Assessing the Historical Trend of Nuclear Power Plant Construction Costs in Japan

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In this study, the authors analyzed the historical data of nuclear power plant (NPP) construction costs in Japan, using an econometric approach. The analysis shows that the escalation of NPP construction costs mainly took place during the period from 1975 to 1980, when the efforts related with the “first & second improvement and standardization (I&S) plans” were made by the manufacturers, etc. During the period of the third I&S plan, which took place from 1981 to 1985, no cost escalation could be observed.

The costs were also affected by the escalation of unit labor cost which almost doubled from 1970 to 1990, and the plant size which has a negative effect on the unit construction cost. On the other hand, the analysis found no significant effect of time trend or power plant construction experience on the unit cost, contrary to the oft-told story that nuclear power is cursed with “negative learning,” or intrinsic cost escalation.

Keywords: Nuclear, Construction, Cost, Econometrics

1. Introduction

In Japan as well as other developed countries, nuclear power generation had long been accounting for a considerable share in its power generation mix. After the Tokai nuclear power station started operation in 1966, Japan’s nuclear power generation gradually expanded to reach 322 TWh accounting for 30% of the total power generation in 2000. Behind this was the recognition that nuclear power can make great contributions to cheap, stable power supply after the first and second oil crises in 1973 and 1979, respectively. Since the climate change issue began to attract attention in the 1990s, nuclear energy has been expected to serve as a major low-carbon power source. The government’s Long-term Energy Supply and Demand Outlook published in August 2009 called for increasing nuclear energy’s share of the power mix further to 41.5% in 2020 and 48.7% in 2030. At that time, the government planned to raise the capacity factor from about 60% to 80% and add nine new nuclear power plants by 2020.

The Fukushima Daiichi nuclear power plant accident in 2011 forced Japan to dramatically change its energy policies. In July 2015, the government published a new Long-term Energy Supply and Demand Outlook seeking to continue using nuclear energy while revising its share of the power mix downward to 20-22% for 2030. Meanwhile, plans to build new nuclear power plants have remained stagnant, with no new nuclear power plant starting operation since the Fukushima accident. Since existing plants are set to successively end their lifetime of 40 years, which could be extended to the maximum of 60 years, it would be indispensable to construct new nuclear power plants if Japan is to continue depending on nuclear power generation.

One of the major issues that must be taken into account when formulating a future energy plan is the economics of power sources. According to a government assessment[1)] conducted in 2015, the unit nuclear power generation cost for a plant starting operation in 2030 was estimated at 8.8 yen/kWh excluding the policy cost or 10.3 yen/kWh including the policy cost, with the discount rate at 3% and the capacity factor at 70%. In this assessment, the unit construction cost for nuclear power plants was given at 370,000 yen/kW, based on costs for plants constructed recently. Added to the unit construction cost is 60.1 billion yen/plant or about 50,000 yen/kW in cost for additional safety measures implemented by electric power companies to meet new regulatory standards after the Fukushima accident. This means that the assessment assumed no cost hike other than that through the additional safety measure cost in the future.

Looking at overseas cases, the unit construction cost for nuclear plants has often been described as escalating, especially for the United States and France[2),3)]. At the same time, however, it has also been pointed out that no such cost hike intrinsic to nuclear plants can be observed for other countries[4)]. Since historical trends in the costs for nuclear power plant

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construction differ widely from country to country, it is important for future policy making to quantitatively analyze past changes in the unit cost, as well as major factors behind such changes. In view of this, this paper analyzes past trends in nuclear power plant construction costs in Japan using an econometric approach, and attempts to draw policy implications.

