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Nuclear Decommissioning Profile USA

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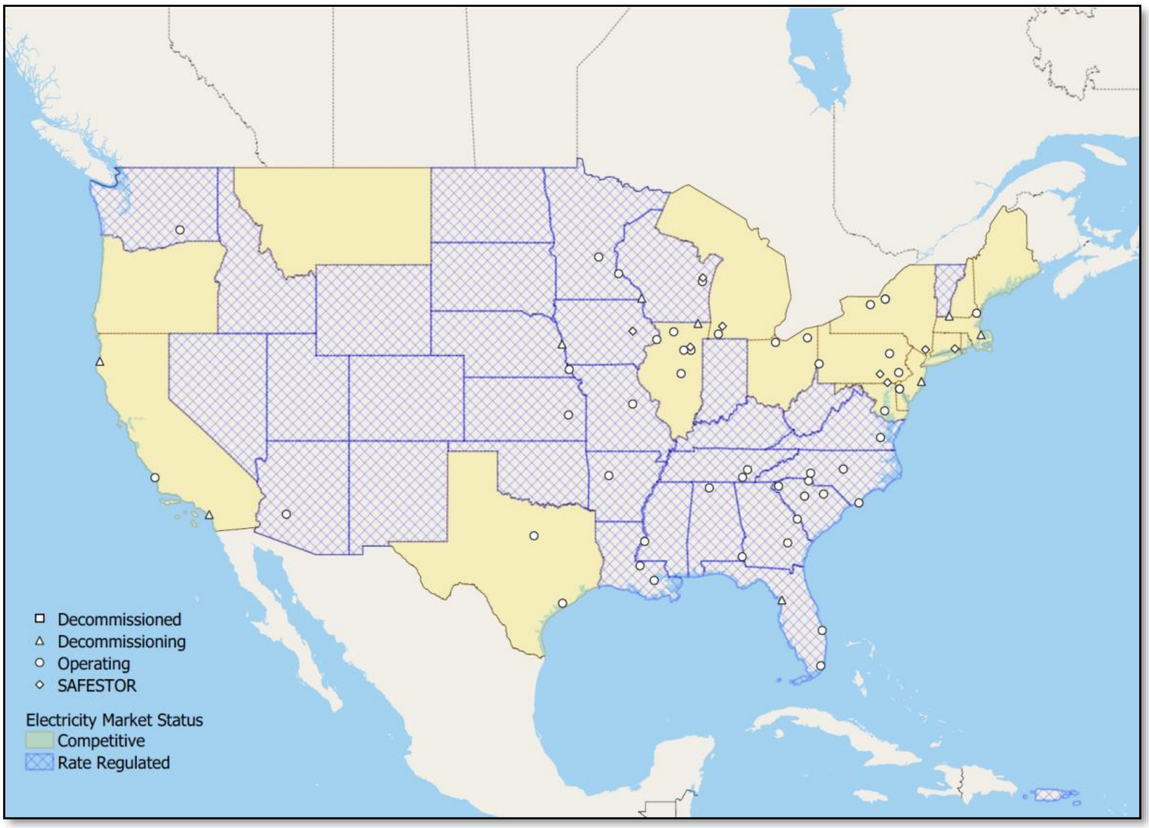
1. Introduction

Development of the commercial nuclear industry in the United States began in earnest during the early 1960s after the passage of the Atomic Energy Act (1954). The introduction of the turnkey contract in the mid-1960s spurred the momentum to construct nuclear reactors. The first commercial nuclear reactors (Shippingport, Dresden-1, Indian Point-1, and Yankee NPS) were commissioned and constructed during mid-1950s and early 1960s. By 1967, U.S. utilities ordered more than 50 nuclear power reactors and by 1973, 40 reactors were operating (Scurlock 2007; Squassoni 2012). At its peak in 1990, the U.S. nuclear industry operated 112 nuclear reactors (Lordan-Perret, Sloan, and Rosner 2021). Today the U.S. commands the largest commercial fleet globally with 92 operating reactors spread across 28 states and accounting for 94.7 GW (see Appendix A). The current nuclear fleet is also the oldest in world with an average age of 41.6 years (Schneider et al. 2022). In terms of new reactor builds, only one reactor has started over the past two decades (i.e., Watts Bar in 2016). Construction is ongoing the Vogtle units 3 and 4 reactors, and they are expected to commence operations in 2023 (WNN 2022). Figure 1 shows the location of all operating commercial reactors and the status of shutdown reactors (decommissioned or decommissioning).

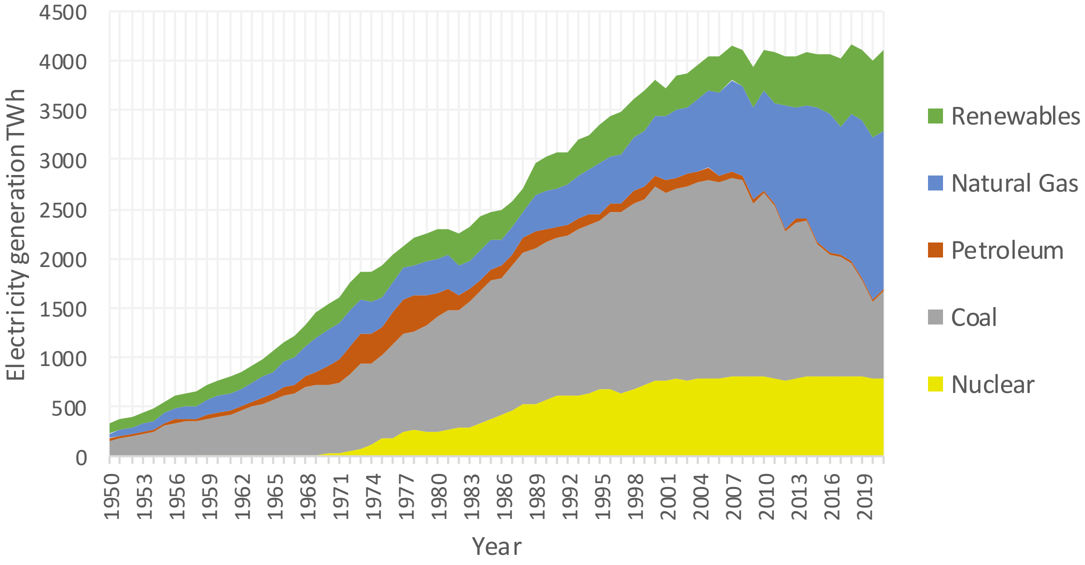
Figure 1: Map of operating commercial nuclear reactors in the U.S.



Source: (Lordan-Perret, Sloan, and Rosner 2021).

Nuclear power currently commands a 19% share of the total electricity generation mix (EIA 2022). Although nuclear power generation has increased markedly from the 1980s, in the past decade, its share in the electricity mix has stagnated in comparison to other sources of energy such as natural gas and renewables as depicted in Figure 2. For example, between 2000 and 2020, the share of natural gas in the electricity mix increased from 16% to 39%, while renewables share[1] expanded from 9% to 20%. Over the same period, the share of nuclear generation contracted marginally from 20% to 19%.

Figure 2: U.S. electricity generation by energy source



Source: own depiction based on (EIA 2022).

The U.S. electricity market has undergone substantial regulatory reforms in the 1990s when energy markets in many states were deregulated. Traditional vertically integrated utilities were split up into distinct activities: generation, transmission, distribution and retailing (Borenstein and Bushnell 2015; Chen 2019). In doing so, many state-owned nuclear plants were sold off to independent power producers, leading to a consolidation of plants into a few large holding companies (see Section 2.2). Today, nuclear power plants (NPP) operate in both regulated and deregulated electricity markets, with approximately 54 GW of generating capacity in regulated markets and 45 GW in deregulated markets (World Nuclear Association 2020). Nuclear plants in regulated markets are compensated based on cost-of-service, while plants in deregulated markets rely on the wholesale market and capacity market as their primary revenue sources. However, nuclear plants may receive additional out-of-market revenues through state subsidy schemes.

From 2017 to as recently as 2020, low wholesale market prices prompted nuclear licensees to seek out-of-market payments to remain competitive in deregulated markets. State support schemes are presently

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[1] Renewable generation comprises of solar, wind, geothermal, biomass and hydropower.

active in five U.S. states (New York, Illinois, New Jersey, Connecticut, New Hampshire) covering 19 reactors with a combined capacity of 19.4 GW. The schemes vary considerably in terms of length and financial provisions. At the federal level, two new schemes were rapidly introduced in late 2021 to counter the threat of early nuclear retirements (Schneider et al. 2022). In November 2021, the Civil Nuclear Credit Program (CNC) was introduced as part of the Infrastructure and Investments Jobs Act (IIJA) with the goal of providing out-of-market payments to NPPs in imminent risk of shutting down in wholesale electricity markets. The Department of Energy (DOE) was tasked with overseeing the $6 billion program over a five-year period from 2022-2027, with the possibility of extending it up to 2031 (DOE 2022b; NIRS 2022). In August 2022, the Inflation Reduction Act (IRA) was signed into law, incorporating provisions for a second federal-level support scheme known as the zero-emission Nuclear Power Production Credit (NPPC). Operating reactors that meet the prevailing wage requirement stand to receive a maximum credit value of $15/MWh for a nine-year period starting in 2024 until 2032 (Schneider et al. 2022). Reactors that do not meet the criteria would still receive credits valued at $3/MWh. This development is also part of an effort of the current administration to reduce emissions and achieve a clean electric grid (Schneider et al. 2021).

Over the coming decades, a wave of reactors in the U.S. will be reaching the end of their operating lifespan and will need to be decommissioned. By 2040 alone, approximately half of the U.S. nuclear fleet will be reaching the end of their operating licenses. The closure of the Palisades reactor in May 2022 brings the total number of shutdown reactors in the U.S. to 41, amounting to approximately 20 GW of capacity. The U.S. nuclear industry has accumulated some decommissioning experience with 17 reactors fully decommissioned (the most of any country). Nevertheless, it stands that the U.S. nuclear industry is just beginning an unprecedented undertaking to decommission the world’s largest fleet. Supporting and shaping this effort are many stakeholders, including public agencies, private firms, regulators, financial institutions.

This report provides an in-depth overview of the nuclear decommissioning landscape in the U.S. This report will cover the nuclear legal framework, decommissioning regulation, financial regulation and current decommissioning status.

2. Legal and Regulatory Framework

2.1 Governmental and regulatory framework

The primary law governing the entire nuclear industry is the Atomic Energy Act of 1954. The Act established the Atomic Energy Commission (AEC) in 1946, which then later split into the Nuclear Regulatory Commission (NRC) and the DOE (formerly the Energy Research and Development Administration, ERDA). Apart from the Atomic Energy Act, other key statues were introduced to regulate specific areas of the nuclear industry (see Box 1).

Box 1: Legal framework of the U.S. nuclear industry

Atomic Energy Act of 1954, as Amended: Permits the use of atomic energy for peaceful applications. It transformed the atomic energy program with a key goal of expanding the growth of the commercial nuclear industry.

