas the Christian Democrats were in favour of giving priority to the private sector. Nevertheless, internal conflict within the Social Democratic Party (SPD) about the use of nuclear power emerged. (Nelkin & Pollak, 1980). The SPD eventually shifted from a pro-nuclear stance in 1979 to the decision to abandon nuclear power within ten years in 1986. A federal-level Green Party later emerged in the 1980s, after the protests of the 1970s, and eventually entered into a government coalition with the SPD in 1998. The red-green alliance engaged in a phasing-out policy and agreed in 2000 to a nuclear phase-out by 2021. The new coalition in 2009 of the Christian Democratic Union (CDU) and the Free Democratic Party (FDP) extended the phase-out by about a decade in the 2030s, intending to remain an industrial powerhouse and a role model for other countries in the fight against climate change (Jahn & Korolczuk, 2012; Wiliarty, 2013; Jarvis et al., 2019).

3.2. The growing choice of dismantlement

3.2.1. Politics before Fukushima

In Germany, the use of nuclear energy has long been controversial, with fierce debates and protests that started in the 1970s. The last reactor commissioned in Germany was in 1989, three years after the accident of Chernobyl. Indeed, as Jarvis et al. (2019) explain, the Chernobyl accident led to growing concern among the German population as the country was affected by the radioactive fallout. The accidents of Chernobyl and Three Mile Island in the United States in 1979 have contributed to a better safety culture within the nuclear industry (Sovacool, 2010). The decision was made during the green-red coalition until 2009 to phase out the nuclear power industry, marking a political shift from its promotion in the 1960s and 1970s (Jahn & Korolczuk, 2012; Jarvis et al., 2019). The first shutdown of nuclear reactors occurred in 2003, with the shutdown of the least economically viable reactors, the Stade reactor and Obrigheim, two years later. Until the complete phasing-out, the nuclear industry and the government agreed that high safety standards must be maintained. In return, the government would commit to respecting the right of utilities to operate existing nuclear power plants and guarantee that operations and waste disposal would be protected from interference (Jahn & Korolczuk, 2012).

3.2.2. Fukushima disaster and subsequent consequences

The Fukushima disaster on March 11th, 2011, was the last step in phasing-out nuclear energy in Germany. As public opinion grew against nuclear power, 250,000 protested nationwide in the days following the disaster (Jarvis et al., 2019). This political pressure led to a three-month moratorium on nuclear power, which checks would have been undertaken by a reactor safety commission. Meanwhile, seven plants built before 1980, totalising a capacity of 8.4 GW, shut down temporally. The ethical committee that was established to reconsider the use of nuclear energy concluded that all German plants featured a high grade of robustness with good predictions, even in extreme scenarios such as floods (Jahn & Korolczuk, 2012; Jarvis et al., 2019; Malischek & Trüby, 2016). Despite that, the German Parliament (Bundestag), with cross-party consensus, voted 513-79 in favour of nuclear phase-out; all functioning 17 reactors with a capacity of 20.5 GW would shut down by 2022, and the use of renewable energy would be expended (Arlt & Wolling, 2015; Jahn & Korolczuk, 2012; Keppler, 2012). This decision is a political shift, as six months prior, the Parliament called for the extension of the German nuclear power plant runtime (Arlt & Wolling, 2015). However, as Keppler (2012) explains, Germany was expected to produce 12.9 GW of new fossil fuel by 2015, of which 10.8 GW would be coal-based.

Jahn & Korolczuk (2012) declare that no other country has been as troubled by the nuclear disaster of Fukushima as Germany. Nevertheless, this catastrophe led to consequences in other countries as well. In France, the decision was made in 2015 to limit the share of nuclear power supply to 50% by 2025 (Malischek & Trüby, 2016). In Switzerland, the National Council voted 101 to 54 to not replace nuclear power plants, with the effective phasing-out by 2034 (Malischek & Trüby, 2016; Jarvis et al., 2019).

Arlt & Wolling (2015) researched the effects of media on public opinion on the Fukushima disaster. As they state, dependency on media is necessary for an individual's awareness of global affairs, and it increases in times of notable conflicts and following unexpected events such as natural disasters or, in that case, accidents. The authors applied the theory of Noelle-Neumann (1973) to this event, declaring that three factors facilitate the strong effects of mass media: consonance, ubiquity and cumulation. Arlt & Wolling found that, during the 1950s and 1960s, media highlighted the positive societal, technological and economic development of the use of nuclear energy in German society, but this changed since the start of the social movement during the 1960s. A survey for the Allensbach Institute showed that, in March 2010, 37% of German people were against the use of nuclear energy, while 44% were in favour (Peterson, 2010). A survey conducted by Goebel et al. (2015) shows that 81% of German residents favoured a nuclear phase-out in 2015. In the days that followed the Fukushima catastrophe, the media mainly covered the protests, and the issues of risks versus security, while the economic issues related to nuclear power remained marginal. Also, the media increase their coverage of nuclear replacement with renewable energies. However, Arlt & Wolling conclude that it is "unreasonable to assume that strong media effects on public opinion are commonplace, and they are less likely when coverage is more diverse, as in this particular case".

3.3. Stances on the choice of use of nuclear energy and decommissioning

3.3.1. The choice of nuclear energy

Researchers debate the choice of using nuclear energy as a sustainable energy source as they consider the risks of an accident, the costs, the social and environmental consequences, and the other solutions, including renewable and fossil-fuelled energies.

Sovacool (2010) discusses the costs and benefits of a nuclear renaissance. On the positive side of nuclear energy, he argues that the production costs are historically low, the performance of reactors has improved, the amounts of created waste are now smaller, and there is better safety culture and plentiful fuel sources. He also declares that nuclear power produces less greenhouse gas emissions than other means of production. This is the main argument of Brook et al. (2014) in favour of nuclear energy, declaring that only nuclear power plants can sustainably and reliably supply large quantities of clean and economical energy needed to run industrial societies with low greenhouse gas emissions. They also argue that renewable energies will not be sufficient to supply large quantities of energy needed sustainably, economically and reliably, as they would need to be backed up by fossil-fuelled energies that do not contribute to the decrease of greenhouse gas emissions. The researchers declare that nuclear energy meets all criteria of sustainability as defined by the UN Brundtland Commission and even argue that industrial nations should take the lead in order to transform the major part of their stationary electrical generating capacity to nuclear-fission based, affirming that it could be achieved in a few decades.

Sovacool (2010) also weighs the disadvantages of nuclear energy. Building nuclear reactors take a lot of time, and the risk of cost overruns as well as the risk of severe accidents exist. In addition, nuclear energy depends on volatile and consolidated sources of uranium, which cost tripled in 15 years, requires large amounts of water, and generates hazardous and extremely long-lived waste.

Jarvis et al. (2019) question the global shift of nuclear phase-put, as the environmental and economic costs of replacement with fossil-based energies are high. It is argued that the phase-out policy results from rational decision-making by risk-averse agents made up of uncertainty on the nuclear accident risks and waste disposal and that the risks associated with nuclear power are more salient than the air pollution costs associated with fossil-fuelled production to citizens. This led policy-makers and the public to overestimate the ex-ante probability that nuclear accidents will occur and the costs of these accidents. Jarvis et al. argue that policy-makers and academics must convey the relative costs of climate change and air pollution versus the nuclear accident risks and waste disposal uncertainties to the public.

Keppler (2012) declares that, because of the phase-out policy, Germany has become a net importer of electricity of about 50 GWh/day, while it used to be a net exporter before March 2011 at 70 GWh/day. This impacted the trade balance of 2.5 billion $€_{2012}$ per year, resulting in the increase of electricity prices at 8 €/MWh higher than they would be in the absence of phase-out.

3.3.2. The strategies and policies for decommissioning

Academics argue about the different decommissioning strategies and policies and their economic or logistic consequences.

According to Malischek & Trüby (2016), decommissioning costs are higher in scenarios that assume a phase-out of nuclear power plants before the end of their technical timeline, due to the investment costs of existing plants being sunk and because of nuclear plants exhibiting very low marginal costs of generation. They remind their readers of the importance of a coordinated energy policy in Europe if France decides on a phase-out policy; France's neighbouring countries need the ability to react rapidly, as they partly depend on France's energy exportations.

Irrek (2019) advocates for measures to improve decommissioning financing schemes, such as increasing the transparency of costs estimates, establishing a system of checks and balances in the governance chain in order to avoid negative effects stemming from conflicts of interest, setting incentives to cost reduction while maintaining the level of radiation protection needed, implementing a system of rules to ensure the full implementation of the polluter-pays principle and that fund assets will be separated from other assets.

Wealer et al. (2019) note that the decommissioning process is often neglected, as experience is still lacking. For instance, countries lack waste disposal facilities, long-term financing is challenged, and costs are often underestimated. Finally, only Germany can count on past experiences with the dismantlement of small reactors.

Lastly, MacKerron (2019) focuses on the issues of nuclear waste. He declares that countries failed to find publicly acceptable and technically convincing ways of dealing with higher activity wastes but notices that some countries have made small advances after the Fukushima disaster.

Chapter 4 — Decommissioning Policies and Strategies

4.1. Decommissioning policies

Nuclear decommissioning is the process in which a nuclear facility is dismantled to the point that it no longer requires measures for radiation protection. Decommissioning policy refers to government policy and includes all governmental choices as described in laws, regulations and mandatory requirements that will influence the framework in which the decommissioning process will take place (OECD, 2003).

