KYOTO UNIVERSITY 京都大学

iDER Project

「分散型電力システムの制度設計と社会経済的評価、
その地域再生への寄与に関する研究」
プロジェクト

"Institutionalization of Decentralized power system
and socio-economic Evaluation,
concerning its contribution to Regional regeneration"
Project

ディスカッションペーパーシリーズ
Discussion Paper Series

No. 13-A-1

Effects of cross-border electricity trade on CO2 abatement cost of Japanese power companies

Aiko AZUMA

Doctoral research fellow

Public Policy School, Hokkaido University

Oct. 2013

〒606-8501　京都市左京区吉田本町
京都大学　大学院　経済学研究科　諸富研究室

Graduate School of Economics, Kyoto University
Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

Effects of cross-border electricity trade on CO2 abatement cost of Japanese power companies

Aiko, AZUMA
Doctoral research fellow
Public Policy School, Hokkaido University
Postal Address: Kita 9 Nishi 7 Kita-ku Sapporo 060-0809, Japan
E-mail: aikoazuma@hops.hokudai.ac.jp

Abstract

This paper investigates the effects of cross-border electricity trade among the Japanese utilities on generation cost, the potential for CO2 reduction, and emissions abatement cost after the Fukushima crisis. We assumed perfect competition among electricity producers. Utilities decide on the quantity of electricity to generate and transmit to electricity-consuming areas connected by power transmission lines in order to maximize their annual profit based on transmission capacities, emissions, and plant capacity constraints.

We simulate the effect of electricity trade between two Japanese general electric utilities, Tokyo Electric Power Company (TEPCO) and Hokkaido Electric Power Company (HEPCO), on their generation cost, CO2 abatement potential, and CO2 abatement cost. From our simulation results, it is clear that we can reduce generation costs and emissions simultaneously by introducing cross-border electricity trade. However, the small capacity of electricity transmission lines in the Japanese system nullifies the benefits from electricity trade.

Key words: electricity generation, transmission, cross-border electricity interchange, CO2 abatement, complementarity.

JEL Classification: Q54, Q55

Effects of cross-border electricity trade on CO_2 abatement cost of Japanese power companies

1. Introduction

Japan faces a difficult situation of electricity shortage during peak hours and an increase in fuel cost and CO_2 emissions after the Fukushima Nuclear Power Plant accident in March 2011. One of the reasons that led to this situation is the Japanese electricity system, which is divided into ten areas, each area monopolized by one private utility. Originally, electricity demand in each area is supplied by a regional monopoly utility, because the transmission capacities of utilities will be too small to trade electricity. Thus, a major issue that has come up after the Fukushima crisis is expansion of cross-border electricity trade among utilities.

In this paper, we analyze the production behavior of electric generators connected by transmission lines by using a spatial electricity market model. Smeers and Jing-Yuan (1997) and Hobbs (2001) combined the transmission capacity constraint in a Cournot–Nash electricity competition market and investigated the effects of a limited transmission capacity on the quantity of electricity trade and equilibrium price. Hosoe and Akiyama (2007) also constructed a spatial electricity market of Japan and investigated the effects of a transmission pricing system on the quantity of trade among utilities. Tanaka (2007) also analyzed the effects of transmission expansion on the trade pattern in a Japanese Cournot electricity market. The last two analyses, which targeted the Japanese electricity market, estimated the effect of summer peak-time demand only, and did not examine the trade pattern through the year. In addition, these studies did not analyze the CO_2 emissions reduction behavior in the power sector.

However, the CO_2 abatement behavior in the power sector was investigated by Azuma (2012, 2013). Azuma (2012) investigated how the decisions of optimal production and investment in the power sector are influenced by Japan's carbon pricing policy. Azuma (2013) further analyzed the effects of a decrease in nuclear power generation on Japan's emission abatement potential and abatement cost. Both studies assumed a regional monopoly electricity market in Japan and did not investigate the effects of cross-border electricity trade among the utilities on CO_2 abatement potential and cost.