2. Data and methodology

2.1 Nuclear power plant construction costs

In this paper, we used the nuclear power plant construction cost data that appear in *genshiro secchi kyoka shinsei-sho* (application documents for reactor installment license) or *genshiro secchi henkou kyoka shinsei-sho* (application documents for the modification of reactor installment license). These are the documents submitted by the utilities to the government before the construction of nuclear facilities or the modification of their specifications, and are accessible at the National Diet Library and at the Nuclear Regulation Authority. While descriptions of detailed specifications of the facilities account for most of these documents, they also include Appendix 3, which specifies costs required for construction. As an example, the construction costs for Unit 1 of the Genkai nuclear power station are shown in Table 1.

Table 1 Construction costs specified in the application document for Genkai Unit 1

Unit: million yen

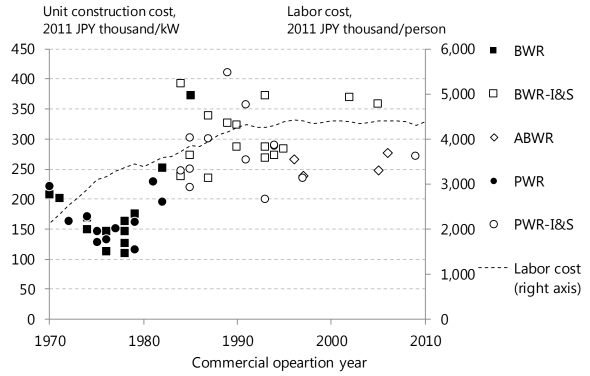
Item	Total cost
Land	1,088
Buildings	2,434
Structures	2,722
Mechanical equipment	26,600
Systems, fixings, temporary facilities	1,104
Total cost	2,866
Interest during construction	3,134
Sharing-related cost	252
Contingency	1,500
Total construction costs	41,700

Detailed specifications of Japanese nuclear reactors usually undergo several changes during the period from the initial submission of the application document to the operation of the reactor. When construction costs largely change due to such changes in the specifications, a new cost table is given in a similar form as in Table 1. In this paper, we adopted the last cost data that appear in the application documents in this form. It must be noted that these data represent estimates during the design stage, rather than actual construction costs assessed after the construction. However, these data are assumed as close to actual costs, since they reflect actual changes in plant specifications until just before or even after the construction start.

Although breakdown items, as given in Table 1, differ by reactor, in most cases they include “interest during construction” (IDC). In this paper, we used the construction costs excluding IDC, which is usually referred to as the “overnight cost” [4]. For Tomari Unit 3, Tohoku Higashidori, Hamaoka Units 3 and 4, Shiga Unit 2 and Ikata Unit 3, the application documents do not specify IDC, although they are supposed to be included in the total cost. We calculated the overnight cost for these reactors under an assumption that IDC accounts for 9% of construction costs. The percentage represents an average for reactors for which IDC has been specified.

We calculated the unit construction cost by dividing the overnight construction cost by the installed capacity. The costs were adjusted for inflation with the GDP deflator and shown in real 2011 prices. It should be noted that the overnight costs in the application documents represent simple summation of nominal construction costs at different time points. Strictly, therefore, they must be corrected using detailed construction cost profile data. Since the impact of such correction is apparently small in Japan, however, unlike in the United States, data without such correction were used in this study. Given that the Tokai nuclear power plant is much smaller in size than other commercial nuclear reactors and is a gas-cooled reactor differing from the others, this paper subjected 54 light-water reactors other than the Tokai reactor to econometric analysis.

Figure 2 plots the unit construction costs versus the plant operation years. For both BWRs and PWRs, the unit cost fell from around 200,000 yen/kW for the first few reactors to less than 150,000 yen/kW. Remarkably, the unit construction cost for reactors that started operation in and after the 1980s was considerably higher than for older ones. We can also see that from the second half of the 1970s to the 1980s, the unit construction cost rose faster than the labor costs. On the other hand, for reactors that launched operation in and after the 1990s, the unit construction cost indicated no increase or decrease.