Both in France and Germany, licence operators are responsible for the dismantling process of their nuclear facilities. The International Atomic Energy Agency (1994) states that national governments have the responsibility of implementing a framework and policies, and of choosing a dismantling strategy regarding the dismantlement of their nuclear facilities. Principles of dismantling are similar between countries (e.g., safety for the population and protection of the environment), but are influenced by individual factors such as:

- the constitutional and legal system of the country,
- the authority and jurisdiction among government agencies and departments,
- the ownership, structure and organisation of the nuclear industry; and
- the available technical, personnel and financial resources.

In France, Article 6 ter of Decree 63-1228 of December 11th, 1963 related to nuclear installations, and modified by Decree 90-78, addressed the different phases of decommissioning. However, it defined neither the decommissioning strategy nor scheduling, as the latter is based exclusively on economic and social considerations. The different phases are defined as followed:

- The first phase of decommissioning referred to operations that could be carried out under the regulatory framework of the initial licence decree, or in other terms, the operating licence. It includes defuelling, the removal of nuclear materials and waste, and equipment decontamination. These operations were performed in accordance with the operating rules and conditions attached to the initial safety report. The operator was required to present a safety study describing these operations to the *Direction de la Sûreté des Installations Nucléaires* (DSIN) six months before the final shutdown, and to send them regular progress reports.

- The second phase concerned the achievement of safe storage conditions, including the dismantlement of non-radioactive equipment and structures and the maintenance of containment barriers. These operations needed a licence decree from the Ministries of the Environment and of Industry, issued after declaring to comply with the requirement of the Ministry of Health, and consultation with the *Commission Interministérielle des Installations Nucléaires de Base* (CIINB). Defined by the Decree of December 11th, 1963, it specified the facility state that intended to be achieved at the completion of the planned activities, the manner in which it was planned to attain it, measures to ensure the facility's safety, and monitoring and maintenance provisions required to maintain safe conditions. These operations were carried out to achieve IAEA Stage 1[6].

- The third and final phase corresponded to the dismantling which could be started at the end of the operations required for achieving safe storage or deferred to take advantage of radioactive decay. A new decree was required to obtain a dismantling licence, allowing the start of dismantling operations after about forty years of safe storage of NPPs. These dismantling operations led either to IAEA Stage 2[7] or Stage 3[8] (IAEA, 1994).

Throughout these phases, safety controls must have continued from the time that the operation of a nuclear facility would cease until all radioactive materials would have been removed.

In Germany, the legal basis for the use of nuclear energy is the Atomic Energy Act (AEA) of December 23rd, 1959. It is the legal foundation of the peaceful utilisation of atomic power in Germany, intending to promote nuclear research and the development and use of nuclear energy (Jahn & Korolczuk, 2012). Section 7 §3 is the central statement on the post-operational phase of stationary installations for the production, treatment, processing or fis-

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[6] IAEA Stage 1 means that the first containment barrier is kept as it was during operation but mechanical openings are permanently sealed. The containment building and atmosphere are kept in a state appropriate to the hazard in the building. Surveillance, monitoring and inspections are carried out to ensure the plant remains in good condition (Feraday, 1985).

[7] IAEA Stage 2 means that the first contamination barrier is reduced to minimum size by removing dismantled parts. After decontamination, the containment building may be modified or removed if it is no longer required for radiological safety. Access to the building is permitted, and non-radioactive buildings can be used for other purposes. Surveillance and inspection can be relaxed but checks should be continued (Feraday, 1985).

[8] IAEA Stage 3 means the all materials, equipment and parts of the plant still containing significant radioactivity are removed. The plant and site are released for unrestricted use. No further inspection or monitoring is required (Feraday, 1985).

sion of nuclear fuel or for the reprocessing of irradiated fuel. The framework of the existing regulations permitted the licensing for decommissioning, though only a few referred specifically to it. The same safety goals used during the operational phase would continue during decommissioning. Decommissioning projects had to comply with the Radiological Protection Ordinance. The licensing procedure was governed by the nuclear licensing procedure ordinance.

A key element of German decommissioning policy was to take into account the future necessity to dismantle the plants at both the design and operational stages. The Reactor Safety Commissions Guidelines for PWRs covered the design stage. Design and arrangement of buildings, components and systems must have made allowance for suitable measures for the ultimate decommissioning of the plant, its security and its disposal. Components had to be designed and arranged in a way to keep the radiation exposure as low as possible in case of their disposal, access or decontamination. During plant operation, consideration of decommissioning had to be made. The applicant for a licence had, and still has, to submit a number of documents to the appropriate authority or the state government. These documents include the safety analysis report, an outline decommissioning plan, a discussion of possible hazards and safety measures, and the expected environmental impact. The general public could decide if its rights were affected by the decommissioning plan (IAEA, 1994).

Due to the ageing of NPPs and the new policies put in place vis-à-vis nuclear dismantling in more and more countries in the 1990s, new international conventions from various supranational and intergovernmental organisations were signed and accepted worldwide in order to implement basic principles. The most important convention regarding nuclear decommissioning is the Joint Convention of 1997 by the International Atomic Energy Agency, adopted by 83 contracted parties, whose objectives are safety regarding spent fuel and radioactive waste, the protection of individuals and the environment, and the prevention of accidents with radiological consequences. In addition, national policy is co-guided by the IAEA, through which standards have been adopted internationally. French and German national policies were modified in the years following the adoption of the Joint Convention.

The first main principle of the Joint Convention is the allocation of responsibilities. In most countries, the person or organisation that creates waste is responsible for it and its safe management, it is the polluter-pays principle (Joint Convention, Art. 21.1). Thus, the operator or licence holder is responsible for the conduct of dismantlement of the facilities. This is the continuity of the principles put in place in Germany and France —and other countries— before the adoption of the Joint Convention. If an operator fails to conduct the dismantlement, the government should be held responsible for the completion of decommissioning and the safe management of waste (Joint Convention, Art. 21.2). The Convention also sets obligations towards national governments. They must establish a legislative and regulatory framework which includes the designation of an independent regulatory body to enforce the regulations of the safe decommissioning of nuclear facilities (Joint Convention, Art. 19 and 20) and define their role in decommissioning policy and strategies. In France, two important acts were promulgated in 2006: the "Transparency and Security in the nuclear field" Act (TSN) and the "Planning Act on sustainable management of radioactive materials and waste". The ASN (Autorité de sûreté nucléaire) is, since the TSN Act of 2006, the independent regulatory body that controls aspects related to nuclear safety, radio protection, environment and information to the public. In Germany, it is the role of the Federal Office for the Safety of Nuclear Waste Management (*Bundesamt für kerntechnische Entsorgung*) as stated in the Atomic Energy Act (Atomic Energy Act, §23d. 3.).

French law, within the *Code de l'environnement*[9]*,* details the steps to follow during the procedure of dismantling of a nuclear facility, slightly modifying the three phases of dismantling that were previously fput in place. (1) The first step is the publication of a declaration of cessation ("*déclaration d'arrêt*") that establishes the operations to conduct, as well as the foremost step of dismantling, the duration, and the end date of the dismantlement. (2) After a maximum of 3 years, the transmission of the dismantlement file leads to public enquiry, presented by the operator with its demand for dismantlement decree. (3) The third step is the definitive cessation of the nuclear facility, which precedes (4) preparation work for dismantlement and, eventually, (5) the decree of dismantlement. Finally, the last step is (6) dismantling until the facility's demolition.

Two primary laws in Germany have been implemented regarding the use of atomic energy and nuclear dismantlement: the Atomic Energy Act (as mentioned before) and the Ra-

[9] First promulgated in 2000, the last modifications were done in 2019.

diation Protection Ordinance of 2001. The Atomic Energy Act came into effect in 1960 and has been adjusted 13 times. This Act provides a regime of licensing and permanent surveillance of export and import, transportation, storage and any sort of handling and processing of nuclear fuel material. Decommissioning, safe confinement or dismantling of nuclear installation requires a license, which may be granted if the prerequisites listed in AEA Art. 7. §2. are met. Also, a set of documents, mentioned before, must be presented to the relevant authority of the federal state. However, a license shall not be required if decommissioning has already been the subject of a license to construct, operate or otherwise hold an installation (AEA Art. 7. §3.). The supreme state authorities (*Länder*) issue licenses. Within the exploitation licence, the shutdown of nuclear plants is called the *Nachbetriebsphase* (post-exploitation phase). The Art. 7 §3. of the law on Atomic Energy (*Atomgesetz*) stipulates that nuclear facilities must be shut down or dismantled to be closed. For authorisation to be given, the operator must send a request to the authorities and give many elements of proof. Only after this phase, the choice of dismantlement strategy has to be undertaken.

The national law is co-guided by the Joint Convention regarding safety objectives. The national policy should protect individuals, society and the environment from the harmful effects of ionising radiation, both during the decommissioning process and in the future (Joint Convention, Art. 4 and 6). It should also require physical protection and the security of facilities to prevent the unauthorised access of individuals in the facilities being decommissioned (Joint Convention, Art. 10). In France, the Transparency and Security in the nuclear field Act of 2006 is a response to this objective. This law includes dispositions regarding safety and radio protection, stipulating that the operator must write a yearly report. Furthermore, it announced the establishment of a High Committee about nuclear transparency and information. This law has been adjusted with the promulgation of the decree of November 2nd, 2007, which refers to nuclear facilities, management of nuclear safety and nuclear substances transportation, and the decree of February 7th, 2012, which refers to nuclear waste. It stipulates that the operator responsible for nuclear waste management must take responsibility for waste sorting and decreasing the dangerousness within its facility. The law n°2015-992 of August 17th, 2015, is a significant law as it is about the energy transition and "green growth" and aims, among other things, to reinforce nuclear safety and provide information to the general public. In Germany, a licence holder must install a management system admitting due priority to nuclear safety (AEA, §7c.). In case of damage caused by a nuclear incident, the operator is responsible, as stipulated by the Atomic Energy Act (AEA, §25.) and in addition to the Paris Convention.