Energy Reorganization Act of 1974: This Act divided the functions of the Atomic Energy Commission (AEC) into two separate agencies. The DOE (formerly ERDA) became responsible for the development of nuclear weapons and promotion of nuclear energy. The NRC assumed the overall nuclear regulatory responsibility.

Nuclear Waste Policy Act of 1982: Sets out the government's responsibility for the identification and development of a suitable geological site for the disposal of civilian and defense spent nuclear fuel, high-level waste and nuclear licensee's responsibility for bearing the cost. The Act also established the Nuclear Waste Fund (NWF) to finance the management and disposal of spent nuclear fuel.

Low-Level Radioactive Waste Policy Amendments Act of 1985: Established the policy for the disposal of low-level radioactive waste. The act grants states the authority to establish and operate facilities for the disposal of low-level waste generated within their borders.

Price-Anderson Act of 1957*:* Established to address nuclear liabilities and sets a limit on total liabilities each licensee faces in the event of an incident.

Uranium Mill Tailings Control Act of 1978: Established a program to stabilize and control mill tailings at uranium- and thorium-ore processing mill sites.

Nuclear Non-Proliferation Act of 1978: The act seeks to provide effective control over the proliferation of nuclear weapons.

Source: (IAEA 2002)

The **NRC** is the federal agency responsible for regulating the civilian use of radioactive materials for the protection of public health. It has a broad range of regulatory responsibilities covering commercial nuclear plants (with jurisdiction over licensing, operation, and decommissioning), research and test reactors[2], and nuclear fuel cycle facilities. The NRC's regulatory oversight also extends to the transport, storage, and disposal of radioactive materials and waste. The NRC adopts a broad array of mechanisms to exert its regulatory authority such as rule making, technical reviews, inspections and investigations, issuance of licenses and evaluating operating experience. Inspections are a major component of the NRC's regulatory authority to ensure that nuclear plants operations and activities meet the NRC regulations.

The **Department of Energy (DOE)** is responsible for policy formulation and funding programs on nuclear energy, fossil fuel and renewable energy. On the nuclear energy front, the DOE conducts a range of activities such as research and development of next generation nuclear plants, funding construction of new nuclear plants, nuclear security and development of advanced fuel cycle technology. The DOE is responsible for the management of high-level nuclear waste and spent nuclear fuel as directed in the Nuclear Waste Policy Act of 1982 (OECD/NEA 2016b). The DOE also oversees

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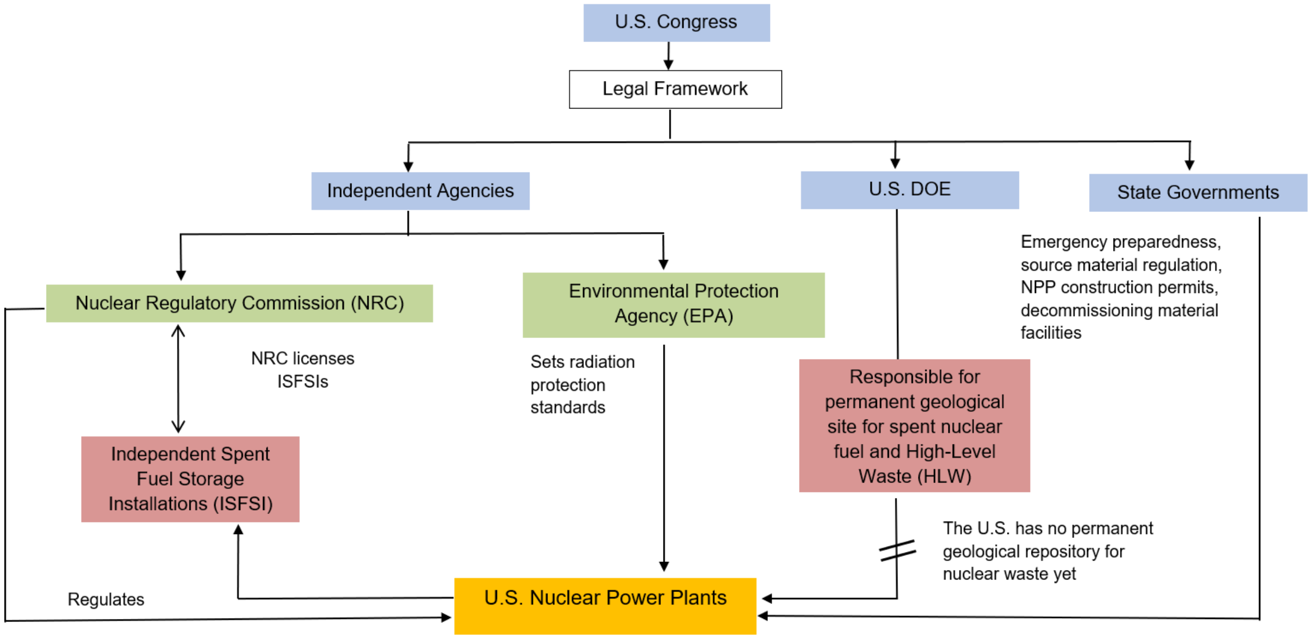
[2] The NRC regulates 31 operating research reactors and three shutdown reactors (NRC 2021a).

and regulates its own fleet of research and test reactors, which do not fall under the jurisdiction of the NRC.

The **Environmental Protection Agency (EPA)** is responsible for setting public health and radiation protection standards as outlined in federal regulation 40 CFR Part 190. The **Department of Transport (DOT)** coordinates with the NRC for the transportation of hazardous radioactive materials and regulates shipments while on transit. The **Department of Defense (DOD)** is primarily responsible for the safety of nuclear materials including nuclear weapons.

State and local governments exercise regulatory control over certain aspects of nuclear energy. For example, under the Atomic Energy Act of 1954, states are permitted to exercise independent authority to license and regulate by-product materials, source materials and selective quantities of special nuclear material as part of the Agreement State Program (Squassoni et al. 2014). Presently, 39 states have signed up to the program. In terms of emergency preparedness, core responsibilities are shared between the NRC and the Federal Emergency Management Agency (FEMA). However, state governments are responsible for implementing public protection protocols during nuclear emergencies. State governments also play a role in the issuance of nuclear construction permits. Figure 3 provides an overview of the various governmental and regulatory bodies and their association with NPPs in the U.S.

Figure 3: Governmental and regulatory actors and their connection to U.S. NPPs



Source: own depiction based on (IAEA 2002; OECD/NEA 2016b).

2.2 Ownership

NPP ownership in the U.S. is fragmented across several ownership structures[3] such as the federal government, publicly owned entities, investor-owned companies and cooperatives. In some cases, NPPs can be owned by several ownership types. NRC regulation (10 CFR 50.38) prohibits foreign ownership or operation of domestic NPPs.

In the case of the federal government, ownership of the reactor falls under the control of a federal agency. For example, the Tennessee Valley Authority (TVA) is a federally owned agency that fully owns the Browns Ferry, Sequoyah and Watts Bar NPPs. Publicly owned NPPs are owned or partly owned by a state utility company or municipality entity. For example, the Municipal Electric Authority of Georgia (MEAG Power) has a 17.7% share in the Edwin Hatch NPP and a 22.7% share in the Vogtle NPP as illustrated in Figure 5.

Turning to investor-owned corporations, following the restructuring of the U.S. energy sector, a considerable number of nuclear reactors were consolidated into a few large private holding energy companies such as Constellation Energy Corporation, Duke Corporation, NextEra and Entergy. These major holding companies are diversified across the energy value chain, with several energy sources in their portfolio. Investor-owned companies own majority of operating commercial reactors. The investor-owned plant ownership structure is comprised of several layers between the holding company and the nuclear power plant. Most holding companies do not directly own nuclear plants, but instead ownership is held by a subsidiary company in the form of a Limited Liability Company (LLC). LLCs are generally the preferred vehicle of ownership amongst multi-tiered nuclear holding companies in the U.S., as they provide a flexible means of transferring funds from subsidiaries and avoiding tax (Schlissel, Peterson, and Biewald 2002). Parent company liabilities are only restricted to the initial investment made in setting up the LLC. This ensures that parent companies are financially shielded from any liabilities (i.e., accident or decommissioning risks) emerging from its subsidiaries (Schlissel, Peterson, and Biewald 2002). An example of investor-owned nuclear reactor ownership is Constellation Energy Corporation, a spin-off from its former parent company Exelon Corporation. Constellation through its chain of subsidiary LLC's, fully owns 16 reactors, apart from Peach Bottom (50% ownership), Quad Cities (75% ownership) and Salem nuclear plant (43%). MidAmerican holdings owns 25% of both Quad Cities reactors while Long Island Power Authority (LIPA) owns 18% of Nine Mile Point 2. Figure 4 provides a graphical representation of Constellation Energy Corporation ownership structure for its nuclear reactor fleet.

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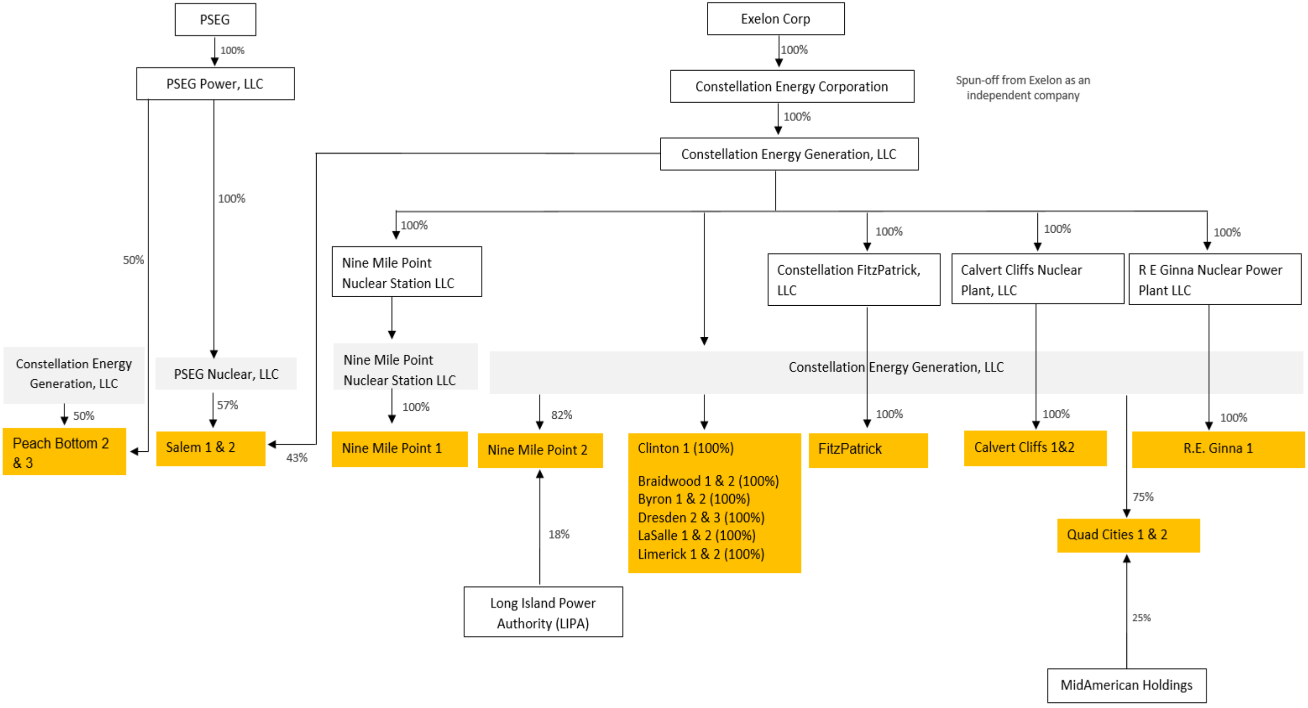
[3] Refer to NEI (2022) for data on reactor ownership shares.

