We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

4,800
Open access books available

122,000
International authors and editors

135M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK
CITATION
INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Construction, Decommissioning, and Replacement of Nuclear Power Plants under Uncertainty

Ryuta Takashima
Department of Risk Science in Finance and Management, Chiba Institute of Technology

1. Introduction

Currently, there exist 54 commercial nuclear power plants, which have a total capacity of 48.85 GW, in Japan. These power plants that have been operating for more than 40 years emerge in 2010 and onward. The framework for the nuclear energy policy describes the measures to be followed for aging nuclear power plants and the enhancement of safety under the assumption of a nuclear power plant operating for 60 years (AEC, 2006). The Tokai Nuclear Power Plant of the Japan Atomic Power Company, and units 1 and 2 of the Hamaoka Nuclear Power Plant of the Chubu Electric Power Company are currently under decommissioning, and this decommissioning can be decided at the discretion of the electric power supplier. In the future, it is also likely that the firm will determine the decommissioning of aging nuclear power plants, taking into account the economics of the plant. Moreover, it is necessary to make decisions not only regarding decommissioning but also regarding the replacement. In this context, although decommissioning and replacement as well as new construction have become important problems, there exist many factors that need to be solved, such as large costs, electricity demand, that is, profit of electric power selling and electricity deregulation.

Deregulation of electricity markets has occurred in several countries, including the United Kingdom, the United States, Nordic countries, and Japan. In the deregulated market, the electricity price is determined by supply and demand, rather than by the cost of generating electricity. Because of the electricity price uncertainty, market deregulation could introduce a new type of risk for power companies. Investment in power plants is planned based on long-term demand forecasts, and it becomes difficult to plan schedules for constructing plants based on only the demand forecast because there is no guarantee of cost recovery. In addition, since the replacement of nuclear power plants requires a great amount of capital investment, a proper method is necessary for valuation and decision making regarding projects considering uncertainty in the electricity price.

For one of economic analysis methods for investment projects under uncertainty, real options analysis has recently attracted growing attention (Dixit and Pindyck, 1994; Trigeorgis, 1996). Using this approach, the investment and operation of power plants has been studied by several research groups. Especially, several studies have examined various investment problems involving nuclear power plants (Gollier et al., 2005; Naito et al., 2010; Pindyck, 1993; Rothwell, 2006; Takashima et al., 2007; Takizawa et al., 2001).

In this chapter, we focus on real options models for analyzing construction, decommissioning, and replacement problems of nuclear power plants under electricity price uncertainty. The models of construction and decommissioning problems are basic models, and in real options studies, correspond to investment option and abandonment option, respectively. The model of replacement problem is an extended model, which combines construction and decommissioning options (Naito et al., 2010). For three models, we show how uncertainty and cost affect decisions of construction, decommissioning, and replacement.

The remainder of this chapter is organized as follows. In Section 2, we describe the model for analyzing construction, decommissioning, and replacement of nuclear power plants. Section 3 derives the solution by numerical calculations and provides some results of numerical analysis. Finally, Section 5 concludes the chapter.

2. The Model

In this section we describe the setting and the assumption of the model, and then derive economic evaluation models for construction, decommissioning, and replacement of nuclear power plants.

2.1 Model setup

The risk factor and uncertainty in the investment of nuclear power plants include construction cost, fuel cost, electricity price, decommissioning cost, litigation, unplanned shutdown, and regulatory change. In this chapter, we consider the model in which uncertainties with respect to profitability are reflected in the electricity prices, and other risks are reflected in a discount rate.

Suppose that the firm is a price taker, and, its actions have no influence on the dynamics of the electricity price. Thus, for a straightforward description of uncertainty, we assume that the electricity price follows the geometric Brownian motion:

$$dP_t = \mu P_t dt + \sigma P_t dW_t, \qquad P_0 = p, \tag{1}$$

where μ is the instantaneous expected growth rate of P_t, and σ is the instantaneous volatility of P_t. W_t is a standard Brownian motion. The capacity factor, taking into account a decreasing due to the aging, is assumed to be expressed by the following equation:

$$\alpha_t = \alpha_0 e^{-\delta t}, \tag{2}$$

where δ is the decreasing rate. From these equations, the profit flow function of a nuclear power plant can be can be represented as follows:

$$\begin{aligned}
\pi_t &\equiv \pi(P_t; \delta, C) = \alpha_t P_t - C, \\
&= \alpha_0 e^{-\delta t} P_t - C,
\end{aligned} \tag{3}$$

where C is the operating cost that is composed of the fuel cost as well as operating and maintenance costs. To obtain the analytical solution, let us change the variable $P_t e^{-\delta t}$ to X_t:

$$X_t := P_t e^{-\delta t}. \tag{4}$$

Then, from Eqs. (1) and (4), the dynamics of X_t can be written as

$$dX_t = (\mu - \delta)X_t dt + \sigma X_t dW_t. \tag{5}$$

In this model, we consider this variable, X_t, as a state variable.

