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Kan Sichao

Abstract

Power generation by the combustion of fossil fuels is a major source of Greenhouse Gas (GHG) emissions. As a study shows that in fiscal year 2005, 38% of Japan's CO_2 emissions came from power generation [1]. Therefore, how to mitigate the Greenhouse Gas (GHG) emissions from the power sector is critical to a nation's overall environmental achievement.

With no doubt that environmental regulations will rise generation cost. Policy makers have to make sure that the increased electricity price is within the range that is acceptable both by power companies and by customers, and meanwhile achieve the most CO_2 emissions reduction. To achieve this goal is not easy, especially when facing a liberalized electricity market, making the problem more complicated.

In order to gain insights into the changes of electricity market due to certain environmental policies and to assess the effectiveness of the policies, this work employed a multi-agent based model to simulate the liberalized electricity market under environmental regulations.

In the first chapter we gave a brief introduction of the global warming by focusing on the global power generation sector. The current electricity market of Japan, based on which our simulation was conducted was also introduced in this chapter.

The description of the basic elements of our model was given in the second chapter. Our model was developed based on multi-agent with the suppliers modeled as self-adaptive agents using Reinforcement Learning algorithm.

In the third chapter, we developed the model to evaluate the Carbon Tax and the Emission Trading policies. From the simulation results, the changes of market performance with the increasing of environmental cost were discussed. And the effectiveness of these policies on CO_2 emissions reduction was also investigated. The simulation of this chapter was based on the wholesale electricity market of Japan, which has been fully liberalized.

Based on the model in chapter 2, we built a model for assessing the CO_2 free electricity trading in chapter 4. The pilot trading has been started in the JEPX (Japan Electric Power Exchange), so the simulation of this chapter was based on the JEPX. We discussed how the suppliers and the demander changed their actions after the introduce of the CO_2 free market. In this chapter the results of our model were also be compared to the results got by using the least-cost approach.

At last in the fifth chapter was the conclusions of this study and the future works.

Keywords:

Deregulated electricity market, Multi-agent, Carbon tax, Emission trading, CO_2 free electricity trading

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Chapter 1 Introduction

1-1 Background

1-1.1 Global warming, and electricity sector mitigation potentials and cost

a) Global warming and Greenhouse Gas (GHG) [2] [3]

In the fourth assessment report of IPCC (Intergovernmental Penal on Climate Change), it was estimated that there was a linear warming trend of 0.74°C ± 0.18°C over the last 100 years (1906–2005). The rate of warming over the last 50 years is almost double that over the last 100 years (0.13°C ± 0.03°C vs 0.07°C ± 0.02°C per decade). In the same raport "Greenhouse gas forcing has *very likely* caused most of the observed global warming over the last 50 years" was pointed out. Carbon dioxide is the most important anthropogenic greenhouse gas. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm[1] to 379 ppm in 2005, which exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores.

Currently, energy-related GHG emissions, mainly from fossil fuel combustion for heat supply, electricity generation and transport, account for around 70% of total emissions including carbon dioxide, methane and some traces of nitrous oxide. For the power generation and heat supply sector, emissions were 12.7 GtCO2-eq[2] in 2004 (26% of total). In 2030, according to the World Energy Outlook 2006 baseline (IEA, 2006b), these will have increased to 17.7 GtCO2-eq.

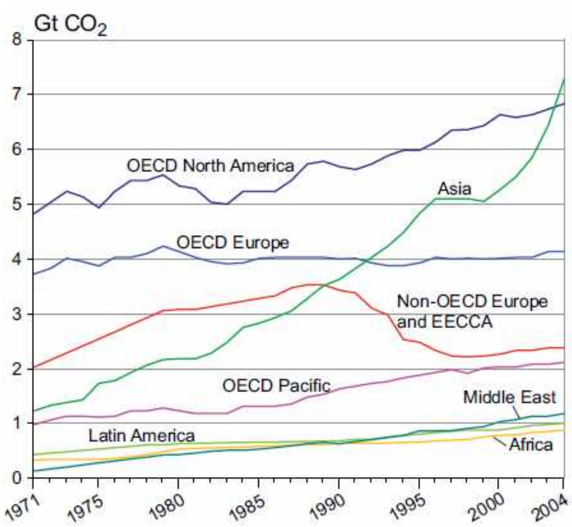


Fig. 1-1 Global trends in carbon dioxide emissions from fuel combustion by region from 1971 to 2004 [3]

Note: EECCA = countries of Eastern Europe, the Caucasus and Central Asia.