Figure 4: Investor-owned nuclear plant ownership structure



Light grey boxes depict reactor operator. Solid black lines signify ownership.
Source: own depiction based on (Constellation Energy Corporation 2021).

Cooperatives are independent not-for-profit member-owned utilities. In the case of nuclear reactors, the members of the cooperative have ownership interest in the reactors and they are also its customers (Sunshine 2020). An example of a Cooperative is Oglethorpe Power Cooperative that owns 30% of the Vogtle 1 & 2 reactors.

In some cases, nuclear reactors are owned by a combination of ownership structures. For example, ownership of the Edwin Hatch and Vogtle NPPs are shared between an investor-owned utility (Georgia Power), publicly owned utilities (Municipal authority of Georgia[4] and Dalton utilities), and a cooperative (Oglethorpe Power Corp). Figure 5 depicts the mixed nuclear plant ownership structure.

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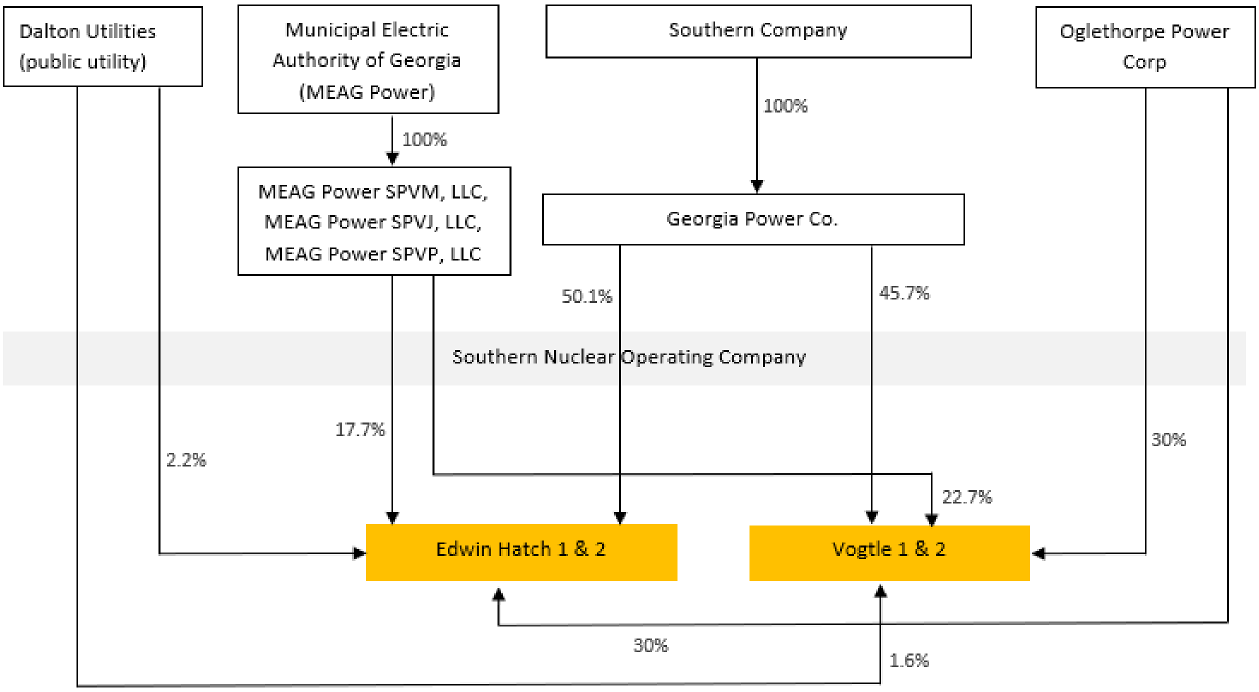
[4] In June 2015, MEAG Power divided its ownership interest (22.7%) in Vogtle 1 and 2 reactors into three separate limited liability companies. In particular, 41.175% of the Vogtle ownership share was transferred to MEAG Power SPVJ, LLC, 33.87% to MEAG Power SPVM, LLC, and 24.95% to MEAG Power SPVP, LLC (MEAG 2017).

Figure 5: Mixed nuclear plant ownership structure



Investor owned: Georgia Power Corporation. Public utilities: MEAG Power and Dalton utilities. Cooperative: Oglethorpe Power Corp. Light grey boxes depict reactor operator.

Source: Own depiction based on (NEI 2022; Southern Company 2021).

2.3 License provision and extension

The NRC oversees licensing regulations for commercial nuclear plants. All the 92 currently operating commercial reactors were licensed under a two-step licensing framework governed by 10 CFR Part 50 regulations. Under the two-step process, the applicant applies for a construction permit first before applying for an operating license once the plant was nearing completion. NRC regulations limits the initial license period for commercial nuclear plants to 40 years. Nuclear plant licenses can be renewed for additional 20-year periods. The decision to apply for a license extension rests with the licensee and often depends on economic considerations and whether a plant can continue to meet the NRC's stringent standards. As of July 2022, 84 currently operating reactors have received a 20-year license extension (Schneider et al. 2022).

Though still a valid way of seeking a license, the two-step process was criticized and the NRC modified the licensing regulation by introducing a streamlined combined license (COL) process under the 10 CFR Part 52(C) regulations. Unlike the two-step process, the COL authorizes the applicant to construct and operate a reactor at a specific site with one unified application. A prospective licensee applies for a COL by referencing either an early site permit or a standard design certification or both (NRC 2009).[5] The early site permit is granted for a period of 10 to 20 years and allows the holder to

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[5] The NRC introduced the early site permit and standard design certification in 1989 under 10 CFR Part 52 regulations, which contribute to the COL process (NRC 2009).

address site safety issues, environmental protection concerns, and emergency plans under the 10 CFR Part 52(A) regulations. Alternatively, a standard design certification[6] is issued to certify a reactor design under 10 CFR Part 52(B) regulations and is valid for 15 years. If the applicant decides not to reference either of the two frameworks, it should provide equivalent information for both certifications. The COL application should also include a preliminary safety analysis report, environmental review and financial and antitrust statements (NRC 2009).

Upon receiving the COL application, the NRC conducts a preliminary review to assess the suitability of the application. Once accepted, the licensing review starts and the NRC organizes public meetings at the proposed reactor site to brief the public about safety and environmental elements of the application (NRC 2020). The NRC publishes its staff review findings in a safety evaluation report and environmental impact statement (NRC 2009). Following the NRC staff review, the independent Advisory Committee on Reactor Safeguards (ACRS) is convened to review each COL application in a mandatory public hearing. At this stage, the public can submit written or oral statements on record or apply to participate in the hearing. Once the review is completed and the application is approved, the NRC issues a COL to the applicant. An overview of the COL process is depicted in Figure 6. Like the two-step process, a COL is issued for 40 years and can be renewed for an additional 20 years. Since 2007, the NRC has received 18 COL applications for 28 reactors and approved eight of the applications covering 14 reactors[7] (NRC 2021a). Six of the issued COL's were terminated[8] at the behest of the licensee.

Moving forward, The NRC has also developed a standard review plan for subsequent license renewals that would extend the operating life of nuclear reactors beyond 60 years and up to 80 years. So far, six reactors Turkey Point 3 & 4, Peach Bottom 2 & 3 and Surrey units 1, 2 & 3 have been issued subsequent license renewals and the NRC is reviewing applications for nine operating reactors[9] (NRC 2022d).

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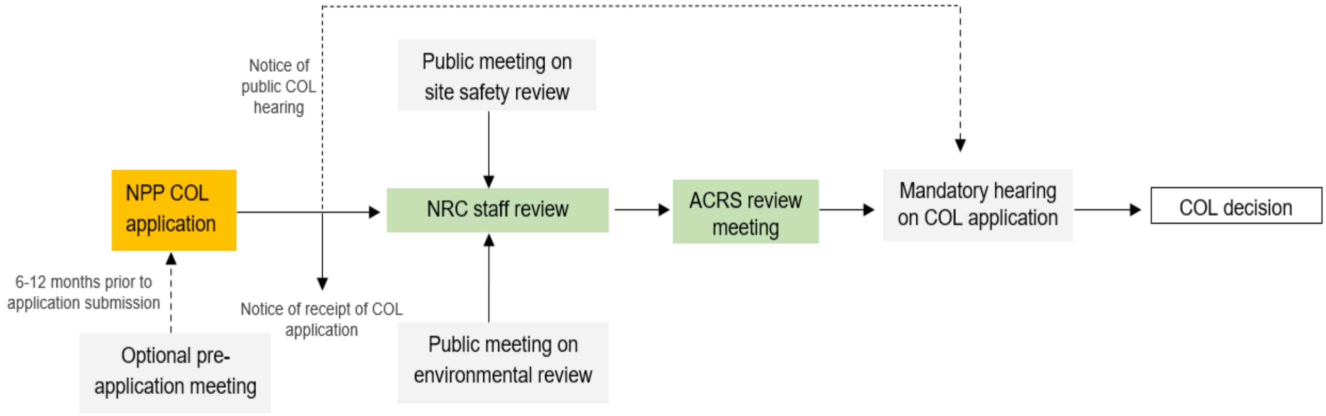
[6] The NRC has thus far issued standard deign certifications for seven Generation III+ reactor designs (NRC 2021a).

[7] Fermi 3, Levy units 1 & 2, North Anna 3, South Texas Project units 3 & 4, Turkey Point units 6 & 7, Virgil Summer Units 2 & 3, Vogtle units 3 & 4 and William States Lee units 1 & 2 . All the approved reactors were Generation III+ large light water reactor designs.

[8] Levy Country units 1 & 2 (terminated April 2018), South Texas Project units 3 & 4 (terminated July 2018) and V.C. Summer units 3 & 4 (terminated March 2019) (NRC 2021a).

[9] Reactor applications under review: St. Lucie units 1 and 2, Oconee units 1, 2 and 3, Peach Bottom units 1 and 2, and North Anna units 1 and 2.

Figure 6: COL licensing process



Light grey boxes represent opportunities for public involvement in the licensing process.
Source: Own depiction based on (NRC 2009).

