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An Ex-Ante Method to Verify Commercial U.S. Nuclear Power Plant Decommissioning Cost Estimates

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Abstract

There are billions of dollars at stake in the US nuclear power plant decommissioning market. Approximately 100 nuclear power plants are still operating but will come offline and need to be decommissioned over the next few decades. The Nuclear Regulatory Commission (NRC) mandates that the operators of these plants set money aside in segregated funds to finance decommissioning work. However, it is hard for external stakeholders to verify the cost estimations, which ultimately determine how much operators are required to save. In this paper, we develop a method to validate the existing cost models and calculate a contingency empirically for these models. We extend Reference Class Forecasting methods using adaptive kernel fitting and the Wilks' formula. Based on this method, and assuming a social tolerance for potential cost overruns of 20%, we calculate a new contingency of 48% of the estimated radiological decommissioning cost. After a "stress test" of the current decommissioning trust funds of operating reactor sites, we find that 48% of reactors have sufficient funding—in many cases substantially more than required—and could therefore finance the potential scale of overrun. However, we find that 28 plants would fall short on average $211 million. Still, overruns at every plant are not a foregone conclusion because—while overruns are probable, based on past experience—the actual scale and frequency is not known. Nevertheless, our results add further evidence to the mounting call for the NRC to revise its cost models in light of new information.

Keywords

nuclear power; decommissioning; cost estimation; contingency; Wilks' formula; reference class forecasting

1 Introduction

Over the next few decades, hundreds of nuclear power plants across the world will need to be decommissioned. Many of these plants were built in the 1980s and 1990s, and thus, they are reaching the end of their operational lifetimes.[1] Decommissioning is a costly process required to remove and dispose of all the radiological contamination and activated materials arising from plant operations

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[1] While regulations vary from country to country, a typical operating lifetime is 40 years.

(e.g., disposing of the reactor internals and pressure vessel, decontaminating walls, etc.), to dismantle the existing infrastructure, and to restore the site such that it is suitable to be used for other purposes.

Over the lifetime of the nuclear power plant, the owner-operators must estimate the costs of decommissioning regularly, both in order to plan decommissioning and to accumulate the necessary funds to finance decommissioning activities in a timely fashion once the plant shuts down. The estimated cost for decommissioning a single-unit nuclear power plant in the US ranges from \$400m to \$1b. The International decommissioning market—for commercial reactors alone (i.e., excluding research reactors, military, medical, etc)—is expected to reach a quarter of a trillion dollars [21]. In the United States billions of dollars are at play with approximately 100 reactors preparing to retire in the next few decades.

Naturally, external stakeholders—such as the NRC—want to ensure that nuclear power plant owner-operators are accurately estimating costs and setting aside enough money to complete decommissioning. These external stakeholders are tasked not only with guaranteeing public safety but also with ensuring that the decommissioning activities are funded by the plant owner-operators themselves rather than allowing the financial burden to be shifted to someone else, such as the government or taxpayers [e.g., 28].

Indeed, inaccurate cost estimates could have significant economic impacts on both owner-operators and external stakeholders. Owner-operators could face financial insolvency and reputation problems, while external stakeholders could become responsible for "legacy sites" with un-financed decommissioning liabilities. Still, owner-operators and external stakeholders alike face barriers in credibly verifying cost estimates, including a lack of experience and information; difficulty applying experience due to project and regulatory differences; unwillingness to share proprietary data; and differences across estimating approaches [13]. But perhaps most importantly, this industry faces a great deal of uncertainty. Nevertheless—in one way or another—all stakeholders place significant weight on these estimations being accurate.

Around the world, countries with nuclear power plants use different methods to estimate the costs of decommissioning and to assure that sufficient funding will be available when decommissioning begins [for a comprehensive overview see 13]. In the United States, the NRC requires that a nuclear power plant owner set aside funds according to a generic cost model that relates plant details to radiological decommissioning costs (Table 1). These cost models calculate a *minimum* standard of funding and include a 25% contingency. However, multiple studies have shown that this minimum standard—even with a 25% contingency—may not be sufficient [e.g., 28] and that adjustments could be made to the model assumptions in light of more experience [40].

Reactor Type	**Thermal Capacity (MW_t)**	**Cost Model (Millions 2019 USD\$)**
Pressurized Water Reactor (PWR)	≤ 3400	\$245.7
	$1200 \leq TC < 3400$, $TC = 1200$ if $TC < 1200$	\$ $(175.5 + 0.021\ TC)$
Boiling Water Reactor (BWR)	≥ 3400	\$315.9
	$1200 \leq TC < 3400$, $TC = 1200$ if $TC < 1200$	\$ $(243.36 + 0.0211\ TC)$

Table 1: Minimum financial assurance models created by Pacific Northwest National Laboratory (PNNL). In the equations, TC stands for Thermal Capacity measured in Megawatts (MW_t) (10 CFR 50.75).

Even when using site-specific estimates,[2] cost overruns[3] have occurred at many of the 10 fully decommissioned commercial sites in the

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[2] Site-specific estimates are detailed, itemized project plans to develop cost estimates that use, for example, the unit-cost method. To use this method, those estimating the costs (e.g., consultants or the nuclear power plant owners themselves) construct a work breakdown structure (WBS) for the decommissioning project. In a WBS, the owner-operators assign costs based on material, equipment and manpower needs. In principle, contingencies can then be determined for each of the WBS tasks, based on past experience, but as we discuss later, the unique aspects of radiological decommissioning suggests that the Reference Class Forecasting method, which focuses on the overall project costs, is likely to be substantially more reliable.

[3] Our definition of a cost overrun throughout this analysis is costs incurred that exceed the costs that were planned

United States.[4] Cost overruns are common because these cost models useful for estimating the *mean* decommissioning costs; however, these models, despite including an ad hoc 25% contingency, have not adequately captured the potentially large deviations in costs due to both knowable failures and unknowable failures/risks, so-called "black swans" (i.e., unanticipated or unknown events). We argue that at least some of these large deviations, particularly knowable failures uncovered through experience, can be incorporated by considering completed decommissioning projects to create a structured, outside view of cost variations.

In addition to estimates lacking both an outside view and an empirical method to calculate contingencies, there are many barriers to being able to verify cost estimates: Private companies do not want to share data regarding their project outcomes, cost estimates are not standardized and so are very difficult to compare (particularly across countries), etc. These difficulties have prompted the nuclear industry to call for changes in the current system, including transparent cost processes and international data clearinghouses.

But until such a reform is undertaken, the practical problem remains. Therefore, we ask the practical question: Given the current constraints, how can we evaluate the adequacy of cost estimations and have some idea *a priori* that our evaluation is useful? In this paper, we combine the method proposed by Daniel Kahneman—Reference Class Forecasting (RCF) [23]—with two statistical methods, namely, adaptive kernel curve fitting and the Wilks' formula, to estimate cost contingencies for radiological decommissioning empirically and to provide a measure of statistical confidence in our estimates.

We demonstrate using the case of the United States how this combined method can benchmark existing cost estimates by modeling the *variance* of decommissioning costs and how it can provide empirical support and a confidence level for a *sufficient* financial standard to complement the *minimum* standard. Using the results from our "Best-Fit" RCF method, we apply a 48% contingency to the NRC-mandated radiological decommissioning estimates to "stress test" the current decommissioning trust funds. Using the Wilks' formula, we determine that we can be 87% confident that 80% of the true population will experience cost overruns less than 124.0%.

2 Theory

The concept of RCF was first proposed by Daniel Kahneman and Amos Tversky in the late 1970s [23]. Kahneman and Tversky proposed RCF to overcome systematic errors in decision making, paying particular attention to a systemic fallacy in planning that leads to inefficient decision-making, that is, underestimating costs and completion times and overestimating benefits. They asserted that the planning fallacy stems from taking a so-called "inside view," or in other words, focusing solely on the details of the project at hand (singular data) and neglecting useful evidence and experience from other similar classes of problems (distributional data). Therefore, Kahneman and Tversky took "the outside view" by incorporating information from distributional data—that is, an appropriate reference class containing actual outcomes from similar projects—into decision making. In doing so, they showed they could improve the accuracy of estimates made under uncertainty.