Therefore, the objective of this study is to investigate the effects of electricity trade among the Japanese utilities on generation cost, the potential for CO_2 reduction, and emissions abatement cost after the Fukushima crisis.

The remainder of this paper is organized as follows. Section 2 describes the electricity trade simulation models. Section 3 presents the data and assumptions employed in simulation. Section 4 discusses the empirical evidence. Finally, Section 5 presents the conclusion.

2. Model

We assume two electricity-consuming areas (n = 1,2) connected by one power transmission line having a capacity of T(kWh). Let y_n(kWh) denote the demand of electricity in area n and $P_n = a_n - b_n y_n$ the demand function.

Each area has one electricity power company (f = 1,2). Let the electricity generation per hour be denoted by x_f(kWh) and the generation cost function by $C_f(x_f)$. Firm f's electricity output is limited by installed plant capacity as follows:

$$0 < x_f \le X_f. \tag{1}$$

X_f(kWh) is the maximum electricity that firm f can generate per hour by using the power plants they have.

The electricity generated by firm f is transmitted to electricity-consuming area n, and the quantity of electricity transmitted from firm f to the consuming location n is denoted by s_{fn} (kWh). The physical quantity of the electricity transmitted to other areas is limited by transmission capacity:

$$|s_{12} - s_{21}| \le T. \tag{2}$$

The electricity generated by firm f is transmitted to both electricity-consuming areas, and there is an energy balance constraint between electricity generation and the quantity of electricity transmitted:

$$\sum\nolimits_n s_{fn} = x_f. \tag{3}$$

The transmission fee w_{fn} depends on the firm that transmits electricity and the area where the electricity is received. In this analysis, we assume that $w_{12} - w_{11} > w_{22} - w_{21}$.

In addition, we assume that a carbon tax is imposed on fossil fuels. Let the carbon intensity of firm f's electricity generation be denoted by β_f(tCO2/kWh) and the carbon tax rate be denoted by δ(yen/tCO2)[1]. Each firm must pay a carbon tax of $\delta\beta_f x_f$(yen) per hour.

The utility decides on the quantity of electricity to generate x_f, and to transmit to both areas s_{fn}, in order to maximize its hourly profit based on transmission capacity and plant capacity constraints:

$$\max_{x_f, s_{fn}} \pi_f = \sum\nolimits_n [P_n(y_n) - w_{fn}]\, s_{fn} - C_f(x_f) - \delta\beta_f x_f \tag{4}$$

$$\begin{aligned} s.t. \quad & x_f \le X_f \\ & |s_{12} - s_{21}| \le T \\ & x_f > 0, s_{fn} \ge 0 \end{aligned}$$

In this analysis, we assume that no utility manipulates electricity prices and transmission fees.

[1] β_f could be changed depending on the utilization rate of the utility's power plants.

The Lagrangian function is represented by equation (5):

$$\mathcal{L} = \sum_n [P_n(y_n) - w_{fn}]\, s_{fn} - C_f(x_f) - \delta\beta_f x_f \;\; + \lambda_f(X_f - x_f)$$
$$+\mu_1(T - s_{12} + s_{21}) + \mu_2(T - s_{21} + s_{12}) \qquad (5)$$

The variable λ_f represents the marginal profit when the plant capacity constraints change marginally, and μ_1 and μ_2 represent the marginal profits when the transmission capacity constraints change marginally.