2.2 Construction option

In this section, we describe the model of Gollier et al. (2005) that extends the model of McDonald and Siegel (1986) deriving the investment timing and its option value by introducing fixed construction time and project lifetime. The firm starts operating a nuclear power plant by incurring investment cost I. The value of the investment opportunity is:

$$F(x) \equiv \sup_{\tau \in \mathcal{V}_i} \mathbb{E}_x \left[\int_{\tau+T}^{\tau+T+L} e^{-\rho t} \pi_t dt - e^{-\rho \tau} I \right], \tag{6}$$

where $\mathbb{E}_x$ is expectation with respect to the probability law of X_t given an initial value x, τ is the investment time, $\mathcal{V}$ is the set of stopping times of the filtration generated by the dynamics of X_t, and $\rho > 0$ is an arbitrary discount rate. We must have $\rho > \mu$ in order to ensure that the firm's value is finite for $L \to \infty$. Given the investment threshold, X^*, the optimal investment time, τ^*, has the following form:

$$\tau^* = \inf \left\{ t \geq 0 \mid X_t \geq X^* \right\}. \tag{7}$$

Prior to determining X^* and $F(x)$, we calculate the now-or-never expected NPV, $V(x)$, of a nuclear power plant.

$$V(x) = \mathbb{E}_x \left[\int_T^{T+L} e^{-\rho t} (\alpha_0 X_t - C) dt - I \right] = \int_T^{T+L} e^{-\rho t} \alpha_0 \mathbb{E}_x[X_t] - C dt - I$$
$$= \int_T^{T+L} e^{-\rho t} \alpha_0 x e^{(\mu-\delta)t} - C dt - I = A_1 \frac{\alpha_0 x}{\rho - \mu + \delta} - A_2 \frac{C}{\rho} - I \tag{8}$$

where $A_1 = e^{-(\rho-\mu+\delta)T}(1 - e^{-(\rho-\mu+\delta)L})$ and $A_2 = e^{-\rho T}(1 - e^{-\rho L})$. The following differential equation, which is satisfied by the investment value, is derived from the Bellman equation (See, for example, (Dixit and Pindyck, 1994)),

$$\frac{1}{2}\sigma x^2 F''(x) + (\mu - \delta)x F'(x) - \rho F(x) = 0, \tag{9}$$

where the primes denote derivatives, that is, $F'(x) = \frac{dF(x)}{dx}$ and $F''(x) = \frac{d^2 F(x)}{dx^2}$. The investment value must satisfy the following boundary conditions:

$$F(0) = 0, \tag{10}$$
$$F(X^*) = V(X^*), \tag{11}$$
$$F'(X^*) = V'(X^*). \tag{12}$$

Condition (10) requires that the investment option becomes zero if the cash flow is close to zero. Conditions (11) and (12) are the value-matching and smooth-pasting conditions, respectively. The value-matching condition means that when the level of X_t is X^*, the firm exercises the construction option, and then can obtain the net value of $V(X^*)$. Additionally, the smooth-pasting condition means that if the construction at X^* is indeed optimal, the differentiation of the value function must be continuous at X_t. From these conditions, we can obtain the investment value as follows,

$$F(x) = \left(\frac{x}{X^*} \right)^{\beta_1} V(X^*), \tag{13}$$

where β_1 is the positive root of the characteristic equation $\frac{1}{2}\sigma^2\beta(\beta-1) + (\mu-\delta)\beta - \rho = 0$, that is,

$$\beta_1 = \frac{1}{2} - \frac{\mu-\delta}{\sigma^2} + \sqrt{\left(\frac{\mu-\delta}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma^2}} > 1. \tag{14}$$

The investment threshold is given by,

$$X^* = \frac{\beta_1}{\beta_1-1}\frac{\rho-\mu+\delta}{A_1\alpha_0}\left(\frac{A_2C}{\rho} + I\right) \tag{15}$$

By contrast, the now-or-never investment threshold is $X_{npv} = \frac{\rho-\mu+\delta}{A_1\alpha_0}\left(\frac{A_2C}{\rho} + I\right) < X^*$, i.e., having the deferral option provides a value to waiting, which then increases the opportunity cost of investing.

2.3 Decommissioning option

We consider that a firm operates a nuclear power plant over few decades, and has the option of decommissioning. The value of the decommissioning project is:

$$F_d(x) \equiv \sup_{\tau_d \in \mathcal{V}_d} \mathbb{E}_x\left[\int_0^{\tau_d} e^{-\rho t}\pi_t dt - e^{-\rho\tau}U\right], \tag{16}$$

where τ_d is the decommissioning time, $\mathcal{V}_d$ is the set of admissible stopping times, and U is the decommissioning cost. Given the decommissioning threshold, X_d, the optimal decommissioning time, τ_d^*, has the following form:

$$\tau_d^* = \inf\left\{t \geq 0 \mid X_t \leq X_d^*\right\}. \tag{17}$$

The following differential equation, which is satisfied by the project value of the decommissioning, is derived from the Bellman equation,

$$\frac{1}{2}\sigma x^2 F_d''(x) + (\mu-\delta)x F_d'(x) - \rho F_d(x) + \alpha_0 x - C = 0. \tag{18}$$

