A Study on the Determinants of Decommissioning Cost for Nuclear Power Plant (NPP)

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Nuclear power plants (NPPs) produce radioactive waste and decommissioning this waste entails additional cost; determining these costs for various types and specifications of radioactive waste can be challenging. The purpose of this study is to identify major determinants of the decommissioning cost and their impact on NPPs. To this end, data from defunct NPPs were gathered and 2SLS (Two Stage Least Squares) regression models were developed to investigate the major contributors depending on the reactor types, viz. PWR (Pressurized Water Reactors) and BWR (Boiling Water Reactors). Additionally, cost estimations and the Monte Carlo simulation were performed as part of performance validation. Our study established that the decommissioning costs are primarily influenced by the level of radioactivity in the decommissioned waste, which can be realized from operational factors like operation period, overall efficiency, and plant capacity, as well as from duration of decommissioning and labour cost. While our study provides an improved statistical approach to recognize these factors, we acknowledge that our models have limitations in forecasting accurately which we envisage to bolster in future studies by identifying more substantive factors.

Keywords: Nuclear power plants, Decommissioning cost, Radioactive waste, 2SLS regression

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1. Introduction

Nuclear power plants (NPP), as any industrial facility, have a finite lifetime and thus shall be permanently suspended and dismantled if operation lifetime is not extended. The term ‘decommissioning’ refers to not only the administrative but also technical actions taken to allow the removal of the regulatory controls from a facility. The decommissioning of nuclear power plants shall be carried out after a permanent shutdown in accordance with relevant laws. Reasons for the permanent shutdown may be poor economic performance, political judgment, severe accidents, and in most cases, economic loss due to aged facility.

Decommissioning involves activities such as removal of fuel, dismantling of plant and equipment, decontamination of structures and components, demolition of buildings, remediation of contaminated ground and recycling or disposal of the resulting waste. Adequate planning and management are needed to ensure throughout implementation until the eventual de-licensing (license termination). Enhancing the regulatory controls that apply to a nuclear site, either entirely or partially, is one of the central decommissioning agenda, which is attained through the progressive and systematic reduction of radiological hazards [1].

Regardless of the end state of the decommissioned site, the underlying key requisite is to ensure the site to ensure public health and safety as well as protection of the environment, and the continued health and safety protection of workers [2].

According to the IAEA PRIS (2020), 442 nuclear power reactors are in operation as of September 2020. There are 192 nuclear power reactors that have been in operation for more than 30 years, 99 of them are over 40 years, and 8 of them are over 50 years [3]. As a result, reliable decommissioning cost estimation gets more importance not only for liability recognition but also for actual cost budgeting from the fiscal point of view.

The decommissioning schedule and a cost estimation can be elaborated through management tools such as WBS (Work Breakdown Structure) and ISDC (International Structure for Decommissioning Costing purposes) [4]. However, it is not easy to make predictions without detailed due-diligence data. There are various factors affecting decommissioning costs such as characteristics of nuclear power plants, operation efficiency, operating period, and regulatory requirements. And that, even a reactor with the same capacity may cause different decommissioning cost depends on the operating period, the decommissioning method, the residual values, and regulatory requirements.

These tools cannot provide generalized decommissioning cost estimate for bundle of NPPs. In accordance with International Accounting Standards, every country should estimate decommissioning cost based on the characteristics of nuclear power plants in order to provide a basis for covering decommissioning cost with liabilities. It is necessary to scrutinize major factors that affect to the decommissioning cost as well as the degree of the monetary impacts.

Consequently, the goal of this paper is to empirically investigate major determinants and degree of their impact on the decommissioning cost. This paper may have academic contributions in threefold: presents comprehensive NPP decommissioning cost data though wide range of research, provides an enhanced regression models, and suggests a Monte Carlo simulation to increase practicality. Meanwhile, the limitations of this study are added in the conclusion.

In the second chapter, we review literatures on decommissioning cost estimation, cost drivers, and policy. Especially, we provide a historical set of permanent NPP shutdown data based on document research. In the third chapter, we introduce research models and basic statistics. In the fourth chapter, we present test result on the effective determinants of decommissioning cost achieved from regression analysis. In the fifth chapter, we show cost estimation result with confidence intervals and compare them against the authority’s official estimation. Monte-Carlo simulation is also performed to check the fitness of suggested model. Finally, we wrap up paper with discussion and conclusion.
2. Literature review

There are not many previous literatures based on statistical analysis with historical cost data in regard to NPP decommissioning. One of the latest and meaningful literatures is Joo et al. (2020) [5]. They developed a multi-regression model to estimate the decommissioning cost of Kori-1, using the historical decommissioning data, which is comprised of 13 boiling water reactors (BWR) and 16 pressurized water reactors (PWR). They found out two major factors that determine the decommissioning cost: a contamination factor which is designed to reflect the operational characteristics, and a decommissioning work period of plants. They measured the contamination factor based on operation period, thermal capacity, and operation factor. They estimated the decommissioning cost range of Kori-1 between 663.4 mil and 928.3 mil USD based on the suggested cost formula.

Geoffrey et al. (2016) [1] provides data on decommissioning cost drivers in Europe and the United States. They suggest three main cost drivers and percent range of costs: dismantling activities (12–50%), project management (14–55%), and waste management (4–26%).

The cost for dismantling activity varies greatly depending on the national decommissioning strategy. The strategy of removing (as a whole or segmentation) large components radioactive waste, and the degree of site restoration and cleanup have been shown to have a significant impact to the dismantling activities. Especially, there is a significant difference in restoring cost of site depends on the degree of ground contamination.

The project management cost is not dependent on capacity but differs whether the project is managed by a licensee or an external contractor. Engineering and security, fixed-cost items take larger portion in smaller plants. In addition, project management cost differs depending on the number of reactors due to an efficiency and integration of project management. For example, a French case showed the lowest ratio of 14% in project management cost as there were four nuclear reactors in the same site.

The cost of radioactive waste management varies significantly in its range due to cost classification such as transporting and disposing of radioactive waste. In addition, it is determined by the usage of the constructed facility, expansion, and a need for new construction.

Monteiro et al. (2019) [4] introduced a management tool and mathematical model for estimating decommissioning budget. Their model aims to estimate the decommissioning cost for budgeting or bidding purpose. After a case study and sensitivity test, they suggested the critical factors are project length, difficulty factors, man-hour cost, waste treatment, remediation, planning length, and on-site exemption wastes.

Lararia et al. (2005) [6] analyzed the factors that determines decommissioning strategy of NPP. The decommissioning cost heavily depends on the national policy and strategy, which factors, of course, impact to the decommissioning cost. They suggested seven factors that national authority should consider when determining decommissioning strategy: meeting policy requirements, availability of resources, costs, spent fuel and radioactive waste management, safety and security, regulatory aspects, multiple facilities, knowledge management, social and economic impacts, and stakeholder considerations.

IAEA (2011) [7] also provides policies and strategies guideline for the decommissioning of nuclear and radiological facilities. A decommissioning policy is a set of established goals or requirements for the safe and effective decommissioning of nuclear facilities. The policy should enable a graded approach to be taken to decommissioning, reflecting the level of the hazard posed by the facility to be decommissioned and its complexity. It emphasizes the decommissioning of nuclear power plant should provide protection of people and the environment, a long-term commitment to ensuring sites and waste, efficiency in the use of resources, open and transparent interactions with stakeholders, and participation in decision making to the public. All these requirements should be considered when budget-
ing a decommissioning project cost. Examples of the main elements to be considered in establishing a national policy for decommissioning are allocation of responsibilities, provision of resources, decommissioning approaches, safety and security objectives, radioactive waste management, hazardous waste minimization, end points for decommissioning, and public information and participation.

ENRESA (2017) [8] case also shows that the increase in the project management period due to delays, a strengthened regulatory requirement, and a change in site restoration requirements can significantly affect the actual decommissioning costs of NPP.

Following the previous research, we identified several candidates for explanatory variables, which can represent the cost drivers. The selected candidates are plant capacity, commercial operation period, ratio of operation to total hours, lifetime quantity of electricity generated during operation period, duration of decommissioning work, real GDP per capita, regulatory site release criteria, reactor types, decommissioning strategies (deferred, immediate, entombment). These variables are available by document research and rationally considered as proxies to the individual causes in part or in collective manner, even though some of them may not be original cause of decommissioning cost.

As of September 2020, 187 nuclear power reactors are permanently shut down. We investigated 123 documents [11-133] to collect historical decommissioning costs along with candidate explanatory variables data, which result is summarized in the [Appendix 1]. Most of them are decommissioned whereas some of them are in progress or planning. All the monetary values are converted into USD, as of FY 2019. The examples of collected items are the actual degree of contamination, in line with the specific release criteria and clean-up levels applied for the plants, technological approaches adopted for dismantling and demolition. For waste management, there is considerable variation to the extent to which the estimates provided incorporate these costs. It is reasonable to expect waste management costs as an increasing function of waste volumes, which may be proportional to capacity, operating period, or efficiency.

3. Research data and model

We build regression models based on a hypothesis that decommissioning cost is determined by plant specification factors, operation characteristics, and decommissioning work. The plant type is treated as a discrete variable to check systematic difference between plant specifications. Following the Han et al. (2020), we try building a synthetic variable of contamination, which reflects the operation characteristics. The plant capacity, year of operation, and efficiency factors are selected to represent the degree or waste of contamination. We include the duration of decommissioning work, level of wage, decommissioning strategy, and minimum environmental requirement as factors for decommissioning work. On top of the former research, we will develop enhanced 2SLS regression analysis to find out more reliable determinants and forecasting formula. Additionally, we will try to suggest model for BWR, which was not able to be explained in previous research.

First, we perform pooled OLS (Ordinary Least Squares) regressions to find out statistically effective determinants on decommissioning cost. Especially, the contamination variable is tested. Second, we improve the first result by substituting and testing a possibility of instrumenting the contamination with the three operation factors: the plant capacity, year of operation, and efficiency. In case it is statistically reliable, we develop a 2SLS (Two Stage Least Squares) models [10]. Finally, we will perform Monte-Carlo Simulation to illustrate the fitness of estimation formula that is derived from the 2SLS parameters.

3.1 Data and statistics

The definitions of selected variables, as discussed in the
above ‘2. Literature Review’, are summarized in the above table.

We collected 187 cases of decommissioning data [Appendix]. And 87 cases are excluded through a data cleaning process (deleting cases with omitted information, irrational value, experimental plants, etc.). As a result, 100 cases are applied to the empirical test. The basic statistics of the data set is summarized in the above table.