From equation (5) and energy balance equation (3), we have the first-order condition for profit maximization. In terms of firm 1, the optimal electricity generation is determined by the relation between the marginal revenue from area 1 and its own marginal generation cost. The optimal electricity sold from firm 1 to consuming area 2 is determined by the relation between the marginal revenue from areas 1 and 2.

$$s_{12} = T, 0 < x_1 \le X_1 \quad if \quad P_2 - w_{12} > P_1 - w_{11} \ge c_1' + \delta\beta_1 \qquad (6)$$
$$0 < s_{12} < T, 0 < x_1 \le X_1 \quad if \quad P_2 - w_{12} = P_1 - w_{11} \ge c_1' + \delta\beta_1 \qquad (7)$$
$$s_{12} = 0, 0 < x_1 \le X_1 \quad if \quad P_2 - w_{12} < P_1 - w_{11} \ge c_1' + \delta\beta_1 \qquad (8)$$
$$s_{12} = 0, x_1 = 0 \quad if \quad P_2 - w_{12} < P_1 - w_{11} < c_1' + \delta\beta_1 \qquad (9)$$

Equations (6) and (7) mean that firm 1 sends its electricity generation to consuming area 2 when its marginal revenue from consuming area 2 equals or is higher than its marginal generation cost, including CO2 cost. However, equations (8) and (9) mean that firm 1 never sends its electricity generation to area 2 when the marginal revenue earned from area 1 exceeds that from area 2. The optimal electricity generation and sales of firm 2 are determined analogously.

Gathering the Kuhn–Tucker condition for firms 1 and 2 and solving these equations simultaneously, we obtain the amount of transmission for each firm in equilibrium:

$$s_{12} = T, s_{21} = 0 \quad if \quad P_2 - w_{12} > P_1 - w_{11}, P_2 - w_{22} > P_1 - w_{21}, \qquad (10)$$
$$0 < s_{12} < T, s_{21} = 0 \quad if \quad P_2 - w_{12} = P_1 - w_{11}, P_2 - w_{22} > P_1 - w_{21}, \qquad (11)$$
$$s_{12} = 0, s_{21} = 0 \quad if \quad P_2 - w_{12} < P_1 - w_{11}, P_2 - w_{22} > P_1 - w_{21}, \qquad (12)$$
$$s_{12} = 0, 0 < s_{21} < T \quad if \quad P_2 - w_{12} < P_1 - w_{11}, P_2 - w_{22} = P_1 - w_{21}, \qquad (13)$$
$$s_{12} = 0, s_{21} = T \quad if \quad P_2 - w_{12} < P_1 - w_{11}, P_2 - w_{22} < P_1 - w_{21}. \qquad (14)$$

These equations mean that the amount of transmission in equilibrium depends on the relation between the marginal revenue from areas 1 and 2 for each firm. For example, in equation (10), firm 1 sends its generation to area 2 up to the maximum transmission capacity T, whereas firm 2 does not send its generation to area 1 because the marginal revenue from area 1 exceeds that from area 2 for both firms.

3. Data

We simulate the effect of electricity trade between two Japanese general electric utilities, Tokyo Electric Power Company (TEPCO) and Hokkaido Electric Power Company (HEPCO), on their generation cost, CO2 abatement potential, and CO2 abatement cost. These two utilities determine the optimal level of power generation of each plant for each hour and the optimal quantity of electricity the utilities should buy or sell based on the model of equation (6).

Table 1 shows the electricity generated from each power source of the two utilities used in this simulation.

Table 1 Simulation Data

Utility	Hokkaido (HEPCO)	Tokyo (TEPCO)
Total electricity demand in 2010 (TWh/year)	36	318
Nuclear Power (%)	45	19
Hydro Power (%)	8	3
Wholesale (%)	14	15

3.1. Electricity demand

The hourly electricity demand for 2010 is based on the actual demand data, and is obtained from the Japanese Ministry of Economy, Trade and Industry. We assume that electricity demand is inelastic to price.

3.2. Nuclear power generation

In this simulation, we assume that the electricity generated by nuclear power plants is fixed and is consumed in each utility area. HEPCO has one nuclear power plant, Tomari, which has three nuclear reactors. The total capacity of the Tomari nuclear power plant is 2070 MW. We assume that all the three nuclear power units of Tomari can be operated at full capacity, in which case, nuclear power generation will account for 45% of the total electricity demand in 2010 in the Hokkaido area[2].