The general solutions of this equation are given as follows:

$$F_d(x) = B_1 x^{\beta_1} + B_2 x^{\beta_2} + \frac{\alpha_0 x}{\rho-\mu+\delta} - \frac{C}{\rho}, \tag{19}$$

where B_1 and B_2 are unknown constants, and β_2 is the negative root of the characteristic equation $\frac{1}{2}\sigma^2\beta(\beta-1) + (\mu-\delta)\beta - \rho = 0$, that is,

$$\beta_1 = \frac{1}{2} - \frac{\mu-\delta}{\sigma^2} - \sqrt{\left(\frac{\mu-\delta}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma^2}} < 0. \tag{20}$$

The decommissioning project value must satisfy the following boundary conditions:

$$\lim_{x\to\infty}\left(B_1 x^{\beta_1} + B_2 x^{\beta_2}\right) = 0, \tag{21}$$

$$F_d(X_d) = -U, \tag{22}$$

$$F_d'(X_d) = 0. \tag{23}$$

Condition (21) requires that the decommissioning option becomes zero if the cash flow is very large. Therefore, from this condition, we have $B_1 = 0$. Conditions (22) and (23) are the value-matching and smooth-pasting conditions, respectively. From these conditions, we can obtain the decommissioning project value as follows,

$$F_d(x) = \frac{\alpha_0 x}{\rho - \mu + \delta} - \frac{C}{\rho} - \left(\frac{\alpha_0 X_d}{\rho - \mu + \delta} - \frac{C}{\rho} + U \right) \left(\frac{x}{X_d} \right)^{\beta_2}. \tag{24}$$

The decommissioning threshold is given by,

$$X_d = \frac{\beta_2}{\beta_2 - 1} \frac{\rho - \mu + \delta}{\alpha_0} \left(\frac{C}{\rho} - U \right). \tag{25}$$

Likewise, the now-or-never decommissioning threshold is $X_{d,npv} = \frac{\rho - \mu + \delta}{\alpha_0} \left(\frac{C}{\rho} - U \right) > X_d$, i.e., having the deferral option provides a value to waiting, which then increases the opportunity cost of decommissioning.

2.4 Replacement option

In this section, following Naito et al. (2010), we consider the valuation of a replacement project of nuclear power plants. The replacement project consists of two components: the decision to decommission an existing plant and the decision to construct a new plant.

The variable cost and the capacity factor of the existing plant are C^0 and α_0^0, respectively, and the variable cost and the capacity factor of the new plant are C^1 and α_0^1, respectively. We assume that the replacement leads to a decrease in the variable cost and an increase in the capacity factor, i.e., $C^0 \geq C^1$ and $\alpha_0^0 \leq \alpha_0^1$.

The value of the replacement project is:

$$F_r(x) \equiv \sup_{\tau_r, \tau_i \in \mathcal{V}_r} \mathbb{E}_x \left[\int_0^{\tau_r} e^{-\rho t} \pi_t^0 dt - e^{-\rho \tau_r} U + \int_{\tau_i}^{\tau_i + L + T} e^{-\rho t} \pi_t^1 dt - e^{-\rho \tau_i} I \right],$$
$$= \sup_{\tau_r, \tau_i} \mathbb{E} \left[\int_0^{\tau_r} e^{-\rho t} \pi_t^0 dt + e^{-\rho \tau_r} (F_i(X_{\tau_r}) - U) \right], \tag{26}$$

where $\pi_t^0 = \alpha_0^0 X_t - C^0$, $\pi_t^1 = \alpha_0^1 X_t - C^1$, and the value of the construction project for the new plant is:

$$F_i(x) = \sup_{\tau_i} \mathbb{E} \left[\int_{s + \tau_i + T}^{s + \tau_i + T + L} e^{-\rho(t-s)} \pi_t dt - e^{-\rho(\tau_i - s)} I \right]. \tag{27}$$

In addition, τ_r is the decommissioning time of the existing plant, τ_i is the construction time of the new plant, and $\mathcal{V}_r$ is the set of the pair of admissible decommissioning and construction times. Given the decommissioning threshold for the existing plant, X_r, the optimal decommissioning time, τ_r^*, has the following form:

$$\tau_r^* = \inf \{ t \geq 0 \mid X_t \leq X_r \}. \tag{28}$$

Likewise, given the construction threshold for the new plant, X_i, the optimal decommissioning time, τ_i^*, has the following form:

$$\tau_i^* = \inf \{ t \geq 0 \mid X_t \geq X_i \}. \tag{29}$$

The replacement option is the sequential one of decommissioning and construction. Therefore, we can solve the investment problem by working backward, i.e., by first finding the value of the construction project and then finding the value of the decommissioning project. Likewise equation (6), the value of the construction project for the new plant is:

$$F_i(x) = \left(A_1 \frac{\alpha_1 X_i}{\rho - \mu + \delta} - A_2 \frac{C_1}{\rho} - I \right) \left(\frac{x}{X_i} \right)^{\beta_1}, \tag{30}$$

where

$$X_i^* = \frac{\beta_1}{\beta_1 - 1} \frac{\rho - \mu + \delta}{A_1 \alpha_1} \left(\frac{A_2 C_1}{\rho} + I \right). \tag{31}$$

By using the value of the construction project, we can obtain the decommissioning threshold for the existing plant and the value of the replacement project. The following differential equation, which is satisfied by the project value of the replacement project, is derived from the Bellman equation,

$$\frac{1}{2}\sigma x^2 F_r''(x) + (\mu - \delta)x F_r'(x) - \rho F_r(x) + \alpha_0 x - C_0 = 0. \tag{32}$$

