Effect of Power Generation Mix and Carbon Emissions Tax on Investment Timing

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Abstract Electricity production accounts for around 40% of global energy-related CO_2 emissions and it is expected that the electricity demand increases to twice the current level in 2050. Therefore it is necessary to invest in low-carbon thermal power plants, nuclear and renewable energy for realizing low-carbon economy. These policies may require a large amount of investment costs, and additionally, the uncertainty increases in a situation surrounding power generation projects and their investments. On the other hand, environmental policy for encouraging use of low carbon emission generation power includes an internalization of the externality for CO_2 emissions such as carbon-emissions tax. In this study, we develop a real option model of power generation investments allowing for two uncertainties of the market risk and the introduction of the policy. We analyze the effect of the uncertainties on the power generation mix and the investment timing.

Keywords Environmental policy • Electricity market • CO_2 emission • Uncertainty • Real options

1 Introduction

Climate change is a global environmental issue and introduction expansion of climate policy is officially discussed in many countries for addressing climate change. Especially, power industry accounts for around 40% of global energy

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related CO_2 emissions [9], climate change is a key issue in power industry. Some power companies are charged for explicit carbon cost. Other companies feel implicit carbon cost at least. These climate policies are very uncertain for power companies because climate policy can be changed over sociopolitical trend in the short term compared with long-lived power plants. On the other hand, companies also face an uncertainty of electricity market. Under the circumstance, it is very important to evaluate the value of power plant investment such as expansion and new construction under uncertainties of climate policy and electricity market.

For one of economic analysis methods for investment projects under uncertainties, real options analysis has recently attracted growing attention. Real options analysis, which is pioneered by Brennan and Schwartz [3] and McDonald and Siegel [10] and is summarized in Dixit and Pindyck [4], has been widely used for problems of power plants investments such as problems of modularity [7, 12, 14], capacity sizing [2], technology choice [15, 17], and problems of replacement and refurbishment [11, 16]. Furthermore, the evaluation of the power generation investment under policy uncertainty in real options framework includes Blyth et al. [1], Fuss et al. [5], Yang et al. [18], and Fuss et al. [6]. Blyth et al. [1] analyze the investment options of coal- and gas-fired power plants, and the power plants associated with carbon capture and storage (CCS) technologies taken into accounts uncertain future climate policy. Fuss et al. [5] examine the investment decisions of coal-fired power plant, the plant including a CCS module[1], and the existing plant with a CCS module when investors face uncertainty from climate change policy as well as from volatile prices in the markets. Yang et al. [18] analyze the effects of government climate policy uncertainty on gas, coal and nuclear power investment. Fuss et al. [6] analyze the impact of the frequency of policy changes on investment decisions for low CO_2-emitting electricity generation technologies such as integrated gasification combined cycle plant, the plant including a CCS module, and wind power.

The policy uncertainty presented in these previous works is represented by the dynamics of CO_2 price such as the jump. Our modeling of the policy uncertainty is different from these papers. We focus on uncertain adoption time of environmental policy. Specifically, our modeling setup with respect to environmental policy uncertainty follows Hassett and Metcalf [8] that investigate the effect of tax policy uncertainty on the investment decisions in which tax incentives reduce the capital cost. In Hassett and Metcalf [8], the uncertainty of the policy adoption is assumed to follow a Poisson process. Likewise the model in this paper, suppose that the uncertainty of environmental policy adoption follows the Poisson process.

In this chapter, we develop a real option model of power generation investments allowing for two uncertainties of the market risk such as future price changes and the introduction of the policy. The numerical results show how the power generation mix and the tax rate influence the investment timing.

[1] The plant including a CCS module means the plant to be invested.

The remainder of this chapter is organized as follows. In Sect. 2, we present the basic model for analyzing the investment of capacity expansion for power generations and the model of environmental policy uncertainty. Section 3 provides some results of numerical analysis in which uncertainty of environmental policy adoption affects the investment timing of power generation. Finally, Sect. 4 concludes the paper.