TEPCO has three nuclear power plants, Fukushima first, Fukushima second, and Kashiwazaki, with a total capacity of 17308 MW. We assume that the Kashiwazaki nuclear power plant is the only utility operated at full capacity, and that the Fukushima first and Fukushima second power plants have been shut down after the Fukushima crisis. Nuclear power generation contributes 19% of the total electricity demand in the Tokyo area.

---

[2] The maximum annual utilization rate is set at 85% in this simulation, because we need to take into account the inspection term.

3.3. Wholesale electricity generation

Wholesale power generation utilities accounted for 14% and 15% of total electricity demand in the Hokkaido and Tokyo areas, respectively.

3.4. Capacity of transmission

The capacity of electricity transmission between the Hokkaido and Tokyo areas is set at 600 MW based on actual data.

3.5. Features of Thermal Power Plants

Table 2 summarizes the features of thermal power plants in each utility in 2010. For example, TEPCO built two new coal plants in the 2000s, operates 4 old oil plants built almost before the oil shock, and 10 gas plants; the total number of units operated by TEPCO is 54. The total capacity of the thermal power sector is 39362 MW, and the ratio of coal, oil, and gas plants of its total thermal power capacity is 4%, 26%, and 70%, respectively. Utilities cannot use the full generation capacity of plants because they need to shut down plants for maintenance and reserve capacity preparing for unexpected situations, and hence, the maximum utilization of each plant is set at 85% in this analysis.

The fuel cost per kWh of each plant (c_i), and CO2 emission per kWh of each plant (β_i) are calculated in the following manner. The data used in the calculation are based on ANRE (2010). The fuel cost per kWh (c_i) is calculated by $c_i = p_i/h_i/TE_i \times 360$, where p_i is the fuel price given by the actual average purchase price from January 2010 to December 2010 based on the Trade Statics of Japan, h_i is the heat value of fuel used in each plant, and TE_i is the thermal efficiency of each plant based on the data provided by ANRE (2005). The CO2 emissions per kWh of each plant (β_i) is calculated by dividing the CO2 emissions coefficient of fuel with $TE_i \times$ 0:36. The data of CO2 emissions coefficient of each fuel is based on MOE (2002)[3]. In Table 2, these figures of each plant are summarized according to fuel type of plants because of space limitations. Table 2 indicates that the fuel cost per kWh (c_i) is the cheapest for coal plants and the highest for oil plants; however, in terms of CO2 emissions per kWh (β_i), gas plants are the most attractive.

[3] Coal: 90.0 g CO2/MJ, Heavy oil: 71.6 g CO2/MJ, Crude oil: 69.0 g CO2/MJ, LNG: 50.8 g CO2/MJ, LPG: 58.6 g CO2/MJ, Natural gas: 51 g CO2/MJ, City gas: 51.3 g CO2/MJ, Light oil: 69.2 g CO2/MJ.

Table 2 Features of thermal power plants

Utility	Fuel type	The number of plants	Start of operation	Installed capacity	Capacity profile	Thermal efficiency	Fuel cost	Emission coefficient
			(year)	(MW)	(%)	(%)	(yen/kWh)	(kgCO2/kWh)
Tokyo	Coal	2	2003.98	1600	4	43.0	2.92	0.76
	Oil	4	1982.14	10328	26	36.6	11.56	0.66
	Gas	10	1991.36	27434	70	44.1	7.92	0.42
	Total			39362				
Hokkaido	Coal	3	1979.59	2250	58	38.4	3.60	0.85
	Oil	4	1984.00	1650	42	38.3	10.63	0.68
	Total			3900				

4. Simulation

4.1. Scenario settings

To estimate the effect of electricity interchange between two utilities on their generation cost, CO2 abatement potential, and CO2 abatement cost, we set scenarios with different settings depending on the capacity of transmission line and CO2 tax rate

The capacity of transmission line set in three patterns, 0 GW, 0.6GW, and ∞GW. The capacity of 0 GW represents the situation where TEPCO and HEPCO cannot trade electricity generation at all, while ∞GW represents the situation where they buy and sell electricity as they want to. The actual capacity between TEPCO and HEPCO in 2013 is 0.6 GW.