### 3.2 OLS (Ordinary Least Squares) model

Radionuclide waste is generated by neutron irradiation

| Variable | Observation | Mean   | Std. Dev. | Min.  | Max.   |
|----------|-------------|--------|-----------|-------|--------|
| dcost    | 100         | 797.49 | 488.79    | 74.37 | 2,527.00 |
| capa     | 100         | 1,536.24 | 1,128.99 | 58.00 | 4,800.00 |
| opyear   | 100         | 29.27  | 11.04     | 1.33  | 48.79  |
| eff      | 100         | 74.60  | 14.18     | 26.80 | 94.50  |
| genq     | 100         | 82.65  | 78.31     | 0.32  | 315.58 |
| workyear | 100         | 40.07  | 27.74     | 5.41  | 88.00  |
| wage     | 100         | 45,099.95 | 13,860.11 | 1,308.32 | 80,212.29 |
| criteria | 100         | 0.07   | 0.10      | 0.01  | 0.25   |
| type*    | 100         | 0.79   | 0.77      | 0.00  | 2.00   |
| str      | 100         | 0.45   | 0.50      | 0.00  | 1.00   |

* Number of reactor type: others = 42, PWR = 37, BWR = 21
** All the monetary values are transferred into USD as of FY 2019

| Variable | Definition | Units | Reference |
|----------|------------|-------|-----------|
| dcost    | decommissioning cost of nuclear power reactor | million USD | [19-133] |
| capa     | capacity of nuclear power reactor | MW | [11] |
| opyear   | operation period of nuclear power reactor from the beginning of commercial operation to shutdown | years | [11] |
| eff      | ratio of operation hours against total hours | percent | [11] |
| genq     | total quantity of electricity generated during operation period | TWh | [11] |
| workyear | decommissioning duration of nuclear power reactor | years | [19-133] |
| wage     | Average GDP per capita at beginning of decommissioning work, modified into 2019 price with GDP deflator | USD | [12-14] |
| criteria | nuclear power plant site release criteria | mSv per yr | [15-18, 51] |
| type     | nuclear power reactor type: others(*) = 0, PWR = 1, BWR = 2 | discrete | [19-133] |
| str      | decommissioning strategy of nuclear power reactor: deferred = 0, immediate = 1 | discrete | [19-133] |

(*) PHWR, GCR, LWGR, FBR, and so on

| Variable | Definition | Units | Reference |
|----------|------------|-------|-----------|
| dcost    | decommissioning cost of nuclear power reactor | million USD | [19-133] |
| capa     | capacity of nuclear power reactor | MW | [11] |
| opyear   | operation period of nuclear power reactor from the beginning of commercial operation to shutdown | years | [11] |
| eff      | ratio of operation hours against total hours | percent | [11] |
| genq     | total quantity of electricity generated during operation period | TWh | [11] |
| workyear | decommissioning duration of nuclear power reactor | years | [19-133] |
| wage     | Average GDP per capita at beginning of decommissioning work, modified into 2019 price with GDP deflator | USD | [12-14] |
| criteria | nuclear power plant site release criteria | mSv per yr | [15-18, 51] |
| type     | nuclear power reactor type: others(*) = 0, PWR = 1, BWR = 2 | discrete | [19-133] |
| str      | decommissioning strategy of nuclear power reactor: deferred = 0, immediate = 1 | discrete | [19-133] |

(**) Number of reactor type: others = 42, PWR = 37, BWR = 21
** All the monetary values are transferred into USD as of FY 2019
and contamination caused by leaked radionuclides during reactor operation. According to IAEA (1998) [9], for all reactor types, the radionuclide composition of activated and contaminated materials may vary with a wide range. A detailed assessment is required including operational information, history, and on-site sampling of nuclear power plants for all the individual cases, which is not feasible. And thus, a proxy variable is required for a modelling purpose. The variation is influenced by numerous factors, among which important ones are the integrated neutron flux, the duration of the operation and the time elapsed after reactor shutdown. In addition, for similar nuclear power plants, the higher the reactor power output, the higher the neutron fluxes and hence the higher the amount of activation products. IAEA (1998) also guides that, with respect to decommissioning a nuclear power plant, an assessment of radionuclide inventory characterization should be carried out to predict the costs of decommissioning, as well as relevant action plan. Considering the above discussions and relevant factors from Joo et al. (2020) [5], a contamination variable is constructed as follows:

$$\text{contam}_i = \text{capa}_i \times \text{opyear}_i \times \text{eff}_i$$

(1)

where, $\text{contam}_i$ = degree of contamination in case $i$

The OLS models are designed and tested based on the assumption that decommissioning cost may depend on the degree of radioactive contamination, factors related with decommissioning activity such as wage and duration, plant specification such as reactor types. The first set of decommissioning cost estimation models, including the ‘contam’ variable, are as follows:

$$\ln_{\text{dcost}} = \alpha_0 + \alpha_1 \ln_{\text{contam}} + \alpha_2 \ln_{\text{workyear}} + \alpha_3 \ln_{\text{wage}} + \alpha_4 \ln_{\text{criteria}} + \text{Dtype} + \text{Dstr} + \varepsilon_i$$

(2)

where, $\ln_{\text{var}_i}$ = natural log of ‘variable $i$’, $\alpha_0$ = coefficients for estimation, $D_n$ = coefficients for discrete variable, $\varepsilon_i$ = error term of $i$

We use p-value in order to check the confidence interval. When a probability sample of n size is $\{x_1, x_2, \cdots, x_n\}$ from a population with a density function $f(x; \theta)$ with parameter $\theta$, lower confidence limit $\theta_L = (\hat{\theta}_L)$ and upper confidence limit $\theta_U = (\hat{\theta}_U)$ for a given significance value of $0 < \alpha < 1$, satisfy $P(\hat{\theta}_L < \theta < \hat{\theta}_U) = 1 - \alpha$ and when $\theta_L < \theta_U$, the intervals $[\theta_L, \theta_U]$ are called as $(1-\alpha)\times 100\%$ confidence level for parameter $\theta$. And thus, it can be expressed as $P\left(\frac{X - \mu}{\sigma/\sqrt{n}} < Z_{\alpha/2}\right) = 1 - \alpha$. We use the STATA commercial tool for the robust OLS estimation.

### 3.3 2SLS (Two Stage Least Squares) model

The estimated coefficients in equation 2 may have critical problem if the synthetic variable of contam does not reliably mimic the degree of contamination for individual cases. We can reasonably doubt this possibility because the equation 1 is made simply by multiplying capa, opyear, and eff, instead of observed data or mathematical calculation. In short, we cannot verify whether the equation 1 is true or not. So, we apply 2SLS methodology to improve this issue, and suggest another explanatory variable that can be well instrumented by the three operational factors (capa, opyear, eff).

The 2SLS model can be expressed as combined equations of 3 and 4, which are the first and second steps respectively [10].

$$y_{i2} = \pi_0 + \sum_{j=1}^{m} \pi_6 z_{ij} + u_i$$

(3)

where, the $z_{ij}$ are exogenous instrument variables, and the $y_{i2}$ is endogenous explanatory variable.

$$y_{i1} = \beta_0 + \beta_1 E(y_{i2}) + \sum_{k=1}^{s} \beta_k x_{ik-1} + v_i$$

(4)

The equation 3 should be estimated through the first
regression analysis and the \( y_{i,2} \) be predicted. Again, the predicted \( E(y_{i,2}) \) is used as an explanatory variable in the equation 4. Basically, the 2SLS has been developed to cope with the endogeneity issue, which can be mathematically expressed as \( \text{cov}(y_{i,2}, v_i) \neq 0 \) in the equation 4. The instrument variables ‘\( z_k \)’ should be correlated with the endogenous explanatory variable ‘\( y_{i,2} \)’ but should not be correlated with error term ‘\( v_i \)’.

In our empirical analysis, we substitute the ‘contam’ variable with ‘\( \text{genq} \)’, which is the quantity of lifetime electricity generation of a system because it can be well instrumented by the three operational variables (\( \text{capa} \), \( \text{opyear} \), \( \text{eff} \)), which were used to explain the degree of contamination in equation 1. We can rationally establish the formula (5) instead of simply using (1) because variables in both the left and right sides can be observed.

\[
\ln_{\text{genq}} = \pi_0 + \pi_1 \ln_{\text{capa}} + \pi_2 \ln_{\text{opyear}} + \pi_3 \ln_{\text{eff}} + u_i \quad (5)
\]

Based on the equation 5, we test whether the estimated coefficients (\( \pi_n \)) are statistically reliable. And, if the result is acceptable, we use the \( \text{genq} \) as a proxy variable for the degree of contamination. Actually, this procedure coincides with the first step of 2SLS, which is discussed with the equation 3. Under this procedure, the \( \text{capa} \), \( \text{opyear} \), and \( \text{eff} \) are exogenous instrument variables (‘\( z_{i,j} \)’ in equation 3) that explain \( \text{genq} \) (‘\( y_{i,2} \)’ in equation 3).

In the second step, we regress \( \text{dcost} \) on \( E(\text{genq}) \) along with other explanatory variables such as \( \text{workyear} \), wage, criteria, and type.

\[
\ln_{\text{dcost}} = \beta_0 + \beta_1 E(\text{genq}) + \beta_2 \ln_{\text{workyear}} + \beta_3 \ln_{\text{wage}} + v_i \quad (6)
\]

where, \( \ln_{\text{\var{variable}}} = \) natural log of ‘\( \text{variable} \)’, \( \beta_k = \) coefficients for estimation, \( v_i = \) error term of \( i \)

We will use the STATA commercial tool for the 2SLS regression analysis and thus the estimated result will be fine-tuned statistically.

3.4 Probabilistic cost estimation

We will forecast decommissioning cost together with 95% of confidence intervals (\( \hat{y}_i \pm t_{a/2} \times \text{SD}(\hat{y}) \)), using the STATA commercial tool. The forecasted results are compared against the actual cost to show the fitness of the models.

And then, we will perform a Monte-Carlo simulation based on the derived formula along with the observed distributions of variables. We will use the Palisade Risk Analysis commercial tool.

4. Empirical test result

4.1 Result of OLS (Ordinary Least Squares)

We estimated the parameters of models from (1) to (6) based on the equation 2. The first group of models (1)–(3) are pooled regressions including all types of reactors. We also did regression analysis based on separate groups of reactors for the robustness check purpose. The result is summarized as the below table.