2.4 Oversight

The NRC is primarily responsible for oversight responsibilities. Within the NRC structures, the Office of Nuclear Reactor Regulation (NRR), Office of New Reactors (NRO) and the Office of Nuclear Material Safety and Safeguards (NMSS) are the three major statutory program offices (OECD/NEA 2016b). The NRR oversees all licensing, oversight, rule-making and incident response for commercial nuclear reactors and research and test reactors. The NRO is responsible for regulating new commercial nuclear plants. Finally, the NMSS maintains regulatory oversight of activities associated with nuclear fuel for commercial reactors, transportation of radioactive materials and high-level nuclear waste. The NMSS is also responsible for decommissioning of nuclear reactors and material sites.

2.5 Liability

Extensive financial regulations are in place that cover financial assurances for decommissioning nuclear reactors (10 CFR 50.33(k), 10 CFR 50.75, 10 CFR 50.82). Before commencing operation, nuclear power plant owners are required to provide financial assurances (i.e., trust fund, government fund, sinking fund) to ensure that sufficient resources are available to ultimately decommission the facility.[10] There has been considerable speculation about the adequacy of the funds, who would be required to finance any potential shortfalls in funds, and how well funds are insulated from, for example, bankruptcy proceedings. In their research article, Lordan-Perret, Sloan, and Rosner (2021) outline four plausible scenarios in which funds might be inadequate and determine who would bear financial responsibility: decommissioning cost overrun, a radiological accident, bankruptcy, decommissioning funds investment downturn.

In the case of inadequate funds and company bankruptcy, the authors discuss two potential routes for a host state to reclaim outstanding decommissioning funds from a licensee. First, assuming

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[10] Refer to Section 4.1 and 4.2 for a detailed description of the decommissioning financial regulation.

an investor-owned corporate structure, the host state could file a lawsuit against the parent company of the licensee (i.e., piercing the corporate veil). However, chances of success is slim since the basic principle of corporate liability ensures that parent companies are not held responsible for decommissioning liabilities of its subsidiary (Barrett et al. 2017). The second route to reclaim decommissioning funds is for a federal body (e.g., EPA) to activate the liability provisions of the Comprehensive Environmental Compensation Liability Act (CERCLA)[11]. Through the CERCLA, a designated body such as the EPA could reclaim outstanding decommissioning funds from all past and current owners of the reactor. Under certain conditions, however, accessing outstanding funds from previous owners may be challenging in certain cases such as a dissolved former owner or a public utility former owner (Lordan-Perret, Sloan, and Rosner 2021). In this case, financial resources from a taxpayer funded trust fund known as the Hazardous Substance Superfund Trust Fund (or Superfund), would be used to pay for decommissioning and site cleanup costs.

In the event of a nuclear accident (e.g., Fukushima), even during decommissioning, the Price-Anderson Act (PAA) passed in 1957, would provide the legal basis to cover liability claims made against nuclear power plant owners for personal injury and property damage (Lordan-Perret, Sloan, and Rosner 2021). The Act sets a cap on the total liability each nuclear plant owner is required to pay in the event of a nuclear accident (Barrett et al. 2017). Nuclear plant owners currently pay an annual insurance premium for off-site liability coverage (see Figure 7). As of 2019, the average annual premium for a NPP site is $1.3 million. If nuclear accident liabilities exceed the first-tier amount ($450 million), a proportional share of the excess, up to $131 million per reactor is allocated to each nuclear plant owner. This leads to a secondary insurance pool with approximately $12 billion in total. Any payout that exceeds 15% of the second tier requires a prioritization plan that is ratified by the federal district court. If the liability is approved to exceed the first and second insurance tiers, each nuclear plant owner is again assigned a proportional share of the increment not exceeding 5% of the maximum deferred premium ($131 million), equating to approximately $6.55 million per reactor (NRC 2019b). Finally, as a backstop, Congress will determine if additional disaster relief fund is needed once the second tier is depleted. The Price-Anderson Act therefore provides substantial insurance coverage for nuclear incidents that is funded entirely by commercial nuclear plants. If nuclear related incident costs exceed the insurance pool, the NRC commits to indemnify the licensee from "public liability...which is in excess of the level of financial protection required of the licensee" (42 U.S. Code § 2210(c)).

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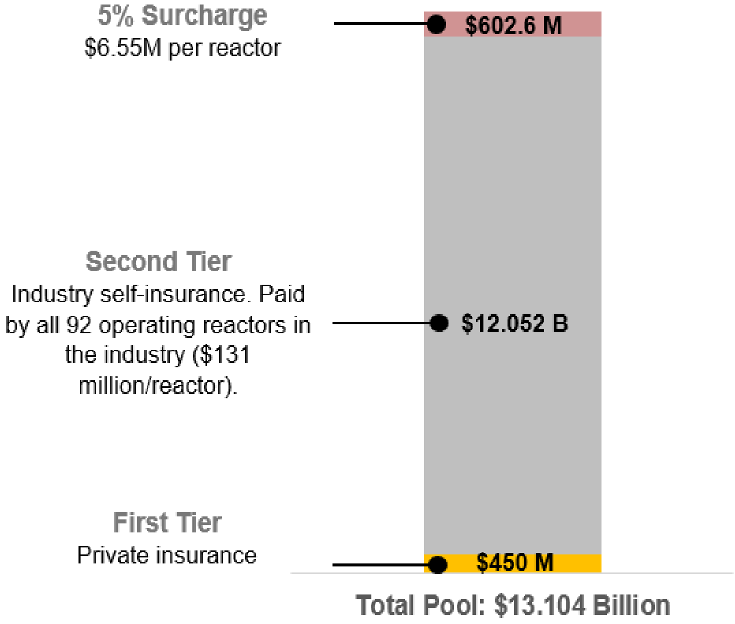
[11] CERCLA was passed into law in 1980 and grants powers to the federal government to clean up contaminated sites and hold parties financially responsible for liabilities associated with cleaning up contaminated sites (Bearden 2012).

Figure 7: Nuclear insurance under the Price-Anderson Act



Source: Own depiction based on NRC (2019b).

3. Decommissioning Regulation

3.1 Decommissioning policy

The NRC recognizes three decommissioning strategies- Decontamination (DECON), Safe Storage (SAFSTOR) and Entombment (ENTOMB). Briefly;

DECON: Immediately following the permanent shutdown of the nuclear facility, radioactive structures, equipment and materials are either removed or decontaminated to a level that allows the facility to be released from regulatory controls and its license terminated (NRC 2022a).

SAFSTOR: Decommissioning is put on hold for a period allowing radioactivity to decay (NRC 2022a). However, the reactor is defueled and radioactive liquids are drained from the systems. Following the 'holding period', which may take up to 50 years, the plant is decontaminated and dismantled (NRC 2022a). This approach is also known as "Deferred Dismantling".

ENTOMB: Under entomb, radioactive plant structures, systems and components are entombed in situ in concrete (NRC 2022a). The facility is monitored until radioactivity decays to safe levels which permits the termination of the license. So far, in the U.S., only three reactors have been entombed: Hallam Nuclear Power Facility (HNPF), Piqua Nuclear Power Facility and Boiling Nuclear Superheating Power Station (BONUS). All three reactors were commissioned under the Atomic Energy Commission (AEC) Power Demonstration Reactor Program (PDRP)[12] and entombed within a year

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[12] The demonstration program commenced in 1955 soon after the passage of the Atomic Energy Act of 1954 with the goal of spurring private investment into the construction and operation of experimental reactors (Allen 1977).

between 1969 and 1970 (Vernon, Birk, and Hanson 2000). The ENTOMB option is deployed for exceptional situations, such as a critical nuclear accident (e.g., Chernobyl), which would require the facility to be sealed in-situ (OECD/NEA 2016a; Borys 2017).

For nuclear licensees, the optimal choice of decommissioning strategy depends on various factors such as the site-specific cost of each decommissioning strategy (DECON/SAFSTOR), availability of an interim spent fuel storage facility, radiation exposure, and public concerns (Gallagher 2019). The licensee can adopt a combination of the first two options. For instance, adopting DECON for certain portions of the plant whilst leaving the remaining portions in SAFSTOR (NRC 2022a). NRC regulations stipulate that decommissioning must be completed within a 60-year timeframe following shutdown (10 CFR 50.82(a)(3)). Decommissioning activities that extend beyond the 60-year timeframe are considered under certain conditions to protect public health and safety (NRC 2022a).

3.2 Regulatory and legal process

The procedures governing nuclear plant decommissioning are outlined in several federal regulations[13]. The NRC has also compiled decommissioning guidance documents[14] to assist both licensees in complying with decommissioning regulations and NRC staff in reviewing submitted documents.

The decommissioning regulatory process in the United States is segregated into three distinct stages; transition activities, major decommissioning activities, and license termination activities (Simeone 2016; NRC 2022a). Once a licensee decides to permanently shut down a NPP, a written notice must be submitted to the NRC within 30 days. The licensee is required to submit another written notice after the reactor has been defueled. Within two years following shutdown, the licensee submits a Post Shutdown Decommissioning Activities Report (PSDAR). The PSDAR details the scheduled decommissioning activities, time schedules, site-specific decommissioning cost estimate (DCE) and estimation of spent fuel management costs. The licensee can start major decommissioning activities 90 days after the submission of the PSDAR without specific approval from the NRC. Major decommissioning activities include dismantlement of major components such as the reactor vessel, steam generators, large piping systems, pumps, and valves (NRC 2022a).

Two years prior to the license termination date, the licensee applies for license termination and includes a License Termination Plan (LTP). The LTP incorporates details such as site characterization, remaining dismantling activities, site remediation plans, site end use, updated site-specific cost estimate, and a supplement to the environmental report. Upon receipt of the LTP, the NRC makes it publicly available and schedules a public meeting near the facility. The LTP is subject to approval by the NRC based on the review plan for license termination (i.e., NUREG-1700) (NRC 2018b). Once decommissioning activities have been completed, the licensee submits a Final Status Survey Report

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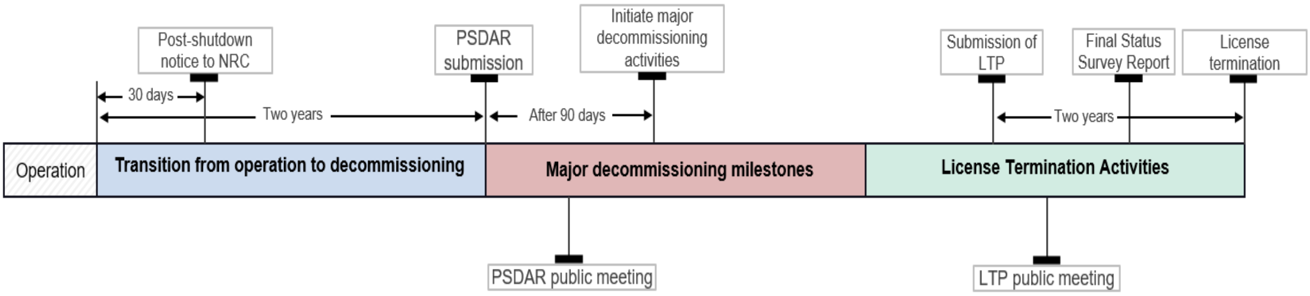
[13] 10 CFR Parts 20(E), 40.42, 50, 51, 70.38, 72.54 and 73 (NRC 2022b).