Source: IEA, 2006b.

1 ppm: parts per million

2 CO2-eq: CO_2 equivalent

b) Electricity sector mitigation [3]

The baseline

By 2010 total power demand is 20,185 TWh with 13,306 TWh generation coming from fossil fuels (65.9% share of the total generation mix), 3894 TWh from all renewables (19.3%), and 2985 TWh from nuclear (14.8%). Resulting emissions are 11.4 GtCO2-eq.

By 2030 the increased electricity demand of 31,656 TWh is met by 22,602 TWh generated from fossil fuels, 6,126 TWh from renewables, and 2,929 TWh from nuclear power. The fossil-fuel primary energy consumed for electricity generation in 2030 produces 15.77 GtCO2-eq of emissions (IEA, 2004a).

Methods, mitigation potentials and costs

The methods employed to reduce baseline GHG emissions of global electricity sector are outlined below:

- Fossil-fuel switching from coal to gas;
- Substitution of coal, gas and oil plants with nuclear, hydro, bioenergy and other renewables (wind, geothermal, solar PV and solar CSP (Concentrating Solar Power));
- Uptake of CCS (Carbon dioxide Capture and Storage).

Fig. 1-2 shows the potential GHG emissions avoided by 2030 for selected electricity generation mitigation technologies if developed in isolation and with the estimated mitigation for each region.

The estimated mitigation potential shares spread across each cost range (2006 US$/t-$CO_2$-eq) for each region are shown in Fig. 1-2~Fig. 1-5.

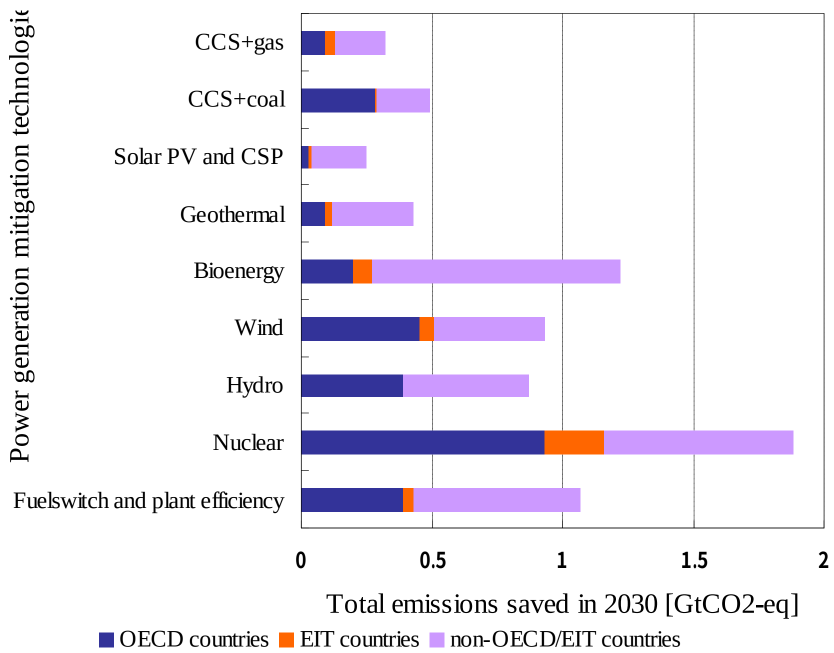


Fig. 1-2 Potential GHG emissions avoided by 2030 for selected electricity generation mitigation technologies

Note: EIT: Economies In Transition, mainly from the former Soviet Union

Source: Based on Table 4.19 in [3]