Since Kahneman and Tversky's insight, many researchers from a variety of sectors have begun to apply and develop RCF as a method to estimate costs and schedules. In infrastructure planning, Flyvbjerg et al. [16] were some of the first to apply the method, for example for the British Department for Transport across a range of government projects (e.g., road, rail, buildings, etc). Other researchers have also used the RCF method for estimating costs and duration in large-scale projects such as hydropower dams [2, 3, 9]; public buildings [6]; transportation [15, 17, 37]; bridges [25]; tunnels [7]; and IT projects [14].

In addition to the industrial applications of RCF discussed above, there are a handful of papers focusing on using RCF in the nuclear industry. Locatelli and Mancini [27] applied RCF to nuclear

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on at a particular juncture of the decommissioning planning/execution process. Thus, cost overruns can be relative to the initial planning phase—so called "pre-project plans"—or relative to cost estimates made during the execution of the project plans. Throughout the paper, we indicate on what cost estimate the cost overrun calculation is based.

[4] There are 10 fully decommissioned commercial nuclear power plant sites and 3 almost completely decommissioned, that is, awaiting license termination approval from the NRC. The Department of Energy also decommissioned 6 research reactors [30].

power plant new builds Olkiluoto 3 (FIN) and Flamanville 3 (FR), concluding that both projects showed signs of optimism bias leading to underestimated costs and duration. Another study used the method to estimate cost overrun of a nuclear waste storage project in Switzerland [8].

RCF has also been widely used and discussed in legal and philosophical settings. For example, RCF was famously used in *United States v. Charles O. Shonubi* to determine the prison sentence of a drug smuggler [11]. Many scholars in these domains debate what has come to be known as the "reference class problem" [e.g., 10, 19]. The reference class problem acknowledges that results derived from distributional data vary significantly depending upon the reference class.

The reference class problem is an issue that has led other scholars to investigate the accuracy and applicability of the method. Indeed, some scholars are critical of the method, saying that RCF does not produce accurate cost estimates and its applicability is limited [43, 46, 26]. Specifically, Locatelli [26] states that it is difficult to apply RCF where projects"are technically, economically, politically and socially complex and very different from one another." Questions about the accuracy and validity of RCF results also arise when the number of comparable projects is low or if projects are too radically different from each other within a reference class (or the reference class is too different from the project one is trying to analyze). In these cases, one should use caution in drawing conclusions. However, the study by Themsen [43] itself suffers from drawbacks as it only analyzes one mega-project.

Other scholars are more optimistic about the validity of the method. Park [36] examines 107 major projects and concludes that using RCF the average cost overrun declined. Servranckx et al. [39] confirm this finding with their empirical study of 52 real-life projects. In two studies comparing RCF to other cost estimation methods [4, 5], the authors confirm that RCF is capable of producing more accurate costs than the alternative methods.

Despite the scientific evidence on the accuracy and applicability of RCF being mixed, we are confident that we do not fall victim to the identified pitfalls: Most criticism concerns the choice of the right reference class [39] and the range of applicability of RCF [43, 46]. First, our reference class only consists of highly similar projects, i.e., US radiological decommissioning projects, and second, we only apply the method to large-scale projects.

Using kernel density estimators, such as the Gaussian, is a non-parametric method used to estimate the density function of a random variable and is a standard technique in statistics [e.g., 18]. We use an adaptive kernel method [24] in which the bandwidth used in estimating the density function varies at each observation according to the density of the data. Thus, the bandwidth of the kernel becomes larger when data is limited and smaller when there is a higher density of data. This helps to avoid over-smoothing (i.e., losing important information) in highly data dense locations [42].

The Wilks' formula was developed for assessing quality in manufacturing processes in the early 20th century [47]. The motivating idea was that one could take a small sample of a manufactured good and calculate, with some determined level of confidence and tolerance range, how many of the total batch manufactured would meet the specified criteria without any parametric/distributional assumptions. One can flexibly use the formula Wilks developed to determine any of the formula inputs (i.e., confidence level, sample size, tolerance range) based on what inputs one has.

Since Wilks' publication, the insights from the formula have been used widely in engineering applications, including nuclear engineering applications, particularly for safety calculations required by regulatory bodies [e.g., 50, 20], so-called Best Estimate Plus Uncertainty analyses (BEPU) [e.g., 12].

The Wilks' approach is particularly useful for applications where threshold values (e.g., upper or lower limits) are required rather than full distributional information. For safety regulations, commercial nuclear power plant operators can use the Wilks' formula, for example, to say that with 95% confidence that 95% of the true temperature realizations inside a reactor will not exceed an upper temperature level. The other leading sampling approach to conduct uncertainty analysis, the Monte Carlo method, is typically used to reconstruct the true population distribution, and thus, requires more samples to reduce the uncertainty of the distribution parameters. The Wilks' formula is limited in the information it can provide relative to Monte Carlo derived distributions or other approaches that assume an underlying distribution; however, the Wilks' formula requires many fewer inputs and assumptions, so it can be powerful in low-information situations as is the case currently in nuclear power plant decommissioning.

Our study contributes to the literature in a few important ways. We extend the RCF method to include two non-parametric statistical methods. In so doing, we strengthen the statistical validity of our results and attach statistically meaningful confidence to our estimates. To our knowledge, we are the first to use this combination of methods. We are also the first to use RCF in the context of nuclear power plant decommissioning and the first to have such a representative, complete set of exclusively radiological decommissioning data. Unlike some other studies, we do not assume all varieties of nuclear projects can be consulted just because they share the characteristic of being *nuclear* in nature, an approach we contend would cause "reference class problems."

We also contribute to policy in a practical way. The adequacy of nuclear decommissioning trust funds in the United States has faced significant scrutiny [e.g., 41, 38, 1, 28, 44, 49, 48]. Our study is one of the only to draw on empirical methods to establish fund adequacy [e.g., 49, 48]. Finally, rather than relying on rules-of-thumb or "inside-view assessments," we provide an empirical method for setting contingency, enabling us to recommend concrete, evidence-based policy changes.

3 Material and Methods

3.1 Reference Class Selection

First, we must carefully define what our target reference class must represent, as RCF results are sensitive to what reference class is chosen [10]. Our objective is to construct a reference class to estimate the potential cost overrun for a generic commercial nuclear power reactor being radiologically decommissioned. We define our hypothetical nuclear power plant to be a light-water reactor design—either Boiling Water Reactor (BWR) or Pressurized Water Reactor (PWR)—and of any commercial capacity (i.e., not a research reactor).

To construct our reference class, we select the completed and almost-completed civilian decommissioning projects in the United States, that is, we only look at commercial nuclear power plants. We exclude any non-nuclear power plants, military and research nuclear reactors as well as any other nuclear material facilities. We exclude non-nuclear power plants because we argue radiological decommissioning requires different methods, precautions, and planning than non-nuclear facility decommissioning. Multiple nuclear experts have also supported this perspective. Next, we exclude military facilities and research reactors because they are regulated by the Department of Energy and thus subject to different regulations and funding. Including only commercial reactors makes our reference class as similar as possible to the fleet of reactors for which we are trying to get estimates. Finally, we limit our reference class to nuclear power plants in the United States first to ensure consistency within the reference class, and second, because the US has the most decommissioning experience of any country, thus providing the largest, consistent reference class possible.