In addition to the liability and dismantling process, the Joint Convention sets conditions for the provision of resources (Art. 26). The national policy should set out the arrangements for (a) the establishment of mechanisms for providing the resources and funds, (b) the guarantee that there are adequate human resources available (including resources for training and research & development), and (c) the provision of institutional controls and monitoring arrangements during the decommissioning process. Finally, the national policy should address the final target of the decommissioning work. This would have implications for the allowable residual levels of radioactive materials at the sites (Joint Convention, Art. 12) (IAEA, 1995). In France, article 8.3.2 of the decree of February 7th, 2012, declares that the final state of facilities should be free of all dangerous and radioactive substances after dismantlement.

As France and German are member-states of the European Union, they signed the Euratom treaty. Entered into force on January 1st, 1958, the main European objectives and responsibilities of Euratom include the promotion of research, the guarantee of the dissemination of technical information and the establishment of uniform safety standards to protect the health of workers and the general public, and the process of making investments easier by encouraging ventures on the part of undertakings. However, the Euratom treaty does not make any provisions regarding dismantling.

4.2. Strategies

4.2.1. Presentation of different strategies

The International Atomic Energy Agency defines three strategies for nuclear decommissioning (IAEA, 1995). Those strategies are, in principle, applicable to all facilities but not always appropriate regarding the safety or environmental concerns, technicality, and finances. Those strategies include:

(a) *Immediate dismantling,* which begins shortly after the permanent cessation of activity. This strategy consists of the removal or decontamination of the equipment, structures and parts of a facility containing radioactive contaminants to a level that permits the facility to be released for unrestricted use or with imposed restrictions. That way, it prevents future generations from taking care of it financially and technically. Furthermore, with the immediate dismantling strategy, workers can benefit from the current teams' knowledge and skills during the facility's functioning, which will be needed during the first dismantlement operations (Cour des Comptes, 2020).

(b) *Deferred dismantling,* which is the strategy in which parts of a facility containing radioactive contaminants are either processed or placed in such a condition that they can be safely stored and maintained until they are eventually decontaminated or dismantled to a level that permits the facility to be released for unrestricted use or with imposed restrictions. With this strategy, investments can be needed to secure installations in the long-term period before the start of operations. However, it can benefit from possible progress of the technique in the meantime and the decreasing radioactive phenomenon.

(c) *Entombment.* It is the strategy in which radioactive contaminants are encased in a structurally long-lived material until radioactivity decays to a level that permits the facility to be released for unrestricted use or with imposed restrictions.

4.2.2. Preferred strategies in studied countries

French regulations state that nuclear facilities have to be immediately dismantled, and the process has to be carried out as fast as possible (Autorité de sûreté nucléaire, 2016) since a policy change which occurred in 2011. Before that, the strategy was long-term enclosure — whose term used by EDF was "safe configuration" or "safe storage". This change reduced the enclosure period from 50 years to only a few years (European Parliament, 2013). The choice of immediate dismantling falls under the doctrine established by the ASN, through the law of 2015, Art. L. 593-25 of the Code of the Environment which stipulates "delays as short as possible" and "acceptable economic costs”. Through this policy, the ASN said one of the “principal arguments” was to prevent or limit the burden of future generations in terms of the management of radioactive waste. It also meant that decommissioning projects were not threatened by any question of the availability of funds, even if the current law guarantees these funds (Nucnet, 2008).

EDF is responsible for the dismantlement of its fleet. However, the CIDEN (Centre ingénierie déconstruction et environnement) is the organ dedicated to the engineering unit created within the utility in 2001. It is responsible for looking after decommissioning operations and environmental aspects.

In France, several reactors have already been decommissioned or are being dismantled. The decrees for dismantling the UNGG reactors of Bugey 1, Saint-Laurent A 1 and A 2, and Chinon A 3, signed between 2008 and 2010, make provision for dismantlement "underwater", meaning that the core of the reactor is filled in order to do dismantlement operations. However, it was announced that the UNGG reactors of Chinon A 1 and A 2 would be dismantled "in the air" because no measures were taken to anticipate potential leaks on these reactors. Finally, the decommissioning of the former military installations of the UNGG reactors of Marcoule G-1, G-2 and G-3 are being dismantled by the public research agency Commissariat à l'énergie atomique et aux énergies alternatives (CEA). EDF initially planned to decommission its shutdown nuclear power plants in two waves within 25 years, with an estimated end in 2036. The first wave included the FBR Super-Phénix, the HWGCR Brennilis, the PWR Chooz-A, and the UNGG reactor of Bugey-1, while the second wave included the UNGG reactors of Chinon A 1-3 and the Saint Laurent reactors A 1-2. However, the plan changed in 2016 when EDF announced a change in its GCR dismantlement strategy to the regulatory authority ASN (Autorité de sûreté du nucléaire): EDF was forced to cancel its target to immediately dismantle all GCRs by 2036 because of underestimated technological challenges. The focus for the next 15 years would lie on dismantling nuclear installations except for the reactors and their buildings. (Wealer et al., 2019). Indeed, it was foreseen that the dry dismantlement of the Chinon-A-1 reactor would start in 2031, with an estimated duration of 25 years. This strategy switch was constrained due to the long immersion times of the reactors, including corrosion and leak tightness (Martelet, 2016). The initial plan with the continuous flow of graphite waste and the very tight focus on the reactor could not be implemented because the actual dismantling technology complex needs more preliminary tests than expected (Wealer et al., 2019).

In Germany, the four private operators must choose the immediate dismantling strategy in nearly all cases in accordance with the recommendation of the IAEA after a new legislation in 2016 about dismantling strategy. Nevertheless, the public company EWN chose a deferred dismantling strategy for the reactor pressure vessels (PWR). Germany has a diverse fleet of nuclear power plants, with different shutdown reactors in different stages of their decommissioning process, including two in Long-Term Enclosure (LTE), three that have been successfully dismantled and released from regulatory control, and two that have been dismantled but await regulatory release. The remaining nuclear plants are currently in different phases of the decommissioning process, including 12 NPPs in the process of being dismantled; most of them are PWRs. Most NPPs are still in the post-operational phase or have just started decommissioning. However, German NPPs face several obstacles to concluding the decommissioning process without escalating costs, with notably insufficient transport and storage casks being produced to "defuel" the reactors. The German Democratic Republic fleet that includes Rheinsberg and Greifswald is being decommissioned by Entsorgungswerk für Nuklearanlagen (EWN), a public company under the control of the Federal Ministry of Finances. The Deferred dismantling strategy was chosen for both sites. The Rheisenberg reactor pressure vessel was transported to the centralised on-site interim facility (Zwischenlager Nord), also operated by EWN. The Greifswald reactors vessel internals of the reactor 1 and 2 were immediately dismantled and conditioned, while the deferred dismantling strategy was chosen for the internals of reactors 3 and 4 as well as the five reactors.

The choice of immediate dismantlement strategy is favoured by the current availability of a qualified and trained workforce that can learn over time. It is associated with a smooth transition and a more straightforward implication locally, benefiting to a better public opinion in this regard. Germany and France, even though they chose different paths regarding the use go atomic power, have clear policies in regard to the use future use of this energy. Having decided on a continued development or a phase-out lowers the risks of choosing the immediate dismantling strategy, as policy changes are less likely to happen. Finally, this strategy is preferred due to uncertainties in cost development and fund management over time (OECD/NEA, 2006). The policy change in 2016 occurred in a period when the French and German governments decided to decrease or abandon the use of nuclear energy, thus accelerating the dismantling processes in the upcoming years.

Chapter 5 — Fuel cycle and nuclear wastes, strategies and policies

5.1. Radioactive waste classification

Before investigating the different policies in place on international and national levels, it is necessary to be acquainted with the classification of radioactive waste and how Germany and France differentiate them.

In France, material and radioactive waste are classified differently. Radioactive material is considered as such when, because of its radioactive, fissile, fertile or fusible properties, subsequent use is planned, or mainly used or being used nuclear combustible, or natural uranium, impoverished, enriched or treated uranium, plutonium and thorium. If no subsequent use is planned, then they are considered waste.

Germany defines radioactive material and waste in Section 2 of the Atomic Energy Act. “Radioactive substances” corresponds to “nuclear fuel” added to “other radioactive substances, whereas nuclear fuel is a special fissionable material in the form of 239Pu and 241Pu, uranium enriched in isotopes 235U or 233U, any material containing one or more of those two substances, substances which permit a self-sustaining chain reaction to be maintained in a suitable installation and which are defined in a statutory ordinance.

While France considers radioactive material as waste if no subsequence use is planned, Germany encompasses all material containing one fissionable substance or more. These definitions highlight the strategy of France to recycle a part of its spent fuel. However, neither of the definitions mentions the type of radioactive waste and the required storage for each, in consideration of the risks they make up.

In comparison, the IAEA differentiates radioactive waste based on the requirement of storage, the period of containment and isolation and is listed as such:

(1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes

(2) Very short-lived waste: Waste that can be stored for decay over a limited period of up to a few years

(3) Very low-level waste (VLLW): Waste that does not need a high level of containment and

isolation can be stored in near-surface landfill-type facilities

(4) Low-level waste (LLW): Above clearance levels but with a limited amount of long-lived radionuclides. It requires robust isolation and containment for up to a few hundred years in near-surface facilities.

(5) Intermediate-level waste (ILW): Its content, mainly long-lived radionuclides, requires a greater degree of containment and isolation. ILW needs no or limited provision for heat dissipation during storage and disposal.

(6) High-level waste (HLW): High enough activity concentration to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations is usually several hundred meters below the surface.