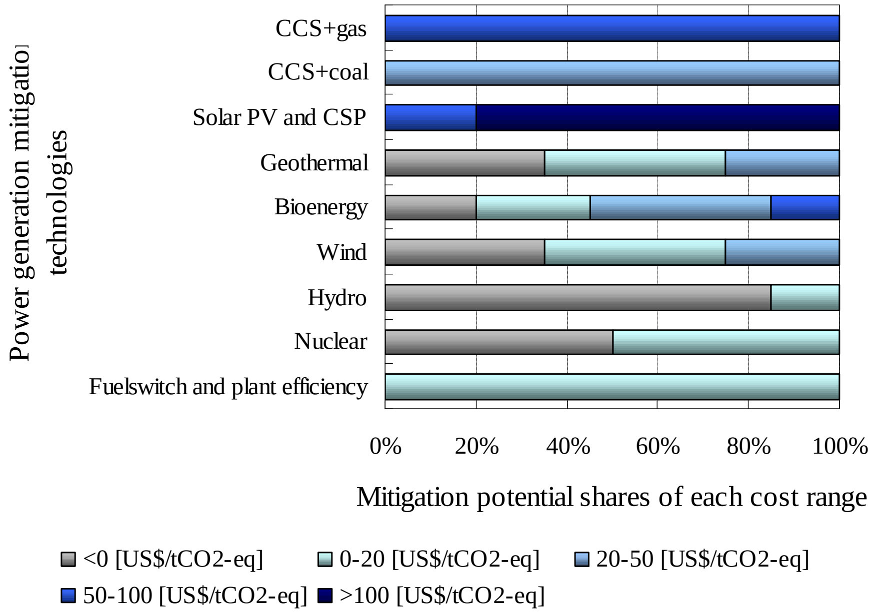


Fig. 1-3 Mitigation cost of OECD countries

Source: Based on Table 4.19 in [3]

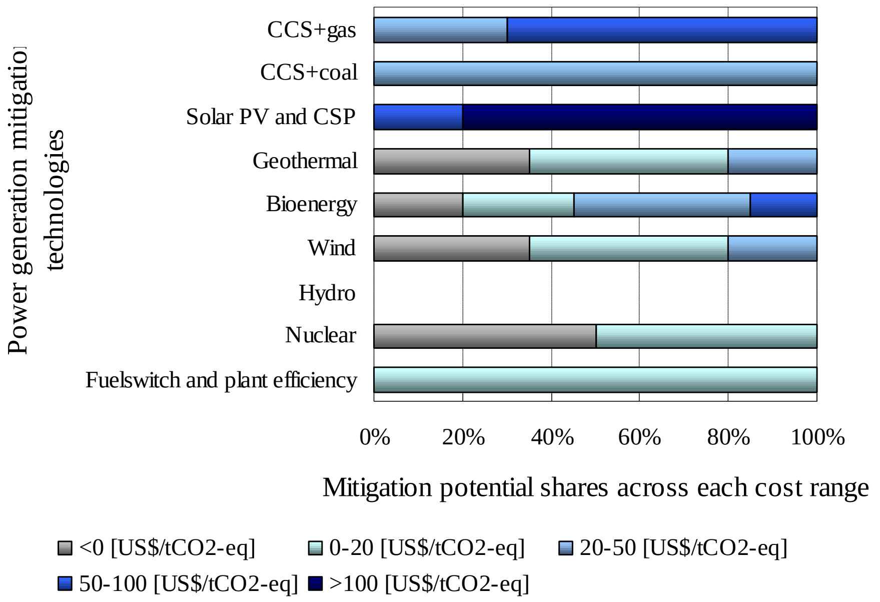


Fig. 1-4 Mitigation cost of EIT countries

Source: Based on Table 4.19 in [3]