At the time of writing, 10 US civilian power reactor sites have been released from their original NRC license (7 sites still house Independent Spent Fuel Storage Installation (ISFSI), 3 sites are completely decommissioned), and 4 more sites with at least one reactor unit that is far enough along in the decommissioning process to have cost data. Still 7 more sites have been retired but are in SAFESTOR (Table 1). Thus, we are limited to 12 possible sites for our reference class. Due to the small sample, we cannot separate our sample by reactor design (i.e., BWR and PWR). Further, we exclude Fort St. Vrain from the sample, for it was a gas-cooled reactor while all the other reactors are light water designs. The RCF method is a relative method meaning that cost assessments are made "within" project. Therefore, we did not concern ourselves with the reactor capacity when forming the reference class. Still, one might be concerned that different sources of cost overruns emerge from different size decommissioning projects. This is an issue we will not be able to address until more decommissioning data is available. We nevertheless feel confident about our choice as the Pacific Northwest National Laboratory study concludes there is no relationship between decommissioning cost estimates and capacity [Figure 3.1 from 40].

We further limited our focus of cost estimates to radiological decommissoning rather than the entire decommissioning process. Radiological decommissioning includes all projects/tasks that contribute to the removal and disposal of any radiological materials or contamination. Thus, for example, the

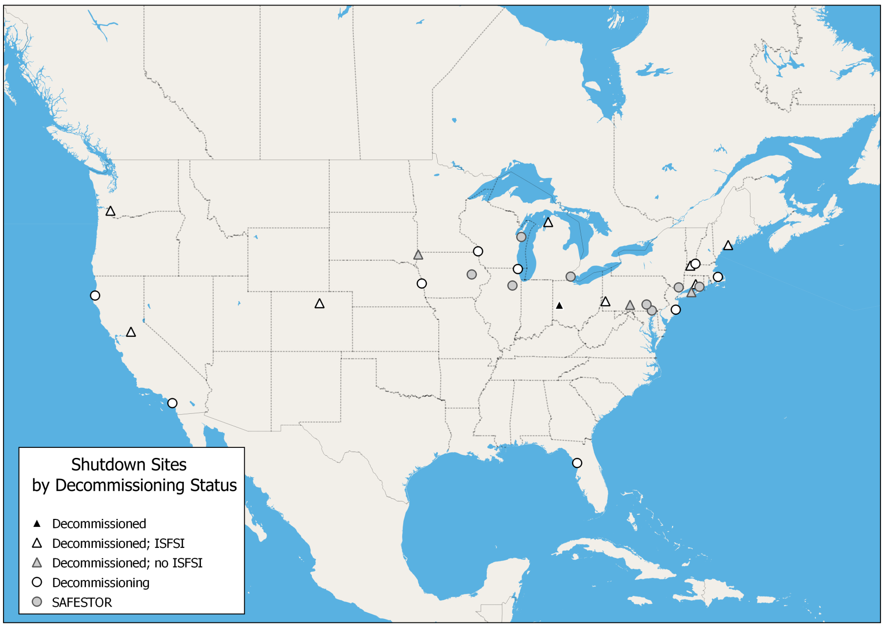

Figure 1: Map of the shutdown commercial nuclear power plant sites labeled according to status. Reactor sites denoted with a black triangle are sites that have been fully decommissioned; reactor sites denoted by a white triangle with a black border are decommissioned with an ISFSI remaining on-site; reactor sites denoted by a grey triangle with a black border are decommissioned reactors without an ISFSI; reactor sites denoted by a white circle with a black border are currently decommissioning, and and reactor sites denoted by a grey circle with a black border are those sites that are in SAFESTOR [30].

costs for demolishing contamination-free buildings are not included in radiological decommissioning costs. The reasons for focusing only on radiological decommissioning are three-fold: first, radiological decommissioning is the part of site decommissioning that involves the most cost uncertainty and risk. Second, radiological decommissioning composes the largest part of the costs [40]. Finally, limiting our focus enables us to make costs as comparable across plants as possible, thus, enabling us to construct a consistent reference class.

We also removed sites that are regulated by DOE rather than the NRC and sites for which radiological decommissioning costs cannot be isolated. While site restoration is an important factor for estimating total decommissioning costs, state-level regulations for site restoration vary significantly (i.e., the requirements for total decommissioning back to green field or brown field), making it difficult if not impossible for us to compare costs across projects. In contrast, the standards and requirements for radiological decommissioning were set by the NRC and are regulated by the NRC at the federal level. Therefore, we can be sure that sites regulated by the NRC are all subject to the same standards and requirements for radiological decommissioning. Given these observations, we exclude Yankee Rowe in Massachussetts and Shoreham in New York. We exclude Shoreham because it was transferred to DOE control, and thus, it was not regulated by NRC. And, we exclude Yankee Rowe because the records on the decommissioning are insufficient to isolate radiological decommissioning costs.

Thus, we are left with 9 reactors/sites: Big Rock Point (Michigan); Connecticut Yankee aka Haddam Neck (Connecticut); Humboldt Bay (California) where decommissioning is almost complete; La Crosse (Wisconsin) where decommissioning is almost complete; Maine Yankee (Maine); Rancho Seco (northern California); San Onofre Unit 1 (southern California) where the radiological decommissioning of this facility is complete, even though the other units have not yet been decommissioned; Trojan (Oregon); and Zion (Illinois) where decommissioning is almost complete (Figure 2).

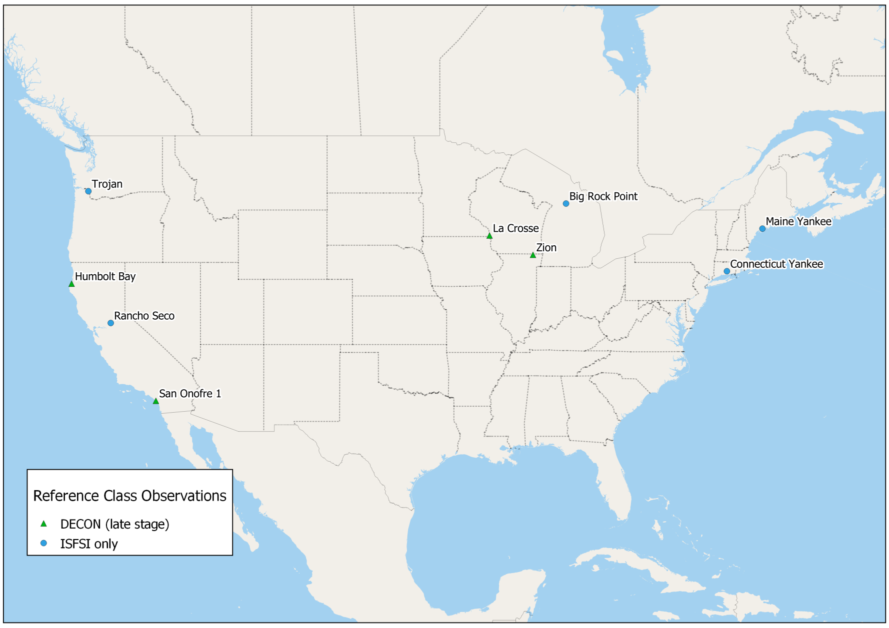

Figure 2: Map of 9 nuclear power plants (and units) that compose our sample. The 4 triangles (green) indicate that the site is still considered to be in the decommissioning phase and awaiting license termination. The 5 circles (blue) indicate that the site is decommissioned but that the site houses an Independant Spent Fuel Storage Installation (ISFSI) [30].

3.2 Data Collection

For each of the sites in our sample, we look at the estimated costs of decommissioning either in the Post-Shutdown Decommissioning Activities Report (PSDAR), which contains a site-specific cost estimation for radiological decommissioning[5] or in the License Termination Plan (LTP) which contains cost estimates made while the project is ongoing. We state where we retrieved the cost information for each individual reactor site (Table 2).