5.2. Fuel cycle and nuclear waste management strategies and policies

Several instruments have been implemented to ensure and improve the safe management of spent fuel and radioactive waste and protect people and the environment from the potential negative effects of ionising radiation. The Joint Convention applies to spent fuel and radioactive waste created through the process of civilian nuclear programmes. It commits the countries to get a safe and sustainable management system of radioactive waste and used fuel. The 83 contracting parties meet every three years to discuss the national reports, subject to a peer review process. Also, bilateral agreements can be signed (Art. L. 542-2-1 of the Code of the Environment) to supervise temporary importations of spent fuel and radioactive waste produced abroad. In the European Union, the Euratom Waste Directive of 19th July 2011 (2011/70) requires appropriate national arrangements for a high level of safety in spent fuel and radioactive waste management. The Directive sets three fundamental principles: protecting people's health and environment, preventing or limiting costs being taken care of by future generations, and the polluter-pays principle that prevails in environmental law. It also intends to ensure adequate public information and participation in managing spent fuel and radioactive waste. Both the Euratom Waste Directive and the Joint Convention require appropriate national arrangements for a high level of safety in spent fuel and radioactive waste management. Also, the IAEA Code of Conduct on the Safety and Security of Radioactive Sources aims to help national authorities ensure that radioactive sources are used within an appropriate radiation safety and security framework. The Code is non-legally binding and receives support from more than 130 member states.

In France, the producers of materials and radioactive waste in France are Areva, the CEA and EDF, which are responsible for managing radioactive waste until their definitive storage. The ANDRA is the public authority responsible for long-term radioactive waste storage (such as the conception and realisation of storage centres, research, and collection and transportation of radioactive waste).

The German institutional framework regarding radioactive waste and fuel is made of two branches, the advisory bodies and the regulatory and supervisory authorities, that are composed of:

(1) *the Bund*, which is the legislative power of the peaceful use of atomic energy (with an amendment in the constitution),

(2) *the Länder*, which are responsible for enforcing existing federal legislation as agents for the Bund,

(3) *ministries* that have responsibilities towards nuclear energy in their own field (Transport, Research, Defence, Finance, Environment…),

(4) *the Federal Office for the Safety of Nuclear Waste Management* (*Bundesamt für kerntechnische Entsorgung*), which is responsible for granting licences for the storage of nuclear fuel outside of government custody,

(5) *the Federal Office for Radiation Protection* (BfS — *Bundesamt für Strahlenschutz, portfolio of Federal Ministry for the environment, Nature conservation and nuclear safety*), which is responsible for the construction and the operations of federal installations for safe containment and the final disposal of radioactive waste, including transfer of these functions to third parties. It is also responsible for the licensing of transport of nuclear fuels, storage and withdrawal or revocation of licenses, and

(6) *the Federal Office of Economics and Expert Control* (*Bundesamt für Wirtschaft und Ausfuhrkontrolle* — portfolio of the federal ministry of economy and technology), which is responsible for the issue of import and export licenses for nuclear material

In France, the law of radioactive waste management of the 28th June, 2006 ensures (1) the sustainable management of radioactive waste and spent fuel, including the management of radioactive waste in respect of people's health, security and environment, solutions so that their management is not deferred to prevent future generations' costs and work, and producers first responsibility of the management of radioactive waste and spent fuel. It also ensures (2) the pursuit of research mainly about medium and high radioactive waste: conditioning of the waste before 2030. It is considered that 80% of all waste produced in France is conventional, while 20% is radioactive. France operates as a closed fuel cycle. Therefore, SNF (spent nuclear fuel) is not declared as a waste but as a resource reprocessed in La Hague by Areva (Wealer et al., 2019), while glass canisters containing high-level wastes (HLW) are stored at production sites of Marcoule, Cadarache and La Hague (Lehtonen, 2015). The final forecast for generated waste of the operational nuclear fleet (assuming average life of 50 years) is expected to be around 10,000m3 (OECD/NEA, 2016). The Code of Environment requires the adoption every three years of a National Plan of management of materials and radioactive waste (PNGMDR) that has to state the existing management modes of materials and radioactive waste and to state the predictable needs of storage facilities and state their capacity. The Code also entrusts the ANDRA to ensure long-term management of waste (to make the inventory of material and radioactive waste in France, to ensure the collection and transportation of nuclear waste, to secure and make polluted sites usable again, and to research solutions for storage and exploit and watch storage centres). The Waste Management Act established the way to treat radioactive waste and set the direction of research undertaken by the ANDRA. Research is ongoing for final storage at 500 meters deep underground rock laboratory Cigar in Bure situated in clays. The central part of the low-level long-lived waste is that the graphite from the GCRs will probably be stored 200 meters underground in a layer of clays or stored with the HLW in the Cigar disposal (Wealer et al., 2019). The *Commission nationale d'évaluation* adopted a favourable opinion in October 2022, though the project still needs authorisation from the ASN, which is not due before 2025. This project echoes the Onkalo project in Finland which is due to open in 2025. HLW will be stored 450 meters underground in layers of granite and quartz. The Onkalo project did not face any opposition, even from the local population, partly due to policies of transparency in relation to nuclear between the government and the population. In comparison, the Cigéo project in France has faced opposition for decades from the local population, NGOs and members of the Parliament and the European Parliament. Another similar storage site is due expected to be constructed in Forsmark, Sweden. This project, called KBS-3, plans to store HLW 500 meters underground. Until the Cigéo project is achieved, HLW is currently conditioned in stainless steel containers in intermediate storage at Orano's La Hague plant. However, given its half-life, and the estimated saturation by 2030, French law stipulates the transfer of these containers to the Cigéo once it is completed, scheduled in 2035.

In Germany, the AEA regulates many aspects of nuclear waste and used fuel. Licensing is obligatory for almost every process related to waste and spent fuel management. This includes the import and export of nuclear fuel (section 3 of the AEA), transport of nuclear fuel and other radioactive substances (section 4 of the AEA & Sections 16 to 18 of the Radiation Protection Ordinance (RPO)), and storage of nuclear fuel and other radioactive substances requires a licence (section 6 of the AEA & section 7 of the RPO). Moreover, operators need to ensure that an interim storage facility for spent fuel is available on or close to the site (Section 6 of the AEA), in which a licence is required to process or use nuclear fuel (Sections 4, 6, 7, 9a to 9c of the AEA). In Germany, high-level radioactive waste consists of SNF and vitrified structures from reprocessing processes. In 1989, a political decision was taken to stop reprocessing in Germany after German operators invested in reprocessing facilities in La Hague in France. As a result, until 2005, nearly half of all the SNF was sent to France or the United Kingdom. After 2005, the policy in place was direct geological disposal: interim storage and no more reprocessing (Hocke & Kallenbach-Herbert, 2015). Two centralised interim storage facilities are in Gorleben, where HLW is stored in casks, and Ahaus and are operated through Gesellschaft für Nuklearservice (GNS). A third facility operated by the public company EWN is located in Zwischenlager Nord. A repository site for low and intermediate-level waste called Konrad is scheduled to be constructed in Salzgitter in Lower Saxony by 2027. In 2016, an institutional framework of the waste management process changed with the introduction of a law aiming to restructure the responsibilities of the nuclear waste management process. The ownership of centralised interim storage facilities was transferred to the newly created public company Gesellschaft für Zwischenlagerung (BGZ, "Company for interim storage"), also taking over decentralised interim-storage facilities and low-level waste repositories. Finally, a site for a deep geological facility is yet to be found in a three-phase process, accompanied by extensive public participation (30,000m3). No disposal solution exists yet for 200,000m3 of low and intermediate waste and salt mixture. The start of the operation of disposal is predicted after 2050, more realistically, after 2080 (Thomauske, 2015).

Despite the intermediate storage for HLW in France and Germany, the absence of final storage facilities in Europe strengthens the risks of saturation in the upcoming, and delays in the search for a solution, especially in Germany, thus increasing safety risks within the nuclear industry. The example of the Finnish facility Onkalo can be a lesson for governments to learn, even though questions about its long-term safety remain.

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Chapter 6 — Financing and costs of dismantlement

6.1. International policy on financing

International agencies also provide regulations regarding financing nuclear facility decommissioning, even though most regulations are the responsibility of national governments. For instance, when building a new nuclear reactor, all national regulations require operators to provide an explanation and justification of assumptions and conditions (including the year of the estimate, the site release criteria, the future of spent nuclear fuel, waste management, etc.) as indicated by the IAEA (2014):

> For a new facility, planning for decommissioning should begin early in the design stage and should continue through to termination of the authorisation for decomissioning; whereas for existing facilities where there is no decommissioning plan, a suitable plan for decommissioning should be prepared by the licensee as soon as possible.

The international policy on financing can be divided into different aspects, as developed below.

6.1.1. Liability principle

The financial responsibility includes dismantling, decontamination, demolition, site clearance, storage, processing, conditioning, waste, and waste and spent fuel disposal. As mentioned, the polluter-pays principle is put in place, meaning that owners or licence holders are responsible for developing cost estimates. It is an essential principle, so the costs are not transferred to future generations or collectivity. According to international law, the state is responsible for the final disposal and radioactive waste. Financial liabilities for final disposal are not always entirely the "polluter" but can be partially transferred to the state. Nuclear facilities operators will not be financially liable for any radiation exposure, radioactive contamination in the uranium value chain before the fuel arrives at the nuclear power plant, and any problems arising after the final disposal facility's final closure. In general, funds for commissioning are set aside from the revenue obtained from the sale of electricity generated by the plant during its operating phase or through a levy on sales of electricity of any origin.