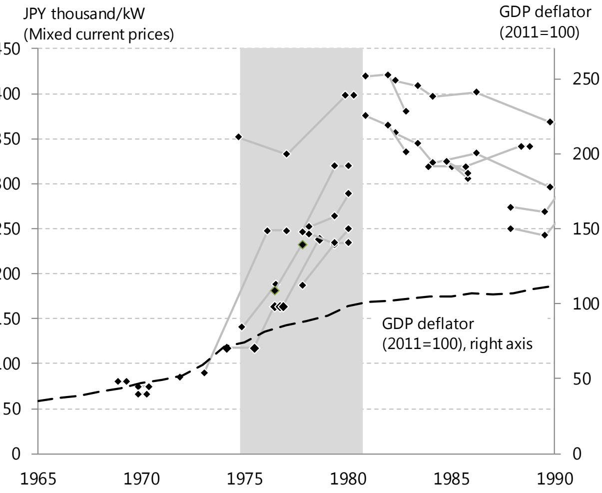
Note: "I&S" indicates that the plant reflects the results of the I&S programs.

Figure 2 Unit nuclear power plant construction cost trend in Japan

As indicated in the figure, most of the reactors that started operation after the mid-1980s reflect the results of the Improvement and Standardization (I&S) program, which took place during FY 1975-1980 and thereafter, led by the Japanese government, and aiming to achieve higher equipment reliability and operational efficiency. Of reactors before the I&S program, meanwhile, four reactors that started operation in the 1980s indicate high unit construction costs, at almost the same level as those after the I&S program. These are Kashiwazaki-Kariwa Unit 1, Fukushima Daini Unit 1, Genkai Unit 2, and Ikata Unit 3, in descending order of the unit costs.

These reactors constructed in the "transitional" period feature sharp construction cost hikes between the initial costs in the application documents and the final ones. For Fukushima Daini Unit 1, nominal construction costs increased from 98.6 billion yen as specified in the application document in 1972 to 272.8 billion yen in 1976. For Genkai Unit 2, nominal construction costs rose from 65.8 billion yen to 91.5 billion yen in 1976 and 133.2 billion yen in 1979. For Ikata Unit 2, such costs soared from 79.5 billion yen in 1975 to 106.7 billion yen in 1977. Kashiwazaki-Kariwa Unit 1 shows a more moderate increase from 386.7 billion yen in 1975 to 438.0 billion yen in 1979.

Figure 3 shows the unit construction cost versus the publication year of the application document for selected plants including the transitional ones (Genkai Units 1 to 4, Ikata Units 1 to 3, Fukushima Daini Units 1 to 4, Kashiwazaki-Kariwa Units 1 to 7, and Takahama Units 1 to 4). Each dot indicates data in an application document, and dots for one plant are connected with a line. The figure indicates that unit construction costs soared faster than inflation during the period from FY1975 to FY1980, when the first and second I&S programs took place. This suggests that the costs for the abovementioned transitional plants may have been escalating in line with the ongoing I&S programs. As indicated by the figure, however, the cost for Kashiwazaki-Kariwa Unit 1 was as high as 352,000 yen/kW in March 1975, just before the I&S program. To explain this, it must be alleged that the plant manufacturers had been foreseeing cost escalation in advance of the official commencement of the I&S program, or that costs had already risen due to other factors.



Note: The shaded area indicates a period for the first and second I&S programs.

Figure 3 Years for submission of the application documents and the unit construction costs

In this way, the unit construction cost increased substantially for the plants designed between 1975 and 1980 and started operation between 1980 and 1985, indicating that the I&S programs or some other event(s) during this period were major factors behind the cost hike, although the abovementioned question exists for Kashiwazaki-Kariwa Unit 1. Under the first I&S program, the construction cost could have risen significantly due to such measures as the enlargement of reactor containment vessels and the improvement of reliability and safety.