The general solutions of this equation are given as follows:

$$F_r(x) = B_3 x^{\beta_1} + B_4 x^{\beta_2} + \frac{\alpha_0 x}{\rho - \mu + \delta} - \frac{C_0}{\rho}, \tag{33}$$

where B_3 and B_4 are unknown constants. The replacement project value must satisfy the following boundary conditions:

$$\lim_{x \to \infty} \left(B_3 x^{\beta_1} + B_4 x^{\beta_2} \right) = 0, \tag{34}$$

$$F_r(X_r) = F_i(X_r) - U, \tag{35}$$

$$F_r'(X_r) = F_i'(X_r^*). \tag{36}$$

Condition (34) requires that the decommissioning option becomes zero if the cash flow is very large. Therefore, from this condition, we have $B_3 = 0$. Conditions (35) and (36) are the value-matching and smooth-pasting conditions, respectively. From these conditions, we can obtain the replacement project value as follows,

$$F_r(x) = \frac{\alpha_0 x}{\rho - \mu + \delta} - \frac{C_0}{\rho} - \left(\frac{\alpha_0 X_r}{\rho - \mu + \delta} - \frac{C_0}{\rho} + U - F_i(X_r) \right) \left(\frac{x}{X_r} \right)^{\beta_2}. \tag{37}$$

We can be solved for X_r by means of a numerical calculation method.

3. Results and Discussion

As shown in tables 1 and 2, we use the following parameter values of regarding the economics conditions and nuclear power plant for our numerical examples. Although we assume a base value of $\sigma = 0.2$, allow it to vary in order to perform sensitivity analyses.

Expected growth rate of P_t	μ	0.01
Volatility of P_t	σ	0–0.5
Discount rate	ρ	0.05
Initial electricity price (yen/kWh)	x	8.0

Table 1. Parameters with respect to economics conditions

Capacity factor for the existing plant	α_0^0	0.6
Capacity factor for the new plant	α_0^1	1.0
Decreasing rate of capacity factor	δ	0.02
Variable cost for the existing plant (yen/kWh)	C^0	5.0
Variable cost for the new plant (yen/kWh)	C^1	3.0
Construction cost (yen/kW)	I	400,000
Decommissioning cost (yen/kW)	U	30,000
Decommissioning cost (yen/kW) (Replacement)	U	40,000

Table 2. Parameters with respect to nuclear power plant
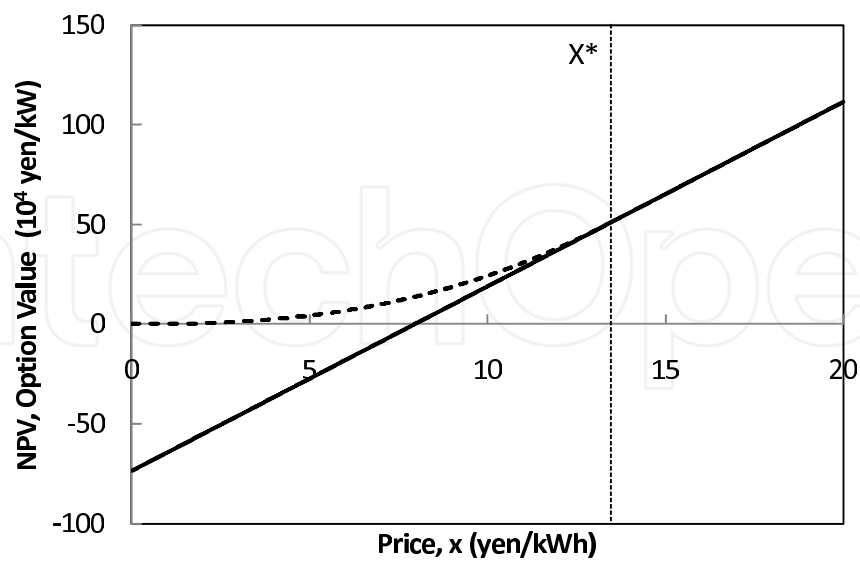
Fig. 1. Expected NPV and investment options ($\sigma = 0.2$). The threshold prices for construction is 13.256 yen/kWh. For Expected NPV, the construction threshold is 7.954 yen/kWh.

3.1 Construction option

In this section we show numerical examples of the model for construction option that is described in section 2.2.