6.1.2. Funding schemes

In most cases, the fund is built up year by year, either over the entire expected lifetime of the facility or over a shorter period. It is based on the calculated decommissioning costs. Funds may be collected over a shorter period to reduce the risk associated with the unplanned and premature shutdown. Different procedures regarding funding include:

- payment of decommissioning activities from the current budget of public authorities (e.g., decommissioning of uranium mines in Germany),
- internal unrestricted fund of a private company (e.g., dismantling and demolition and waste processing of NPPs in Germany),
- internal restricted fund of a private liable company with public regulation (e.g., NPPs in France),
- external restricted fund,
- external unrestricted fund.

Estimating the contribution to be paid to the fund is a crucial part of fund management. Calculations are based on both estimated decommissioning costs and on other various assumptions, such as the estimated time when the cost will arise, the inflation, or the anticipated nominal interest rate on the accumulated capital.

The amounts to be collected to cover the costs of decommissioning are not only influenced by the estimations of the decommissioning liability but also by the investment strategy and expected rates of return on investment of fund assets. Risk-balancing is required, as well as sufficient return on investment for those making the payments, but also an investment strategy yielding a lower rate of return vis-à-vis a higher degree of security over the accumulated funds for this, having the responsibility for the general funds or exercising regulatory oversight.

6.1.3. Management of funds

High-quality fund management is crucial for maintaining or increasing the value of the funds so that sufficient funds will be available at the time decommissioning activities have to be paid. Public or private fund managers can manage funds, and restrictions can be imposed by law. The typical investment restrictions or guarantees for internal or external

funds are:
- Restrictions regarding the degree of risk allowed to be taken (e.g. in France), assets of the restricted internal funds have to present a sufficient degree of security and liquidity
- Restrictions that do not allow investment in companies associated with the legally obliged parties or that have invested most of their assets in nuclear facilities (Irrek et al., 2007; Däuper et al., 2014; OECD/NEA, 2016).

The EU Commission recommends that a security risk profile be sought in the investment of the assets, ensuring a positive return. A 100% security of a positive return over any given period cannot be guaranteed over the many decades of the lifetime of such a fund.

The strategy of decommissioning funds should aim to match the total decommissioning cost and to ensure its availability when needed, under the control of the national body. The goal is to cover the expected decommissioning costs and have the finances available when the costs are incurred.

Funds need to be managed in a way to ensure that they retain their value, and it is important that the real value of assets in the fund is safeguarded against periods of high inflation (can be entrusted in national/international currency bonds, national/international equities, investment in real estate). A range of specific models for decommissioning funds run:
- as external segregated funds
- by utility/operator within its own assets
- by utility/operator within a separated account or segregated fund
- as internal funds
- as external funds, either managed by the utility or operator within a separate account or managed by a different entity.

6.2. Identification of costs

6.2.1. Dismantlement and wastes estimate

The International Structure for Decommissioning Costing (ISDC) identifies the costs of nuclear decommissioning according to different categories, such as labour, capital, expenses or contingency. This approach is the preferred one internationally and is divided into categories as such:

1. Pre-decommissioning actions
2. Facility shutdown activities
3. Additional activities for safe enclosure and entombment
4. Dismantling activities within the controlled area
5. Waste processing, storage and disposal
6. Site infrastructure and operation
7. Conventional dismantling, demolition, site restoration and landscaping
8. Project management, engineering and support
9. Research and development
10. Fuel and nuclear material
11. Miscellaneous expenditures

The ISDC is not the only existing approach regarding the identification of costs, and another example of categorisation of decommissioning costs includes the "bottom-up technique" based on the work breakdown structure (WBS) approach; it entails a sufficiently detailed subdivision of a decommissioning project into discrete and measurable work activities.

6.2.2 Uncertainties

Uncertainty risks are risks that can postpone a process, with consequences on costs and timing. There is no harmonisation in the treatment of uncertainties between cost estimates (unlike cost structure estimates in the application of the ISDC).

The ISDC approach is addressed through the application of contingency as part of the cost estimate (Contingency according to the ISDC: "specific provisions for unforeseeable elements of costs within the defined project scope"), and the guidance is provided on how costs estimate should reflect contingency provisions to deal with uncertainties.

6.3. National policies

6.3.1 French national policies

French operators have thorough obligations regarding nuclear dismantlement. Among these obligations, operators of nuclear facilities are fully responsible for paying the full costs of the decommissioning process. They set up internal restricted funds covered by dedicated assets managed under a separate account, which funds are required to account for all future costs related to decommissioning as well as waste management. The decommissioning cost estimates must be established from the beginning of operations of each given nuclear installation. They are reviewed annually by both the utility or decommissioning entity and the government or nuclear regulator. Finally, the operator controls decommissioning funds.

Before 2011, dismantlement works of the CEA were financed by generated resources by assets of dedicated funds, essentially dividends given by Areva, EDF and Cogema. The triennial convention signed on 3rd January 2012 has changed this method. Financing is now based on the liquidity of residual assets owned by dedicated funds, as well as on annual subventions allocated to the CEA, and the establishment of a debt on the state covering the constituted provision on the passive of the organism (Cour des Comptes, 2020). Since 2011, operators have to maintain the cover rate of their provisions at not less than 100%.

Finance investments now correspond to the dismantlement and conditioning of waste by the CEA and the management by the ANDRA. The ANDRA receives two funds from the operator's internal funds at the time they are needed. Operators make payments from their internal funds to the ANDRA's general budget, received through a tax, to finance operations related to the storage facilities for short-lived and medium-level waste.

The AREVA and EDF were forced to advance their back-end provisions and accountancy practices because of partial privatisations. Both have now set up restricted internal segregated funds for the financing of the nuclear back-end. EDF feeds its fund by a charge of 0.14 €/kWh included in the price of electricity. Since the law on waste of 2005, assets in the funds of EDF and Areva have to be accounted for separately and the market value has to be at least as high as the provisions to be covered. In case of insolvency or bankruptcy of an operator, the state can claim right over the assets. Internal funds are supervised by an administrative authority, which is authorised to impose corrective measures. It also includes the right to impose payments to the ANDRA's budget.

Regarding the costs of nuclear waste, financing of nuclear and other waste is assured by operators under the polluter-pays principle and is controlled by the state. The law of 28th June, 2006 indicates the securitisation of financing of long-term nuclear costs. Indeed, operators must evaluate the costs of long-term nuclear costs, including dismantling and waste costs, and cover the upcoming costs. This is controlled by the state through an administrative authority under the Ministries of the Economy and the Environment.

Malischek et al. (2016) list the characteristics to take into account in order to evaluate the costs. They mention that costs are generally higher if the phase-out is immediate, not allowing for a transition period. These additional costs are evaluated at 91 billion $€_{2022}$ in a scenario with an immediate nuclear phase-out within four years, compared to a scenario without a nuclear phase-out, where it is possible to prolong existing nuclear reactors. The demand for electricity is expected to increase slightly to 543 TWh in 2030 and moderately decrease to 522 TWh in 2050 (from 152 TWh in 2020). The cost of fossil fuels is also expected to increase; the price of oil is expected to double for oil and multiply by 1.5% for natural gas. A continuous increase in renewable energies is also expected throughout Europe, amounting to 1616 TWh in the continent. Finally, with the introduction of several new or improved technologies, investment costs are expected to decrease over time due to learning effects (Malischek et al., 2016).

6.3.2. German national policies

Under the Atomic Energy Act and in compliance with the polluter-pays principle, the operator must pay for the decommissioning and dismantling of the NPPs and for the management of the nuclear waste, including the cost of final storage. As these costs will be incurred over several decades, the federal government decided to appoint a commission called the Commission to Review the Financing for the Phase-out of Nuclear Energy. This commission was asked to conduct an assessment as to how the financing for decommissioning and dismantling of NPPs and for nuclear waste disposal can be organised so that the companies responsible will be financially capable of meeting their obligations arising from nuclear power operations, including in the long term.

Under the Transparency Act, the Federal Office for Economic Affairs and Export Control has the right to access certain information from the operators. Operators must provide a detailed list of the provisions they have made, based on the company's annual financial statement and feature a forecast of the expenditure for each task and for the coming financial years (BWE, 2016).

The funding system in Germany differs between 1) public-owned facilities, 2) facilities with mixed ownership, and 3) facilities in private ownership.

The decommissioning costs of public-owned facilities, such as the power plants of Greifswald and Rheinsberg are financed from the current budget by the Ministry of Finance through the company EWN GmBH, owned by the state. For most projects, the federal government covers the costs of dismantlement, but for some projects, part of the costs are covered by the state governments (*Länder*), whether they are owned by the federal or state government. Until the 31st December, 2007, EWN GmbH received 2.7 billion $€_{2022}$ for its nuclear obligations. Expenditures since 2008 are taken from the Ministry of Finance's annual budget. The public funding of EWN GmbH until 2020 amounted to approximately 4.3 billion $€_{2022}$ (Bundestag, 2019; FOES, 2020; Irrek, 2006). EWN is responsible for the dismantling of nuclear power plants in the East as well as the exploitation of installations of temporary storage in the North of Germany.

The mix-owned facilities are proportionally split between the public and the private utilities and are clarified by special arrangements. Finally, privately-owned facilities have the majority of their costs related to the nuclear back-end of them (Wealer et al., 2019).

The financing system for nuclear waste and storage has changed in 2017. Liabilities for interim storage and final disposal of radioactive materials have been transferred to the state against a lump sum of 24.1 billion $€_{2019}$. The nuclear plant's operator will not have to bear any cost exceeding this amount. In parallel, Germany took over two central interim storages. From 2019, the German state will also be responsible for the decentral interim storage at nuclear power plant sites, and from 2020 it will be responsible for all interim storage sites as well as final disposal activities (Irrek, 2019).