[14] Consolidated Decommissioning Guidance (NUREG-1757) and the Standard Review Plan for Evaluating Nuclear Power Reactor License Termination Plan (NUREG-1757).

(FSSR) that provides information on the radiological conditions of the site and requests that the NRC either terminates the 10 CFR Part 50 license or reduces the geographical boundaries of the license to the Independent Spent Fuel Storage Installation (ISFSI) site (Simeone 2016). The NRC terminates the operating license if the licensee shows that the remaining dismantling activities complied with the approved LTP and the final radiation survey (10 CFR 50.82). Licensees that store spent fuel on site maintain a general license limited only to the ISFSI under the 10 CFR 50.72(K) regulation.[15] Figure 8 illustrates the decommissioning regulatory process in the U.S.

Figure 8: U.S. decommissioning regulatory process



Source: own depiction based on (NRC 2019a).

3.3 Oversight

The NRC is primarily responsible for decommissioning regulatory oversight of all commercial nuclear power reactors, materials and fuel cycle facilities, research reactors, and uranium mining facilities. When a plant begins the transition from operating to decommissioning, regulatory oversight responsibilities are transferred from the office of NRR to the office of NMSS. The transition of responsibilities begins when a nuclear plant licensee announces plans to cease operations and submits the required notices (shutdown & defueling) to the NRC (Baker 2019).

For plants undergoing decommissioning, the NRC has established a decommissioning power reactor inspection program. Following a permanent shutdown of operations, one resident inspector will provide initial short-term oversight. The decommissioning inspection program commences once the reactor is defueled and extends until license termination. NRC inspectors may be present at the facility two or three times a month and during significant decommissioning activities. For plants in SAFSTOR, the intensity of inspections reduces to several times a year (NRC 2003; 2017).

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[15] Refer to Section 4.1 and 6 for additional insights into nuclear waste management.

4. Financial Regulation

4.1 The funding of decommissioning

The NRC mandates all licensees to preserve decommissioning funds using a variety of financial mechanisms such as prepayment, external sinking fund, statement of intent, surety method or a combination of methods as outlined in 10 CFR 50.75(e). The main reason for the funds, collectively referred to as Decommissioning Trust Funds (DTF), is to provide reasonable assurances that sufficient funds are available for decommissioning activities once a reactor shuts down (OIG 2021). Funding assurances are based on a minimum decommissioning amount calculated using precise equations (Table 1). The equations specifically estimate costs for radiological decommissioning[16] that would be sufficient to terminate the reactor's operating license (See Section 4.2). Alternatively, licensees can provide funding assurances based on a Site-Specific Cost Estimate (SSCE), as long as the estimate is not less than the value obtained from the minimum fund formula (NRC 1999).

Traditional rate-regulated utilities accumulate decommissioning funds by charging customers a fee (0.1 to 0.2 cents/kWh) which is then deposited into the DTF. About 70% of rate-regulated or indirectly regulated licensees are authorized to accumulate decommissioning funds over the lifetime of the plant (NRC 2022a). The remaining licensees must provide financial assurances via alternative approaches such as prepaid decommissioning funds, surety method or parent company guarantee (Simeone 2016; Moriarty 2020). Licensees are required to submit DTF status reports biennially to the NRC, and annually once the plant approaches within five years of expected shutdown (10 CFR 50.75(f)(2)). NRC staff review the DTF reports to ensure decommissioning funds meets the minimum decommissioning funding requirements. If funding shortfalls are identified in the biennial DTF reports for operating reactors, the NRC considers it to be a 'temporary lapse' that can be corrected by providing evidence of a parent company guarantee, trust fund growth, or trust fund contributions (Lubinski 2021). The licensee should ensure that the shortfall is rectified by the subsequent biennial fund status report. Likewise, if a shortfall is identified in the funds for reactors undergoing decommissioning, the licensee is mandated to provide additional financial guarantee to cover the estimated costs of decommissioning (10 CFR 50.82(a)(8)(vi)). If a reactor shuts down prematurely, the NRC will determine the schedule for collection of outstanding funds on a case-by-case basis.

Strict regulations govern how licensees should spend the accumulated DTF amount. Funds should only be used for the purpose of decommissioning the facility (10 CFR 50.82(a)(8)). Licensees are required to submit written request to the NRC for DTF withdrawals that are not for decommissioning. During the planning stages of decommissioning, licensees are permitted to use 3% of the DTF amount. An additional 20% of the funds become available 90 days after the NRC receives

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[16] According to the NRC regulations, "*Decommission* means to remove a facility or site safely from service and reduce residual radioactivity to a level that permits (1) release of the property for unrestricted use and termination of the license; or (2) release of the property under restricted conditions and termination of the license" (10 CFR 50.2).

the PSDAR. The remainder (77%) can be withdrawn once the licensee submits the site-specific decommissioning cost estimate, which is typically provided in the PSDAR (10 CFR 50.82(a)(8)(ii)).

Funding of nuclear waste storage

Turning to nuclear waste funding, the Nuclear Waste Policy Act of 1982 established the Nuclear Waste Fund (NWF) to finance the management and disposal of spent nuclear fuel at a permanent geological repository. Presently, the U.S. does not have a permanent geological repository for nuclear waste. Yucca Mountain was selected by Congress as the ideal location for a geological repository in 1987, but the program was disbanded by the DOE in 2009 (Rusco 2013). Initially, nuclear plant operators deposited a one-tenth of a cent per-kWh fee (known at the "millage fee") into the fund amounting to $750 million annually. As of 2019, the waste fund has accumulated a total of $43.5 billion (DOE 2019). However, following the disbandment of the protracted Yucca Mountain program by the DOE, the U.S. Court of Appeals ordered the federal government to suspend the collection of fees in 2013 (Hurley 2013). Hence, nuclear licensees are storing nuclear waste on-site in cooling pools and then in dry cask storage systems. In order to recuperate the costs of this long-term storage, nuclear plant owners are suing the federal government for breaching its contractual obligations to accept the fuel for final disposal (for further details and analysis on the situation, see Rosner and Lordan 2014). As of 2020, the federal government has spent approximately $9 billion compensating nuclear power plant owners for the costs of storing fuel on site[17] (GAO 2021). The DOE estimated that the federal government's outstanding spent fuel litigation liability stands at $30.9 billion (DOE 2021a). The funds in the NWF are restricted and accessed through Congressional appropriation process, and since legal settlements are not subject to appropriations, settling lawsuits are a way "around" the appropriations process. In December 2020, Congress signed into law the Consolidated Act of 2021 that included $7.5 million appropriation[18] for NWF oversight activities and $20 million appropriation to the DOE to pursue a consolidated interim storage facility program (DOE 2021b).

4.2 Cost assessments

Decommissioning cost assessments for nuclear plants in the U.S. are derived from the minimum decommissioning fund formula (Table 1). Some nuclear power plant operators have also opted to have a Site-specific Cost Estimate (SSCE) done; however, these estimates incorporate costs for managing spent fuel and site restoration, which is excluded from the decommissioning costs defined in the federal regulations. Although, both estimates often appear at utility hearings on decommissioning costs, SSCE's are the preferred approach for cost estimations and there are incentives for conducting such SSCE in the financial assurance regulations (10 CFR 50.75(b)(1)).

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[17] About 86,000 metric tons of commercial spent nuclear fuel is stored at 75 sites across the U.S. The U.S. has also accumulated 14,000 metric tons of high-level waste and spent nuclear fuel from the defense sector (GAO 2021).

[18] The $7.5 million appropriation is drawn out of the NWF balance.

Minimum decommissioning cost estimate

The minimum standard cost estimates, are produced with a financial model developed for reference PWR and BWR reactors in the late 1970s (Smith 1991; Short et al. 2011). These models are for radiological decommissioning and therefore should not be used to estimate the costs of returning a site to “greenfield” status. Power plant licensees are required to adjust the baseline decommissioning costs (Table 1) to current year dollars based on the escalation factors that consider three important and regionally variable cost components:

(1) Labor, materials and services.

(2) Energy and waste transportation.

(3) Radioactive waste burial.

The decommissioning fund formula only considers decommissioning costs that are consistent with the definition of decommissioning in the NRC regulations. Costs that fall outside the definition such as on-site spent fuel management costs and costs associated with the dismantlement of non-radiological structures and components are considered ‘non-NRC decommissioning costs’ and hence not factored into the decommissioning fund formulas (NRC 1999). The NRC minimum decommissioning cost estimate ranges between $393 million to $1 billion with an average of $522 million per reactor (Holian 2018).

Table 1: Minimum decommissioning fund formula

Reactor type	Thermal Capacity (TC)	Cost (millions USD 2020)
Pressurized Water Reactor (PWR)	≥ 3400 MW$_t$	$247.9 million
	1200 MW$_t \leq$ TC $<$ 3400 MW$_t$ TC = 1200 MW$_t$ if TC $<$ 1200 MW$_t$	$(177.1+0.02*TC*) million
Boiling Water Reactor (BWR)	≥ 3400 MW$_t$	$318.8 million
	1200 MW$_t \leq$ TC $<$ 3400 MW$_t$ TC = 1200 MW$_t$ if TC $<$ 1200 MW$_t$	$(245.6 +0.02*TC*) million
Adjustment equation	0.65L+0.13E+0.22B Where L, E and B refer to escalation factors for labor, energy and low-level waste (LLW) burial.	

Notes: MW$_t$ = Megawatt thermal

Source: 10 CFR 50.75(C).

Site specific cost estimate (SSCE)

SSCE are detailed cost estimates developed by licensees in fulfillment of two key regulatory requirements[19]. Typically, SSCE are either developed by the licensee themselves or outsourced to a decommissioning planning company. Most licensees opt to outsource the development of decommissioning cost assessments to a specialized company (Short et al. 2011). Two companies are engaged in this field. TLG Services, Inc is arguably the largest and most experienced provider of decommissioning cost estimates. The Entergy-owned company has developed decommissioning cost estimates for approximately 85-90% of U.S. commercial nuclear reactors (Goff 2000). Energy*Solutions*, a decommissioning specialist company, developed a smaller fraction of decommissioning cost estimates. SSCE elements are classified into three cost categories;

1. **License Termination/Radiological decommissioning:** Comprised of activities required to dismantle and dispose of all contaminated structures. These costs are sufficient to terminate the plant's 10 CFR Part 50 license.
2. **Spent fuel management:** Comprised of costs associated with the transfer of spent fuel from the spent fuel pool to an ISFSI and from the ISFSI to a DOE permanent geological repository. Costs associated with the temporary management of the ISFSI until eventual handover to the DOE are also factored into the management costs.
3. **Site restoration:** Constitutes costs that are associated with the dismantling and demolition of structures and buildings not exposed to radiological contamination.

Table 2 provides a breakdown of the SSCE costs elements developed by TLG Services.

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[19] (1) A preliminary decommissioning cost estimate is required as the nuclear plant approaches within five years of shutdown (10 CFR Part 50.75(F)(3)). (2) The licensee is required to submit a site-specific decommissioning cost estimate prior to or within two years following plant shutdown (10 CFR Part 50.82(a)(4)(i)).