We proxied the quantity of radioactive waste with the contam variable, as identified in the equation 1. From the models (1) through (3), the contam variable seems statistically reliable. A comprehensive review from the models (1) through (3) suggest that the amount of radioactive waste or the radionuclide inventory may account for the decommissioning cost.

Both the \( \text{workyear} \) and wage show 99% of confidence level in all the models from (1) to (3), and at the same time, they provide stable parameter estimates. We may think the decommissioning duration and the level of labor cost per capita also affect to the decommissioning costs.

However, it is surprising to find out that the parameters
of the criteria and str are different from expectation. As is shown from models (1) to (3), the difference in minimum environmental requirement criteria, and decommissioning strategies would not significantly affect the overall decommissioning cost. We may conclude that decommissioning strategy and minimum environmental requirement criteria do not significantly change the total cost. As the strategy is closely related with workyear variable, it could have caused a multicollinearity issue.

Again, we separated groups based on the three reactor types and performed same robust regression analysis as in models from (4) to (6). The results show that the estimated coefficients not only for contam but also for workyear and wage are significantly different among reactor types. We conclude that the groups with different type of reactors are heterogeneous, and thus the pooled OLS regression cannot be applied. It is also found that the contam variable is valid only in the type 2 group, and thus we conclude that the contam variable cannot be accepted properly as proxy variable for the degree of radioactive waste.

### 4.2 Result of 2SLS (Two Stage Least Squares)

Using the same dataset, we performed 2SLS analysis as suggested by the equations from 3 through 6 with each group of reactor types: the type 0 is others, type 1 is PWR,
and type 2 is BWR. The result is summarized in the below table: From the Table 4, the first stage estimators show the genq can berationally instrumented by the three explanatory variables: capa, opyear, and eff. We included three of them in model (7) and (9), and two of them in model (8), considering p-values. The range of R-squared values are from 78.9% to 99.6%, which result verifies there is no concern for a ‘weak instrument problem’ for the 2SLS methodology. And the estimated coefficients of capa, opyear, and eff are statistically significant under 99% confidence level.

After the 2SLS regressions, we performed the Sargan and Basmann tests to check overidentification issue. We also did Durbin and Wu-Hausman tests to check endogeneity. In overall, the model (8) shows the best result for using 2SLS. The result in model (7) is not satisfactory but close to 90% of criteria in confidence levels. The model (9) does not have overidentification issue. But there is no evidence of endogeneity so simple OLS estimator can be used instead of 2SLS for the model (9). However, we select the 2SLS because it improved parameters and R-squared values. In summary, we have no reason to reject 2SLS methodology for the models from (7) through (9).

From the three test results of Table 4, we found that 2SLS regression can generate better estimators than simple OLS, and the genq can be properly instrumented by the three operational variables, which represent the compara-

### Table 4. Decommissioning Cost Estimation (2SLS model)

| Variables       | (7) type 0 |         | (8) type 1 |         | (9) type 2 |         |
|-----------------|------------|---------|------------|---------|------------|---------|
|                 | First Stage| Second Stage | First Stage| Second Stage | First Stage| Second Stage |
| ln_genq         | ln_dcost   | ln_genq | ln_dcost   | ln_genq | ln_dcost   |         |
| ln_genq         | 0.117**    | (0.0551)| 0.284***   | (0.108) | 0.353***   | (0.107) |
| ln_capa         | 1.072***   | (0.0402)| 1.214***   | (0.128) | 1.064***   | (0.0166)|
| ln_opyear       | 0.696***   | (0.0667)|           |         | 1.084***   | (0.0418)|
| ln_eff          | 1.032***   | (0.155 )| 1.567***   | (0.438 )| 0.725***   | (0.138 )|
| ln_workyear     | 0.0664     | (0.0568)| 0.341***   | (0.0899)| 0.0206     | (0.121 )| 0.462*** | (0.130 )|
| ln_wage         | 1.062*     | (0.0906)| 0.334***   | (0.102 )| −0.00973   | (0.0696) | 0.676*   | (0.414 )|
| Constant        | −10.79***  | (0.534 )| 4.735***   | (0.361 )| −13.15***  | (2.297 )| 0.403    | (1.089 )| −10.04*** | (0.746 )| −2.276   | (4.158 )|
| Observations    | 42         | 42      | 37         | 37      | 21         | 21      |
| R-squared       | 0.974      | 0.352   | 0.789      | 0.493   | 0.996      | 0.462   |

*Genq is instrumented by the capa, opyear, eff, and workyear, where the capa, opyear, and eff are explanatory variables for genq but the workyear is exogeneous variable in model (7).

**Standard Errors in parentheses: *** p < 0.01, ** p < 0.05, * p < 0.1
The estimated parameters can be translated as elasticity because all variables are in the form of natural logarithm. Based on the second stage estimators in models (7) through (9), it is found that the instrumented $E(\text{genq})$ variable is statistically reliable. The results can be translated that if genq, or level of radioactive waste, increase one percent, the decommissioning cost increase 11.7% in type 0, 28.4% in type 1, and 35.3% in type 2 reactors.

The workyear, duration of decommissioning, makes critical impact on type 0, and type 1 reactors. It is found that, if the duration increases one percent, the decommissioning cost increase 34.1% and 46.2%, respectively. The wage, which is a comparative level of labour cost, affects 33.4% and 67.6% to type 1 and type 2 reactors by one percent change.

Similar to the OLS analysis result, it is proved that decommissioning strategy and environmental requirements do not significantly change the decommissioning cost. It seems that the duration factor reflected most of the strategy effect.

In summary, we conclude that level of radioactive waste along with the decommissioning duration and the level of labor cost per capita significantly determine the decommissioning cost. And the level of radioactive waste can be explained by the operation factors such as period of operation, capacity of plant, and efficiency.

The decommissioning cost of PWR type is significantly determined by plant capacity, efficiency, duration of decommissioning work, and level of wage. The capacity factor may impact thorough two routes: increasing the dimension of structure as well as radioactive waste. Both the capacity and efficiency factors explain the degree of radioactive waste by instrumenting the total electricity generation. The duration of work and level of wage explain themselves. Additionally, we infer the cost impact from the different decommissioning strategies is already reflected by the duration of work because they are highly correlated. The site release criteria have smaller value in stricter countries and thus negatively correlated to cost, which direction is reasonably shown in the model (1) of Table 3. However, this variable is not selected as one of major determinants due to lack of confidence.

The decommissioning cost of BWR type is mainly determined by plant capacity, operation period, efficiency, and level of wage. The BWR type additionally includes the operation period, which explains the degree of radioactive waste, however it does not include the duration of decommissioning work as a major cost determinant. The operation period not only the capacity and efficiency factors explain the degree of radioactive waste by instrumenting the total electricity generation in this group.

Even though the main purpose of current study is to investigate determinants of decommissioning cost, we formulate the cost estimation models for simulation purpose. The equation 7 is derived from the model (8) of Table 4 and

| Issues          | Tests     | Model (7)    | Model (8)     | Model (9)     |
|-----------------|-----------|--------------|---------------|---------------|
| Overidentification | Sargan chi2 | 4.31 (p = 0.11) | 10.23 (p = 0.00) | 5.04 (p = 0.08) |
| Basmann chi2    | 4.23 (p = 0.12) | 12.23 (p = 0.00) | 5.06 (p = 0.07) |
| Durbin chi2     | 2.40 (p = 0.12) | 5.06 (p = 0.02) | 0.16 (p = 0.68) |
| Wu-Hausman      | 2.30 (p = 0.13) | 5.08 (p = 0.03) | 0.16 (p = 0.69) |
Fig. 1. Cost estimation result for type 1 (PWR).

*dcost_real = historical decommissioning cost expressed in real (year of 2019) value; dcost_LB = lower bound of estimated cost with 95% confidence level; dcost_hat = point estimation of decommissioning cost based on the equation 7; dcost_UB = higher bound of estimated cost with 95% confidence level.

Fig. 2. Cost estimation result for type 2 (BWR).

*dcost_real = historical decommissioning cost expressed in real (year of 2019) value; dcost_LB = lower bound of estimated cost with 95% confidence level; dcost_hat = point estimation of decommissioning cost based on the equation 7; dcost_UB = higher bound of estimated cost with 95% confidence level.
corresponds to type 1 reactors (PWR).

\[ d\text{cost}_i = \text{capa}_i^{0.344} \times \text{eff}_i^{0.445} \times \text{workyear}_i^{0.467} \times \]
\[ \text{wage}_i^{0.379} \times e^{-3.328} \]  
(7)

We also present the equation 8, which is derived from the model (9) of Table 4 and accounts for type 2 (BWR) reactors.

\[ d\text{cost}_j = \text{capa}_j^{0.375} \times \text{eff}_j^{0.256} \times \text{opyear}_j^{0.382} \times \]
\[ \text{wage}_j^{0.672} \times e^{-5.820} \]  
(8)

### 5. Simulation

We performed static cost estimation using the STATA commercial tool based on the models (8) and (9) of Table 4. After the static cost estimation, we also drew 95% of confidence intervals (\( \hat{y}_i \pm t_{0.975} \times SD(\hat{y}) \)). The input data for individual cases are from the [Appendix]. The monetary values are million USD basis as of FY 2019. The cost estimation result and their actual cost are illustrated in Fig. 1 and 2.

The Fig. 1 shows that the estimation results tend to have deviation from the actual value among the cases with high and low levels of decommissioning costs. We conclude that the model (8) fits well for PWR type NPPs with decommissioning costs from 1,265 mil to 400 mil USD. The Fig. 2 shows a little bit different range of fitness of the model (9) for BWR NPPs from 1,963 mil to 376 mil USD of decommissioning costs.

We performed the same cost estimation process for the KORI-1, which case was reserved (excluded from the regression modelling). The input data of KORI-1 is as follows: The estimated static decommissioning cost of KORI-1 is 691.7 mil USD (in 2019 FY value), which is about 3.1% lower than the authority’s official estimation of 714.4 mil USD.
USD (in 2019 FY value). The 95% confidence interval is calculated as [554 mil, 862 mil] by the STATA statistics tool.

We again performed a Monte Carlo Simulation for the KORI-1 as illustrated in Fig. 3. The input data of Table 6 along with the standard deviations from Table 2 are applied to the equation 7. We ran 10,000 times of simulation with the PALISADE tool.