Until 2016, financial resources to cover decommissioning and waste disposal were managed by private companies in internal non-segregated funds with no public authority controlling them. Companies set up the provisions according to international accounting standards and were free to choose where to invest them. OECD/NEA (2016) highlighted the unregulated and uncontrolled system of internal non-segregated funds itself as the most critical aspect of the German system. In case of bankruptcy of the operator, financial resources to cover future costs would probably have been lost, and the public budget would have been obliged to cover the costs. The risks that private utilities would not be able to cover all future liabilities with their internal non-segregated financial resources due to high cost increases, between 2.9 and 6%, higher than the general inflation rate or the nuclear-specific inflation rate, pushed to a new legislation published in December 2016 (BT 768/16).

This law was a fundamental change in German policy, with the establishment of an external segregated fund, which will have to finance all aspects of waste disposal. Utilities are still responsible for decommissioning and the conditioning of wastes, but all tasks and operations of the interim storage facilities will be done by public companies and paid from the fund. NPP operators must have paid a total of 17.4 billion $€_{2016}$ into the fund. They could have opted to pay an additional risk surcharge of 35.47%, from which the German government would have discharged them of any obligation to make additional contributions to the fund if it was found that additional liquidity was required. The risk surcharge would also cover any cost and interest-related risks that exceed the calculated disposal costs. Responsibility and risks (including the financial ones in the case of insufficient set-aside money) will have to be borne by the public, infringing the polluter-pays principle (Wealer et al., 2019).

6.4. Results

As previously explained, according to the NEA, operators are usually responsible for developing cost estimates. This methodology might be needed to provide input for the decommissioning funding during plant operational life, compare costs associated with different strategies for the decision-making process, prepare long-term budgeting and cash flow, and provide a tool for project control. The standard reporting structure provided by the International Structure for Decommissioning Costing (ISCD) will be used for comparison.

Generic-FR is the example of estimated decommissioning costs of a French PWR producing 3,600 MWe (4 units of 900 MWe). The cost of shutdown is estimated at 108 million $€_{2022}$, the dismantlement at 532 million $€_{2022}$, the waste management at 246 million $€_{2022}$, the site infrastructure and operation at 76 million $€_{2022}$, the cost of conventional dismantling, demolition, site restoration and landscaping at 113 million $€_{2022}$, the project management, engineering and site support at 107 million €2022, and the miscellaneous at 118 million $€_{2022}$. The costs of pre-decommissioning, research and development, and fuel and nuclear material are not taken into account. The total costs for this power plant are thus estimated at 1,310 million $€_{2022}$ and per unit 328 million $€_{2022}$ (OECD, 2016).

Another EDF report in 2017 evaluates the costs of the dismantlement of all French nuclear reactors at 89 billion $€_{2022}$, including 20,727 million €2022 for spent fuel management, 33,270 million $€_{2022}$ for long-term radioactive waste management (Cigéo), 29,885 million $€_{2022}$ for the nuclear plants decommissioning, and 4,877 million $€_{2022}$ for the last chores. Critical reports say these costs are underestimated (especially regarding the nuclear plants decommissioning). EDF argues that costs will be lower due to the high standardisation degree of their fleet and because multiple reactors are situated on the same site (Assemblée Nationale, 2017). However, these estimated costs were expected to increase by 10 billion € from 2012 and 2015. The provisions were discounted with an interest rate of 4.2% and an assumed inflation rate of 1.5%. Nonetheless, it is worth noting that little changes in estimated interest or inflation can greatly influence the calculation, leading to the underestimation of needed financial resources.

In order to analyse the results of France and Germany, the estimated costs mentioned above provided by the two reports will be calculated in comparison with the given inflation rate of 1.5% every year on the period 2016-2099 in the table below:

Table 6.1: Estimated costs of nuclear phase-out in France

Cost categories	(EDF report) Undiscounted costs 2016-2099 in millions €$_{2022}$	(EDF report) Discounted costs 2016-2099 with an inflation rate of 1.5% in millions €$_{2022}$	(Generic-FR 3,600MWe) Undiscounted costs 2016-2099 in millions €$_{2022}$	(Generic-FR 3,600MWe) Discounted costs 2016-2099 with an inflation rate of 1.5% in millions €$_{2022}$
Shutdown	-	-	108	291
Decommissioning and dismantling	29,885	80,092	532	1,431
Spent fuel management	20,727	59,651	-	-
Waste management	-	-	246	662
Long-term radioactive waste management	33,270	89,164	-	-
Site infrastructure and operation	-	-	76	204
Conventional dismantling, demolition, site restoration, landscaping	-	-	113	304
Engineering and site support	-	-	107	288
Last chores	4,877	13,070	118	317
Total costs	**88,759**	**238,520**	**1,310**	**3,524**

The discounted costs for a total nuclear dismantling in France are estimated at about 238.5 billion €$_{2022}$, and at 3.5 billion €$_{2022}$ for a NPP with a capacity of 3,600 MWe. However, the inflation rate can vary; indeed, the inflation rate in France in 2016 was low, at 0.18%, and was at 2.06% in 2021. For reference, Germany had comparable inflation rates, at 0.5% in 2016 and 3.1% in 2021. Also, as it can be observed in this table, the EDF report of 2017 does not detail the costs such as shutdown, site restoration and engineering.

According to the ASN, the costs of long-term radioactive waste storage, through the project Cigéo, have been evaluated at 30 billion €$_{2022}$ for the period 2016-2156. This evaluation includes uncertainties such as the evolution of working costs, materials, energy and technological progress over 140 years. It also includes technical optimisation and efforts in the long term of the ANDRA (Agence de sureté nucléaire, 2016a). Finally, the costs of uncertainty, given by comparing a stochastic scenario state to the corresponding deterministic scenario, are relatively small in Europe, with a maximum cost, in France, of 7.2 billion €$_{2022}$ with a phase-out and no possibility of prolongation for existing nuclear plants (Malischek et al., 2016).

On behalf of the German government, the auction company Warth & Klein Grant Thronton AG published in 2015 an estimation of the full costs for the dismantling of 23 nuclear power plants, totalling almost 54 billion €$_{2022}$, and almost 192 billion €$_{2022}$ with an inflation rate of 1.97% for the period between 2015 and 2099. The detailed categories can be found in the table below. All estimations are subject to uncertainties related to expectations about future inflation rates, cost increases, and time delays.

Table 6.2: Estimated costs of nuclear phase-out in Germany

Cost categories	**Undiscounted costs 2015-2099 in millions €$_{2022}$**	**Discounted costs 2015-2099 with nuclear-specific inflation rate of 1.97% in millions €$_{2022}$**
Decommissioning and dismantling	22,261	34,109
Casks, Transport, Operational Wastes	11,193	59,651
Interim Storage	6,574	30,221
Low and medium waste disposal (Schacht Konrad)	4,233	10,178
High-level waste disposal	9,394	57,536
Total costs	**53,653**	**191,697**

The differences in estimated discounted costs based on the inflation between the categories come from the different phases of the dismantling process. Due to the learning process, the inflation rate of decommissioning and dismantling costs would decrease to 0% by 2030. An additional increase of 1% related to transport, operational waste and interim storage is expected, as these steps are partially covered by existing contractual agreements. However, for low, medium and high-level waste disposal, the rates could be reflected by the general inflation rate and not by the nuclear-specific inflation rate; thus, it would not lead to new nuclear-specific costs increase. Among the nuclear plants in the process of dismantlement in East Germany, the actual (public) expenditures between 1990 and 2020 for decommissioning and dismantling are around 4.75 billion €$_{2022}$. Overall, the dismantling costs of EWN GmbH are estimated at 7.4 billion €$_{2022}$, and at least 2.9 billion €$_{2022}$ still need to be incurred before dismantling is completed. However, the realistic cost estimate will only become apparent during the demolition measures. Finally, the final costs of dismantling, such as site restoration and landscaping, were not taken into account by the estimates either of Warth & Klein Grant Thornton AG or EDF.

Dismantling costs can be calculated over time through different phases developed earlier in this paper[10]. These phases only include dismantling costs and thus do not include other costs such as storage, transportation and late-stage costs. Based on the parameters detailed by Scherwath et al. (2019) in consideration of the schedule and estimated costs of each phase, the discounted and undercounted costs will be calculated for the French and German cases in the following tables:

Table 6.3: Estimated costs of nuclear dismantling in France by phases

Phases	Undiscounted costs 2016-2099 in millions €$_{2022}$	Discounted costs 2016-2099 with nuclear-specific inflation rate of 1.5% in millions €$_{2022}$
Post-operational phase (47%) (~ 5 years)	14,046	37,643
Phase I (5.8%) (~ 3 years)	1,733	4,645
Phase II (14.6%) (~ 4 years)	4,363	11,693
Phase III (18.3%) (~ 3 years)	5,469	14,657
Phase IV (14.5%) (~ 2 years)	4,333	11,613
Total costs of dismantling	**29,885**	**80,092**

Source: EDF report (2017)

Table 6.4: Estimated costs of nuclear dismantling in Germany by phases

Phases	Undiscounted costs 2015-2099 in millions €$_{2022}$	Discounted costs 2015-2099 with nuclear-specific inflation rate of 1.97% i n millions €$_{2022}$
Post-operational phase (47%) (~ 5 years)	10,463	16,031
Phase I (5.8%) (~ 3 years)	1,291	1,978
Phase II (14.6%) (~ 4 years)	3,250	4,980