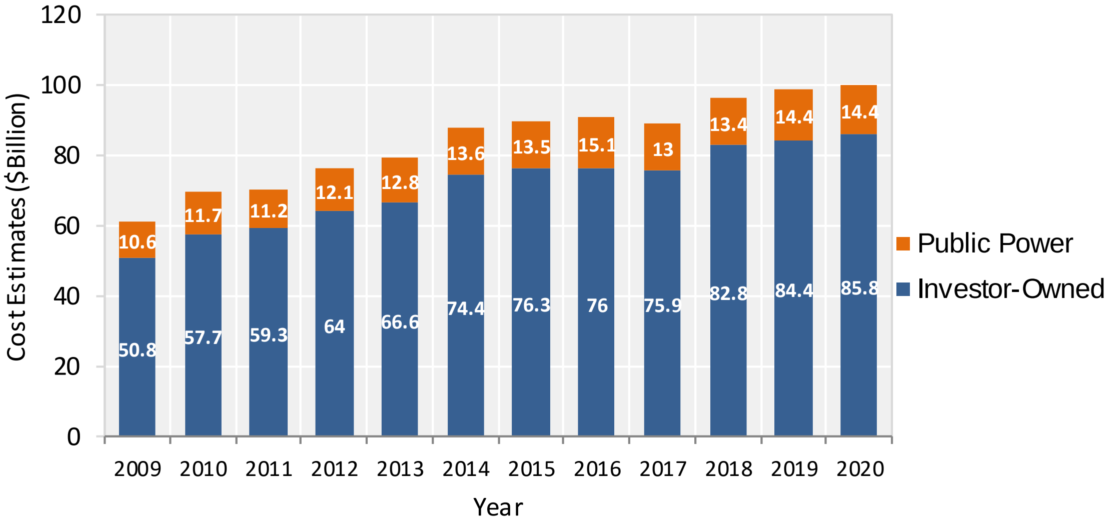
Table 2: TLG Services site specific decommissioning cost estimate breakdown

Core activity	Cost element	Cost category
(1) License Termination /Radiological Decommissioning 10 CFR 50.75	Decontamination Removal Packaging Transportation Waste Disposal Waste processing Spent fuel pool isolation Miscellaneous equipment	**Direct Costs**
	Program management Spent fuel management (non 10 CFR 50.54(bb) activities) Site operations and management	**Management Costs**
	Insurance and regulatory Energy Characterization and licensing Property taxes	**Other costs**
(2) Spent Fuel Management 10 CFR 50.54(bb)	Spent fuel storage and management Insurance and regulatory Property tax Program management	
(3) Site Restoration	Decontamination Program management Insurance and regulatory Site remediation/restoration	

Source: (Short et al. 2011).

Figure 9 illustrates historical SSCE for investor-owned and publicly owned NPPs in the U.S. Over the past decade, decommissioning cost estimates have risen by approximately 60% from $61.5 billion in 2009 to approximately $100 billion in 2020 (Moriarty 2021). Investor-owned estimates have accounted for an average of 84% of total decommissioning estimates over the past decade. The rise in decommissioning cost estimates over time can be attributed to Low-Level Waste (LLW) and spent fuel management costs (Short et al. 2011; Laraia 2012).

Figure 9: Nuclear reactor decommissioning cost estimates



Source: own depiction based on data from (Moriarty 2021).

4.3 Cost experience and accuracy of assessments

A total of 17 nuclear reactors[20] have completed decommissioning in the U.S. The final decommissioning costs, however, vary across the plants, and the estimated costs for these plants have generally underestimated the actual decommissioning costs to various degrees. Table 3 compares the minimum decommissioning cost estimate to actual decommissioning costs for five decommissioned reactors. Four of the five reactors experienced decommissioning cost overruns to various degrees, signifying that the NRC minimum decommissioning cost formula is underestimating true decommissioning costs (Short et al. 2011).

Decommissioning costs for the Trojan reactor remained closely aligned to estimated decommissioning costs. This is because decommissioning completed without any major radiological remediation issues which allowed the licensee, Portland General Electric (PGE) to keep decommissioning costs low (Short et al. 2011). Another reason for the low decommissioning costs was the decision to remove the reactor vessel and internal components in one-piece. Total estimated waste

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[20] Out of the 17 decommissioned reactors, 14 were commercial reactors, two reactors were experimental reactors (CVTR, Pathfinder) and Saxton was a research and training facility. Refer to Appendix C for additional details on decommissioned reactors.

volumes from the one-price removal were within the Class C waste category, which permitted PGE to classify the vessel as a low-level waste and dispose it in a low-level waste facility. The one-piece removal option was estimated to cost $23.8 million in 1996 dollars ($39.3 million in 2020 dollars), approximately $15 million less than the segmented approach (Wallis 2000). In contrast, decommissioning costs of the Haddam Neck reactor far exceeded estimated costs. Several factors contributed to the cost overruns including, reverting from a decommissioning contractor to self-management[21], costs of constructing an ISFSI and the complexity of segmenting the reactor vessel internals (Short et al. 2011). The Humboldt Bay reactor took 12 years to decommission and experienced significant cost overruns, primarily due to complicated remediation works and unplanned removal of the entire reactor caisson[22] (CPUC 2014). Note that the estimates in Table 3 are based on costs estimates for radiological decommissioning as defined in the NRC regulations. Other researchers incorporate estimates from the SSCE and therefore arrive at different decommissioning cost overruns (Lordan-Perret et al. 2022).

Table 3: Comparison of decommissioning cost estimates for selected NPPs (million USD, 2020)

Plant	Reactor type [Net capacity MW]	Operational years	Decommissioning duration (years)	Minimum decommissioning cost estimate	Actual decommissioning cost	Cost difference %
Haddam Neck	PWR [560]	1967-1996	1997-2007 (10)	491.38	1,090.17	121.86%
Maine Yankee	PWR [860]	1972-1997	1997-2005 (8)	532.92	618.61	16%
Rancho Seco	PWR [873]	1974-1989	1997-2009 (12)	533.6	608.17	14%
Trojan	PWR [1,095]	1975-1992	1993-2005 (12)	349.4	334.76	-5%
Humboldt Bay	BWR [63]	1963-1976	2009-2021 (12)	470.13	797.32	70%

Notes: Decommissioning duration recorded from the year actual decommissioning works started. Values for minimum decommissioning cost and actual decommissioning cost represents only radiological decommissioning and does not include spent fuel management cost. All values were adjusted to 2020 dollars.
Source: (Short et al. 2011; PG&E 2019).

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[21] Initially, Connecticut Yankee Atomic Power Company (CYAPCO) planned to oversee the decommissioning of Haddam Neck following shutdown in 1996. In 1999, CYAPCO contracted Bechtel Power Corporation to oversee the decommissioning operations on a fixed price contract (Short et al. 2011). Four years later, in 2003, CYAPCO decided to terminate the contract and oversee the remaining decommissioning activities.

[22] The Humboldt Bay reactor was encased in concrete and buried 80 feet underground. The owner PG&E initially planned to leave the reactor in place, but the discovery of contamination on the reactor bioshield wall forced PG&E to remove the caisson structure costing $191.6 million in 2012 dollars ($216 million in 2020 dollars) (CPUC 2014).

Several studies have reviewed the NRC's minimum decommissioning funding formula and recommended that the formula needs to be revised, yet it remains unchanged. An audit conducted by the U.S. Office of the Inspector General (OIG) in 2016 recommended that the minimum decommissioning cost estimate be reevaluated given that the formula was based on outdated values and most licensees rely on site-specific cost estimates (OIG 2016). The report further claimed that the current unchanged formula may not provide a realistic estimate of decommissioning costs. Another audit report found that site-specific decommissioning costs were typically higher than the NRC formula and recommended an update of the formula taking into account the relationship between formula based and site-specific estimates (OIG 2006).

4.4 Current balance in individual decommissioning funds

The latest review of the Decommissioning Fund Status (DFS) reports published by the NRC in December 2021 covers a total of 95 operating reactors[23] and 24 reactors undergoing decommissioning. The total Decommissioning Trust Fund (DTF) balance accumulated for operating nuclear reactors stands at $71.1 billion, an increase of approximately $14.6 billion from the 2019 DFS review (Lubinski 2021). All operating reactors met the minimum decommissioning funding requirements and no shortfalls were identified. For plants undergoing decommissioning, total accumulated decommissioning funds from 22 reactors stands at $12.3 billion (Lubinski 2021) and is documented in Table 4. Likewise, all reactors undergoing decommissioning met the decommissioning financial requirements by either having sufficient funds or providing additional financial provisions (Lubinski 2021).

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[23] Three reactors have retired since then.

Table 4: Decommissioning fund balance for reactors undergoing decommissioning (million USD, 2020)

Plant Name	Operational duration	Estimated year of completion of decommissioning	DTF Balance (as of 2020)	Estimated remaining cost to complete decommissioning
Crystal River-3	1977-2013	2026	635.90	450.17
Dresden-1	1960-1978	2036	421.08	458.96
Duarne Arnold	1974-2020	2036	632.82	705.44
Fermi-1	1966-1972	2032	38.00	24.00
Fort Calhoun	1973-2016	2026	542.09	590.96
Humboldt Bay-3	1963-1976	2021	170.10	4.00
Indian Point-1	1962-1974	2026	631.25	606.15
Kewaunee	1974-2013	2073	780.40	561.30
LaCrosse	1968-1987	2022	60,000	60,000
Millstone-1	1970-1998	2056	697.50	370.70
Oyster Creek	1969-2018	2025	713.00	615.00
Peach Bottom-1	1967-1974	2034	148.82	276.85
Pilgrim	1972-2019	2025	881.00	824.00
San Onofre-1	1967-1992	2028	468.50	184.30
San Onofre -2	1982-2013	2028	1,596.10	1,402.60
San Onofre-3	1983-2013	2028	1,894.10	1,641.20
Three Mile Island-1	1974-2019	2079	742.50	955.10
Three Mile Island-2	1978-1979	2037	862.55	1,044.36
GE Vallecitos	1957-1963	2025	15.58	15.58
Vermont Yankee	1972-2014	2030	388.03	348.32
Zion-1	1973-1998	2022		
Zion-2	1973-1998	2022	3.20 (both units)	3.00 (both units)
Total			**$12,262.57**	**$11,082.06**

Note: Zion 1 and 2 units completed decommissioning in 2020 and are awaiting final release from regulatory controls. Nuclear Savannah Ship and General Electric ESADA Vallecitos Experimental Superheat Reactor (GE EVESR) are omitted from the list.
Source: (Lubinski 2021).

5. Production

5.1 Overview

On a global scale, the U.S. has the largest operating reactor fleet (92), closed reactors (41) and the most decommissioning experience with 17 reactors fully decommissioned (9 PWR, 6 BWR, 1 HTGR & 1 PHWR). Out of the 17 decommissioned reactors, two were experimental reactors (CVTR, Pathfinder) and one was a research and training facility (Saxton). The remaining 14 were commercial reactors. Active decommissioning is currently ongoing at 11 reactors and 13 reactors are in long-term enclosure (i.e., SAFSTOR). Table 5 provides an overview of the current decommissioning status of nuclear plants in the U.S. Refer to Appendix B and C for information on reactors undergoing decommissioning and decommissioned reactors respectively. The following section provides an overview on the current progress in decommissioning and companies engaged in decommissioning.