We take the *realized* costs from one of three sources: (1) a report conducted by PNNL (2) a report conducted by EPRI (epri) and (3) from the annual decommissioning fund reports. PNNL published its report in 2011 [40]. The purpose of the PNNL study was to determine whether the NRC minimum formula (used to determine how large decommissioning provisions should be) was sufficient to cover radiological decommissioning. The authors of the study compared the formula-based estimate for four decommissioned reactors with actual costs reported by the operators: Connecticut Yankee, Maine Yankee, Trojan, and Rancho Seco. The report has detailed information on realized costs, obtained by the authors of the study through interviews with the operators. epri released its report on San Onofre Unit 1 in 2008, detailing estimated and realized costs in detail [29]. Typically, this level of detail and transparency is not available. Thus, for the other plants (Big Rock Point, Humboldt Bay, La Crosse, and Zion I & II), we relied on the decommissioning fund reports that operators must file annually once the facility is in decommissioning. In these reports, the operators must disclose how much money remains in the Decommissioning Trust Fund (DTF); how much money was spent on *radiological decommissioning* since the beginning of decommissioning expenditures from the funds; and how much was spent in the last calendar year.

We are aware of some limitations that arise through our data collection method. First, PSDAR estimates are pre-project estimates and therefore we expect these estimates are less well-developed than the LTP, which are done once the project is underway. Unfortunately, given data availability, we use a mix of PSDAR and LTP estimates.

Second, some of these cost estimates contain contingency, but the contingency is not listed sepa-

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[5] Site-specific decommissioning cost estimates should be clearly distinguished from the minimum decommissioning cost estimates calculated using the generic formulas given in 10 CFR 50.75. These formulas are intended to provide a *minimum* provision of funds to be collected over the course of the plant's lifetime.

rately. For this reason, our sample cost estimates mainly come from LTPs because these reports often list contingency separately. We must remove any assumed contingency to accurately quantify the cost overrun. If we use costs containing the contingency, we may underestimate a cost overrun.

Third, some costs include litigation costs related often to contractors.[6] We include all of these litigation costs. We do not consider these costs to be changes in the fundamental scope of the project, rather, these costs (and settlement benefits) should be included as normal project risks.

Fourth, the annual decommissioning fund reports do not contain any detail about how the money was spent. According to law, the funds must be used expressly for radiological decommissioning. Prior to withdrawing money from the DTF, operators must document the purpose and have the expenditure approved by the NRC. Nevertheless, we cannot separate out the costs of any specific decommissioning activities. Finally, where the final costs were not available, for example, for plants that are not completely released from their license—though within an order of magnitude—we made assumptions to "construct" the final costs. While we inevitably introduce some error into the data with these assumptions (all detailed assumptions can be found by nuclear site in the Appendix A), we think including these observations is important and that such estimates within a couple of million dollars still provide valuable information.

3.3 The Wilks' Formula

The formula, based on the multinomial distribution, says that the density function of x is distributed across the selected range with some probability, p, and that, with a certain level of confidence, β, we can say, given our sample size, what proportion of the true population will lie in a designated range. Alternatively, we can determine how large a sample we would need to be 95% confident that the true population would lie in the designated range. For the Wilks' formula to be valid, we must assume that x is a random, independent variable. We can use the formula for one-sided or two-sided analyses. The generalized formula is described by the following:

$$\beta = \frac{n!}{(r-1)!(n-r)!} \int_{\gamma}^{1} (1-Q)^{r-1} Q^{n-r} dQ, \tag{1}$$

where β is the level of confidence, Q is the density function of x, γ is the proportion of the true population, n is the sample size, and r is a sample observation identifier. We simply choose β, γ, and r. When $r = 1$, the results are in terms of the last observation (i.e., when the observations are sorted in ascending order). When $r = 2$, the results are in terms of the second-to-last observation, and so on. To obtain $r = i$, take the i^{th} integral of the β equation and evaluate that integral over the designated probability limits.

We interpret $\beta_{r=1}$ by saying, "Given our sample, n, we are β % confident that γ % of the true population is less than the value taken on by the greatest sample observation. Likewise, we would interpret $\beta_{r=2}$ by saying, "Given our sample, n, we are β % confident that γ % of the true population is less than the value taken on by the second-to-last (second largest) sample observation." And so on.

4 Results

4.1 Calculating Empirical Contingency

We compare the site-specific, radiological decommissioning cost estimates with realized cost outcomes from the 9 nuclear power plant sites. Zion is the only site with two reactors in our sample, and we aggregate these costs for the whole site. It is important to note that Zion is neither an outlier nor does it unduly influence the results as the only two-reactor site. San Onofre is a multi-unit site, though we only consider the radiological decommissioning costs of unit 1. This may underestimate

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[6] For example, the contractors at Haddam Neck did not perform the tasks they were contracted to do; thus, the Haddam Neck operators had to sue the contractors to cover the costs to self-perform the decommissioning tasks subsequently.

the total radiological decommissioning costs if the remaining components to be decommissioned (that are shared across all units) experience a significant cost overrun during decomissioning. Given that many of the shared aspects of a multi-unit site are not complex in nature to decommission (unlike, for example the reactor pressure vessel), we do not think this will heavily influence our conclusions.

Radiological decommissioning costs do not include spent fuel storage, spent fuel management, and site restoration. Some other costs that may or may not be included (though consistent across reactor site) are insurance, final survey costs, etc. In the cases where these costs are itemized in both cost estimates and the final costs, we do not include them. We are purely trying to capture the cost overrun risks related to the planning and execution of radiological decommissioning.

Reactor Site	Cost Estimate ($M USD)	Estimate Source	Actual Cost ($M USD)	Overrun	Overrun %
Big Rock Point	422	LTP	454	321	7.63%
Connecticut Yankee	616	LTP	1029	412	66.9%
Humboldt Bay*	344	PSDAR	771	427	124%
La Crosse*	70.2	LTP	83.4	13.2	18.8%
Maine Yankee	360	LTP	554	194	53.4%
Rancho Seco	489	PSDAR	531	42.4	8.67%
San Onofre-1*	528	PSDAR	676	148	28.0%
Trojan	357	LTP	323	-34.4	-9.62%
Zion I & II*	722	LTP	669	-52.5	-7.28%

Table 2: A table of the estimated costs, realized costs, and cost over- or under-runs for our sample of 9 commercial nuclear power plant sites. All costs have been inflated to $2020 USD using the Bureau of Labor Statistics CPI indices [45]. The meaning of the acronyms in this table are PSDAR and LTP. The asterisk (*) denotes the reactor sites are not completely decommissioned; thus, we made some assumptions to arrive at the numbers presented in this table (see Appendix).

We plot the raw cost under-/ overruns in ascending order in Figure 3a. Typically, the RCF method proceeds by connecting the data points with piece-wise linear fits (Figure 3b). Using the piece-wise fits, the traditional RCF method derives the contingency by choosing a "risk preference" (e.g., P80)[7] and finding the corresponding x-value. This approach estimates the contingency based on two points in rank order.

Instead of estimating from the linear connections between empirical observations, we estimate a best-fit of the cumulative distribution function (CDF) function using an adaptive Gaussian kernel (Figure 4) and estimate the potential cost overruns over a range of modeled x-values. We call this the "Best-Fit-RCF" method. This best-fit curve takes into account the entire set of data rather than the relationship between two points alone.

We proceed by assuming that this estimated best-fit CDF curve is representative of the "true population," as the RCF method does with the piece-wise curve. Of course, in the future, this curve will change to reflect more data points and correspondingly, our estimates will improve. With the "standard RCF" curve in Figure 3b, we estimate additional contingency level for radiological decommissioning of 56.7% corresponding to a risk preference of P80[8]. However, using the best-fit CDF, the contingency level drops to 48.4%. Thus, the consideration of all the data points results in a less conservative contingency that is informed by more observations.