At the initial electricity price, x, the expected NPV is 0.428×10^4 yen/kW. On the other hand, since the option value is 13.895×10^4 yen/kW, it is optimal to wait to invest in construction (see Figure 1). As shown in Figure 1, at more than the initial electricity price of 13.256 yen/kWh, it is better to construct rather than to wait now.
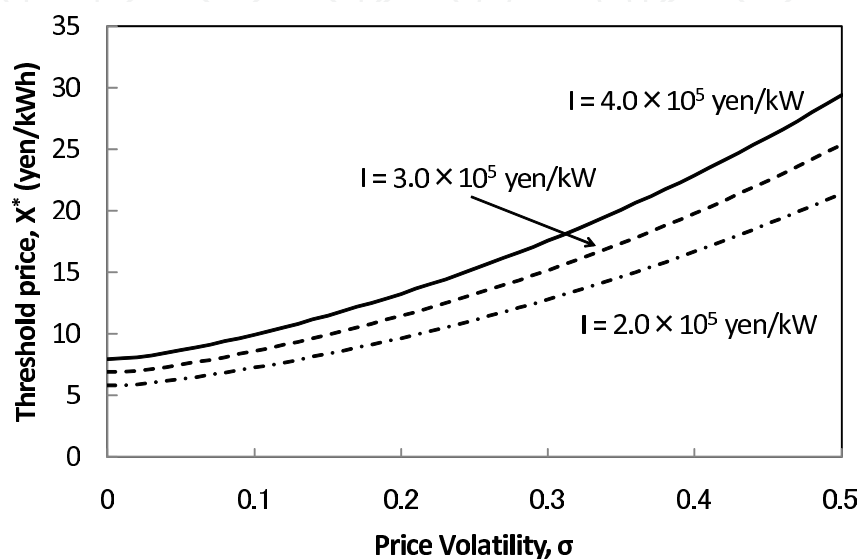

Fig. 2. Effect of uncertainty on the investment threshold

In general real options framework, as uncertainty increases, the value of waiting also goes up. Indeed, a more volatile electricity price increases the opportunity cost of immediate action. Consequently, although the option value of the entire investment opportunity increases, the cost of killing the deferral option also increases, thereby making it optimal to delay investment. For example, if the degree of uncertainty, that is, volatility increases from 0.2 to 0.3, then the investment threshold increases from 13.256 yen/kWh to 17.542 yen/kWh (see Figure 2).

In order to increase the competitiveness of nuclear power, it is effective to decrease the construction cost (OECD, 2000). Consequently, we analyze the effect of construction cost on the investment threshold. It can be seen from Figure 2 that as the construction decreases from 4.0×10^5 yen/kW to 3.0×10^5 yen/kW and 2.0×10^5 yen/kW, the investment threshold decreases, and consequently, the opportunity of investment increases. As volatility increases, the degree of the increase in the investment opportunity increases further. Therefore, it is found that when uncertainty is large, the effect of the decrease in construction cost on the investment decision.

Furthermore, likewise the investment threshold, the investment project value have a large influence on uncertainty. Figure 3 shows the effect of volatility on the investment project value at the initial electricity price. It is found that as volatility increases, the investment project value becomes large. This is because when volatility is large, the postponement of the investment is selected, and consequently, the probability of the investment at larger level of electricity price increases.
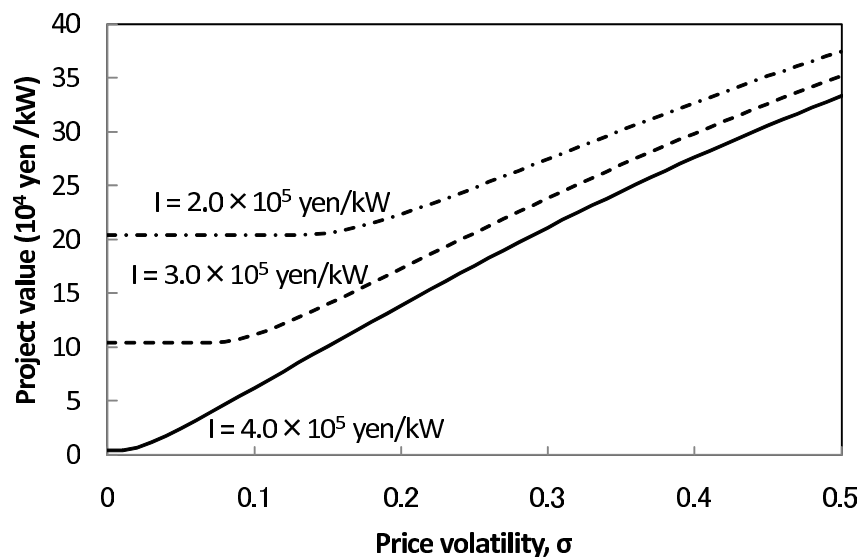
Fig. 3. Effect of uncertainty on the investment value

As the construction decreases from 4.0×10^5 yen/kW to 3.0×10^5 yen/kW and 2.0×10^5 yen/kW, the investment project value increases. Unlike the threshold, as volatility is large, the effect of decrease in construction cost becomes small.

3.2 Decommissioning option

In this section we show numerical examples of the model for decommissioning option that is described in section 2.3.

At the initial electricity price, x, the expected NPV is -1.752×10^5 yen/kW. On the other hand, since the value of decommissioning option is 8.012×10^4 yen/kW, it is optimal to wait to invest in construction (see Figure 4). It can be seen from Figure 4 that at less than the initial electricity price of 4.772 yen/kWh, it is better to decommission rather than to wait now.