The most likely estimation value is 736.07 mil USD, which is 3.03% higher than the authority’s estimation. The 95% confidence interval is calculated as [175 mil, 1,372 mil]. The Fig. 4 illustrates the input variables that have critical impact and their degree of contributions to output variance. The capa variable could have been reported as one of the highly determining factors, in case we forecast decommissioning cost for unidentified project, but we did not include it as one of simulation variables because there is low possibility of deviation once the KORI-1 plant is constructed.

6. Conclusion

The empirical tests showed that the level of radioactive waste along with the decommissioning duration and the level of labor cost per capita significantly determine the decommissioning cost. And the degree of radioactive waste can be explained by the operation factors such as period of operation, capacity of plant, and efficiency.

We found that the plant groups with different type of reactors are heterogeneous, and thus the pooled OLS regression cannot be applied. And the contam variable has a shortfall of not testable. For the purpose of improving this issue, we applied 2SLS methodology and suggested genq variable, which could be instrumented by the three operational factors (capa, oyear, eff). From the test results of Table 4, we found that 2SLS regression analysis can generate better estimators than simple OLS. And the genq can be properly instrumented by the three operational variables, which represent the comparative amount of radioactive waste.

The results can be translated that, if the level of radioactive waste (measured by proxy variables) increases one percent, the decommissioning cost increases 28.4% in the PWR type NPPs. The cost increases 46.2% and 33.4% due to one percent increase in work duration and level of labour cost, respectively. The test results also present that the decommissioning cost increases 35.3% in the BWR type NPPs, if the level of radioactive waste (measured by proxy variables) increases one percent. The cost also increases 67.6% due to one percent increase in labour cost level.

We illustrated static cost estimation as well as confidence intervals in Fig. 1 and 2, using the STATA statistics tool. We did the same analysis on the KORI-1. The most likely value is estimated at 691.7 mil USD and the 95% interval is calculated at [554 mil, 862 mil], where the authority’s official estimation is 714.4 mil USD. The Monte-Carlo simulation provided 736.07 mil USD of the most likely value and [175 mil, 1,372 mil] of the 95% confidence level.

As the second stage R-squared values of models (8) and (9) in Table 4 indicate, we clearly admit that the cost estimation models (equation 7 and 8 can explain only 49% for PWR and 46% for BWR type NPPs. The forecasting ability will be enhanced either by adding determining factors or improving models through further studies.

Acknowledgment

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### Appendix 1. Permanent shutdown nuclear power reactors [19-133]