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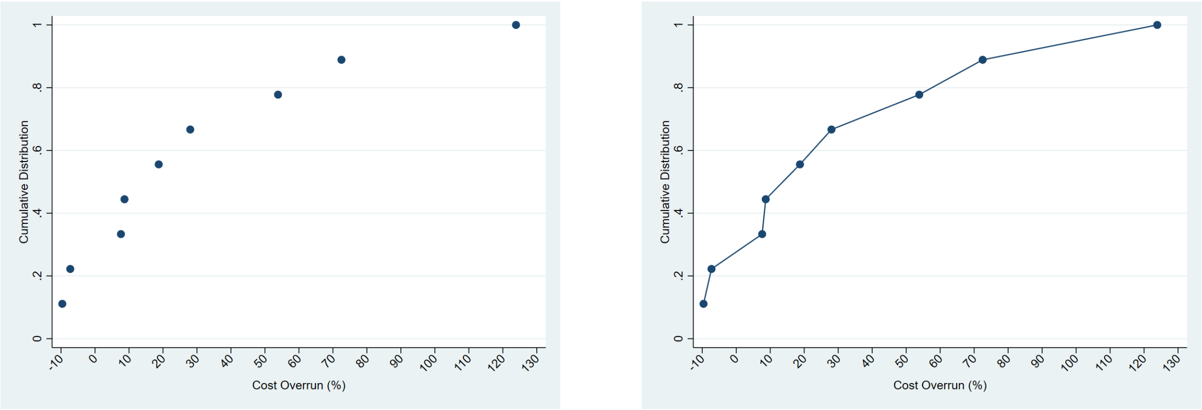
[7] For example, a 20% probability of a cost overrun corresponds to P80, whereas a 50% probability of cost overrun corresponds to P50, the average costs.

[8] The exact percentage is obtained by calculating the slope of the line between the two points and solving for the corresponding y-value, $y = 0.006x + 0.46$



(a) Cost over-/under-run data points plotted in ascending order.

(b) Cost over-/under-run data points plotted in ascending order with linear connections.

Figure 3: Realized cost overruns (2020 USD) sorted in ascending order like a cumulative distribution function for the 9 nuclear power plants in our sample plotted both as a simple scatter (Figure 3a) and with linear connections (Figure 3b). The RCF uses the linear connections to estimate how much additional contingency should be set aside given a risk preference (y-axis e.g., P80) by looking at the corresponding cost overrun values on the x-axis.

4.2 Evaluating Individual Sites

We apply this 48% contingency to the NRC-mandated cost-model estimates to each of the currently operating plants.[9] We then compare the NRC-mandated with the additional contingency estimates to the projected balance of the individual DTFs prior to decommissioning to see whether the funds are sufficient to limit the chance of a cost overrun to 20% (Figure 5). Note that the risk preference for a 20% chance of cost overrun is chosen somewhat arbitrarily and depends on the risk appetite of the project manager. According to the literature, P80 is rather conservative and should be applied where project cost overrun must not occur [17].

In total, the NRC projects that nuclear power plant operators will set over $88.5 billion (2020) USD aside for decommissioning at the 54 nuclear power plant sites in Figure 5 [35]. These funds are first and foremost for radiological decommissioning (10 CFR 50.75). Once radiological decommissioning is complete, the power plant owners can use the funds for site restoration and non-radiological demolition work. Figure 5 shows the difference between the projected funds for each nuclear power plant site and the estimated decommissioning costs (using the 10 CFR 50.75 cost models) with the 48% additional contingency included. We aggregated across sites because in most cases, reactor units at one site are owned by the same entity. Thus, it is plausible that this entity could apply some funds from one DTF to compensate shortfalls (once the reactor is successfully radiologically decommissioned) and/or that some shared infrastructure will result in common decommissioning costs.

The reported funds of 26 reactor sites are sufficient to cover the additional contingency we estimated by Best-Fit-RCF, in some cases, by extremely wide margins (right-side of the graph, bars in positive region of the graph). On the other hand, 28 plants do not have enough projected funds to include this contingency (left-side of the graph, bars in negative region of the graph). To be clear, these 28 sites may not need these extra funds, nor are we inferring they do not have enough money set aside to meet their legal obligations.[10] Rather, we are conducting a "stress test" on fund adequacy for hypothetical cost overruns. These plants' funds may benefit from additional NRC scrutiny and a reevaluation of site-specific estimates vis-à-vis their DTF.

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[9] Cost-model estimates are at the reactor-unit level. Thus, we aggregated these by power plant site. We exclude sites that have only published site-specific estimates, as these will not be comparable to the other plants or accurately reflect radiological decommissioning. Sites where data for all units are not available, we note which units are included in the summation.

[10] Nuclear power plants are not obliged to report the full amount that exists in their funds, rather that it is adequate to meet the NRC-mandated estimate. Therefore, we can be confident that inadequate funds prior to the addition of the contingency are indeed inadequate.

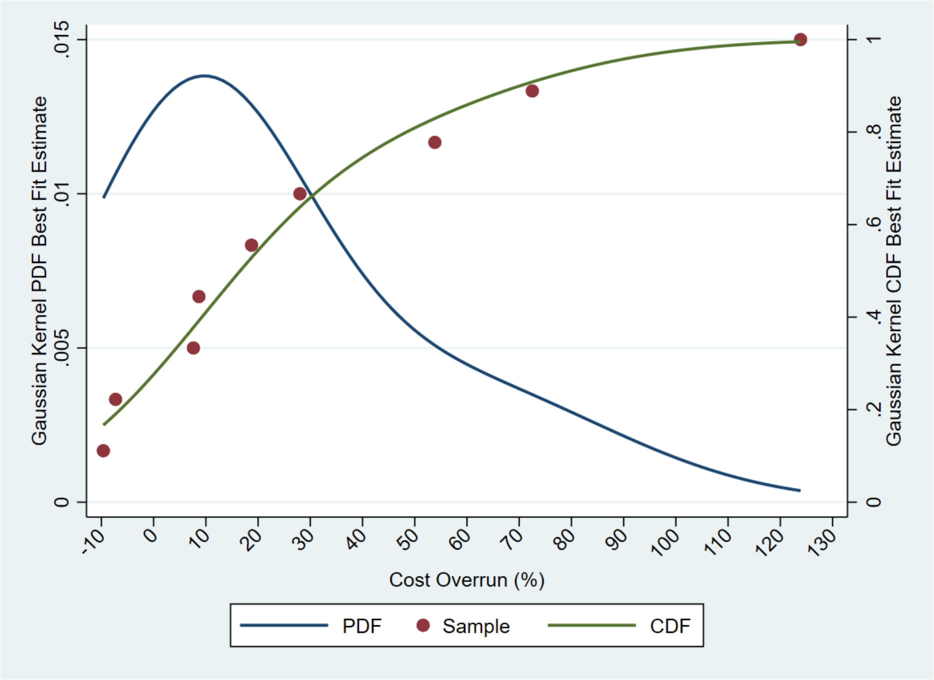

Figure 4: Plot of our empirical sample, the best fit cumulative distribution of the cost overruns, and the corresponding probability density function. We estimated the best fit using a Gaussian kernel. With the best fit CDF, we can estimate the potential cost overruns corresponding to different risk preferences (P80, etc).

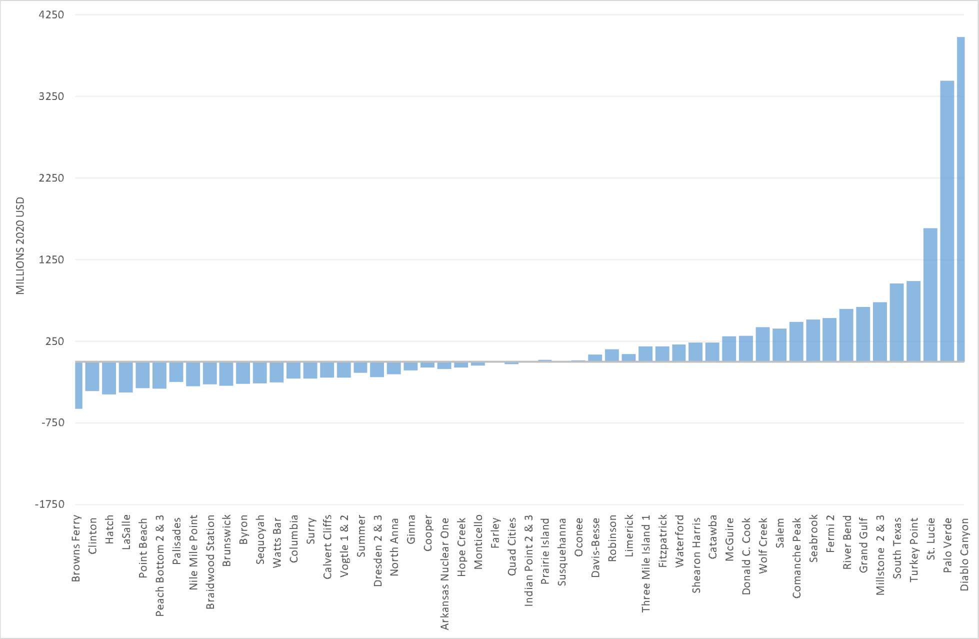

Figure 5: Bar graph showing the difference between the projected Decommissioning Trust Fund prior to planned decommissioning and the NRC minimum estimated cost of decommissioning with 48% contingency added. We indicate the magnitude of the funding shortfall in the negative region of graph and the funding excess in the positive region of the graph. These values are reported by nuclear power plant site in 2020 USD.