5.2 Progress

As of 2022, the most recent reactors to complete decommissioning are the Zion 1 and 2 reactors. Official decommissioning works began in September 2010, approximately 13 and 14 years after official shutdown respectively. In 2015, all spent nuclear fuel were transferred from the spent fuel pool to 61 dry cask storage containers on site. The decommissioning operator, Zion*Solutions* opted to segment the reactor vessel internals underwater and subsequently section the reactor vessel (Hylko 2014). The reactor vessel components were then shipped to the Clive disposal facility in Utah. Physical cleanup works were completed in 2020, eight years behind the original plan. In August 2021, the NRC issued an order approving a one-year extension to transfer the operating license of both units back to Exelon Generation, the original license holder, thereby delaying the full release of the reactors from regulatory control (Nuclear Engineering 2021).

The completion of the Zion reactors closely follows the decommissioning of Humboldt Bay, a one-reactor unit 63 MW BWR plant located in Eureka, California. The plant officially shut down in 1976 after 13 years of service and was subsequently placed in SAFSTOR by its owner Pacific Gas and Electric Company (PG&E). Decommissioning activities commenced in June 2009 and concluded 12 years later in in July 2021. In November 2021, the NRC terminated the operating license of Humboldt Bay and released the site for unrestricted use (NRC 2021d). The ISFSI site was licensed separately and therefore remains active until the spent fuel is removed and the site decommissioned. Total cost for radiological decommissioning is estimated to be $797 million (PG&E 2019).

Decommissioning experience varies significantly across the decommissioned reactors in terms of both time horizons and cost. The plant with the shortest decommissioning period so far was a relatively small reactor, Shippingport (60 MW), which took 4 years to decommission at an estimated cost[24] of $28.7 million in 1990 dollars ($56.83 million in 2020 dollars) (GAO 1990). In contrast, the LaCrosse reactor was placed in SAFSTOR for an extended duration following shutdown in 1987 and completed decommissioning in 2019. Total cost for radiological decommissioning was estimated to be $83.3 million in 2020 dollars (LaCrosseSolutions 2021). These dramatic differences—and those anticipated in the future—could result from any host of sources, for example: technology difference; plant operations and record keeping; project management; essential equipment and resource bottlenecks.

In May 2022, Entergy permanently closed Palisades, a single reactor unit located in Michigan. The operator decided to bring forward the closure date due to deterioration of a control rod drive seal. Shortly following the closure of the plant, in June 2022, Entergy finalized the transaction[25] to transfer both the operating and general ISFSI license of Palisades unit to Holtec Decommissioning International (HDI) for the purpose of decommissioning the facility (Holtec International 2022). Holtec proposed an expedited 20-year timeframe to complete the decommissioning project once the reactor fuel has been transferred from the spent fuel pool to ISFSI. The closure of the Palisades reactor closely follows the retirement of Entergy owned Indian Point 3 reactor in April 2021. In May 2021, Entergy finalized the sale of all three shutdown Indian Point units to Holtec for decommissioning. The sale agreement includes the transfer of operating licenses, spent fuel, liabilities and the DTF's (Entergy 2019; 2021). Over the past years, Entergy has gradually sold off or retired its merchant nuclear plant fleet as part of a strategy to withdraw from the merchant nuclear generation sector. The closure of Palisades and Indian Point completes Entergy's complete exit from the commercial nuclear market. Entergy now fully owns and operates four reactors (Arkansas 1 & 2, River Bend 1 and Waterford 3) and is a majority owner of the Grand Gulf 1 reactor. These remaining reactors are all rate regulated.

Table 5: Current status of decommissioning in the United States as of June 2022

United States	June 2022
Warm-up-stage	7
of which defueled	*7*
Hot-zone-stage	3
Ease-off-stage	1
LTE	13
Completed	17
of which released from regulatory control	*6*
Total Closed Reactors	**41**

Notes: LTE: Long term enclosure
Source: (Schneider et al. 2022)

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[24] Only for radiological decommissioning.

[25] The NRC ratified the agreement in December 2021. The agreement also includes the transfer of the decommissioned Big Rock Point's ISFSI to Holtec (NRC 2021b).

5.3 Actors involved in the decommissioning process

In the U.S., nuclear licensees are increasingly gravitating towards an asset sale decommissioning model, whereby the licensee engages with a specialized decommissioning company to take over the facility and complete the decommissioning of the plant. Currently, there are three variations on outsourcing decommissioning: License Stewardship, License Acquisition, and Fleet Models.[26]

License Stewardship involves a license transfer from the licensee holder to the decommissioning firm. Under this arrangement, the decommissioning firm undertakes all the responsibility for decommissioning such that the original licensee can be released from its 10 CFR part 50 license—at least that the license would be reduced to an ISFSI. The firm also gains full access to the DTF and assumes all liability for cost overruns. Once the decommissioning work is completed, the decommissioning firm returns the remaining assets to the original licensee. The decommissioning firm never takes possession of the fuel or the site.

License Acquisition enables the decommissioning firm to take ownership of all the plant assets (e.g., DTF and land) and liabilities—including the spent nuclear fuel. Thus, the original licensee effectively discharges its decommissioning liability in total, though some legal instruments may, in some aberrant circumstances, still require the original licensee to bear some responsibility in case of unfunded decommissioning liability (Lordan-Perret, Sloan, and Rosner 2021).

Finally, Fleet Models[27] are a financial arrangement whereby a financial company manages the DTFs of a fleet of plants. The idea is that through prudent investments and economies of scale, such a company stands to gain a lot from pooling the risk of shortfalls and cost savings over multiple plants. In such a model, this financial company would also be liable for unfunded decommissioning liabilities.

In theory, by outsourcing with one of these models, licensees can be rid of a large liability and decommissioning can be accomplished much faster and more cost-effectively that if it were undertaken by the owner itself. A brief overview of a few major decommissioning specialist companies and their current decommissioning activities is provided below.

Energy*Solutions* is arguably one of the largest specialized nuclear services company operating both domestically and internationally. The Utah-based firm provides a wide range of services spanning the entire decommissioning spectrum, from transition activities to major decommissioning activities and license termination services. Energy*Solutions* leverages its extensive physical assets and facilities for waste transfer, processing and disposal. The company owns the Clive disposal facility in Utah and operates the Barnwell disposal facility in South Carolina. The company follows the license stewardship decommissioning model. Energy*Solutions* has provided support for decommissioning projects at Fort St Vrain, Trojan, Haddam Neck, Maine Yankee and Yankee Rowe (Schneider et al. 2020). The

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[26] It is important to note that individual contracts will vary.

[27] The NRC has not approved this model yet.

company through its subsidiary LaCrosse*Solutions* has recently decommissioned the 50 MW LaCrosse reactor located in Genoa, Wisconsin. Energy*Solutions* undertook the decommissioning project in May 2016 under a license stewardship structure from Dairlyland Power Cooperative (DPC) and announced the completion of physical dismantling works in November 2019. In addition, the company also completed decommissioning works at Zion 1 and 2 reactors as elaborated above. In March 2022, the NRC approved the transfer of the 566 MW single reactor Kewaunee nuclear plant's license from its current owner Dominion Energy to Energy*Solutions* for decommissioning (NRC 2022c). The license transfer also includes the ISFSI site. The company is currently overseeing decommissioning projects at the Three Mile Island (TMI) unit 2 reactor and the Fort Calhoun nuclear plant in Nebraska. The company is also providing technical support for the ongoing decommissioning of Fort Calhoun reactor as a decommissioning contractor (WNN 2019).

Another company actively engaged in the decommissioning scene is **Holtec International** and its wholly owned subsidiary company **Holtec Decommissioning International (HDI)**. Holtec is a versatile energy technology company that manufactures and sells wet and dry storage technologies to nuclear plants domestically as well as globally. On the decommissioning front, Comprehensive Decommissioning International (CDI), a joint venture between Holtec and SNC-Lavelin is the general decommissioning contractor for Holtec. The company has not completed any decommissioning projects to date, but it is involved in four ongoing decommissioning projects at several NPPs such as Oyster Creek, Pilgrim, Indian Point and recently Palisades. For its decommissioning portfolio, Holtec is relying on a fleet model[28], whereby standardized processes and procedures are adopted at both the corporate level and decommissioning sites (Reuters 2019). In March 2017, Holtec and Eddy-Lea Energy Alliance (ELEA) submitted a license application to the NRC for an autonomous consolidated interim storage facility (CISF) in Southeast New Mexico. The facility known as HI-STORE CIS will accommodate 500 Holtec manufactured underground dry cask storage casks and operate for a 40-year duration (Holtec International 2017). The license application remains under review and a final decision is expected in January 2023.

A relatively new entrant into the decommissioning domain is the New York based **NorthStar Group Services (NorthStar)**. To date, the company's nuclear decommissioning experience is only limited to research reactors. In February 2017, the company submitted a joint license transfer application with Entergy to the NRC for expedited decommissioning of the Vermont Yankee Nuclear Power Station. The transfer included the nuclear DTF and spent fuel storage installation and was approved by the NRC in October 2018 (NRC 2019c). As part of the agreement, decommissioning activities should be completed by 2030. The company has also acquired the Crystal River-3 plant as a

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[28] This approach merely describes Holtec's organizational approach to decommission the fleet and differs from the outsourcing fleet model described earlier. Holtec is closely aligned with the license acquisition decommissioning strategy.

licensed decommissioning operator through its joint venture subsidiary (Accelerated Decommissioning Partners) in April 2020. The reactor is currently in the warm-up stage and Accelerated Decommissioning aims to complete decommissioning by 2027, 50 years earlier than the original decommissioning plan (WNN 2020).

In total, out of the 24 reactors currently undergoing decommissioning, 10 units were transferred to specialized decommissioning companies (see Appendix B).

6. Country specific nuclear and decommissioning developments

As more nuclear plants are expected to shut down over the coming years, the focus inevitably turns towards the management of nuclear waste and spent nuclear fuel. Presently, spent nuclear fuel is stored on site at ISFSI facilities since the US has no permanent geological repository for nuclear waste. In 2019, the House and Senate put forward the Nuclear Waste Policy Amendments Act of 2019 (H.R. 2699) which directs the DOE to commence a consolidated interim nuclear waste storage program alongside the development of a permanent repository (Larson 2020). However, plans to revive the Yucca mountain permanent geological repository has stalled and is unlikely to continue given recent developments. In particular, the Biden administration has signaled its opposition to the Yucca mountain plan and is instead pursuing the idea a consent-based citing of a federal CISF (Fettus and McKinzie 2021; DOE 2022a). In September 2022, the DOE launched a $16 million fund to spur community interest in nuclear waste management and consent-based siting of a federal CISF. Furthermore, in the same month, the State of Nevada formally requested the NRC to lift the Yucca Mountain license review suspension[29] with the aim of permanently blocking the project (Sanchez 2022).