| Country  | Reactor           | Type | Capa. (MWth) | Op. factor (%) | Total generation (TWh) | Decom. work period | Cost (M USD) |
|----------|-------------------|------|--------------|----------------|------------------------|--------------------|--------------|
| ARMENIA  | ARMENIAN-1        | PWR  | 1,375        | 67.8           | 25.3                   | 50                 | 212.0        |
| BELGIUM  | BR-3              | PWR  | 41           | 51.5           | 0.8                    | 21                 | 10.7         |
| BULGARIA | KOZLODUY-1        | PWR  | 1,375        | 73.0           | 61.1                   | 18                 | 401.1        |
| BULGARIA | KOZLODUY-2        | PWR  | 1,375        | 79.2           | 62.8                   | 18                 | 401.1        |
| BULGARIA | KOZLODUY-3        | PWR  | 1,375        | 81.4           | 62.8                   | 18                 | 401.1        |
| BULGARIA | KOZLODUY-4        | PWR  | 1,375        | 82.6           | 61.0                   | 18                 | 401.1        |
| CANADA   | DOUGLAS POINT     | PHWR | 704          | 67.1           | 15.6                   | NA                 | -            |
| CANADA   | GENTILLY-1        | HWL  | 792          | 7.5            | 0.8                    | 3                  | -            |
|          | GENTILLY-2        | PHWR | 2,156        | 81.2           | 124.2                  | 54                 | 1,098.7      |
|          | PICKERING-2       | PHWR | 1,744        | 62.5           | 71.4                   | 59                 | 520.5        |
|          | PICKERING-3       | PHWR | 1,744        | 70.8           | 80.0                   | 59                 | 520.5        |
|          | ROLPHTON NPD      | PHWR | 92           | 72.4           | 32.7                   | NA                 | -            |
| FRANCE   | BUGEY-1           | GCR  | 1,954        | 70.1           | 55.3                   | 18                 | 509.3        |
|          | CHINON A-1        | GCR  | 300          | 39.8           | 3.0                    | 53                 | 333.8        |
|          | CHINON A-2        | GCR  | 800          | 75.0           | 24.9                   | 44                 | 333.8        |
|          | CHINON A-3        | GCR  | 1,170        | 49.1           | 30.6                   | 22                 | 333.8        |
|          | CHOOZ-A           | PWR  | 1,040        | 71.0           | 38.6                   | 18                 | 272.0        |
|          | EL-4              | HWGCR| 250          | 75.4           | 6.3                    | 12                 | 461.1        |
|          | FESENHEIM-1       | PWR  | 2,785        | 74.0           | 225.7                  | NA                 | -            |
|          | FESENHEIM-2       | PWR  | 2,785        | 71.9           | 216.9                  | NA                 | -            |
|          | G-2 (MARCOULE)    | GCR  | 260          | 66.2           | 0.9                    | NA                 | -            |
|          | G-3 (MARCOULE)    | GCR  | 260          | 78.8           | 10.5                   | NA                 | -            |
|          | PHENIX            | FBR  | 345          | 41.2           | 24.4                   | 14                 | 1,074.6      |
|          | ST. LAURENT A-1   | GCR  | 1,650        | 71.9           | 45.3                   | 27                 | 330.9        |
|          | ST. LAURENT A-2   | GCR  | 1,475        | 64.4           | 46.9                   | 22                 | 330.9        |
|          | SUPER-PHENIX      | FBR  | 3,000        | 14.4           | 3.4                    | 18                 | 1,165.7      |
| GERMANY  | AVR JUELICH       | HTGR | 46           | 65.9           | 1.5                    | 33                 | 922.6        |
|          | BIBLIS-A          | PWR  | 3,517        | 68.7           | 232.8                  | 16                 | 878.0        |
|          | BIBLIS-B          | PWR  | 3,733        | 74.5           | 247.4                  | 16                 | 878.0        |
|          | BRUNSBUETTEL      | BWR  | 2,292        | 57.9           | 120.4                  | 15                 | 1,240.2      |
|          | GRAFENRHEINFELD   | PWR  | 3,765        | 88.7           | 315.6                  | 18                 | 1,354.8      |
|          | GREIFSWALD-1      | PWR  | 1,375        | 84.6           | 35.5                   | 34                 | 1,324.8      |
|          | GREIFSWALD-2      | PWR  | 1,375        | 85.1           | 36.6                   | 34                 | 1,324.8      |
|          | GREIFSWALD-3      | PWR  | 1,375        | 82.5           | 33.3                   | 34                 | 1,324.8      |
|          | GREIFSWALD-4      | PWR  | 1,375        | 79.4           | 28.9                   | 34                 | 1,324.8      |
|          | GREIFSWALD-5      | PWR  | 1,375        | 0.0            | 0.0                    | 34                 | 1,324.8      |
| Country          | Reactor          | Type   | Capa. (MWth) | Op. factor (%) | Total generation (TWh) | Decom. work period | Cost (M USD) |
|------------------|------------------|--------|--------------|----------------|------------------------|--------------------|--------------|
| GUNDREMMINGEN-A  | BWR              |        | 801          | 81.2           | 13.8                   | 47                 | 2,782.3      |
| GUNDREMMINGEN-B  | BWR              |        | 3,840        | 90.4           | 314.5                  | 22                 | 1,693.5      |
| HDR GROSSWELZHEIM| BWR              |        | 100          | 42.4           | 0.0                    | 16                 | -            |
| ISAR-1           | BWR              |        | 2,575        | 86.0           | 198.3                  | 16                 | 1,182.9      |
| KNK II           | BWR              |        | 58           | 26.8           | 0.3                    | 31                 | 475.0        |
| KRUEMMEL         | BWR              |        | 3,690        | 69.2           | 201.7                  | NA                 | -            |
| LINGEN           | BWR              |        | 520          | 42.2           | 9.1                    | NA                 | -            |
| MUELHEIM-KAERLICH| PWR              |        | 3,760        | 76.0           | 10.3                   | 21                 | 1,036.6      |
| MZFR             | PHWR             |        | 200          | 73.3           | 4.8                    | 35                 | 449.0        |
| NECKARWESTHEIM-1 | PWR              |        | 2,497        | 84.7           | 186.8                  | 16                 | -            |
| NIEDERAIachbach  | HWGCR            |        | 321          | 9.0            | 0.0                    | 20                 | 173.6        |
| OBRIGHEIM        | PWR              |        | 1,050        | 83.7           | 86.8                   | 17                 | 770.1        |
| PHILIPPSBURG-1   | BWR              |        | 2,575        | 80.3           | 187.6                  | 21                 | -            |
| PHILIPPSBURG-2   | PWR              |        | 3,950        | 88.2           | 347.1                  | 20                 | -            |
| RHEINSBERG       | PWR              |        | 265          | NA             | NA                     | 31                 | 1,153.2      |
| STADE            | PWR              |        | 1,900        | 85.3           | 145.9                  | 16                 | 1,264.7      |
| TTR-300          | HTGR             |        | 760          | 56.0           | 2.8                    | 33                 | 837.2        |
| UNTERWESER       | PWR              |        | 3,900        | 83.7           | 289.8                  | 15                 | 1,264.7      |
| VAK KAHL         | BWR              |        | 60           | 67.8           | 2.1                    | 22                 | 194.6        |
| WUERGASSEN       | BWR              |        | 1,912        | 71.9           | 69.7                   | 17                 | 1,461.1      |
| ITALY            |                  |        |              |                |                        |                    |              |
| CAORSO           | BWR              |        | 2,651        | 43.5           | 27.7                   | 32                 | 376.0        |
| ENRICO FERMI(TRINO)| PWR          |        | 870          | 50.0           | 24.3                   | 32                 | 273.2        |
| GARIGLIANO       | BWR              |        | 506          | 44.8           | 12.3                   | 27                 | 432.4        |
| LATINA           | GCR              |        | 660          | 71.7           | 25.5                   | 28                 | 316.1        |
| JAPAN            | FUGEN ATR        | HWL    | 557          | 63.7           | 8.5                    | 31                 | 623.2        |
| FUKUSHIMA-DAIICHI-1| BWR           |        | 1,380        | 56.1           | 82.4                   | 39                 | -            |
| FUKUSHIMA-DAIICHI-2| BWR           |        | 2,381        | 64.3           | 148.2                  | 39                 | -            |
| FUKUSHIMA-DAIICHI-3| BWR           |        | 2,381        | 67.6           | 155.9                  | 39                 | -            |
| FUKUSHIMA-DAIICHI-4| BWR           |        | 2,381        | 71.9           | 154.3                  | 39                 | -            |
| FUKUSHIMA-DAIICHI-5| BWR           |        | 2,381        | 67.5           | 156.4                  | NA                 | -            |
| FUKUSHIMA-DAIICHI-6| BWR           |        | 3,293        | 65.3           | 206.7                  | NA                 | -            |
| FUKUSHIMA-DAINI-1| BWR              |        | 3,293        | 59.4           | 205.7                  | NA                 | -            |
| FUKUSHIMA-DAINI-2| BWR              |        | 3,293        | 57.2           | 190.6                  | NA                 | -            |
| FUKUSHIMA-DAINI-3| BWR              |        | 3,293        | 51.2           | 163.1                  | NA                 | -            |
| FUKUSHIMA-DAINI-4| BWR              |        | 3,293        | 53.8           | 161.4                  | NA                 | -            |
| GENKAI-1         | PWR              |        | 1,650        | 69.0           | 127.7                  | 27                 | 332.8        |
| GENKAI-2         | PWR              |        | 1,650        | 64.2           | 118.2                  | 35                 | 325.0        |
| Country            | Reactor | Type | Capa. (MWth) | Op. factor (%) | Total generation (TWh) | Decom. work period | Cost (M USD) |
|-------------------|---------|------|--------------|----------------|------------------------|-------------------|--------------|
| HAMAOKA-1         | BWR     | 1,593| 50.1        | 73.6            | 0.9                    | 27               | -            |
| HAMAOKA-2         | BWR     | 2,436| 60.8        | 129.6           | 0.9                    | 27               | -            |
| IKATA-1           | PWR     | 1,650| 69.9        | 125.7           | 0.9                    | 40               | 364.3        |
| IKATA-2           | PWR     | 1,650| 68.4        | 115.9           | 0.9                    | 38               | -            |
| JPD              | BWR     | 90   | 0.1         | 0.0             | 0.1                    | 15               | 181.4        |
| MIHAMA-1          | PWR     | 1,031| 50.2        | 60.1            | 0.1                    | 29               | 295.3        |
| MIHAMA-2          | PWR     | 1,456| 58.6        | 101.6           | 0.1                    | 29               | 326.4        |
| MONJU             | FBR     | 714  | 0.0         | 0.0             | 0.0                    | 30               | 1,342.1      |
| OHI-1             | PWR     | 3,423| 56.0        | 213.3           | 0.1                    | 29               | 530.2        |
| OHI-2             | PWR     | 3,423| 61.5        | 231.7           | 0.9                    | 29               | 532.0        |
| ONAGAWA-1         | BWR     | 1,593| 52.6        | 81.8            | 0.9                    | 34               | 375.3        |
| SHIMANE-1         | BWR     | 1,380| 64.7        | 101.9           | 0.9                    | 29               | 341.9        |
| TOKAI-1           | GCR     | 587  | 78.6        | 28.2            | 0.9                    | 29               | 828.0        |
| TSURUGA-1         | BWR     | 1,070| 62.4        | 80.1            | 0.9                    | 23               | 331.9        |
| KAZAKHSTAN        | AKTAU   | FBR  | 1,000       | 51.6            | 1.9                    | NA               | -            |
| KOREA, REP. OF    | KORI-1  | PWR  | 1,729       | 79.5            | 148.6                  | 16               | 714.4        |
| WOLSONG-1         | PHWR    | 2,061| 68.7        | 140.3           | 0.9                    | NA               | -            |
| LITHUANIA         | IGNALINA-1 | LWGR | 4,800 | 68.5 | 86.4 | 0.9 | 26 | 1,962.1 |
| LITHUANIA         | IGNALINA-2 | LWGR | 4,800 | 76.0 | 155.2 | 0.9 | 26 | 1,962.1 |
| NETHERLAND        | DODEWAARD | BWR  | 183  | 86.0 | 10.9 | 0.9 | NA | 227.8 |
| RUSSIA            | APS-1 OBINSK | LWGR | 30   | NA   | NA   | NA | NA | - |
| RUSSIA            | BELOYARSK-1 | LWGR | 286  | NA   | NA   | NA | NA | - |
| RUSSIA            | BELOYARSK-2 | LWGR | 530  | 72.1 | 22.0 | NA | NA | - |
| RUSSIA            | BILIBINO-1 | LWGR | 62   | 75.0 | 2.1  | NA | NA | - |
| RUSSIA            | LENERGRAD-1 | LWGR | 3,200 | 73.1 | 244.1 | 33 | 227.3 |
| RUSSIA            | NOVOVORONEZH-1 | PWR | 760  | NA   | NA   | NA | NA | - |
| RUSSIA            | NOVOVORONEZH-2 | PWR | 1,320 | 71.1 | 49.9 | NA | NA | - |
| RUSSIA            | NOVOVORONEZH-3 | PWR | 1,375 | 80.3 | 109.3 | NA | NA | - |
| SLOVAKIA          | BOHUNICE A1 | HWGCR | 560  | 52.4 | 0.9  | 54 | 505.6 |
| SLOVAKIA          | BOHUNICE-1  | PWR  | 1,375 | 79.2 | 71.6 | 13 | 717.3 |
| SLOVAKIA          | BOHUNICE-2  | PWR  | 1,375 | 80.8 | 77.0 | 13 | 717.3 |
| SPAIN             | JOSE CABRERA-1 | PWR | 510  | 78.9 | 34.6 | 11 | 258.2 |
| SPAIN             | SANTA MARIA DE GA- | BWR  | 1,381 | 81.6 | 127.0 | 11 | 528.4 |
| SWEDEN            | VANELLOS-1  | GCR  | 1,670 | 86.0 | 53.6 | 5  | 133.8 |
| SWEDEN            | AGESTA     | PHWR | 80   | 43.4 | 0.4  | NA | 10.7 |
| SWEDEN            | BARSEBACK-1 | BWR  | 1,800 | 81.4 | 93.8 | 15 | 273.6 |
| Country       | Reactor       | Type | Capa. (MWth) | Op. factor (%) | Total generation (TWh) | Decom. work period | Cost (M USD) |
|--------------|---------------|------|--------------|----------------|------------------------|--------------------|-------------|
| SWITZERLAND  | LUCENS        | HWGCR | 28           | NA             | NA                     | 10                 | -           |
|              | MUEHLEBERG    | BWR  | 1,097        | 90.4           | 122.5                 | 15                 | 931.0       |
| UK           | BERKELEY-1    | GCR  | 620          | 82.4           | 21.0                   | 87                 | 806.2       |
|              | BERKELEY-2    | GCR  | 620          | 82.9           | 21.6                   | 87                 | 806.2       |
|              | BRADWELL-1    | GCR  | 481          | 83.9           | 27.2                   | 86                 | 801.9       |
|              | BRADWELL-2    | GCR  | 481          | 83.9           | 27.2                   | 86                 | 801.9       |
|              | CALDER HALL-1 | GCR  | 268          | 82.3           | 14.0                   | 92                 | -           |
|              | CALDER HALL-2 | GCR  | 268          | 82.7           | 14.0                   | 92                 | -           |
|              | CALDER HALL-3 | GCR  | 268          | 82.7           | 14.0                   | 92                 | -           |
|              | CALDER HALL-4 | GCR  | 268          | 82.7           | 14.0                   | 92                 | -           |
|              | CHAPEL CROSS-1| GCR  | 260          | 94.2           | 14.2                   | 82                 | 598.0       |
|              | CHAPEL CROSS-2| GCR  | 260          | 94.2           | 14.2                   | 82                 | 598.0       |
|              | CHAPEL CROSS-3| GCR  | 260          | 94.2           | 14.2                   | 82                 | 598.0       |
|              | CHAPEL CROSS-4| GCR  | 260          | 94.2           | 14.2                   | 82                 | 598.0       |
|              | DOUNREAY DFR  | FBR  | 60           | 34.5           | 0.5                    | 17                 | -           |
|              | DOUNREAY PFR  | FBR  | 60           | 38.2           | 7.1                    | 17                 | -           |
|              | DUNGENESS A-1 | GCR  | 840          | 86.5           | 59.2                   | 85                 | 863.0       |
|              | DUNGENESS A-2 | GCR  | 840          | 86.9           | 60.7                   | 85                 | 863.0       |
|              | HINKLEY POINT A-1 | GCR  | 900          | 89.0           | 46.5                   | 86                 | 494.1       |
|              | HINKLEY POINT A-2 | GCR  | 900          | 89.0           | 46.5                   | 86                 | 494.1       |
|              | HUNTERSTON A-1 | GCR  | 595          | 94.5           | 28.7                   | 85                 | 963.0       |
|              | HUNTERSTON A-2 | GCR  | 595          | 94.5           | 28.7                   | 85                 | 963.0       |
|              | OLDBURY A-1   | GCR  | 730          | 85.5           | 62.3                   | 87                 | 981.7       |
|              | OLDBURY A-2   | GCR  | 660          | 88.9           | 65.6                   | 87                 | 981.7       |
|              | SIZEWELL A-1  | GCR  | 1,010        | 84.3           | 56.8                   | 83                 | 848.6       |
|              | SIZEWELL A-2  | GCR  | 1,010        | 80.9           | 53.3                   | 83                 | 848.6       |
|              | TRAWSFYNYDD-1 | GCR  | 850          | 92.0           | 35.2                   | 88                 | 821.3       |
|              | TRAWSFYNYDD-2 | GCR  | 850          | 92.0           | 35.2                   | 88                 | 821.3       |
|              | WINDSCALE AGR | GCR  | 120          | 56.8           | 3.3                    | 29                 | -           |
|              | WINFRITH GHWR | SGHWR| 318          | 60.9           | 11.0                   | 28                 | -           |
| UKRAINE      | CHERNOBYL-1   | LWGCR| 3,200        | 75.3           | 97.3                   | NA                 | -           |
|              | CHERNOBYL-2   | LWGCR| 3,200        | 81.1           | 76.0                   | NA                 | -           |
|              | CHERNOBYL-3   | LWGCR| 3,200        | 67.3           | 98.0                   | NA                 | -           |
| Country       | Reactor            | Type       | Capa. (MWh) | Op. factor (%) | Total generation (TWh) | Decom. work period | Cost (M USD) |
|--------------|-------------------|------------|-------------|----------------|------------------------|--------------------|--------------|
| USA          | CHERNOBYL-4       | LWGR       | 3,200       | NA             | NA                     | NA                 | -            |
|              | BIG ROCK POINT    | BWR        | 240         | 73.0           | 12.7                   | 9                  | 582.7        |
|              | BONUS             | BWR        | 50          | NA             | NA                     | 3                  | -            |
|              | CRYSTAL RIVER-3   | PWR        | 2,568       | 66.9           | 167.6                  | 61                 | 1,303.8      |
|              | CVTR              | PHWR       | 65          | NA             | NA                     | 42                 | -            |
|              | DRESDEN-1         | BWR        | 700         | 70.6           | 16.5                   | 43                 | 611.7        |
|              | ELK RIVER         | BWR        | 58          | NA             | NA                     | 2                  | 25.3         |
|              | FERMI-1           | FBR        | 200         | NA             | 0.0                    | 1                  | 26.2         |
|              | FORT CALHOUN-1    | PWR        | 1,500       | 77.3           | 130.7                  | 51                 | 1,472.9      |
|              | FORT ST. VRAIN    | HTGR       | 842         | 31.1           | 5.4                    | 7                  | 295.7        |
|              | GE VALLECITOS     | BWR        | 50          | NA             | NA                     | NA                 | 11.5         |
|              | HADDAM NECK       | PWR        | 1,825       | 76.0           | 105.7                  | 11                 | 1,074.4      |
|              | HALLAM            | SGR        | 256         | NA             | NA                     | 3                  | 17.0         |
|              | HUMBOLDT BAY      | BWR        | 220         | 84.0           | 4.8                    | 38                 | 1,153.1      |
|              | INDIAN POINT-1    | PWR        | 615         | 51.9           | 13.5                   | 12                 | 657.5        |
|              | INDIAN POINT-2    | PWR        | 3,216       | 77.5           | 282.9                  | 12                 | 717.0        |
|              | KEWAUNNE          | PWR        | 1,772       | 85.1           | 150.1                  | 60                 | 1,199.9      |
|              | LACROSSE          | BWR        | 165         | 63.2           | 3.9                    | 23                 | 74.4         |
|              | MAINE YANKEE      | PWR        | 2,630       | 73.0           | 118.7                  | 8                  | 672.8        |
|              | MILLSTONE-1       | BWR        | 2,011       | 69.2           | 101.4                  | 56                 | 498.5        |
|              | OYSTER CREEK      | BWR        | 1,930       | 78.2           | 196.2                  | 18                 | 900.4        |
|              | PATHFINDER        | BWR        | 220         | NA             | NA                     | 1                  | 17.5         |
|              | PEACH BOTTOM-1    | HTGR       | 115         | 71.2           | 1.4                    | 41                 | 268.0        |
|              | PILGRIM-1         | BWR        | 2,028       | 75.8           | 193.6                  | 63                 | 1,690.2      |
|              | PIQUA             | OCMR       | 46          | NA             | NA                     | 1                  | -            |
|              | RANCHO SECO-1     | PWR        | 2,772       | 46.4           | 44.8                   | 13                 | 572.5        |
|              | SAN ONOFRE-1      | PWR        | 1,347       | 55.1           | 51.1                   | 39                 | 259.6        |
|              | SAN ONOFRE-2      | PWR        | 3,438       | 77.1           | 219.2                  | 39                 | 2,256.1      |
|              | SAN ONOFRE-3      | PWR        | 3,438       | 78.4           | 215.7                  | 39                 | 2,527.0      |
|              | SAXTON            | PWR        | 24          | NA             | NA                     | 1                  | 11.2         |
|              | SHIPPINGPORT      | PWR        | 236         | NA             | NA                     | 4                  | 184.4        |
|              | SHOREHAM          | BWR        | 2,436       | NA             | NA                     | 3                  | 288.4        |
|              | THREE MILE ISLAND-1 | PWR    | 2,568       | 77.0           | 245.1                  | 64                 | 1,268.0      |
|              | THREE MILE ISLAND-2 | PWR   | 2,772       | 74.6           | 2.0                    | NA                 | 1,313.1      |
|              | TROJAN            | PWR        | 3,411       | 57.9           | 84.4                   | 12                 | 378.8        |
|              | VERMONT YANKEE    | BWR        | 1,912       | 86.3           | 163.4                  | 39                 | 1,142.8      |
|              | YANKEE NPS        | PWR        | 600         | 77.4           | 33.9                   | 15                 | 739.1        |
|              | ZION-1            | PWR        | 3,250       | 63.9           | 124.4                  | 10                 | 343.7        |
|              | ZION-2            | PWR        | 3,250       | 65.9           | 124.5                  | 10                 | 343.7        |
REFERENCES