CO2 tax rate also set in three pattern, 289 yen/tCO2, 15000 yen/tCO2, and 25000 yen/tCO2. Japanese government introduced CO2 tax in 2012, and the actual tax rate is 289 yen/tCO2.

4.2. Results of simulation

Each utility determines its optimal electricity generation of each thermal power plant for each hour and the optimal quantity of electricity the utilities should buy or sell in order to maximize its hourly profits and meet the several constraints shown in the model.

Table 3 shows the difference in annual electricity generation in the thermal power sector and the annual utilization rate of plants according to fuel type among the scenarios[4]. Table 4 shows total annual fuel cost, average generation cost, annual CO2 emissions, and average CO2 coefficient per kWh among the scenarios. The annual average generation cost is calculated by dividing the total fuel cost with the sum of annual electricity generation in the thermal power sector. The annual average CO2 coefficient per kWh is also calculated by dividing the total CO2 emissions with the sum of annual electricity generation.

Table 3 The results of the simulation part 1

scenarios	Annual generation of thermal power sector (TWh)			Annual utilization rate (%)				
	HEPCO	TEPCO	Total	HEPCO		TEPCO		
				Coal	Oil	Coal	Oil	Gas
T=0								
CO2 tax=289	12.8	202.2	214.9	61.4	4.4	85.0	18.3	72.3
CO2 tax=15000	12.8	202.2	214.9	61.4	4.4	85.0	18.3	72.3
CO2 tax=25000	12.8	202.2	214.9	61.4	4.4	82.2	18.3	72.5
T=0.6								
CO2 tax=289	16.8	198.5	215.3	77.8	10.1	85.0	16.6	71.4
CO2 tax=15000	16.6	198.6	215.3	77.3	9.8	85.0	16.6	71.4
CO2 tax=25000	11.8	203.5	215.3	52.6	9.8	83.3	16.6	73.6
T=∞								
CO2 tax=289	19.6	196.1	215.7	85.0	19.5	85.0	15.6	70.8
CO2 tax=15000	19.2	196.5	215.7	83.8	18.7	85.0	15.6	70.9
CO2 tax=25000	10.5	205.3	215.7	39.3	18.7	83.8	15.6	74.7

[4] The figure of annual electricity generation is the sum of optimal hourly electricity generation of all fuel type of plants. The annual utilization rate, that is summarized according to fuel type because of space limitations, calculated by dividing the sum of hourly optimal electricity generation of each plants by the sum of maximum hourly generation of each plants.

Table 4　The results of the simulation part 2

scenarios	Fuel cost (billion yen)			Unit Generation cost (yen/kWh)			CO2 emission (MtCO2)	CO2 coefficient (kgCO2/kWh)		
	HEPCO	TEPCO	Total	HEPCO	TEPCO	Total		HEPCO	TEPCO	Total
T=0										
CO2 tax=289	48	1579	1628	3.79	7.81	7.57	103.2	0.820	0.459	0.480
CO2 tax=15000	185	2899	3084	14.54	14.34	14.35	103.2	0.820	0.459	0.480
CO2 tax=25000	278	3796	4074	21.85	18.77	18.96	103.1	0.820	0.458	0.480
T=0.6										
CO2 tax=289	68	1543	1611	4.05	7.78	7.49	104.5	0.816	0.457	0.485
CO2 tax=15000	246	2837	3082	14.75	14.28	14.32	104.4	0.817	0.457	0.485
CO2 tax=25000	260	3814	4076	22.10	18.74	18.93	102.6	0.810	0.457	0.476
T=∞										
CO2 tax=289	88	1520	1608	4.48	7.75	7.45	105.3	0.810	0.456	0.488
CO2 tax=15000	290	2798	3088	15.08	14.24	14.32	105.2	0.810	0.456	0.488
CO2 tax=25000	237	3844	4081	22.65	18.73	18.92	101.9	0.791	0.456	0.473