2 The Model

2.1 Model Setup

In this section, we model a profit flow that is obtained from operations of power generations.

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 at time t, P_t 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.

Consequently, the profit flow from plant operating at time t, π_t^i can be represented by the following equation,

$$\pi_t^i = Q^i P_t - \sum_{j=1}^{n} q_j^i c_j, \tag{2}$$

where $i = \{0, 1\}$ denote the states before and after the investment[2], respectively, $Q^i = \sum_{j=1}^{n} q_j^i$ is a total capacity of n power generations for any state, q_j^i is a capacity for power generation j, and c_j is the operating cost that is composed of the fuel cost as well as operating and maintenance costs for power generation j. If an internalization of the externality for CO_2 emissions such as carbon-emissions tax is introduced, the profit flow can be rerepresented as follows:

$$\pi_t^i = Q^i P_t - \sum_{j=1}^{n} q_j^i c_j - \tau \sum_{j=1}^{n} q_j^i \eta_j, \tag{3}$$

[2] In this paper, we do not consider the investment in the module retrofitting, but that in the generation expansion.

where τ is a tax rate for carbon-emission, and η_j is a emission basic unit for power generation j.

2.2 Capacity Expansion Investment

In this section, we describe the model that derive the investment timing of the capacity expansion and the change of the generation mix, and its project value. We consider that a firm operates power generations at the present time, and has the investment options of the capacity expansion and the change of the generation mix. Suppose that the firm can determine the investment timing of power generations with a fixed output, Q. The value of the investment opportunity is:

$$F(p) \equiv \sup_T \mathbb{E}\left[\int_0^T e^{-\rho t}\pi_t^0 dt - e^{-\rho T} I(q_j^i) + \int_T^\infty e^{-\rho t}\pi_t^1 dt\right], \tag{4}$$

where T is the investment time, $\rho>0$ is an arbitrary discount rate, $I(q_j^i) = \sum_{j=1}^n \delta_j \max(q_j^1 - q_j^0, 0)$ is the total investment cost for capacity expansion, and δ_j is the investment cost per kW for power generation j.

Prior to determining the investment threshold p^* and $F(p)$, we calculate the now-or-never expected NPV, $V(p)$, of a power generation mix after the investment:

$$\begin{aligned} V(p) &= \mathbb{E}\left[\int_0^\infty e^{-\rho t}\pi_t^1 dt - I(q_j^i)\right] \\ &= \frac{Q^1 p}{\rho - \mu} - \frac{\sum_{j=1}^n q_j^1 c_j}{\rho} - \sum_{j=1}^n \delta_j \max(q_j^1 - q_j^0, 0). \end{aligned} \tag{5}$$

Following standard arguments as in [4], the value of the investment option satisfies the following differential equation

$$\frac{1}{2}\sigma^2 p^2 F''(p) + \mu p F'(p) - \rho F(p) + Q^0 p - \sum_{j=1}^n q_j^0 c_j = 0, \tag{6}$$

where the primes denote derivatives, that is, $F'(p) = \frac{dF(p)}{dp}$ and $F''(p) = \frac{d^2F(p)}{dp^2}$. The general solution of (6) is given by the following equation:

$$F(p) = A_1 p^{\beta_1} + A_2 p^{\beta_2} + \frac{Q^0 p}{\rho - \mu} - \frac{\sum_{j=1}^n q_j^0 c_j}{\rho}, \tag{7}$$

where A_1 and A_2 are constants, and $\beta_1 > 1$ and $\beta_2 < 0$ are the positive and the negative root of the characteristic equation $\frac{1}{2}\sigma^2\beta(\beta - 1) + \mu\beta - r = 0$, respectively. The unknown constants A_1 and A_2 together with the investment threshold of the capacity expansion and the change of the generation mix, p^* are determined by the following boundary conditions,