[1] E. Neri, F. Amanda, M.E. Urso, D. Marc, G. Rothwell, I. Rehak, I. Weber, S. Carroll, and V. Daniska. Costs of Decommissioning Nuclear Power Plants, Nuclear Energy Agency of the OECD Report, NEA-7201 (2016).

[2] E. Bertel, E. Lazo, and M. Condu, Decommissioning Nuclear Power Plants: Policies, Strategies and Costs, 13, OECD Nuclear Energy Agency, Paris (2003).

[3] International Atomic Energy Agency–Power Reactor Information System. “Operational Reactors by Age.” IAEA PRIS. Accessed Sep. 15 2020. Available from: https://pris.iaea.org/PRIS/WorldStatistics/Operational-ByAge.aspx.

[4] D.B. Monteiro, J.M.L. Moreira, and J.R. Maiorino, “A New Management Tool and Mathematical Model for Decommissioning Cost Estimation of Multiple Reactors Site”, Prog. Nucl. Energy, 114, 61-83 (2019).

[5] H.Y. Joo, J.W. Kim, S.Y. Jeong, and J.H. Moon, “Decommissioning Cost Estimation of Kori Unit 1 Using a Multi-Regression Analysis Model”, J. Nucl. Fuel Cycle Waste Technol., 18(2(E)), 2470260 (2020).

[6] M. Laraia, D.W. Reisenweaver, and International Atomic Energy Agency. Selection of Decommissioning Strategies: Issues and Factors, IAEA Report, IAEA-TECDOC-1478 (2005).

[7] International Atomic Energy Agency. Policies and Strategies for the Decommissioning of Nuclear and Radio logical Facilities, IAEA, Vienna (2011).

[8] Empresa Nacional de Residuos Radiactivos, S.A. Decommissioning Report: Vandelllos I Nuclear Power Plant, Empresa Nacional de Residuos Radiactivos, S.A. Report (2007).

[9] International Atomic Energy Agency. Radiological Characterization of Shut Down Nuclear Reactors for Decommissioning Purposes, IAEA Report, TRS-389 (1998).

[10] G.C. Lim, R.C. Hill, and W. Griffiths, Principles of econometrics, 4th ed., 452-460, Wiley, New Jersey (2011).

[11] International Atomic Energy Agency, Nuclear Power Reactors in the World: 2020 Edition Reference Data Series 2, IAEA, Vienna (2020).

[12] World Bank. “GDP per Capita (Current US$).”, Accessed Oct. 10 2020. Available from: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

[13] World Bank. “GDP Deflator (Base Year Varies by Country).”, World Bank. Accessed Oct. 10 2020. Available from: https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS.

[14] Economic Statistics System. “The Exchange Rate of Major Currencies against the U.S. Dollars”, ECOS. Accessed Oct. 10 2020. Available from: http://ecos.bok.or.kr/flex/ClassSearch.jsp?langGubun=K&topCode=022Y013.

[15] International Atomic Energy Agency, Release of Sites from Regulatory Control on Termination of Practice: Safety Guide WS-G-5.1, IAEA, Vienna (2006).

[16] U.S. Nuclear Regulatory Commission. “10 CFR 20.1402-Radiological Criteria for Unrestricted Use.” (2018).

[17] European Commission. “Recommended Radiological Protection Criteria for the Clearance of Buildings and Building Rubble from the Dismantling of Nuclear Installations, Radiation protection 113.” (2000).

[18] European Commission. “Practical Use of Concepts of Clearance and Exemption: Guidance on General Clearance Levels for Practices, Radiation protection 122.” (2000).

[19] E. Bertel, E. Lazo, and M. Condu, Decommissioning Nuclear Power Plants: Policies, Strategies and Costs, 19, OECD Nuclear Energy Agency, Paris (2003).

[20] International Atomic Energy Agency. Decommissioning Costs of WWER-440 Nuclear Power Plants: Interim Report: Data Collection and Preliminary Evaluations, IAEA Interim Report, IAEA-TECDOC-1322 (2002).

[21] G. Varley and NAC International Inc. Ågesta-BR3 De-
commissioning Cost Comparison and Benchmarking Analysis, Swedish Nuclear Power Inspectorate Technical Report, SKI-R-2003-11 (2002).

[22] Mycle Schneider Consulting. Comparison among Different Decommissioning Funds Methodologies for Nuclear Installations, European Commission Report, 4-15, TREN/05/NUCL/S07.55436 (2006).

[23] European Commission. Report from the Commission to the European Parliament and the Council on the Implementation of the Work Under the Nuclear Decommissioning Assistance Programme to Bulgaria, Lithuania and Slovakia in 2018 and Previous Years, European Commission Report, COM(2019) 215 final (2019).

[24] TLG Services Inc. “Preliminary Decommissioning Plan for the Gentilly-2 Nuclear Generating Station.” (2015).

[25] Ontario Power Generation. “A Preliminary Assessment to Determine the Financial Impact of Using a Prompt Decommissioning Approach for OPG’s Nuclear Generating Stations.” (2016).

[26] Cour des comptes. The Costs of the Nuclear Power Sector, Thematic Public Report (2012).

[27] Nuclear Safety Authority. Abstracts on the State of Nuclear Safety and Radiation Protection in France in 2017, ASN Annual Report, L. 592-31 (2018).

[28] B. Ines, H. Johann, K. Andreas, K. Kerstin, N. Katarzyna, P. Frank, and W. Ralf. Statusbericht zur Kernenergienutzung in der Bundesrepublik Deutschland 2018, Nukleare Entsorgung Report, BfE-KE-04/19 (2019).

[29] B. Wealer, C. Gerbaulet, J.P. Seidel, and C. von Hirschhausen, Stand und Perspektiven des Rückbaus von Kernkraftwerken in Deutschland (∘Rückbau-Monitoring 2015), DJW Berlin, Berlin (2015).