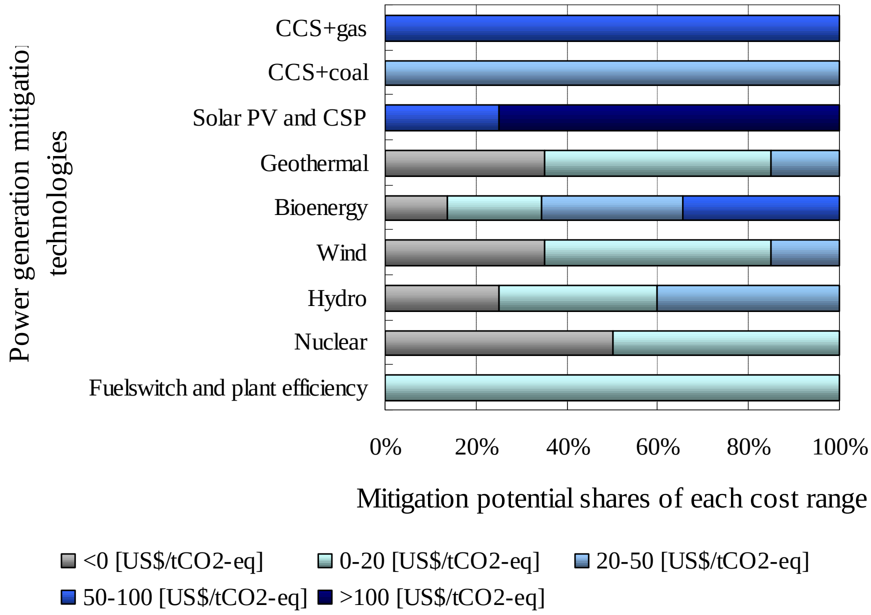


Fig. 1-5 Mitigation cost of non-OECD/EIT countries

Source: Based on Table 4.19 in [3]

1-1.2 Electric power sector in Japan

Current market structure

There are six types of entities in Japan's power industry: general electric utilities (electric power companies, who also run the transmission and distribution networks), IPPs (Independent Power Producers), PPSs (Power Producers and Suppliers), self-generators, special electric utilities and other utilities.

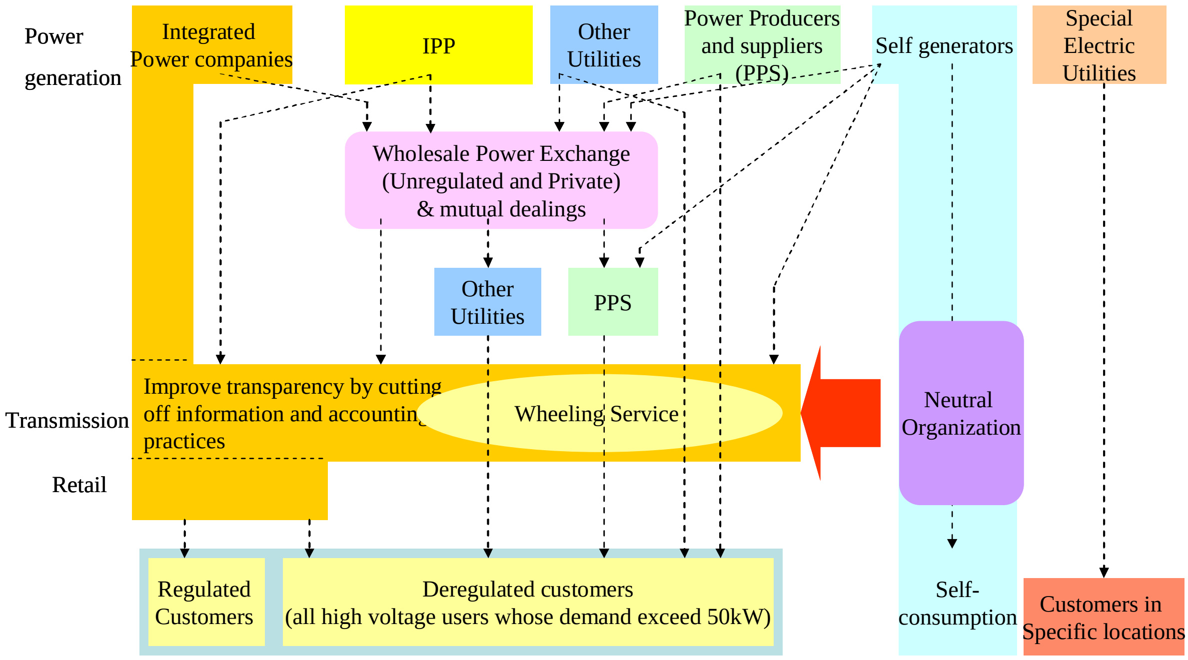


Fig. 1-6 Current structure of Japan's power industry

The special electric utilities only sell electricity to customers in specific locations. The other types of entities trade electricity at a wholesale level through the wholesale power exchange or through mutual dealings. The generators also compete to sell electricity to the deregulated customers at the retail level. Only the general electric power utilities are allowed to sell electricity to regulated customers. As the transmission and distribution networks are owned by the general electric power companies, to improve fair and transparency information and accounting practices were cut off from the generation part. Other entities can use the networks through wheeling services.