First, we assess the effects of transmission capacity on the amount of electricity generation, the generation cost, and CO2 emissions, assuming that the CO2 tax rate is kept at the actual level, 289 yen/tCO2. Electricity generation increases with the expansion of transmission capacity because it could reduce the shortage of electricity. If TEPCO and HEPCO cannot trade in electricity generation at all, T = 0, TEPCO will have an electricity shortage, especially during summer peak time, because we assume that TEPCO cannot use the Fukushima first and second nuclear power plants. Table 3 shows that TEPCO’s coal and gas power plants work at almost full capacity to substitute for nuclear power generation. When transmission capacity between TEPCO and HEPCO is expanded, TEPCO can buy electricity from HEPCO. Therefore, HEPCO sells its coal power generation except during winter peak time, and the sum of electricity generation increases from 214.9 TWh to 215.7 TWh. Table 4 shows that electricity interchange can save on annual fuel costs. Although electricity generation in the thermal power sector increases because of electricity trade, the total annual fuel cost reduces from 1628 billion yen to 1608 billion yen.

We note two reasons for this cost savings. The first is the large difference in installed capacities of coal, oil, and gas power plants between TEPCO and HEPCO. As shown in Table 2, HEPCO has no gas power plants and depends on coal plants, whereas TEPCO has a large proportion of gas plant capacity. The generation cost of coal power plants is the cheapest because of the very low CO2 tax rate, 289 yen/tCO2. Therefore, HEPCO increases its coal power generation and sells electricity to TEPCO all through the year except winter peak time, while TEPCO reduces its electricity generation from gas power plants. This leads to reduction in the total fuel and generation costs per kWh. The second reason is the difference in demand patterns between the two areas. The peak demand in the Hokkaido area comes in winter, whereas the peak hours in the Tokyo area is summer daytime. Therefore, HEPCO can sell cheap coal electricity through the year except winter peak time, whereas TEPCO will be able to sell gas electricity cheaper than oil electricity during winter peak time when the transmission capacity increases. Thus, electricity interchange leads to a decrease in the operation of most expensive oil plants and enables cost savings.

However, both the total CO2 emission and the CO2 coefficient per kWh would increase with an increase in transmission capacity because the utilization of coal power increases[5]. The CO2 coefficient increases from 0.480 kgCO2/kWh to 0.488 kgCO2/kWh. Therefore, we need to be concerned about how to control CO2 emissions with an expanding electricity trade.

We assess how electricity trade, the unit generation cost, and CO2 emissions have changed after raising the CO2 tax rate. Table 4 shows the generation cost per kWh reverse between HEPCO and TEPCO when the CO2 tax rate is over 15000 yen/tCO2. For example, in the scenario where T = 0 and the CO2 tax rate = 15000, the generation cost in HEPCO is 14.54 yen/kWh while that in TEPCO is 14.34 yen/kWh. This means that a gas power plant becomes attractive in terms of generation cost per kWh including CO2 cost, and that the base load plant gradually changes from coal to gas when the CO2 tax becomes over 15000 yen/tCO2. This fuel shift from coal to gas induced by CO2 tax leads to changes in trade pattern. Table 3 shows that TEPCO tends to increase generation from gas power plants and sell less-carbon-intensive gas electricity during off-peak periods, while the generation of electricity from coal plants comes down in HEPCO when the CO2 tax is raised up to 25000 yen/tCO2.