[30] Jülicher Entsorgungsgesellschaft für Nuklearanlagen mbH. “Was Kostet der Rückbau, und Wer trägt die Kosten? AVR-Hochtemperaturreaktor.” JEN. Accessed Oct. 20 2020. Available from: https://www.jen-juelich.de/projekte/avr-hochtemperaturreaktor/.

[31] Atommüllreport. “Daten Zum AKW Biblis A.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-biblis-a.html.

[32] Atommüllreport. “Daten Zum AKW Biblis B.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-biblis-b.html.

[33] Atommüllreport. “Daten Zum AKW Brunsbüttel.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-brunssuettel.html.

[34] Atommüllreport. “Daten Zum AKW Grafenrheinfeld.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-grafenrheinfeld.html.

[35] Atommüllreport. “Daten Zum AKW Greifswald 1-5.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-greifswald-1-5.html.

[36] Atommüllreport. “Daten Zum AKW Gundremmingen B.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-gundremmingen-b.html.

[37] Atommüllreport. “Daten Zum HDR Großwelzheim.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/hdr-grosswelzheim.html.

[38] Atommüllreport. “Daten Zum AKW Ohu 1/Isar 1.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-ohu-1-isar-1.html.

[39] U. Schönberger, Atommüll-Eine Bestandsaufnahme Für Die Bundesrepublik Deutschland-Sorgenbericht Der Atommüllkonferenz Incl. DIN A1-Plakat-Buch Gebraucht Kaufen, 1st ed., Arbeitsgemeinschaft Schacht KONRAD e.V., Salzgitter (2013).

[40] Atommüllreport. “Daten Zum AKW Mülheim-Kärlich.” Atommüllreport. Accessed Oct. 20 2020.
Available from: https://www.atommuellreport.de/daten/akw-muelheim-kaerlich.html.

[41] Atommüllreport. “Daten Zum MZFR Karlsruhe.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/mzfr-karlsruhe.html.

[42] Atommüllreport. “Daten Zum AKW Obrigheim.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-obrigheim.html.

[43] Atommüllreport. “Daten Zum AKW Rheinsberg.” Atommüllreport. Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-rheinsberg.html.

[44] Atommüllreport. “Daten Zum AKW Stade.” Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-stade.html.

[45] Atommüllreport. “Daten Zum AKW Esenshamm.” Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-esenshamm.html.

[46] Atommüllreport. “Daten Zum AKW Würgassen.” Accessed Oct. 20 2020. Available from: https://www.atommuellreport.de/daten/akw-wuergassen.html.

[47] SOGIN. “Caorso Nuclear Power Plant.” SOGIN. Accessed Oct. 20 2020. Available from: https://www.sogin.it/en/closureoftheitaliannuclearcycle/italian-nuclear-sites/caorsonuclearpowerplant/Pagine/default.aspx.

[48] SOGIN. “Trino Nuclear Power Plant.” SOGIN. Accessed Oct. 20 2020. Available from: https://www.sogin.it/en/closureoftheitaliannuclearcycle/italian-nuclear-sites/trinonuclearpowerplant/Pagine/default.aspx.

[49] SOGIN. “Garigliano Nuclear Power Plant.” SOGIN. Accessed Oct. 20 2020. Available from: https://www.sogin.it/en/closureoftheitaliannuclearcycle/italian-nuclear-sites/gariglianonuclearpowerplant/Pagine/default.aspx.

[50] SOGIN. “Latina Nuclear Power Plant.” SOGIN. Accessed Oct. 20 2020. Available from: https://www.sogin.it/en/closureoftheitaliannuclearcycle/italian-nuclear-sites/latinanuclearpowerplant/Pagine/default.aspx.

[51] M. Schmittem, “Nuclear Decommissioning in Japan–Opportunities for European Companies–”, EU-Japan Centre, 1-102, March, 2016, Tokyo.

[52] Japan Atomic Industrial Forum. “Current Status of Nuclear Power Plants in Japan.” (2019).

[53] World Nuclear Association. “Japan Nuclear Fuel Cycle.” World Nuclear Association Library. Accessed Oct. 20 2020. Available from: https://www.world-nuclear.org/information-library/country-profiles/countries-gen/japan-nuclear-fuel-cycle.aspx.

[54] Nuclear Regulatory Agency. “Results of Examination on Conformity of Decommissioning Plan for Reactor 1 of Genkai Nuclear Power Station, Kyushu Electric Power Co., Ltd. to Approval Standards Provided for in Article 119 of the Ordinance on Commercial Reactors.” (2017).

[55] Nuclear Regulatory Agency. “Conformity of the Decommissioning Plan for Reactor 2 of the Genkai Nuclear Power Station in Accordance with the Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors Result of Examination.” (2020).

[56] Nuclear Regulation Authority. Annual Report, FY 2018 (2019).

[57] Nuclear Regulation Authority. “Shikoku Electric Power Co., Ltd. Results of Examination of Conformity of Decommissioning Plan for Reactor 1 of Ikata Power Station to Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors.” (2017).

[58] Shikoku Electric Power Company, Inc. “Decommissioning, Initiatives Associated with the Abolition of Unit 1 and 2.” Yonden. Accessed Oct. 21 2020. Available from: https://www.yonden.co.jp/energy/atom/ikata/decommissioning.html.
[59] K.J. Jung, S.T. Paik, U.S. Chung, K.W. Lee, G.H. Chung, S.K. Park, D.G. Lee, and H.R. Kim. Study on the Promotion of International Cooperation for Nuclear Facility Decommissioning between OECD/NEA Member Countries, Korea Atomic Energy Research Institute Technical Report, KAERI/RR-2202 (2001).

[60] Nuclear Regulation Authority. “Results of Examination on Conformity of the Decommissioning Plan for the Mihama Power Station 1 and 2 of Kansai Electric Power Co., Ltd. to the Approval Standards Provided for in Article 119 of the Ordinance on Commercial Reactors.” (2017).

[61] Nuclear Regulatory Commission. “Examination on the Application for Approval of the Decommissioning Plan for Power Reactors in Monju, Japan Atomic Energy Agency (JAEA) Fast Breeder Prototype Reactor.” (2018).

[62] Nuclear Regulation Authority. “Results of Examination on Conformity of Decommissioning Plan for Reactor No. 1 of Kansai Electric Power Co., Ltd. to Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors.” (2019).

[63] Nuclear Regulation Authority. “Results of Examination on Conformity of Decommissioning Plan for Reactor No. 2 of Kansai Electric Power Co., Ltd. to Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors.” (2019).

[64] Nuclear Regulation Authority. “Tohoku Electric Power Co., Ltd. Results of Examination on Conformity of Decommissioning Plan for Reactor 1 of Onagawa Nuclear Power Station with the Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors.” (2020).

[65] Nuclear Regulation Authority. “Results of Examination of Conformity of Decommissioning Plan for Reactor 1 of Shimane Nuclear Power Station, China Electric Power Co., Ltd. to Approval Standards Provided for in Article 119 of the Ordinance on Commercial Reactors.” (2017).

[66] Japan Atomic Power Company. “Decommissioning of Tokai Power Plant.” JAPC. Accessed Oct. 21 2020. Available from: http://www.japc.co.jp/tokai/haishi/tokai_haishi.html.

[67] Nuclear Regulation Authority. “Results of Examination on Conformity of Decommissioning Plan for Reactor 1 of Tsuruga Power Station, Japan Atomic Power Co., Ltd. with the Approval Standards Prescribed in Article 119 of the Ordinance on Commercial Reactors.” (2017).

[68] Wolfgang Irrek, Lutz Jarczynski, and Lars Kirchner, Comparison among Different Decommissioning Funds Methodologies for Nuclear Installations, Country Report the Netherlands, TREN/05/NUCL/S07.55436 (2006)

[69] “Nuclear Trap: LNPP Will Not Be Able to Close the Shutdown Unit for a Long Time.” Accessed Oct. 21 2020. Available from: https://www.rbc.ru/spb_sz/29/12/2018/5c2633749a7947f8833fc998?from=main&fbclid=IwAR3QZnqVK7sked7iWykzK94Rgj1IdIKQB_oBwmd6AeDQe5imHnNUM-eqA.

[70] O. Bodrov, D. Matveenkova, A. Talevlin, K. Album, F. Maryasov, and Y. Ivanov. Decommissioning of Russian NPPs, SNF and RW Management in 2016, Decommission Network. (2016).

[71] I. Wolfgang. Comparison Among Different Decommissioning Funds Methodologies for Nuclear Installations, European Commission Final Report, 36, TREN/05/NUCL/S07.55436 (2006).

[72] Jadrova a vyradovacia spolocnost, a.s. “Decommissioning Of Nuclear Facilities Jaslovské Bohunice Site Nuclear Facility A1 Nuclear Power Plant.” (2016).

[73] Ministry for Ecological Transition and the Demographic Challenge. “7th General Plan for Radioactive Waste.” (2020).

[74] G. Emilio, J. Borque, and A. Abreu, “Comparison of Estimated and Actual Decommissioning Cost of José Cabrera NPP”, Proc. of Int. Conf. on the Financing of Decommissioning, September 20-21, 2016, Stock-
holm.

[75] World Nuclear News. “Decommissioning Application Submitted for Garoña.” WNN. Accessed Oct. 21 2020. Available from: https://world-nuclear-news.org/Articles/Decommissioning-application-submitted-for-Garona.

[76] Empresa Nacional de Residuos Radiactivos. S.A. Decommissioning Report: Vandellós I Nuclear Power Plant, Empresa Nacional de Residuos Radiactivos, S.A. Report (2007).

[77] Svensk Kärnbränslehantering AB. Plan 2019 Costs from and Including 2021 for the Radioactive Residual Products from Nuclear Power–Basis for Fees and Guarantees for the Period 2021-2023, Svensk Kärnbränslehantering AB Technical Report, SKB TR-19-26 (2019).

[78] B. Hansson, Bewon, and L.O. Jönsson. Comparative Analysis of the Oskarshamm 3 and Barsebäck Site Decommissioning Studies, Svensk Kärnbränslehantering AB Technical Report, 1-44, SKB R-09-55 (2009).

[79] H. Larsson, Å. Anunti, and M. Edelborg. Decommissioning Study of Oskarshamn NPP, Svensk Kärnbränslehantering AB Technical Report, 1-181, SKB R-13-04 (2013).