$$\lim_{p \to 0} (A_1 p^{\beta_1} + A_2 p^{\beta_2}) = 0, \tag{8}$$

$$F(p^*) = V(p^*), \tag{9}$$

$$F'(p^*) = V'(p^*). \tag{10}$$

Condition (8) requires that the investment option becomes zero if the price level is close to zero. Thus, $A_2 = 0$. Conditions (9) and (10) are the value-matching and smooth-pasting conditions, respectively. The value-matching condition means that when the level of P_t is p^*, the firm exercises the investment option, and then can obtain the net value of $V(p^*)$. Additionally, the smooth-pasting condition means that if the capacity expansion and the change of the generation mix at p^* is indeed optimal, the differentiation of the value function must be continuous at p^*. From these conditions, we can obtain the investment threshold as follows:

$$p^* = \frac{\beta_1}{\beta_1 - 1} \frac{\rho - \mu}{Q^1 - Q^0} \left[\frac{\sum_{j=1}^{n} (q_j^1 - q_j^0) c_j}{\rho} + I(q_j^i) \right]. \tag{11}$$

Furthermore, the unknown constant A_1 is given by,

$$A_1 = \frac{1}{\beta_1} \frac{Q^1 - Q^0}{\rho - \mu} {p^*}^{1-\beta_1} . \tag{12}$$

When the policy is implemented, it is necessary to consider the CO_2 emissions cost. Thus for the case, the term of the emission cost is embedded in (4), and then, the investment threshold (11) can be rerepresented as follows:

$$p^* = \frac{\beta_1}{\beta_1 - 1} \frac{\rho - \mu}{Q^1 - Q^0} \left[\frac{\sum_{j=1}^{n} (q_j^1 - q_j^0) c_j}{\rho} + I(q_j^i) + \frac{\tau \sum_{j=1}^{n} (q_j^1 - q_j^0) \eta_j}{\rho} \right]. \tag{13}$$

When the relatively high emission power generation increases, the emission cost becomes large, and then the investment threshold increases, whereas when the low or zero emission power generation increases, the investment threshold decreases.

2.3 Investment Decision under Environmental Policy Uncertainty

In this section we consider the policy instrument that is a carbon tax at a given rate τ. If the policy is implemented, the CO_2 emissions cost as in (3) is incurred. The government can switch from a present regime to policy regime, one in which the emission cost is not imposed, and the other in which it is. The switches from present state to policy regime follow Poisson process with an constant intensity λ. The probability that the policy will be implemented in the next short interval of time dt is λdt. Suppose that p_0 and p_1 are investment thresholds for the present state and the policy regime, respectively. As shown in Fig. 1, over an interval of $0 \le p < p_1$, the firm will not invest regardless of whether the environmental policy is adopted. Over an interval of $p_1 \le p < p_0$, if the environmental policy is not adopted, the firm will postpone the investment with the expectation not only that the price increases but also that the environmental policy is adopted, whereas if the environmental policy is adopted the firm will invest. In $p_0 \le p$, the firm will invest irrespective of the policy adoption.

The value of the investment option for $p<p_1$ in adoption region, $F_1(p)$ is given by

$$F_1(p) = B_1 p^{\beta_1} + \frac{Q^0 p}{\rho - \mu} - \frac{\sum_{j=1}^n q_j^0 c_j}{\rho} - \frac{\tau \sum_{j=1}^n q_j^0 \eta_j}{\rho}, \tag{14}$$

where B_1 are a unknown constant, The expected NPV for $p_1 \le p$ in adoption region, $V_1(p)$ is

$$V_1(p) = \frac{Q^1 p}{\rho - \mu} - \frac{\sum_{j=1}^n q_j^1 c_j}{\rho} - \frac{\tau \sum_{j=1}^n q_j^1 \eta_j}{\rho}. \tag{15}$$