There are ten private owned electric power companies in Japan: Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa (Fig. 1-7). The ten power companies are responsible for providing local operation from power generation to distribution and supplying electricity to their respective service areas. In addition, the ten electric power companies cooperate with each other to ensure a stable supply to customers nationwide [4].

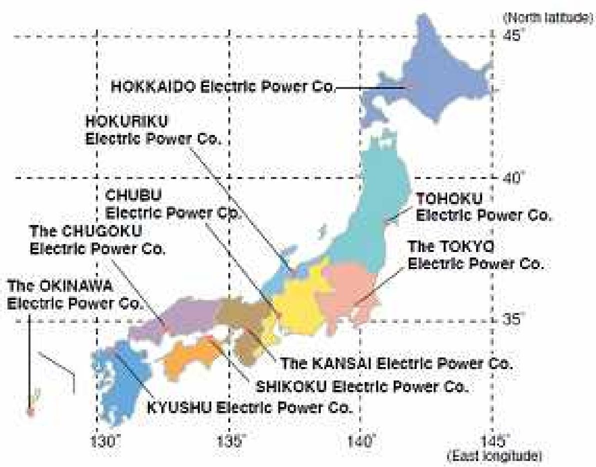


Fig. 1-7 The ten general electricity utilities by service area [4]

IPPs are always steel, chemical, or oil companies with power plants. They are selected through a bidding system implemented by each general electric power utility to supply that utility with electric power. They are not allowed to enter the industry before 1995.

After the partial liberalization in 2000, PPSs were allowed to engage in retail electricity to certain deregulated customers (above 2MW, 20kV). This unique player is generator and retailer for eligible customers of specified scale [4]. They use the tranmission lines of the integrated power companies.

History of deregulation [4][5]

The privatization of the Japan's power industry was starded in 1951.The former government-owned generation and transmission company with regional distribution companies was corporatized and restuctured into nine reginoal electric utilities. The introduction of competitive principle in 1995 led to the first revision of the Electricity Utilitity Industry Law, paving the way for such reforms: the introduction of a competitive bidding systems in the electricity wholesale sector; and the establishment of special electric utilities which were permitted to engaged in retail electric power sales to meet demand at designated delivery points.

The retail competition was started from 2000. In March 2000, the retail market was partially liberalized to allow PPSs to sell electircity to extra-high voltage (20kV or above) users whose demand is approximately over 2MW. From April 2005, the scope of liberalization was expanded to all high-voltage users (6kV or above) whose demand exceeds approximately 50kW. All customers in the regulated market continue to receive electricity supplied by each regional electricity company that is responsible for supplying electricity within its designated service area. Full liberalization, including residential customers, has been under discussed from April 2007.

Japan Electric Power Exchange [5]

In November 2003, a private non-profit organization, Japan Electric Power Exchange (JEPX), was established through investments by the participants including electric power companies, PPSs and non-utility generators, to provide electric power in both spot and forward trading. JEPX started operation on April 1, 2005, and aims to promote competition and revitalize the distribution of electricity nationwide. The electricity is transacted at the wholesale level. There are three types of markets [6]:

- Spot Market

The market where the electricity to be delivered next day is traded. 48 products are traded every 30 minutes in 24 hours a day. The bidding is done by a single price auction system. Under the single price auction system, a bid is made for the combination of price and quantity of each product. A point of intersection where the buying and selling conditions comply with each other is sought, and the price and contract quantity are decided at this point.

- Forward Market (Fixed-Form Products)

The market where the electricity to be delivered in a certain period of time is traded. As of 2005, there are 24-hour type products that are delivered at anytime a month and daytime products that are delivered during a certain time period a month. The bidding is done by the so-called continuous session system.

- Forward Market (Bulletin Board Products)

In the forward market for bulletin board products, participants freely post matters related to electricity trading.