[80] T. Hansson, T. Norberg, A. Knutsson, P. Fors, and C. Sandebert. Ringhals Site Study 2013–An Assessment of the Decommissioning Cost for the Ringhals Site, Svensk Kärnbränslehantering AB Technical Report, SKB-R-13-05 (2013).

[81] H. Wanner, “Decommissioning in Switzerland”, Regulatory Information Conference 2017, March 15, 2017, Maryland.

[82] Swissnuclear. “Estimation of Swiss Nuclear Power Plant Disposal Costs, 2016 Cost Study (KS16).” (2016).

[83] Swissnuclear. “Court Report, 2016 Cost Study (KS16).” (2016).

[84] BKW Energie. “Mühleberg Nuclear Power Plant Ceases Operations.” BKW. Accessed Oct. 21 2020. Available from: https://www.bkw.ch/en/about-us/media/detail/muehleberg-nuclear-power-plant-ceases-operations.

[85] Great Britain and Nuclear Decommissioning Authority, NDA Draft Business Plan 2020 to 2023, HM Government, London (2020).

[86] Great Britain and Nuclear Decommissioning Authority, Nuclear Decommissioning Authority Strategy: Effective from April 2016, HM Government, London (2016).

[87] Great Britain, Nuclear Decommissioning Authority, J. Clarke, and S. Henwood, Nuclear Decommissioning Authority Annual Report and Accounts: Financial Year: April 2015 to March 2016, HM Government, London (2016).

[88] C. Halliwell, “The Windscale Advanced Gas Cooled Reactor (WAGR) Decommissioning Project a Close Out Report for WAGR Decommissioning Campaigns 1 to 10”, WM2012 Conference, February 26-March 1, 2012, Phoenix.

[89] World Nuclear News. “Decommissioning Campaign Complete at UK Reactor.” WNN. Accessed Oct. 21 2020. Available from: https://world-nuclear-news.org/Articles/Decommissioning-campaign-complete-at-UK-reactor.

[90] K.M. Haas. Big Rock Point Plant, Post Shutdown Decommissioning Activities Report, Revision 4, Consumers Energy Report (2005).

[91] A.J. Vitale. Big Rock Point, Big Rock Point License Termination Plan, Revision 3, Entergy Report, PNP 2013-030 (2013)

[92] U.S. Department of Energy. Environmental Assessment for Authorizing the Puerto Rico Electric Power Authority (PREPA) to Allow Public Access to the Boiling Nuclear Superheat (BONUS) Reactor Building, Rincon, Puerto Rico, U.S. Department of Energy Report, DOE/EA-1394 (2003).

[93] J. Elnitsky. Crystal River Unit–3Post-Shutdown Decommissioning Activities Report, Duke Energy Re-
port, 3F1213-02 (2013).
[94] E.G. Delaney. “Decommissioning US DOE Nuclear Facilities”, IAEA Bulletin, 27(4), 30-34 (1985).
[95] R. Harms, M. Schneider, G. MacKerron, W. Neumann, A. Turmann, and A. Jungjohann. The World Nuclear Waste Report 2019 Focus Europe (2019).
[96] R.P. Tuetken. Dresden Nuclear Power Station Unit 1 Post-Shutdown Decommissioning Activities Report, Commonwealth Edison Company Report (1998).
[97] U.S. Nuclear Regulatory Commission, “Fact Sheet: Decommissioning Nuclear Power Plants.” U.S.NRC Office of Public Affairs (2008).
[98] K.M. Harmon, C.E. Jenkins, D.A. Waite, R.E. Brooksbank, B.C. Lunis, and J.F. Nemec. Decommissioning Nuclear Facilities, Pacific Northwest Laboratories Report, BNWL-SA-5834 (1976).
[99] H.D. Oak, G.M. Holter, W.E. Kennedy, Jr., and G.J. Konzek. Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, Pacific Northwest Laboratory Report, NUREG/CR-0672 (1980).
[100] TLG Services, Inc. Fort Calhoun Station, Unit No. 1, Post-Shutdown Decommissioning Activities Report, TLG Services, Inc. Report, LIC-17-0033 (2017).
[101] Omaha Public Power District, Fort Calhoun Station, Unit No. 1–2019 Annual Decommissioning Funding/Irradiated Fuel Management Status Report, Omaha Public Power District Report, LIC-19-0005 (2019).
[102] K. David. Fort St Vrain. Site Specific Decommissioning Cost Estimate Basis for Preliminary Decommissioning Plan, Public Service Company Report, EE-DEC-0020 (1989).
[103] M. Fisher, “Fort St. Vrain Decommissioning Project”, Proc. of a Technical Committee meeting, IAEA-TECDOC-1043,123-131, IAEA, Vienna (1997).
[104] L.E. Boing, “An Overview of U.S. Decommissioning Experience–A Basic Introduction”, IAEA/USA Interregional Training Course on Decontamination and Decommissioning of Research Reactors and other Small Nuclear Facilities, March 9, 1998, Argonne.
[105] Ge Hitachi Nuclear Energy Americas, LLC. “Vallecitos Nuclear Center Decommissioning Funding Plan.” (2017).
[106] U.S. Nuclear Regulatory Commission. U.S.NRC Office of Nuclear Material Safety and Safeguards, Status of the Decommissioning Program 2019 Annual Report (2019).
[107] S.M. Short, M.C. Bierschbach, R.F. Layton, and B.E. Greenfield. Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula Office, Pacific Northwest National Laboratory Report, PNNL-XXXX (2011).
[108] B. Buerger. Revision 4 of the Haddam Neck Plant PSDAR, Connecticut Yankee Atomic Power Company Report, CY-14-021 (2014).
[109] W.F. Heine and B.F. Ureda, “Decontamination and Disposition of Hallam and Piqua Reactors”, Proc. of the First Conference On Decontamination And Decommissioning (D&D) Of Erda Facilities, August 19-21, 1975, Idaho Falls.
[110] J.M. Welsch. Decommissioning Funding Report for Humboldt Bay Power Plant, Unit 3, Pacific Gas and Electric Company Report, HBL-19-007 (2019).
[111] Holtec Decommissioning International. Post Shutdown Decommissioning Activities Report Including Site-Specific Decommissioning Cost Estimate for Indian Point Nuclear Generating Units 1, 2, and 3, Holtec Decommissioning International Report (2019).
[112] Dominion Energy. Kewaunee Power Station: Revision to Post-Shutdown Decommissioning Activities Report, Dominion Energy Kewaunee Report (2014).
[113] Dominion Energy. Kewaunee Power Station: Decommissioning Funding Status Report, Financial Test and Independent Public Accountants’ Letter of Attestation, Dominion Energy Kewaunee Report (2019).
[114] Lacrossesolutions. Report on Status of Decommissioning Funding for Shutdown Reactor, Lacrosseso-
lutions Report, LC-2019-0014 (2019).

[115] R. Aker, Maine Yankee Decommissioning Experience Report Detailed Experiences 1997–2004, New Horizon Scientific Report (2004).

[116] Dominion Energy. Millstone Power Station Unit 1 Decommissioning Funding Status Report, Dominion Energy Nuclear Connecticut Report, 19-048 (2019).

[117] Holtec Decommissioning International. Notification of Revised Post-Shutdown Decommissioning Activities Report and Revised Site-Specific Decommissioning Cost Estimate for Oyster Creek Nuclear Generating Station, Holtec Decommissioning International Report, 2905001 (2018).

[118] Exelon Generation. Report on Status of Decommissioning Funding for Reactors and Independent Spent Fuel Storage Installations, Exelon Generation Report, RS-19-045 (2019).

[119] Entergy Nuclear Operations. Post Shutdown Decommissioning Activities Report Pilgrim Nuclear Power Station, Entergy Nuclear Operations Report (2018).

[120] C.W. Wheelock. Retirement of The Piqua Nuclear Power Facility, Aec Research and Development Report, AI-AEC-12832 (1970).

[121] Sacramento Municipal Utility District. Change in Rancho Seco Decommissioning Schedule: Rancho Seco Post Shutdown Decommissioning Activities Report, Sacramento Municipal Utility District Report, DPG 14-071 (2014).

[122] R.C. Woodard and B.S. Sims. Testimony On 2016 SONGS 1 Decommissioning Cost Estimate, Rosemead, California: EnergySolutions Report, 164007-DCE-017 (2016).

[123] M.S. Williams and B.S. Sims. San Onofre Nuclear Generating Station, Units 2 and 3 Site Specific Decommissioning Cost Estimate, EnergySolutions Report, 164001-DCE-001 (2014).

[124] J.E. Joseph, M.A. Kruslicky, and P.A. Olson. Shippingport Decommissioning—How Applicable Are the Lessons Learned, U.S.GAO Report, GAO/RCED-90-208 (1990).

[125] C. Giacomazzo and J.K. Hadden. “Shoreham Decommissioning Technology: Simple and Effective.” Power engineering. Accessed Oct. 21 2020. Available from: https://www.power-eng.com/1996/02/01/nuclear-decommissioning/#gref.

[126] U.S. Nuclear Regulatory Commission, “NRC Staff Terminates Shoreham License; Authorizes Release of Site”, 95-42, U.S. NRC, Maryland (1995).

[127] Exelon Generation. Three Mile Island Nuclear Station, Unit 1–Post-Shutdown Decommissioning Activities Report, Exelon Generation Report, TM-19-025 (2019).

[128] TLG Services, Inc. Decommissioning Funding Status Report for the Three Mile Island Nuclear Station, Unit2, GPU Nuclear Report, TMI-15-036 (2015).

[129] TLG Services, Inc. Post Shutdown Decommissioning Activities Report Vermont Yankee Nuclear Power Station, TLG Services, Inc. Report, BVY 14-078 (2014).

[130] NorthStar Group Services. Notification of Revised Post-Shutdown Decommissioning Activities Report (Revised PSDAR) Vermont Yankee Nuclear Power Station, NorthStar Group Services Report 50-271 & 72-59 (2017).

[131] D. Lochbaum, “Life After Nuclear: Decommissioning Power Reactors”, Bull. At. Sci., 70(4), 26-36 (2014).

[132] U.S. Nuclear Regulatory Commission. “Yankee Nuclear Power Station–Release of Land from Part 50 License.” (2007).

[133] ZionSolutions. Revised Report on Status of Decommissioning Funding for Shutdown Reactors, ZionSolutions Report, ZS-2019-0056 (2019).

[134] South Korean Ministry of Trade, “Industry and Energy. Regulations on the calculation criteria of radioactive waste management costs and spent nuclear fuel management charges.” (2019).