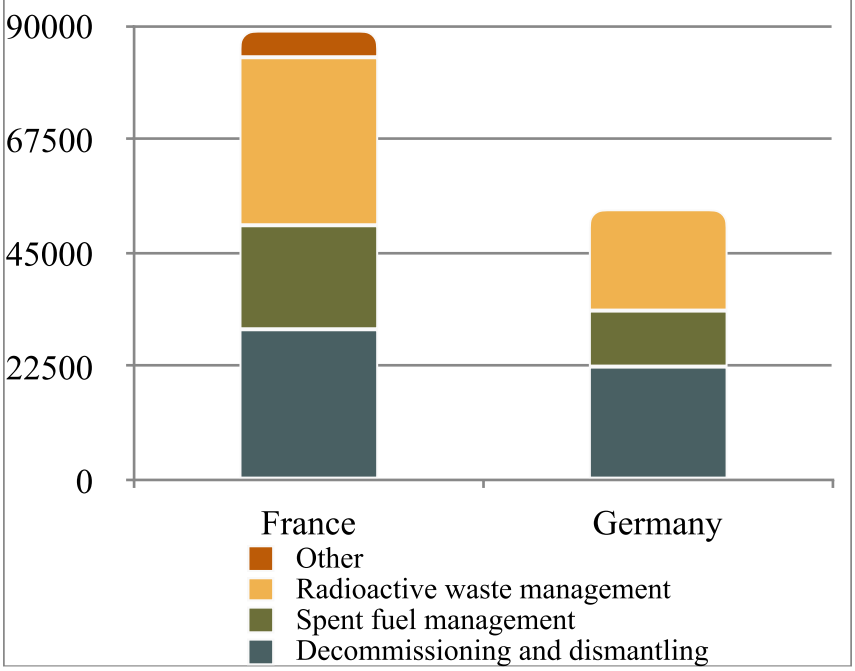
[10] *see chapter 4.1.1.*

Table 6.4: Estimated costs of nuclear dismantling in Germany by phases

Phases	Undiscounted costs 2015-2099 in millions €$_{2022}$	Discounted costs 2015-2099 with nuclear-specific inflation rate of 1.97% i n millions €$_{2022}$
Phase III (18.3%) (~ 3 years)	4,074	6,242
Phase IV (14.5%) (~ 2 years)	3,228	4,946
Total costs of dismantling	**22,261**	**34,109**

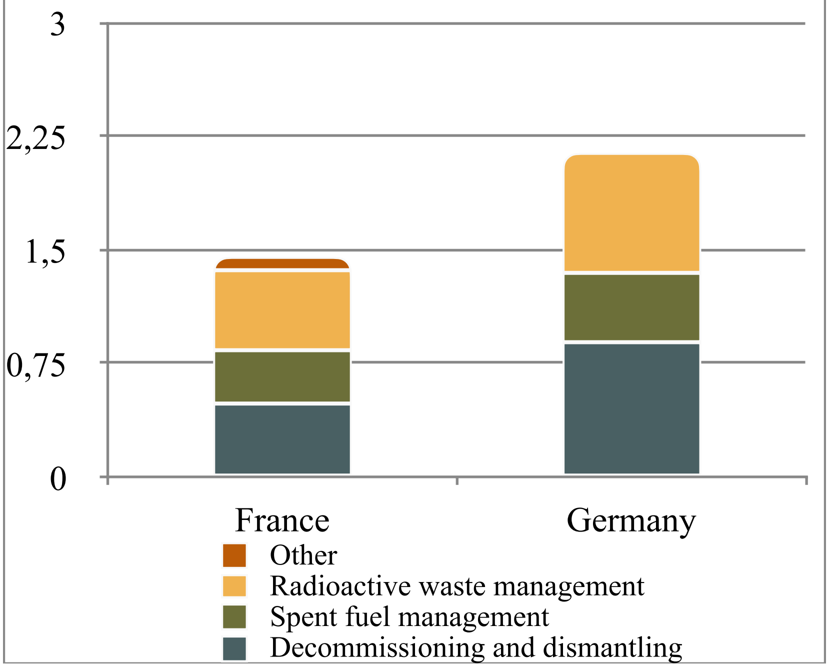
Source: Warth & Klein Grant Thronton AG (2015)

Figure 7.1: Estimated undiscounted costs of dismantling in France and Germany (in millions €)



Source: EDF (2017) & Warth & Klein Grant Thronton AG (2015)

Figure 2 — Estimated undiscounted costs of dismantling in France and Germany per MWe (in millions €)



Source: EDF (2017) & Warth & Klein Grant Thronton AG (2015)

The estimated costs of dismantling overtime are concentrated in the majority during the post-operational phase lasting for about five years. This phase generally ends when the spent fuel from the reactor building is removed, significantly reducing radiation and allowing decontamination and dismantling to pursue. The rest of these costs are spread over about the twelve next years during the remaining phases. During the decommissioning process, the other costs have to be taken into consideration at the due time. During the early stages, shut-down costs represent about 8% of the total costs of decommissioning. Costs such as waste management and transportation are spread during the decommissioning process as the construction process of storage sites advances. Estimated costs for the final stages, such as site restoration and landscaping, represent between 8 and 15% of the total costs.

To conclude this chapter, the cost estimates of nuclear dismantling do not take into consideration the construction of fossil-fuelled power plants and of new renewable sources to compensate for a nuclear phase-out, as well as the reduction in export revenues and import costs. Moreover, a total nuclear phase-out will affect the rest of Europe, as neighbouring countries rely on the exports of electricity produced by nuclear power plants, especially from France.

Chapter 7 — Conclusion

Facing the dangers of climate change and the energy crisis, the European Union is choosing the path to achieve carbon neutrality by 2050. In order to attain it, the choice of energy sources has to be made, and member states are choosing different paths. Nuclear power could be one solution, as some countries have decided to rely on it, while other countries have decided to phase it out to rely exclusively on renewable energies in the future, like Germany. As debates strike about the choice of nuclear power, countries must be prepared in case of a nuclear phase-out is decided.

International organisations and national authorities have settled policies for nuclear dismantlement, depending on their role. The major organisation regarding nuclear power and nuclear dismantlement is the International Atomic Energy Agency. National policy is co-guided by this agency through its Joint Convention adopted worldwide in 1997. The Joint Convention sets allocations of responsibilities, by which the operator is responsible for dismantlement through the polluter-pays principle, sets conditions for the provision of resources, and addresses safety objectives. This applies to the dismantlement process and spent fuel and radioactive waste.

European member-states have signed the Euratom treaty. It promotes research on nuclear power, establishes safety standards for the population and environment, informs the public, and obligates member-states to create a national authority for safety and radioactive waste. While the IAEA Joint Convention is significant regarding nuclear dismantling, the Euratom treaty is detached from the current reality. It has barely been amended since its ratification and does not set policies regarding nuclear dismantlement, nor help member-states to achieve it.

National governments establish the legislative and regulatory framework. It includes the designation of an independent regulatory body that enforces regulation, addresses the final target of decommissioning work, and is responsible for nuclear safety. France and Germany have slightly different dismantlement strategies; France and German private operators have favoured the immediate dismantlement strategy, and the German public operator, EWN, has chosen the deferred dismantlement strategy. France's regulatory body is the ASN for the account of the Ministry of Ecology. Germany has various advisory and regulatory authorities on regional and national levels and on account of ministries. As for waste management, the French government agency is the ANDRA, and the German public company for interim storage is BGZ.

Regarding the financing of nuclear dismantlement, operators are responsible for it under the polluter-pays principle and also for developing cost estimates. As for waste and final disposal, it varies between France and Germany. In France, it is financed by operators but controlled by the state through the ANDRA. In Germany, the state is now responsible for interim and final storage against a lump of 24.1 billion $€_{2019}$, and exceeding costs are not to be borne by the operator. Again, this violates the polluter-pays principle. To analyse the estimated costs of nuclear dismantlement in France and Germany, a comparison of the costs per MWe will be made.

Table 7.1: Comparison of Germany and France's nuclear estimated undiscounted costs of dismantling

Cost categories	**Estimated costs in France[1] (in millions $€_{2022}$)**	**Per MWe[1] (in millions $€_{2022}$)**	**Estimated costs in Germany[2] (in millions $€_{2022}$)**	**Per MWe[2] (in millions $€_{2022}$)**
Total dismantling	29,885	0,49	22,261	0,89
Total spent fuel management	20,727	0,34	11,193	0,45
Total radioactive waste management	33,270	0,54	20,201	0,8
Miscellaneous	4,877	0,08	-	-
Total phase-out	**88,759**	**1,45**	**53,655**	**2,13**

Data: [1]EDF, 2017 [2]Warth & Klein Grant Thornton AG, 2015

As seen in the table and the graphs, a nuclear phase-out in France is estimated at almost 89 billion €$_{2022}$, corresponding to 1.45 million €$_{2022}$ per MWe. In Germany, it is estimated at almost 53.7 billion €$_{2022}$, corresponding to 2.13 million €$_{2022}$ per MWe. In this comparison, 56 reactors, totalising a net production of 61,370 MWe, have been estimated to be dismantled in France, in comparison to 23 in Germany, totalising a net production of 25,132 MWe. This difference in estimated costs could be explained by the various models of reactors in the German nuclear fleet, compared to the homogeneous fleet in France, in which engineers could learn from previous dismantlements. However, only two models of reactors (BWR and PWR) are analysed in the German fleet. Therefore, scholars and experts argue that the estimated costs by EDF in France are underestimated. This can also be determined by the fact that France, when constructing new nuclear power plants, replicated its models by upgrading the plateaus regarding energy production. Finally, these costs were determined at a specific date —2017 for EDF and 2015 for W&KGT— and, therefore, can not predict the exact inflation rates in the future.

The IAEA co-guides national governments regarding nuclear dismantlement. Germany and France have already decommissioned or have started to dismantle several nuclear facilities. However, the costs of a nuclear phase-out are very high and do not compensate for the creation of other energy production. These costs have to be carried out by operators, but in the end, states will have to pay at least for a part of it, as EDF is in the process of being nationalised, and some nuclear power plants are state-owned in Germany. Also, it is not a certainty that nuclear operators will have the financial needs in the upcoming decades for nuclear dismantling.