The industry-wide contingency we calculate amounts to an additional \$25 billion (USD 2020) spread across all 54 operating nuclear power plant sites (93 reactors). That is approximately NASA's 2021 budget of \$23 billion.[11] Given some plants have excess funds, the pooled funding "insufficiency" to cover the additional contingency across these operating plants totals \$6 billion. The average shortfall by site is \$211 million. The shortfalls range from \$6.5 million to \$571 million (USD 2020). Still, the actual size of eventual cost overruns is uncertain. Our Best-Fit RCF analysis provides an empirical basis for what the range of hypothetical overruns *is likely* to be, but we cannot provide a crystal ball for what overruns *will* be.

The contingency we add is intended to cover uncertain but statistically probable cost overruns; in other words, not every plant will overrun, but according to experience, some overruns are probable in the entire fleet. We consider the risks of overruns across the entire fleet of currently operating nuclear power plants with a different statistical method, namely using the Wilks' formula.

4.3 Evaluating the Fleet

We use the Wilks' formula to establish confidence in our sample and to quantify the proportion of the true population (here the US commercial nuclear power plant fleet) that will experience overruns of a selected range. We consider the cases for the 3 largest observations of cost overruns; that is, we can say with a specific confidence level what proportion of the true population will likely have cost overruns below the greatest observed cost overrun, the second-largest observed cost overrun, and the third-largest observed cost overrun. Then, we calculate what proportion of the true population have overruns between 54.0% and 73.0% (Figure 6). Of course, we could do this for every observation; however, we have chosen these examples, as we deem them most relevant for policy.

Sample Size (n)	Ordered Observation (r)	Cost Overrun (%)	Confidence Level (β)	Proportion Population < r obs (γ)
9	r=1	124%	87%	80% aka P80
9	r=2	72.5%	56%	80% aka P80
9	r=3	53.9%	26%	80% aka P80
9	r=2 - r=3	btwn 53.9% - 72.5%	30%	80% aka P80

Table 3: Results from using the Wilks' formula to determine our confidence in what proportion of the true population will have cost overruns less than observed values in the sample. We show P80 in this table, although other risk tolerances can be chosen.

4.3.1 Solving for the Confidence Level

Table 3 shows the results from our analysis using the Wilks' formula for P80; that is, we determine how confident we are that 80% of the true population will have cost overruns below the particular observation of interest (designated by r). These results can be reproduced for other tolerance thresholds (e.g., P90, P70, etc).

As we show in the first row, we are 83% confident that 80% of the true population will not have cost overruns greater than 124%. However, our confidence level declines quickly as we narrow our observations. We have 56% confidence that 80% of the true population will experience cost overruns less than 72.5%. The confidence declines further as r increases.

We create a band between r=2 and r=3 (53.9 and 72.5%) (Figure 6). Unfortunately, without a greater number of observations, we cannot improve our confidence above 30% that 80% of the true population will have overruns between 53.9 and 72.5%. Nor can we fruitfully use the two-sided version of the Wilks' formula to narrow the range of possible overruns.

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[11] https://www.planetary.org/space-policy/nasas-fy-2021-budget

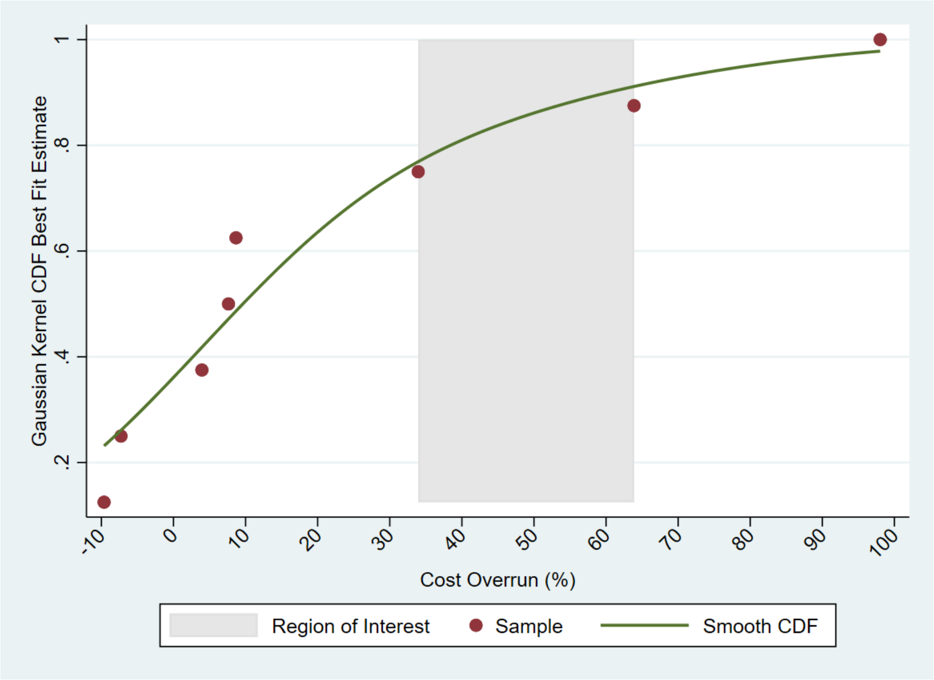

Figure 6: Plot of our empirical sample, the best fit cumulative distribution of the cost overruns. The shaded area corresponds to the region of cost overruns between 53.9 and 72.5% where we estimate with 30% confidence that 80% of the true decommissioning population will lie.

Sample Size (n)	Ordered Observation (r)	Cost Overrun (%)	Confidence Level (β)	Proportion Population $>$ r observation (γ)
9	r=1	124%	95%	72%
9	r=2	72.5%	95%	57%
9	r=3	53.9%	95%	45%
9	r=1	124%	80%	84%
9	r=2	72.5%	80%	70%
9	r=3	53.9%	80%	58%

Table 4: Results from using the Wilks' formula to determine our what proportion of the true population will have cost overruns less than observed values in the sample, given confidence thresholds. We show 95% and 80% confidence levels, although others may be calculated.

4.3.2 Solving for the Proportion of the True Population

We solve for the proportion of the population numerically by choosing our preferred confidence level, here we show 95% and 80% (Table 4).[12] From a policy perspective, the most interesting and important case is when r=3 because it narrows the range of cost overruns significantly. We are 80% confident that more than half of all the nuclear power plants will have overruns of less than 34.0% and 95% confident that 40% of the fleet will not exceed 34.0% overrun.

Finally, we calculate that we will need to observe 58 decommissioning projects to be 95% confident that 95% of the true population will have cost overruns less than the greatest observed cost overrun (not yet observed). In other words, a nuclear fleet the size of France's would have to be completed to achieve this level of confidence.

5 Discussion & Conclusion

In this paper we use a novel combination of methods to assess the risk and magnitude of cost overruns in decommissioning the currently operating US nuclear power plants. We first further develop the

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[12] Using this numerical approach, we cannot calculate the difference between r=2 and r=3.