Finally, we compare how power generation costs and CO2 emissions have changed in accordance with changes in transmission capacity with a CO2 tax rate of 25000 yen/tCO2. When two utilities cannot trade in electricity, the unit generation cost and CO2 coefficient are 18.96 yen/kWh and 0.480 kgCO2/kWh, respectively. When two utilities trade in electricity up to 0.6 GW, the unit generation cost and CO2 coefficient reduce to 18.93 yen/kWh and 0.476 kgCO2/kWh, respectively. In case there is no limit to transmission capacity, the unit generation cost and CO2 coefficient reduce to 18.92 yen/kWh and 0.473 kgCO2/kWh, respectively. These results indicate that we can reduce the generation costs and emissions simultaneously by introducing cross-border electricity trade. However, the benefits from electricity trade are

[5] Azuma (2012) estimated the CO2 marginal abatement cost of fuel change in Japanese power companies as 10000–15000 yen/tCO2. The current CO2 tax rate is far from the level to induce fuel changes, and leads to increases in the utilization of coal power plants.

nullified because the capacity of the transmission lines between TEPCO and HEPCO is limited to 0.6 GW. Thus, if we have a larger capacity for our transmission lines, we will be able to enjoy more savings in fuel costs and larger CO2 emission reductions.

5. Concluding Remarks

This paper analyzes the effect of cross-border electricity trade between two Japanese utilities, TEPCO and HEPCO, on generation cost, CO2 abatement potential, and CO2 abatement cost.

Our simulation results using actual data of Japanese utilities indicate that cross-border electricity interchange reduces the total generation costs and increases the CO2 abatement potential of utilities.

We note two reasons why cross-border electricity trade leads to cost savings and additional CO2 abatement potential. One is the difference in installed capacities between thermal power plants, and the other is the difference in electricity demand patterns between two utilities. Owing to these differences, two utilities can use thermal power plants cost-effectively through the year when they trade electricity generation.

However, at present, we cannot fully enjoy the benefits of cross-border electricity trade because the capacity of the electric power transmission lines connecting Hokkaido and Tokyo is very small. The costs of expanding transmission capacity is not considered in this paper, but our cross-border electricity trade benefit analysis provides very useful evidence to investigate the effect of the Japanese power system reforms, including the expansion of transmission capacity in the future.

reference

- Azuma, A. (2012), ``CO2 Abatement in the Japanese Power Sector'', *Review of Environmental Economics and Policy Studies*, vol.5, No.2, pp.46-57.
- Azuma, A. (2013), ``CO2 Reduction without Nuclear Power Generation'', Hokkaido University Public Policy School, Discussion Paper Series No.15.
- Agency for Natural Resources and Energy (2005), *Electric Power Supply and Demand 2004*, Chuwa Insatsu Co.,Ltd. (in Japanese)
- Agency for Natural Resources and Energy (2010), *Electric Power Supply and Demand 2009*, Chuwa Insatsu Co.,Ltd. (in Japanese)
- Hobbs, B. F. (2001)],``Liner Complementarity Models of Nash-Cournot Competition in Bilateral and POOLCO Power Market", *IEEE Transaction on Power Systems*, vol. 16, pp. 194-202.

- Hosoe, N., Akiyama, S (2007), ``Effect of the transmission fee reform '', Hatta ,T. and Tanaka, M., *Kiseikaikaku no Keizai Bunseki*, Nikkei Publishing Inc, pp.75-99.
- Ministory of Environment (2002), ``The Method for Calculation of Green House Gas", http://www.env.go.jp/earth/ondanka/santeiho/kento/h1408/ene$_01$.pdf. (in Japanese)
- Smeers, Y. Jing-Yuan (1997), ``Spatially Oligopolistic Model with Oppotunity Cost Prising for Transmission Capacity Reservations- A Variational Inequality Approach'', University Catholique de Louvain, CORE Discussion Paper 9717.
- Tanaka, M (2007), ``Simulation Analysis of Market Power in Japanese electricity Market '', Hatta ,T., *Kiseikaikaku no Keizai Bunseki*, Nikkei Publishing Inc, pp.101-132.