To discuss this topic further, it could be relevant to analyse the costs of a nuclear phase-out compared to the construction of a 100% renewable energy production mix in studied countries. Also, it has not been discussed in this paper the environmental and human costs of a nuclear phase-out, as well as the production of non-renewable energies during the process of nuclear dismantlement, as neither France nor Germany achieved a 100% renewable energy production mix.

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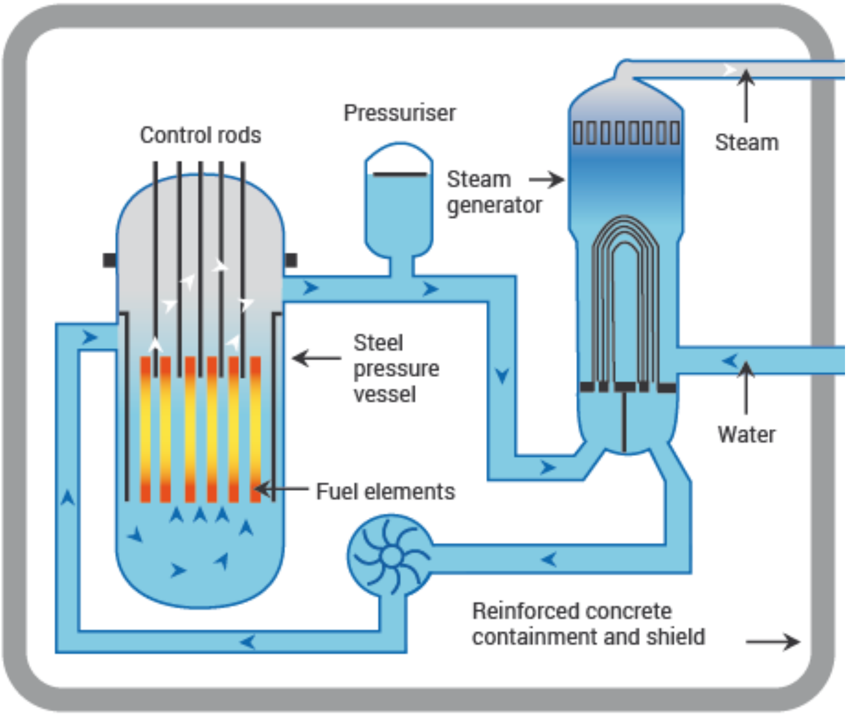
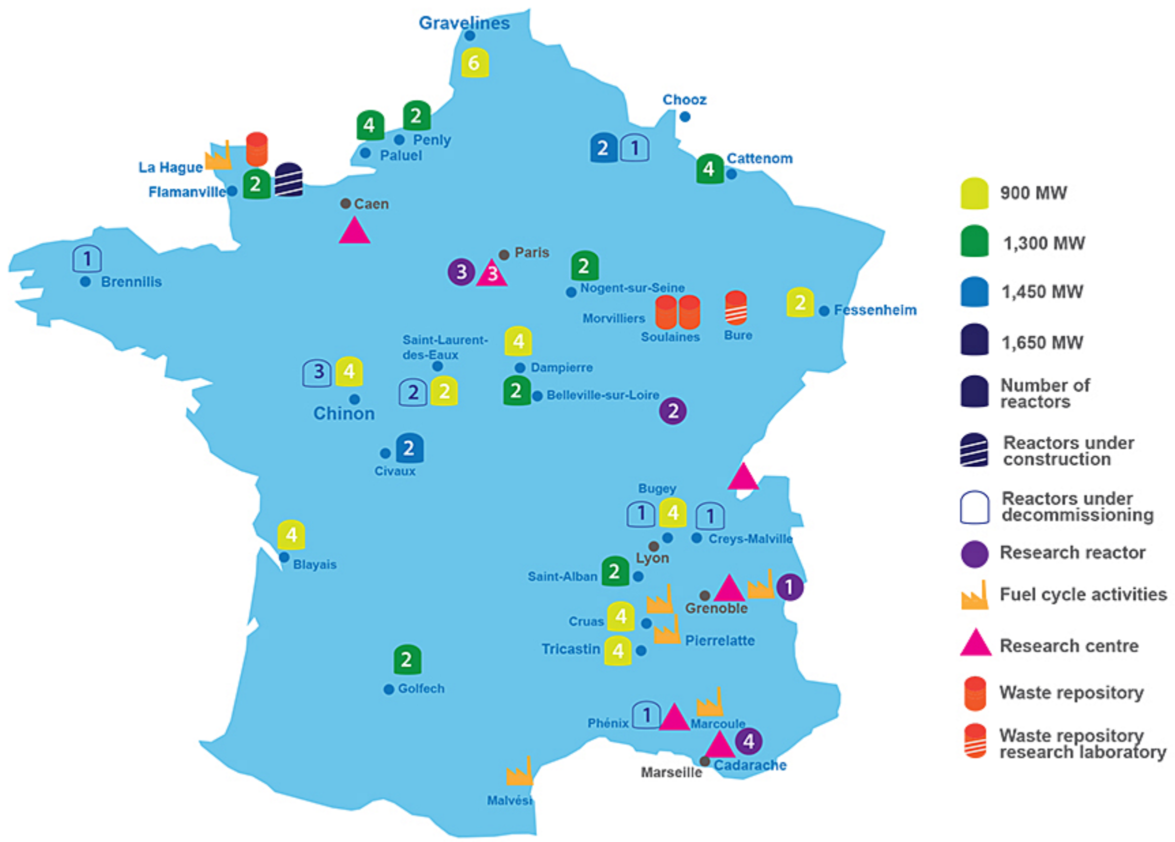
Appendix A: Functioning of a PWR



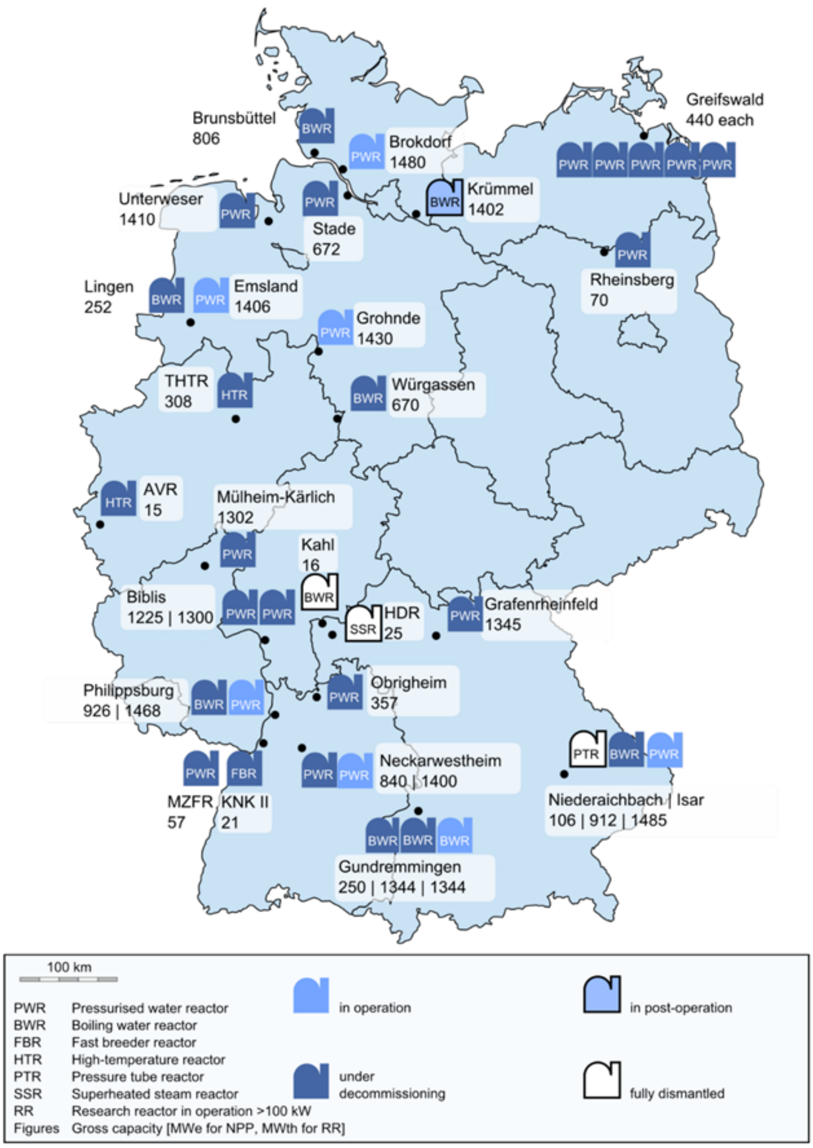
Source: World Nuclear Association (2022)

Appendix B: Map of the French nuclear facilities



Source: CEA

Appendix C: Map of the German nuclear reactors by model



Source: IAEA (2020)

Appendix D: Survey of the dismantling costs data, according to the ISDC

Cost item	Cost group					
	Labour		Capital	Expenses	Contingency	Total
	Hours	NCU	NCU			NCU
01 Pre-decommissioning						
02 Facility shutdown						
03 Additional activities for safe enclosure						
04 Dismantling activities within the controlled area						
05 Waste processing, storage and disposal						
06 Site infrastructure and operation						
07 Conventional dismantling demolition and site restoration						
08 Project management, engineering and site support						
09 Research and development						
10 Fuel and nuclear material						
11 Miscellaneous expenditures						
Total						

NCU = National currency unit.

Source: OECD/NEA (2016)