Unit construction cost levels exceeded 200,000 yen/kW for 37 of the 56 nuclear power plants other than the Tokai power station. The 37 include six designed before the I&S program. Of 19 plants for which unit construction cost levels were lower than 200,000 yen/kW, Ohi Unit 4 is the only I&S plant. One reason for the low construction cost may be that Ohi Units 3 and 4 are twin plants with some common costs booked only for Unit 3. A simple t-test indicates that unit construction costs were significantly higher for plants after the I&S program, with the t-value at 7.94 and the p-value at $1.25x10^{-10}$. Thus, we can say that it is extremely unlikely that any factor having no correlation with the I&S program was a major factor behind the rise in the nuclear construction cost in Japan. It cannot be denied, however, that some factor such as the revision of the Building Standards Act as mentioned below or some regulatory changes which coincided with the I&S programs also boosted the construction cost. A remarkable cost hike was seen only through the first and second I&S programs covering nuclear plants that started operation after the mid-1980s. The third I&S program had no or far less impact on the construction cost.

The Building Standards Act has been revised several times since its enactment in 1950. Particularly, a 1981 revision made great changes in response to the 1978 Miyagi Prefecture earthquake. Although the nuclear construction cost hike came before the revision, it cannot be denied that the anticipated revision could have been reflected in plant designs.

2.2 Other costs

(1) Labor cost and materials prices

Past hikes in the construction cost for nuclear power plants could have reflected increases in materials prices and labor cost. Particularly, average nominal annual wage income rose remarkably from 1 million yen per person in 1970 to 4.78 million yen per person in 1990. Even after adjustment for inflation, real wage income almost doubled. Therefore, we considered real wage income per person as an explanatory variable. As indicated in Figure 2, it increased rapidly until around 1990 before leveling off generally.

Meanwhile, prices of building materials such as steel and cement rose in line with general inflation from the 1960s to the 1980s. They soared during the first and second oil crises in 1973 and 1979, respectively, roughly in proportion to other commodity prices. Thus, we did not adopt materials prices as explanatory variables.

(2) Installed power generation capacity

The unit cost for large facilities usually declines in line with its installed capacity, showing the economy of scale. Several studies show, however, that this is not the case with nuclear power plants. In view of this, this paper adopted installed power generation capacity as one of the explanatory variables.

Figure 4 plots the unit construction cost against the installed capacity. The plants are roughly divided by the I&S programs into two groups. In each group, the unit construction cost seems to decline moderately as the capacity expands. The two 1,100 MW BWRs with high unit costs constructed before the I&S programs are Fukushima Daini Unit 1 and Kashiwazaki-Kariwa Unit 1, built during the abovementioned transitional period.

The significance of the economy of scale seen in Figure 4 will be discussed in the next section.

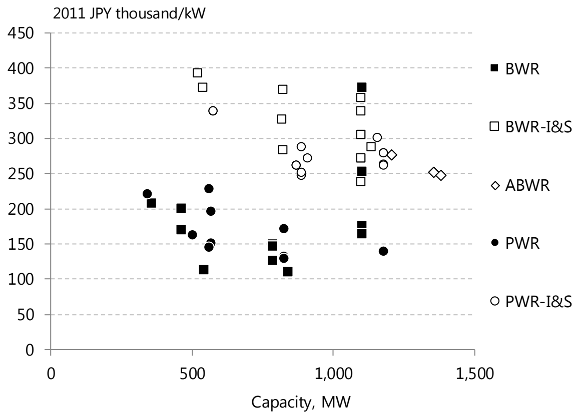


Figure 4 Relationship between the unit construction cost and the installed capacity

(3) Nuclear reactor construction experience

Past experience of nuclear power plant construction has been conceived as a factor that exerts significant influence on the unit construction cost. Although nuclear power plant construction costs have been viewed as possibly falling due to learning, as is the case with other facilities such as solar photovoltaic plants, some analyses show that they actually increase showing "negative learning" effects, due to increased complexity of the system and regulation. In this paper, we used nuclear power plant construction experience, shown in the number of the plants built before a plant, counted separately before and after the beginning of the I&S programs, as an explanatory variable for the analysis.