$U(10^4$ yen/kW)	Price volatility, σ					
	0	0.1	0.2	0.3	0.4	0.5
1.0	9.886	6.591	4.943	3.735	2.863	2.232
2.0	9.772	6.514	4.886	3.692	2.830	2.206
4.0	9.543	6.362	4.772	3.606	2.764	2.155

Table 3. Effect of uncertainty on the decommissioning threshold

As shown in Table 3, as volatility is large, the threshold of decommissioning decreases. Thus, likewise the construction option, as uncertainty becomes large, the probability for the postponement of decommissioning increases. In Table 3 the effect of decrease in decommissioning cost on the threshold is shown. For example, for $\sigma = 0.2$, if the decommissioning cost decreases from 4.0×10^4 yen/kW to 1.0×10^4 yen/kW, then the decommissioning threshold increases from 4.772 yen/kWh to 4.943 yen/kWh, and consequently, the probability of decommissioning increases. We also show the effect of uncertainty on the increase in the decom-
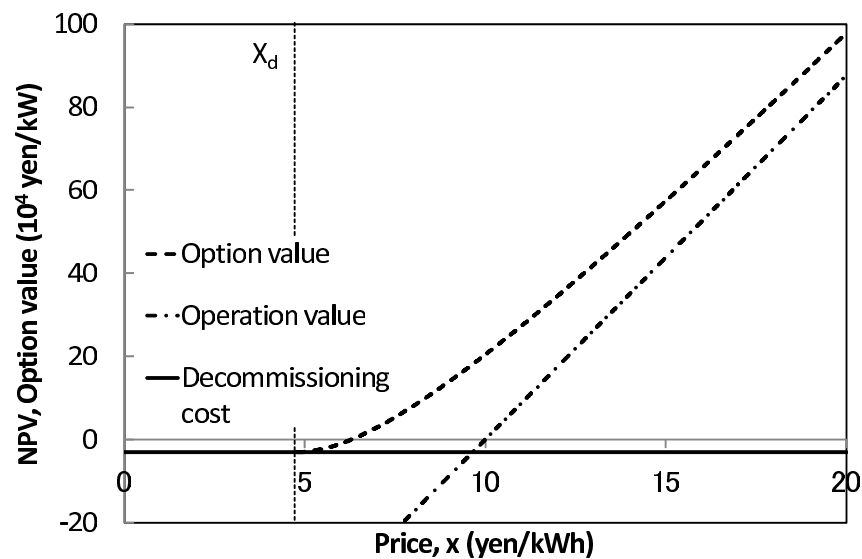
Fig. 4. Expected NPV and decommissioning options ($\sigma = 0.2$). The threshold prices for decommissioning is 4.772 yen/kWh. For Expected NPV, the decommissioning threshold is 9.543 yen/kWh.

missioning opportunity due to decreasing the decommissioning cost. Unlike the construction option as uncertainty is large, the degree of the increase in the probability of decommissioning becomes small.

Figure 5 shows the effect of uncertainty on the value of decommissioning project. Likewise the construction option, the project value increases with volatility. This is because when volatility becomes large, the postponement of decommissioning is selected, and consequently, the probability of decommissioning at smaller level of electricity price increases. Additionally, we also analyze the effect of the decrease in decommissioning cost on the project value. It is clear from Figure 5 that as decommissioning cost decreases, the project value increases.

3.3 Replacement option

In previous section, the decommissioning for existing plant is analyzed. However if the replacement project is evaluated, it is necessary to consider not only the decommissioning for existing plant but also the construction for new plant. Therefore, in this section, we show numerical examples of the model for replacement option that is described in section 2.4.

As described above, at the initial electricity price, x, the expected NPV for decommissioning project is -1.752×10^5 yen/kW. On the other hand, since the option value taking into account replacement is 9.895×10^4 yen/kW, it is optimal to wait to invest in construction (see Figure 6). The value of replacement option is larger than that of decommissioning option, 8.012×10^4 yen/kW, and consequently, it is found that the construction investment for new plant influences the value of decommissioning project. As shown in Figure 6, at less than the initial electricity price of $X_r = 6.298$ yen/kWh, it is appropriate to decommission, and after decommissioning, when the level of electricity price is more than $X_i = 13.256$ yen/kWh, it is appropriate to construct the new plant.