In parallel to developments at the federal level, two private companies have submitted license applications to develop commercial CISF's. In 2016, Interim Storage Partners (ISP) LLC[30] submitted a license application for a CISF at Andrews County in Texas. The facility will be built in stages and initially store up to 5,000 metric tons of spent fuel and 231.3 metric tons of Greater than Class C (GTCC) low-level radioactive waste (NRC 2021c). In September 2021, the NRC approved ISP's application and granted a 40-years license to the proposed facility. The company expects to begin receiving the first batch of spent nuclear waste by July 2023 (ISP 2020). As elaborated earlier, as recently as 2017, Holtec International also applied for a license for a CISF in Lea County in New Mexico. The application remains under review (NRC 2018a).

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[29] The NRC suspended the Yucca mountain license review process in September 2011, roughly three years after initiating it in October 2008.

[30] Interim Storage Partners, LLC is a joint venture between Waste Control Specialists (WCS) and Orano CIS, LLC. Orano CIS is the majority owner of Interim Storage Partners (51%) and is wholly owned by Orano USA LLC.

Appendix

Appendix A: Commercial operating reactors in the U.S. as of July 2022

Reactor Name	Type	Capacity (MWe)	Grid Connection	Age (2022)	License expiry
Arkansas Nuclear One-1	PWR	836	1974	48	2034
Arkansas Nuclear One- 2	PWR	988	1978	44	2038
Beaver Valley-1	PWR	908	1976	46	2036
Beaver Valley-2	PWR	905	1987	35	2047
Braidwood-1	PWR	1194	1987	35	2046
Braidwood-2	PWR	1160	1988	34	2047
Browns Ferry-1	BWR	1200	1973	49	2033
Browns Ferry-2	BWR	1200	1974	48	2034
Browns Ferry-3	BWR	1210	1976	46	2036
Brunswick-1	BWR	938	1976	46	2036
Brunswick-2	BWR	932	1975	47	2034
Byron-1	PWR	1164	1985	37	2044
Byron-2	PWR	1136	1987	35	2046
Callaway-1	PWR	1215	1984	38	2044
Calvert Cliffs-1	PWR	877	1975	47	2034
Calvert Cliffs-2	PWR	855	1976	46	2036
Catawba-1	PWR	1160	1985	37	2043
Catawba-2	PWR	1150	1986	36	2043
Clinton-1	BWR	1062	1987	35	2026
Columbia	BWR	1131	1984	38	2043
Commanche-Peak-1	PWR	1205	1990	32	2030
Commanche-Peak-2	PWR	1195	1993	29	2033
Cook-1	PWR	1030	1975	47	2034
Cook-2	PWR	1168	1978	44	2037
Cooper	BWR	769	1974	48	2034
Davis-Besse-1	PWR	894	1977	45	2037
Diablo Canyon-1	PWR	1138	1984	38	2024
Diablo Canyon-2	PWR	1118	1985	37	2025
Dresden-2	BWR	894	1970	52	2029
Dresden-3	BWR	879	1971	51	2031
Farley-1	PWR	874	1977	45	2037
Farley-2	PWR	883	1981	41	2041
Fermi-2	BWR	1115	1986	36	2045
Fitzpatrick	BWR	813	1975	47	2034
Ginna	PWR	560	1969	53	2029
Grand Gulf-1	BWR	1401	1984	38	2044
Harris-1	PWR	964	1987	35	2046
Hatch-1	BWR	876	1974	48	2034
Hatch-2	BWR	883	1978	44	2038
Hope Creek-1	BWR	1172	1986	36	2046
Lasalle-1	BWR	1137	1982	40	2042
Lasalle-2	BWR	1140	1984	38	2043
Limerick-1	BWR	1134	1985	37	2044
Limerick-2	BWR	1134	1989	33	2049
Mcguire-1	PWR	1158	1981	41	2041

Mcguire-2	PWR	1158	1983	39	2043
Millstone-2	PWR	869	1975	47	2035
Millstone-3	PWR	1210	1986	36	2045
Nine Mile Point-1	BWR	613	1969	53	2029
Nine Mile Point-2	BWR	1277	1987	35	2046
Monticello	BWR	628	1971	51	2030
North Anna-1	PWR	948	1978	44	2038
North Anna-2	PWR	944	1980	42	2040
Oconee-1	PWR	847	1973	49	2033
Oconee-2	PWR	848	1973	49	2033
Oconee-3	PWR	859	1974	48	2034
Palo Verde-1	PWR	1311	1985	37	2045
Palo Verde-2	PWR	1314	1986	36	2046
Palo Verde-3	PWR	1312	1987	35	2047
Peach Bottom-2	BWR	1300	1974	48	2053
Peach Bottom-3	BWR	1331	1974	48	2054
Perry-1	BWR	1240	1986	36	2026
Point Beach-1	PWR	591	1970	52	2030
Point Beach-2	PWR	591	1972	50	2033
Prairie Island-1	PWR	522	1973	49	2033
Prairie Island-2	PWR	519	1974	48	2034
Quad Cities-1	BWR	908	1972	50	2032
Quad Cities-2	BWR	911	1972	50	2032
River Bend-1	BWR	967	1985	37	2045
Robinson-2	PWR	741	1970	52	2030
Salem-1	PWR	1169	1976	46	2036
Salem-2	PWR	1158	1981	41	2040
Seabrook-1	PWR	1246	1990	32	2050
Sequoyah-1	PWR	1152	1980	42	2040
Sequoyah-2	PWR	1139	1981	41	2041
South-Texas-1	PWR	1280	1988	34	2047
South-Texas-2	PWR	1280	1989	33	2048
St. Lucie-1	PWR	981	1976	46	2036
St. Lucie-2	PWR	987	1983	39	2043
Summer-1	PWR	973	1982	40	2042
Surrey-1	PWR	838	1972	50	2052
Surrey-2	PWR	838	1973	49	2053
Susquehanna-1	BWR	1257	1982	40	2042
Susquehanna-2	BWR	1257	1984	38	2044
Turkey Point-3	PWR	837	1972	50	2052
Turkey Point-4	PWR	821	1973	49	2053
Vogtle-1	PWR	1150	1987	35	2047
Vogtle-2	PWR	1152	1989	33	2049
Waterford-3	PWR	1168	1985	37	2044
Watts Bar-1	PWR	1157	1996	26	2035
Watts Bar-2	PWR	1164	2016	6	2055
Wolf Creek	PWR	1200	1985	37	2045
		Total: 94,718 (94.72 GW)		**Average**: 41.6	

Source: (NRC 2021a; IAEA 2022).

Appendix B: Reactors undergoing decommissioning as of June 2022

Reactor	Net Capacity in MW	Reactor Type	Grid Connection Year	Shutdown year	Operating Years	Defueled	Decommissioning licensee
Warm-up stage							
Crystal River-3	860	PWR	1977	2009	32	yes	Northstar/Orano
San Onofre-2	1,070	PWR	1982	2012	30	yes	Southern California Edison Co.
San Onofre-3	1,080	PWR	1983	2012	29	yes	Southern California Edison Co.
Kewaunee	566	PWR	1974	2013	39	yes	Energy*Solutions*
Vermont Yankee	605	BWR	1972	2014	42	yes	NorthStar/Orano
Indian Point-2	998	PWR	1973	2020	47	yes	Holtec (HDI)
Indian Point-3	1030	PWR	1976	2021	45	yes	Holtec (HDI)
Hot zone stage							
Fort Calhoun-1	482	PWR	1973	2016	43	yes	Omaha Public Power District
Oyster Creek	619	BWR	1969	2018	49	yes	Holtec (HDI)
Pilgrim-1	677	BWR	1972	2019	47	yes	Holtec (HDI)
Ease-off stage							
San Onofre-1	436	PWR	1967	1992	25	yes	Southern California Edison Co.
Long Term Enclosure							
GE Vallecitos	24	BWR	1957	1963	6	yes	GE-Hitachi Nuclear Energy Americas, LLC
Hallam	75	Other	1963	1964	1	yes	Department of Energy (DOE)
Piqua	12	Other	1963	1966	3	yes	DOE
Bonus	17	BWR	1964	1968	4	yes	Puerto Rico Water Resources Authority
Fermi-1	61	FBR	1966	1972	6	yes	DTE Electric Company
Indian Point-1	257	PWR	1962	1974	12	yes	Holtec (HDI)
Peach Bottom-1	40	HTGR	1967	1974	7	yes	Exelon
Dresden-1	197	BWR	1960	1978	18	yes	Constellation Energy Generation, LLC
Three Mile Island-2	880	PWR	1978	1979	1	yes	TMI-2 *Solutions* (Energy*Solutions*)
Millstone-1	641	BWR	1970	1995	25	yes	Dominion Energy Nuclear Connecticut, Inc
Three Mile Island-1	819	PWR	1974	2019	45	yes	Constellation Energy Generation, LLC
Daurne Arnold	601	BWR	1974	2020	46	yes	NEDA
Palisades	805	PWR	1971	2022	51	yes	Holtec (HDI)

Notes: HDI: Holtec Decommissioning International; NEDA, NextEra Energy Duarne Arnold, LLC
Source: (NRC 2021a; Schneider et al. 2022)

Appendix C: Decommissioned Reactors

Reactor	Net Capacity in MW	Reactor type	Operational duration	Decommissioning duration (years)	License Status
CVTR	17	PHWR	1963-1967	1967-2009 (42)	Terminated
Pathfinder	59	BWR	1966-1967	1968-1993 (25)	Terminated
Elk River	22	BWR	1963-1968	1971-1974 (3)	Terminated
Saxton	3	PWR	1967-1972	1996-2005 (9)	Terminated
Shippingport	60	PWR	1957-1982	1985-1989 (4)	Terminated*
Shoreham	820	BWR	1986-1989	1992-1994 (2)	Terminated
Fort St. Vrain	330	HTGR	1976-1989	1989-1997 (8)	ISFSI only
Rancho Seco-1	873	PWR	1974-1989	1997-2009 (12)	ISFSI only
Yankee NPS (Yankee Rowe)	167	PWR	1960-1991	1993-2007 (14)	ISFSI only
Trojan	1,095	PWR	1975-1992	1993-2005 (12)	ISFSI only
Maine Yankee	860	PWR	1972-1997	1997-2005 (8)	ISFSI only
Haddam Neck	560	PWR	1967-1996	1996-2007 (11)	ISFSI only
Big Rock Point	67	BWR	1962-1997	1997-2006 (9)	ISFSI only
LaCrosse	48	BWR	1968-1987	1994-2019 (25)	Pending
Humboldt Bay	63	BWR	1963-1976	2009-2021 (12)	ISFSI only
Zion 1	1,040	PWR	1973-1998	2007-2020 (13)	Pending
Zion 2	1,040	PWR	1974-1998	2007-2020 (13)	Pending
	Total: 7,124 (7.12 GW)				

Notes: *DOE regulatory jurisdiction. Decommissioning duration recorded from the year actual decommissioning works started.
Source: (OECD/NEA 2016a; Wealer and Hirschhausen 2020; NRC 2021a).

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