(4) First-of-a-kind (FOAK) status

As indicated in Figure 2, the unit construction cost is high for the first few plants and stable at lower levels for subsequent plants, until the commencement of the I&S program. It has been widely known that the costs of very first facilities are significantly higher than those of the subsequent ones. To assess the effect of this factor, we applied a dummy variable which takes value 1 if and only if the plant is the first BWR or PWR, and zero otherwise. This variable indicates the effect of learning in the very early stages of nuclear development, while the variable described in 2.2 (3) shows the effect of construction experience over a longer term.

2.3 Methodology

We used the following equation for a multiple regression analysis:

$$\ln UC_i = a_0 + a_1 \ln CAP_i + a_2 \ln LC_i + a_3 \ln EXP_i + a_4 dumIS_i + a_5 dumFOAK_i + u_i \qquad (1)$$

The variables are as follows:

i : Suffix denoting the plants
UC_i : Unit construction cost in 2011, thousand yen/kW
CAP_i : Installed power generation capacity in megawatts (MW)
LC_i : Unit labor cost in 2011, thousand yen/person/year
EXP_i : Plant construction experience in units
$dumIS_i$: Dummy variable with value 1 if the plant reflects the results of the I&S programs, and zero otherwise
$dumFOAK_i$: Dummy variable with value 1 if the plant is the first PWR or BWR, and zero otherwise
u_i : Error term

3. Results and discussion

Table 2 shows the results of the multiple regression analysis through Equation (1). Of the explanatory variables used for the equation, plant construction experience (*EXP*) alone was not significantly affecting the unit cost. The coefficients of other variables (*CAP, LC, dumIS* and *dumFOAK*) were significant at least at the 10% level. Therefore, we gave the estimation results excluding and including *EXP* (Models 1 and 2, respectively).

As indicated by the results, the unit cost was high for the first BWR and PWR and declined later, before rising significantly during and after the first I&S program. The cost was also affected by the installed capacity and the unit labor cost.

It is noteworthy that the *CAP* coefficient is significantly negative. The coefficient of -0.24±0.11 in Model 1 indicates that as the plant size doubles, the unit cost declines by 15% (8-22%), reflecting the moderate economy of scale as shown in Figure 4. Thus, nuclear power plant construction experience in Japan indicates an ordinary economy of scale, contrary to the experience in the U.S. and France.

Table 2 Multiple regression analysis results

	Model 1	Model 2
ln *CAP*	-0.24**	-0.24**
(Standard error)	(0.11)	(0.12)
(t value)	(-2.08)	(-2.08)
ln *LC*	0.61**	0.80*
(Standard error)	(0.28)	(0.47)
(t-value)	(2.23)	(1.70)
dum *IS*	0.42***	0.36**
(Standard error)	(0.10)	(0.16)
(t-value)	(4.00)	(2.22)
dum *FOAK*	0.39*	0.40*
(Standard error)	(0.20)	(0.20)
(t-value)	(1.92)	(1.96)
ln *EXP*		-0.03
(Standard error)		(0.07)
(t-value)		(-0.49)
Intercept	1.78	0.40
(Standard error)	(1.99)	(3.46)
(t-value)	(0.90)	(0.12)
Adjusted R^2	0.63	0.62

Note: '***', '**', and '*' denote significance at the 1%, 5% and 10% levels, respectively.

As shown in Figure 2, the unit labor cost almost doubled in real terms between 1970 and 1990. The results of the regression analysis indicate that the unit labor cost rise led the unit construction cost to increase about 1.5-fold, or from 1.3- to 1.9-fold if the standard error is taken into account.