The effect of uncertainty on the thresholds are presented in Figure 7. The solid line denotes threshold in replacement option model, and the dotted and the dashed lines represent the
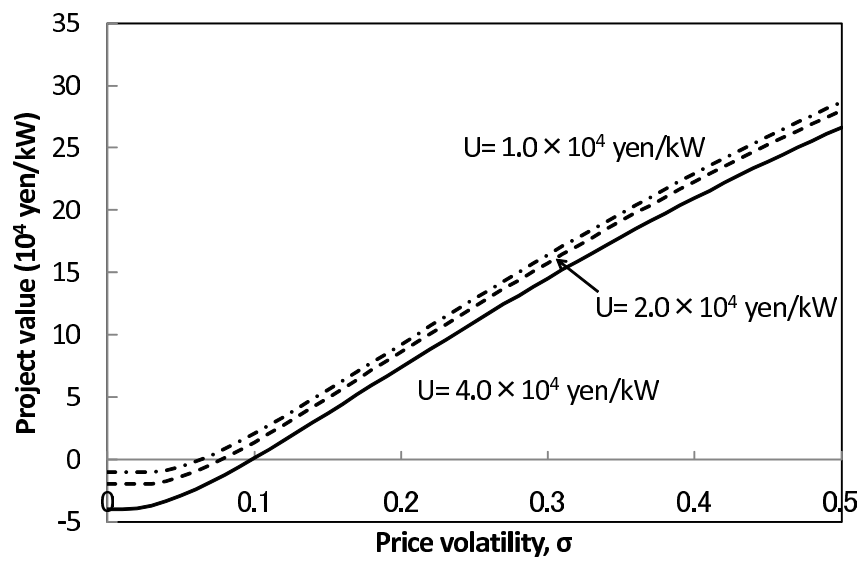
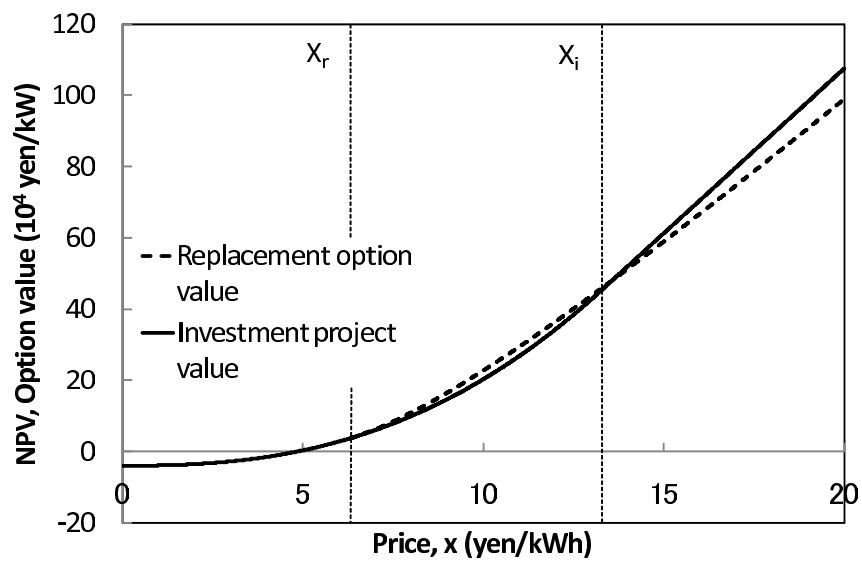Fig. 5. Effect of uncertainty on the value of decommissioning project

Fig. 6. Value of the replacement project ($\sigma = 0.2$). The threshold prices for replacement, X_r, is 6.298 yen/kWh. The construction threshold is 13.256 yen/kWh.
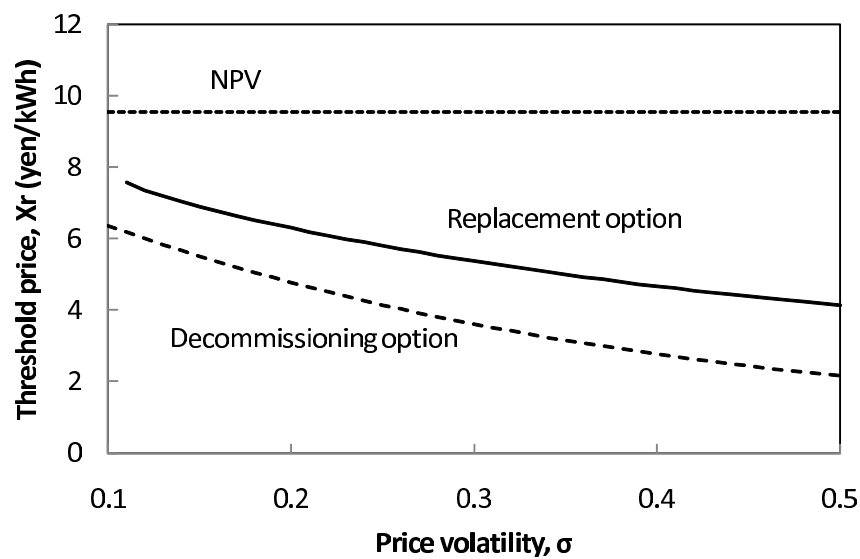
Fig. 7. Comparison of thresholds for expected NPV, decommissioning option, and replacement option ($U = 40,000$ yen/kW)

thresholds for the expected NPV and the decommissioning option model, respectively. The threshold for expected NPV is larger than those for the replacement option and the decommissioning option, and furthermore, the threshold for the replacement option is larger than that for the decommissioning option. This means that the decommissioning decision of the existing plant should stochastically be made earlier if the firm takes into account the replacement of the new plant.

Table 4. Effect of uncertainty on the replacement threshold

$U(10^4$ yen/kW)	Price volatility, σ			
	0.2	0.3	0.4	0.5
1.0	6.775	5.702	4.937	4.368
2.0	6.605	5.587	4.845	4.290
4.0	6.298	5.366	4.666	4.138

Table 4 shows the effect of decommissioning cost on the threshold of replacement. It can be seen from this table that as the decommissioning cost decrease, the threshold of decommissioning increases. Thus, likewise the decommissioning option, the probability of decommissioning increases due to the decrease in decommissioning cost. Additionally, when volatility is large, the effect of the decrease in decommissioning cost on the threshold becomes small. However, for replacement option the effect of the decrease in decommissioning cost, that is, the increase in threshold due to the decrease in decommissioning cost is large compared to decommissioning option. In replacement option the incentive to decommissioning is large due to taking into account the construction of the new plant, and consequently, the effect of the decrease in decommissioning cost on the probability of decommissioning becomes large.