Reference Class Forecasting method by fitting the empirical distribution with a Gaussian adaptive kernel. With our Best-Fit RCF results, we estimate that adding a 48% contingency over and above the current NRC-mandated cost-model for radiological decommissioning would suffice to limit the risk of a cost overrun to 20% at each power plant. We calculated this contingency based on the data from 9 commercial power plants in the US, 5 of which have been entirely decommissioned and 4 that are very close to license termination. This is the first attempt, to our knowledge, to calculate decommissioning contingency empirically.

We stress test the adequacy of the segregated decommissioning trust funds in the US by adding the 48% contingency to the plants' radiological decommissioning cost estimates calculated using the generic NRC cost-model (10 CFR 50.75). We then calculate the difference between the amount of funds that are projected to accumulate in the decommissioning trust funds prior to decommissioning. We find that 26 of the reactor sites considered have adequate funds to finance cost overruns of 48%, and in many cases, much more available funding. Twenty-eight sites' reported trust funds would be insufficient if faced with cost overruns of up to 48%. Given the caveat that not all funds in DTFs must be reported, we cannot be sure these plants would face funding shortages. Nevertheless, we echo the repeated recommendation that the NRC update their cost-model to reflect the most up-to-date information and experience [40]. In our case, we recommend that the NRC apply a greater contingency to their cost-model to ensure that radiological decommissioning is adequately funded at every site by the operators.

We assess the fleet risk using the Wilks' formula, a method adopted from manufacturing and nuclear engineering. We apply the Wilks' formula both in determining a given proportion of the population (e.g., P80) and to determine a given confidence level. We are 87% confident that 80% of the US fleet will experience cost overruns of less than 124%. Note that our empirical distribution includes cost under-runs. This result enables us to put an upper bound on the cost overruns of 124%. With a fixed confidence level of 95%, we estimate 72% (approximately 72 reactors) of the entire US fleet will experience cost overruns less than 124%. While these figures still reach the hundreds of millions of dollars, applying a 48% contingency, recommended by the Best-Fit RCF we calculated, would go a long way to reducing these liabilities. In fact, if we applied a 48% contingency, our results show that we can be 95% confident that we would reduce the upper limit of cost overruns to approximately 76% and that 72% of the fleet would have cost overruns of 76% or less, including potential cost under-runs.

The results found in our study can provide useful guidelines for the financing of nuclear decommissioning in other countries. Many countries, such as Germany, Sweden, Belgium or Switzerland, are planning on phasing out nuclear energy and thus, their nuclear power reactors will shut down and consequently be decommissioned over time. Ensuring adequate financing is an especially difficult venture for regulators and external stakeholders. Our study provides an empirical method for regulators and external stakeholders to calculate required contingency, and the method will only become more informative as more nuclear decommissioning experience is obtained.

Our research is subject to some limitations and offers some direction for future work. First, the Best-Fit RCF method itself is quite sensitive to the choice of the reference class and the quality of available data. While we are confident we have chosen the correct reference class for decommissioning commercial nuclear power reactors, without more experience, we cannot test it statistically. The current cumulative distribution function that we use to calculate our contingency will be refined as more plants are decommissioned. These additional data points will naturally reflect changes in technology, waste storage options, and new business models (i.e., third party decommissioning specialists).

We recommend that the NRC adopt the insights from this outside view, requiring more contingency for radiological decommissioning. In the future, we would like to apply the Best-Fit RCF method and these results to other decommissioning reactors in other countries. We would also like to apply different cost estimation and contingency methods and compare them to our Best-Fit RCF results.

A Appendix: Data Collection Assumptions

We provide a short profile of each of the nuclear power plant sites that are in our sample along with any assumptions we made to construct the costs in our reference class. We indicate the NRC ADAMS

Public Document Accession numbers (ML#########).

Big Rock Point

Big Rock Point was located near Charlevoix, Michigan. It was a single-unit boiling water reactor owned and operated by Consumers Energy Company. It joined the grid in 1962 and was brought offline in 1997, supplying some 12.7 TWh. The design capacity was 75 MWe [22, 31].

We used the decommissioning fund reports to estimate the actual, final costs of decommissioning (ML060820303). The last report was in 2006, the year Big Rock Point was released from its 10 CFR part 50 license. In that report, the amount remaining to be spent was estimated at 25.9 million (2006) and the amount already spent was approximately 317 million. Thus, we had to assume that the final 25.8M were realized costs. The currency years were not always carefully stated, so we assumed that they currency were reported in the same year as the document was written. We use the LTP revision 0 for the site-specific cost estimate (ML031010399).

Connecticut Yankee

Connecticut Yankee, also known as Haddam Neck Plant, was located in Haddam, Connecticut in the United States. The plant contained a single reactor unit. Westinghouse designed the PWR 4-loop closed-cycle nuclear steam supply system with dry containment, while the reactor itself was built by Combustion Engineering. The balance of plant was built by Stone & Webster. Connecticut Yankee had a 590 MW capacity and operated for approximately 28 years (1968-1996). Decommissioning began in earnest in 1998 following an immediate decommissioning strategy. There were some significant delays in decommissioning this plant due to changes in scope and decommissioning contractors. Finally, additional delays were caused by overlapping layers of regulation (federal and state) leading to further remediation requirements, and difficulties segmenting the reactor internals [for additional details see 40].

We draw our cost information about Connecticut Yankee from the PNNL study [40]. For our Haddam Neck reference class entry, we use the LTP estimate rather than the PSDAR estimate because the LTP cost estimate explicitly quantifies contingency, and therefore, we can remove it. We further modify their estimates to remove litigation costs that were incurred over the course of the decommissioning project for legal disputes between CY and its contractors. The legal fees totaled about $35.7M (2020 USD). We remove these legal fees from the realized costs of radiological decommissioning.

Humboldt Bay

Humboldt Bay was a single-unit BWR located in Eureka, California. Like La Crosse, Humboldt Bay was a relatively small reactor, designed with 65 MWe. It was producing electricity between 1963-1976. Its owner-operator, Pacific Gas and Electric decided to shut the reactor down for economic reasons following routine maintenance in 1976. The NRC released the facility from its 10 CFR part 50 operating license in November 2021 [22, 32].

We found cost estimations for Humboldt Bay in its PSDAR (ML101020034). A consulting firm, TLG Services, Inc. prepared the PSDAR and used contingencies in their line-item estimates. They state there is a composite contingency of 25%. Thus, we remove 25% contingency from this cost estimate. The available LTP (2018) had progressed too far into the project to be considered an "estimate," with only and estimated $184M USD (2018) remaining to be spent of some $1 billion.

For realized costs, we used the annual funding reports (ML21088A435). We assumed that the estimated remaining costs to complete radiological decommissioning amounting to $4M USD (2021) were realized costs. The used fuel management numbers were not reliable as the PSDAR assumed that the Department of Energy (DOE) would retrieve the used fuel by 2020. As a result, we do not use the used fuel management numbers from Humboldt Bay.

La Crosse

La Crosse was a single reactor unit owned and operated by Dairyland Power Cooperative. La Crosse was located in Genoa, Wisconsin. According to the NRC, La Crosse was a demonstration BWR plant with design capacity of 50 MWe. The Atomic Energy Commission—the NRC's predecessor—partially financed the plant. The unit first produced power for the grid in 1968 and shut down in 1987 when it was placed in SAFESTOR [33]. Over the course of its operations, La Crosse produced approximately 4 TWh of electricity [22].

We collected the cost estimations and realized costs from the NRC-mandated reports. We use the LTP (ML18169A246) for La Crosse because the PSDAR was prepared for Dairyland Power Cooperative using a decommissioning strategy of SAFESTOR. This plan was approved in 1991; however, in 2016 Dairyland Power Cooperative entered into a license stewardship contract with Energy*Solutions* to complete the decommissioning of the plant. The limited liability company, La Crosse*Solutions*, filed an LTP in 2018. While mainly redacted, the LTP contains one mention of the total costs from which we could "backout" the radiological decommissioning costs. The contingency level is not given, so we assume the same contingency level provided in the LTP for radiological decommissioning at the Zion station: approximately 9%.