It is also an important finding that plant construction experience (*EXP*) indicated no significant influence on the unit construction cost. The Japanese experience shows learning effects only for the very first plants, and exhibits no cost decline or increase thereafter. Although nuclear power plant cost experienced a significant hike in the history in Japan, as is the case in the United States and France, it was only attributable to the I&S programs that started around 1975, or some other factor(s) coinciding with the program. Since the I&S program aimed at, and actually resulted in, enhanced capacity factors and safety[1], the cost hike could be viewed as

[1] Capacity factor showed a significant increase from an average 68% for plants before the I&S programs to an average 75% for those after the programs. The number of accident and failure reports has been decreasing in the past, with the number for plants after the I&S

expenses justifiable some extent. In any case, the Japanese experience suggests no upward (or downward) trends in the unit construction cost, other than the effect of explicit plant design improvements.

4. Conclusion

In this paper, the authors analyzed factors behind changes in Japan's unit nuclear plant construction cost, using data that appear in official documents submitted by the utilities. The most remarkable result is that the unit construction cost in Japan showed no significant change from the I&S program, that started in 1975, to the 2000s. As is the case with France, the cost escalation took place in explicit relation with influencing factors such as design improvements. This means that there is no reason for assuming any future cost changes, either a fall or rise through learning or negative learning, except for those caused by specific events such as explicit changes in plant design or regulation, when projecting the future cost of nuclear energy.

The 2015 estimation of nuclear costs by the Japanese government assumed the unit construction cost in 2030 at 370,000 yen/kW in 2014 prices, as well as the cost of additional safety measures at 50,000 yen/kW. Since the latter cost was estimated based on actual expenses spent by electric power companies to meet new regulatory standards after the Fukushima accident, it is reasonable to assume that figure to assess future cost escalation for similar plants. Given that plant construction experience had no significant influence on the unit cost, the government's approach of adding the additional safety measure cost to the unit construction cost after the I&S programs should be viewed as adequate.

The unit construction cost of 370,000 yen/kW is assumed to include interest during construction (IDC). Given that IDC accounted for 9% of the past unit construction cost on average, the overnight cost excluding IDC could be estimated at 340,000 yen/kW. The simple and capacity-weighted average of the overnight costs for plants after the I&S programs stand at 292,000 yen/kW and 286,000 yen/kW, respectively, in 2014 prices. Thus, the government-assumed unit construction cost is higher than the average for the existing I&S plants. The gap may reflect differences in the ways of inflation adjustment, or the selection of the sample plants. As far as no significant increase has been seen in the construction unit cost since the I&S programs, it would also be adequate to add the additional safety measure cost to the historical average cost of 286,000 yen/kW.

In the wake of the Fukushima accident, it may be difficult to construct any new nuclear power plant in Japan at least in the immediate future. According to Japan's past experience, the lead time to new plant construction has once been extended to about 10 years, with no significant changes in the construction cost. If no construction is implemented over a longer period, however, the cost may substantially rise, as currently seen in Western countries.

The analysis of Japanese data found that the plant size has a negative effect on the unit construction cost, meaning that nuclear plant construction costs have the economy of scale. This is quite a reasonable but important finding. Although Japanese electric utilities have been constructing various sizes of nuclear plants according to the demand sizes in the past, they have tended to build larger plants in line with technological improvements. Given that nuclear plants have the economy of scale, it would be adequate to choose large light-water reactors rather than small modular ones in a country with a large economy such as Japan. As liberalization has been making considerable progress in Japan's electricity market, however, how to fund the huge initial investments will become a key issue for future nuclear power development.

Future work would include more accurate correction of the overnight costs using plant construction profiles, as well as more detailed analysis of the factors behind the cost changes. It would also be useful to collect and analyze data for countries other than the United States and France, such as South Korea, China and India, where detailed quantitative analysis has not been attempted so far.

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programs significantly smaller than that for plants before the programs. (Japan Nuclear Energy Safety Organization (JNES), *genshiryoku shisetsu unten kanri nempou*, "Annual Report on Operation and Management of Nuclear Facilities")

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