The unknown constant, B_1 and the investment threshold of the capacity, p_1 are determined by the following value-matching and smooth-pasting conditions,

$$F_1(p_1) = V_1(p_1), \tag{16}$$

$$F_1'(p_1) = V_1'(p_1). \tag{17}$$

From these conditions, we can obtain the investment threshold as follows:

$$p_1 = \frac{\beta_1}{\beta_1 - 1} \frac{\rho - \mu}{Q^1 - Q^0} \left[\frac{(C^1 - C^0) + (C_\tau^1 - C_\tau^0)}{\rho} + I(q_j^i) \right], \tag{18}$$

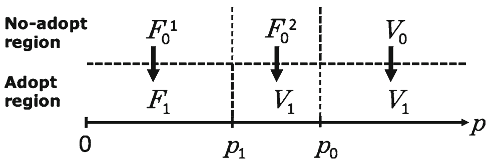

Fig. 1 Value functions and investment thresholds for each region

where $C^i = \sum_{j=1}^{n} q_j^i c_j$, and $C_\tau^i = \tau \sum_{j=1}^{n} q_j^i \eta_j$ $(i = 0, 1)$. Furthermore, the unknown constant B_1 is given by,

$$B_1 = \frac{1}{\beta_1} \frac{Q^1 - Q^0}{\rho - \mu} p^{*1-\beta_1}. \tag{19}$$

For $p<p_1$ in no adoption region, the Bellman equation is given by

$$F_0^1(p) = \left(Q^0 p - \sum_{j=1}^{n} q_j^0 c_j \right) dt + e^{-\rho t} \left[\lambda \mathbb{E}[F_1(P + dP)] + (1 - \lambda)\mathbb{E}[F_0^1(P + dP)] \right]. \tag{20}$$

Following standard arguments, the following differential equation, which is satisfied by the value of the investment option, is derived from the Bellman equation,

$$\frac{1}{2}\sigma^2 p^2 F_0^{1\prime\prime}(p) + \mu p F_0^{1\prime}(p) - \rho F_0^1(p) - \lambda(F_0^1(p) - F_1(p)) + Q^0 p - \sum_{j=1}^{n} q_j^0 c_j = 0, \tag{21}$$

The general solution of (21) is given by the following equation:

$$F_0^1(p) = B_2 p^{\beta_1} + B_3 p^{\gamma_1} + \frac{Q^0 p}{\rho - \mu} - \frac{C^0}{\rho} - \frac{\lambda C_\tau^0}{(\rho + \lambda)\rho}, \tag{22}$$

where B_2 and B_3 are unknown constants, and $\gamma_1 > 1$ is the positive root of the characteristic equation $\frac{1}{2}\sigma^2\gamma(\gamma - 1) + \mu\gamma - (r + \lambda) = 0$. Following standard arguments as in Hassett and Metcalf [8], $B_2 = B_1$. For $p_1 \le p < p_0$ in no adoption region, the investment opportunity value $F_0^2(p)$ is given by

$$F_0^2(p) = B_4 p^{\beta_1} + B_5 p^{\gamma_2} + \frac{(\rho - \mu)Q^0 + \lambda Q^1}{(\rho - \mu)(\rho + \lambda - \mu)} p - \frac{\rho C^0 + \lambda C^1}{\rho(\rho + \lambda)} - \frac{\lambda C_\tau^1}{(\rho + \lambda)\rho} - \frac{\lambda I(q_j^i)}{\rho + \lambda}, \tag{23}$$

where B_4 and B_5 are unknown constants, and $\gamma_2<0$ is the negative root of the characteristic equation $\frac{1}{2}\sigma^2\gamma(\gamma - 1) + \mu\gamma - (r + \lambda) = 0$. The expected NPV for $p_0 \le p$ in no adoption region, $V_0(p)$ is given by

$$V_0(p) = \frac{Q^1 p}{\rho - \mu} - \frac{\sum_{j=1}^{n} q_j^1 c_j}{\rho} - \frac{\lambda C_\tau^1}{(\rho + \lambda)\rho}. \tag{24}$$