La Crosse*Solutions* has not yet completely finished decommissioning. Thus, we assumed the remaining $60,000 USD (2020) were realized costs. We take these numbers from the annual decommissioning funding report filed in March 2021 (ML21084A217).

Maine Yankee

The Maine Yankee nuclear power plant was a single reactor unit station in Wiscasset, Maine. The plant started commercial operation in December 1972 and was permanently shutdown in December 1996. It was a Combustion Engineering PWR 3-loop, dry containment design with a 774 MWe capacity. Over its lifetime, the plant had a 70.5% capacity factor. Decommissioning work began in 1998. The Maine Yankee Atomic Power Company chose to decommission the facility with an immediate decommissioning strategy (DECOM) [for additional details see 40].

The PNNL study attributes delays in the decommissioning schedule and cost overruns to a change in scope and difficulties with contractors Specifically, MYAPC had not planned to build an ISFSI facility in their PSDAR, but ended up planning and building the facility during decommissioning. MYAPC also had problems with an insolvent decommissioning contractor that was unable to complete its tasks.

The realized decommissioning costs that we use do not contain any litigation costs. As breifly mentioned, the MYAPC hired a contractor to do some of the decommissioning work; however, MYAPC had to fire the contractor because they did not carry out the work they had engaged themselves to do. The operators paid the contractor $77.4M (2020 USD) and incurred $7.3M (2020 USD) in legal fees. In court, the operators received $71.5M performance bond settlement and $40.6M damages settlement from the contractors. The credits were given in various parts of the decommissioning project. All told, MYAPC ended with a net positive of 27.7M; however, this settlement likely offsets some of the delays and administrative hurdles that resulted from the contractor's negligence. We decided not to include any credits associated with the litigation. Thus, the realized costs are reflect—as close as possible—only costs related to the project itself.

Rancho Seco-1

Ranco Seco-1 was a single unit reactor located in Herald, California. It was owned and operated by the Sacramento Municipal Utility District (SMUD). The PWR was designed by Babcox & Wilcox with a capacity of 913 MWe. The plant operated for approximately 14 years, from 1972 to 1989 [for additional details see 40].

Originally, SMUD had planned a SAFESTOR strategy. However, after some 8 years of delay, SMUD engaged in 'incremental DECON' in 1997, which as far as we can tell, amounts to slightly delayed DECON. Rather than hiring contractors, SMUD and the staff at Ranco Seco self-performed the decommissioning and was able to conduct various decommissioning tasks according to their own analysis of available resources. The NRC-reporting—PSDAR and LTP—during this delay reflect the flux in decision-making. In 1999, SMUD moved to a DECON strategy, which was followed until SMUD completed radiological decommissioning in 2009. The Ranco Seco site has both an ISFSI and an Interim Onsite Storage Building (IOSB) for LLW of classes B and C.

The estimates provided in the PNNL study are not as detailed as those provided for Maine Yankee or Connecticut Yankee. In addition, the documentation in the report is not always totally clear. The realized costs are provided in a table by year and the used fuel management costs are distributed within that table by the authors of the PNNL study. We inflate the costs for the radiological decommissioning, assuming that costs are provided in the currency year that the work was completed. For the used fuel management, we use the lump sum estimate given in 2010 USD and we assume that the estimated \$22.2M remaining used fuel management costs are realized. No estimates are provided for site restoration.

San Onofre-1

San Onofre-1 was one reactor unit located at a generating station with 3 total units (San Onofre 1, 2, and 3) in San Clemente, California. Unit 1 was a PWR Westinghouse 3-Loop with a design capacity of 436 MWe. It was owned and operated by Southern California Edison Company (SCE) and began operating in 1968. SCE shut Unit 1 down in 1992 [22, 34].

Originally, SCE had planned to place Unit 1 in SAFESTOR until the other two units were ready to begin decommissioning. However, in 1998 SCE submitted a PSDAR and began to decommission Unit 1. This change in decommissioning strategy came on the heels of an NRC decommissioning regulation change. The entire decommissioning plan consisted of 3 Phases: Phase I, Phase II and Phase III. Phase I corresponded to radiological decommissioning of Unit 1 and removal of the main structures of Unit 1. Phase I was successfully completed in 2008 after about 9 years of work. The decommissioning project is now in Phase II, moving, storing and monitoring the spent fuel from the three units in an ISFSI. In Phase III, the license for Unit 1 will be terminated along with the other two units. While Unit 1 could be released earlier in theory, it makes more sense to couple this task with the other units due to requirements of the site owner—the United States Navy [29].

We use the cost estimates provided in the PSDAR with a site-specific estimate in 1998 (ML13184A353 / Y2013). For the realized costs, we use the information provided in the appendix of Naughton (2008), Table B-1. Table B-1 also provides a "Budget" of the costs, which might also be considered a cost estimate. However, to be consistent with the other sample observations and because no clarification is made on what the authors mean by budget, we use the cost estimates from the PSDAR. As indicated in the title of the Table B-1, these costs correspond to all the activities included in Phase I. While this is not strictly limited to radiological decommissioning—there was some demolition included—we do not believe such a small part of the project should overly influence the results. We also do not include the costs in Table B-1 that correspond to the construction and operation of the ISFSI.

Trojan

The Trojan plant was a single reactor unit with design net capacity of 1130 MWe located north of Portland, Oregon. Westinghouse Electric Corporation designed the 4-loop PWR. The facility began commercial operation in 1976 and came offline in 1992, after only 17 years of operation because the unit was no longer financially viable [40]. The operators of the plant decided to immediately decommission with a 7-year schedule for radiological decommissioning planned. There were many scope changes during the decommissioning process due to changes in the NRC regulations for License Termination and radiological release limits [for additional details see 40].

A unique fact about the decommissioning of Trojan was that the entire reactor pressure vessel, with the internal components in place, was shipped directly for disposal at the US Ecology facility in Washington state. Not needing to segment the reactor internals reduced the decommissioning costs for Trojan significantly. It took 13 years to decommission Trojan from shutdown to release from 10 CFR part 50 operating license.

Our cost data for Trojan come from the PNNL study. When the study was conducted, Trojan was not completely decommissioned; therefore, the actual costs include some estimates (assumed to be realized) for completing site restoration (approx. \$3.9M (2020 USD)) and for ISFSI operation and decommissioning. There are no statements about contingency, and we therefore make no adjustments for it.

Zion 1 & 2

Zion Power Station, located in Illinois, has two PWR units on site. The total capacity of the station was 2080 MW, with two identical units of 1040 MW each. The reactors were connected to the grid in 1978 and permanently shutdown in 1998. Exelon decided to decommission the reactors after a delay of approximately a decade, so-called "delayed DECON". However, in 2010, Exelon entered into a license Stewardship agreement with Energy*Solutions* in order to decommission the reactor more quickly. Zion*Solutions*, LLC—the subsidiary of Energy*Solutions* created to decommission the facility—began decommissioning the facility immediately.

We collected data from the NRC for both the site-specific estimate for decommissioning and the actual costs. The site-specific estimate we use is while the facility has already begun being decommissioned because it does not include contingency (ML18052A930). While the detailed costs contained in this document are normally redacted from public view, the redaction was not done correctly. Therefore, we were able to obtain the numbers. We combine this with the realized costs taken from the annual decommissioning fund report (ML15091A303) to estimate the site-specific cost of radiological decommissioning for the entire Zion Power Station. We compare this with the realized costs, which are also taken from the annual decommissioning fund report from 2019 (ML20097C644). This is the last required decommissioning fund report before the facility was fully decommissioned; however, when it was filed, the decommissioning was not complete. The report estimates that there was \$3.3M remaining. Nevertheless, we feel this is relevant because it gets us into the "ballpark" of decommissioning costs. And, in our case, order of magnitude estimates are still very helpful. Therefore, we assume that the \$3.3M are realized costs.

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Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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