$U(10^4$ yen/kW)	Price volatility, σ			
	0.2	0.3	0.4	0.5
1.0	13.325	21.569	28.910	35.176
2.0	12.489	20.760	28.092	34.340
4.0	10.876	19.172	26.474	32.681

Table 5. Effect of uncertainty on the value of replacement project

Likewise, we show the effect of decommissioning cost of the project value in Table 5. As the decommissioning cost decrease, the project value increase. The degree of the increase is larger than that of decommissioning option. For example, for $\sigma = 0.2$, when the decommissioning cost decreases from 4.0×10^4 yen/kW to 1.0×10^4 yen/kW, then whereas the value of decommissioning option increases by 1.821×10^4 yen/kW from 7.412×10^4 yen/kW to 9.234×10^4 yen/kW, the value of replacement option increases by 2.448×10^4 yen/kW from 10.876×10^4 yen/kW to 13.325×10^4 yen/kW. Consequently, likewise the threshold, for replacement option the effect of the decrease in decommissioning cost is large.

4. Summary

For CO_2 emissions reduction, it is necessary to maintain adequately the nuclear generating capacity, and moreover, to discern investment decisions such as decommissioning and refurbishment for aging nuclear power plants. In the future, the increase in uncertainty is expected, and consequently, economic evaluations under uncertainty are required.

In this chapter we have developed real options models to evaluate construction, decommissioning, replacement. For each problem, we show the effect of uncertainty and cost on optimal decision rules.

The models of construction, decommissioning, and replacement, which are represented in this chapter, are evaluation models for each single project. However, realistically, decommissioning and refurbishment for aging nuclear power plants must be considered as a problem that concerns the entire investment decision. Therefore, extension of this chapter's model towards choice model of investment decisions such as decommissioning, refurbishment, and replacement would be warranted.

5. References

AEC (Japan Atomic Energy Commission) (2006). *Framework for Nuclear Energy Policy*, Tokyo.

Dixit, A.K. & Pindyck, R.S. (1994). *Investment under Uncertainty*, Princeton University Press, Princeton, NJ.

Gollier, C., Proult, D., Thais, F. & Walgenwitz, G. (2005). Choice of nuclear power investments under price uncertainty: Valuing modularity, *Energy Economics*, Vol. 27: 667–685.

McDonald, R. & Siegel, D. (1986). The value of waiting to invest, *Quarterly Journal of Economics*, Vol. 101: 707–727.

Naito, Y., Takashima, R., Kimura, H. & Madarame, H. (2010). Evaluating replacement project of nuclear power plants under uncertainty, *Energy Policy*, Vol. 38: 1321–1329.

OECD NEA (Nuclear Energy Agency) (2000). *Nuclear Power in Competitive Electricity Markets*, Paris.

Pindyck, R.S. (1993). Investment of uncertain cost, *Journal of Financial Economics*, Vol. 34: 53–76.

Rothwell, R. (2006). A real options approach to evaluating new nuclear power plants, *Energy Journal*, Vol. 27: 37–53.

Takashima, R., Naito, Y., Kimura, H. & Madarame, H. (2007). Decommissioning and equipment replacement of nuclear power plants under uncertainty, *Journal of Nuclear Science and Technology*, Vol. 44: 1347–1355.

Takizawa, S., Omori, R., Suzuki, A. & Ono, K. (2001). Analysis of critical electricity price for the investment for constructing a nuclear power plant using real options approach, *Journal of Nuclear Science and Technology*, Vol. 38: 907–909.

Trigeorgis, L. (1996). *Real Options: Management Flexibility and Strategy in Resource Allocation*, MIT Press, Cambridge, MA.
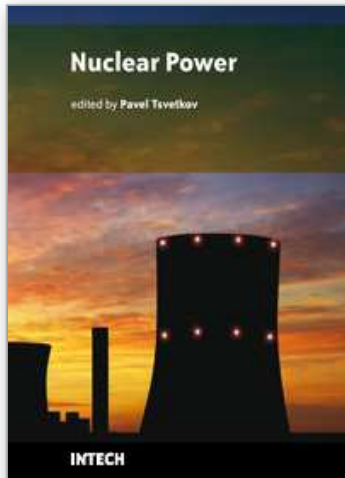
Nuclear Power

Edited by Pavel Tsvetkov

The world of the twenty first century is an energy consuming society. Due to increasing population and living standards, each year the world requires more energy and new efficient systems for delivering it. Furthermore, the new systems must be inherently safe and environmentally benign. These realities of today's world are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. Today's nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. The goal of the book is to show the current state-of-the-art in the covered technical areas as well as to demonstrate how general engineering principles and methods can be applied to nuclear power systems.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Ryuta Takashima (2010). Construction, Decommissioning, and Replacement of Nuclear Power Plants under Uncertainty, Nuclear Power, Pavel Tsvetkov (Ed.), ISBN: 978-953-307-110-7, InTech, Available from: http://www.intechopen.com/books/nuclear-power/construction-decommissioning-and-replacement-of-nuclear-power-plants-under-uncertainty

INTECH
open science | open minds