The investment threshold in no adoption region, p_0, along with endogenous constants, B_3, B_4 and B_5, are determined via the following boundary conditions:

$$F_0^1(p_1) = F_0^2(p_1), \tag{25}$$

$$F'^1_0(p_1) = F'^2_0(p_1), \tag{26}$$

$$F_0^2(p_0) = V_0(p_0), \tag{27}$$

$$F'^2_0(p_0) = V'_0(p_0). \tag{28}$$

Conditions (25) and (26) are the continuity and high-contact conditions for p_1, respectively. Conditions (27) and (28) are the value-matching and smooth-pasting conditions for p_0, respectively. Since these four equations are highly non-linear, it is not possible to find an analytical solution to the system. However, numerical solutions may be obtained for specific parameters.

3 Numerical Analysis

In the previous section, we presented a model that can analyze the effect of the generation mix change and environmental policy uncertainty on the investment timing. In this section, using this model we present the numerical analysis of various scenarios and the effect of the possibility of policy adoption on the investment thresholds for each region. The solutions for the model can be obtained by means of a numerical calculation method such as the Newton method.

We solve the model numerically using the following base case parameter values: the expected growth rate of the electricity price, μ is 0, the volatility of the electricity price, σ is 20% per year, and the discount rate, ρ is 5% per year. For the parameter values regarding the power generations, we use the data as shown in Table 1 based on OECD/NEA [13]. In this table, the difference of fuel cost between coal-based plants is derived from the assumed power generation efficiency. Suppose that at the present time power generation mix of 3,000 MW is composed of 1,000 MW of aged coal-fired generation, 1,000 MW of gas-fired generation, and 1,000 MW of nuclear power. For present condition, total operating cost, which is composed of the fuel cost as well as operating and maintenance costs, is \$25.9/MWh (579 million\$/year), and CO_2 emissions of present generation mix is 0.465 t-CO_2/MWh (10,390 kt-CO_2/year). We consider the investment projects of the capacity expansion of 5,000 MW for the following four cases: For the case i, the power generation mix is composed of 2,500 MW of gas-fired generation and 2,500 MW of nuclear power. For the case ii, the power generation mix is composed of 2,500 MW of coal-fired generation with CCS and 2,500 MW of nuclear power. For the case iii, the power generation mix is composed of 1,250 MW of coal-fired generation with CCS, 1,250 MW of gas-fired generation, and 2,500 MW of nuclear power. For the case iv, the power generation mix is composed of 625 MW

Table 1 Parameter values with respect to power generations

	Initial cost	O&M cost	Fuel cost	Load factor	Emission intensity
	(US$/kW)	(US$/kWh)	(US$/kWh)	(%)	(t-CO_2/MWh)
Coal	1,300	5.0	15.8	85.0	0.830
Coal with CCS	1,600	23.0	18.0	85.0	0.095
Aged coal	–	11.0	20.3	85.0	1.064
Gas	600	2.4	20.3	85.0	0.331
Nuclear	1,750	6.5	5.2	85.0	0

Table 2 Investment cost, operating cost, and CO_2 emissions data and investment thresholds for each case

Case	i	ii	iii	iv
Coal	0	0	0	625
Coal with CCS	0	2,500	1,250	625
Aged coal	0	0	0	0
Gas	2,500	0	1,250	1,250
Nuclear	2,500	2,500	2,500	2,500
Investment cost ($/MW)	3,525	6,625	4,775	4,588
Operating cost ($/MWh (million$/year))	23.3 (867)	26.4 (981)	24.8 (924)	22.3 (830)
CO_2 emissions (t-CO_2/MWh (kt-CO_2/year))	0.166 (6,167)	0.047 (1,761)	0.106 (3,964)	0.198 (7,389)
p_0 ($/MWh)	54.329	84.202	67.393	57.385
p_1 ($/MWh)	50.135	75.510	60.947	54.447

of coal-fired generation, 625 MW of coal-fired generation with CCS, 1,250 MW of gas-fired generation, and 2,500 MW of nuclear power.

In Table 2, the investment cost per MW, the operating cost per MWh, CO_2 emissions per MWh and the investment thresholds for each case are shown. In this numerical example, we use a tax rate of $15/t-$CO_2$. The threshold of the investment for case i is the lowest one due to low investment cost. Therefore case i have the highest incentive of the investment decisions, however the reduction of CO_2 emissions in kt-CO_2/year for case i leads to about 60% of CO_2 emissions prior to the investment. On the other hand, although the threshold for case ii is the highest one because of high investment and operating costs of coal-fired generation with CCS technology, the reduction of CO_2 emissions in kt-CO_2/year for case ii induces less than 20% of CO_2 emissions prior to the investment. As the fraction of coal-fired generation with CCS technology in the generation mix decreases as in case iii and then case iv, the thresholds considerably decreases. It can be seen from this table that for cases ii and iii, the difference between p_0 and p_1 are relatively large. Thus this shows that there exists a high possibility that the firm invests at once if the environmental policy is adopted.

Table 3 shows the effect of the tax rate on the investment thresholds for cases iii and iv. In each case, the differences between p_0 and p_1 increases as the tax rate becomes high. This is because the incentive of the investment for power generations of low-carbon emissions becomes large as the tax rate increases. For low tax rate, the threshold, p_1 for case iii is larger than that for case iv, whereas for high tax rate, p_1 for case iii is smaller than that for case iv. It is found that when

Table 3 Effect of the tax rate on the investment thresholds for cases iii and iv

		Tax rate ($/t-$CO_2$)				
		15	20	25	30	35
Case iii	p_0 ($/kWh)	67.393	65.702	64.121	62.666	61.349
	p_1 ($/kWh)	60.947	56.929	52.911	48.893	44.875
Case iv	p_0 ($/kWh)	57.385	56.529	55.696	54.888	54.107
	p_1 ($/kWh)	54.447	52.571	50.694	48.818	46.941

the tax rate is relatively high, the incentive of the investment for power generations of low-carbon emissions such as CCS technology becomes large even if the construction cost is somewhat high.

4 Conclusions

In this chapter we have developed real options models to evaluate the investment decisions of power generations under environmental policy uncertainty. We show the threshold of the power generations investments in each case for various costs and CO_2 emissions degrees. The effect of tax rate on optimal decision rules is indicated.

The model that is resented in this chapter considers uncertain adoption time of environmental policy. However, realistically, uncertainty over tax rate must be considered as a problem that concerns the entire investment decision of power generations under environmental policy uncertainty. Therefore, extension of this chapter's model towards uncertain tax rate would be warranted. Other directions for future work focus on uncertainty of CO_2 prices in the emissions trading market, capacity choice, and sequential investments.

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Appendix A. List of Symbols

P_t	Electricity price at time t
p	Initial electricity price
μ	Instantaneous expected growth rate of electricity price
σ	Instantaneous volatility of electricity price
π_t	Profit flow from plant operating at time t
$I = \{0, 1\}$	States before and after the investment
j	Type of power generation
q_j^i	Capacity for power generation j
Q^i	Total capacity of power generations
c_j	Operating cost for power generation j
C^i	Total operating cost

(continued)

τ	Tax rate for carbon-emission
η_j	Emission basic unit for power generation j
ρ	Arbitrary discount rate
δ_j	Investment cost per kW for power generation j
$I(q_j^i)$	Total investment cost for capacity expansion
p^*	Investment threshold for the case without policy uncertainty
λ	Poisson intensity for the state transition
p_0	Investment threshold for the present state
p_1	Investment threshold for the policy regime

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