Power source mix and CO_2 emissions [5][7]

Taking into consideration of the high dependence on energy importing as well as environmental issues, nuclear has been promoted for a long time. According to the Federation of Electric Power Companies of Japan, by fiscal year 2016, the total capacity of the electric power companies will get to 28.82 GW, the 43% (12.26 GW) of which will be accounted for by nuclear power (Fig. 1-8).

In fiscal year 2007 (2007.04~2008.03), the total electricity consumption in Japan is 920 billion kWh with 417 million t-CO_2 emissios. The CO_2 emissions idensity (user end electricity) of fiscal year 2007 is 453e-6 [t-CO_2/kWh]. To mitigate CO_2 emissions, the electric utility industry has set their own CO_2 emissions suppression goal: from fiscal 2008 to fiscal 2012, future reduce CO_2 emissions idensity (emissions per unit of user end electricity) by an average of approximately 20% from the 1990 level to about 340e-6 [t-CO_2/kWh] [7]. The CO_2 emissions by electric utility from 1970 to 2006 (fiscal year) can be understood from Fig. 1-9.

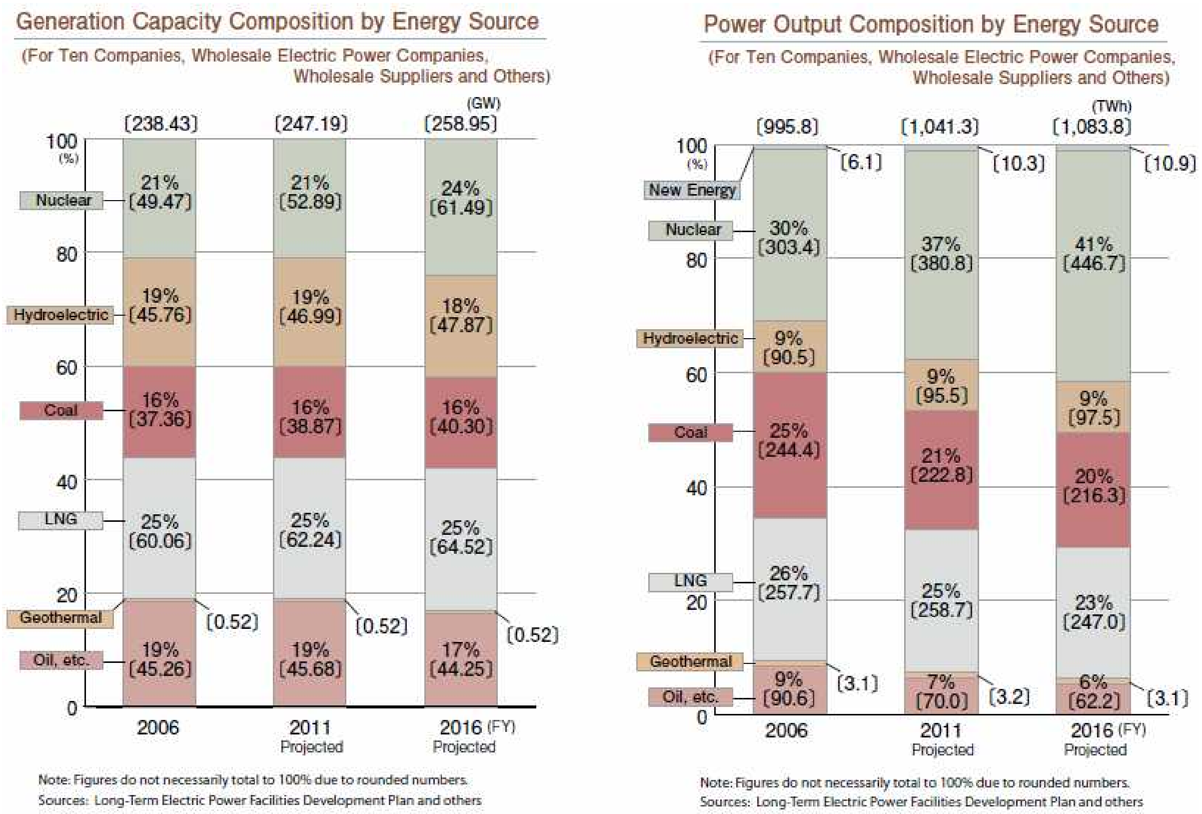


Fig. 1-8 Generation capacity and power output [5]

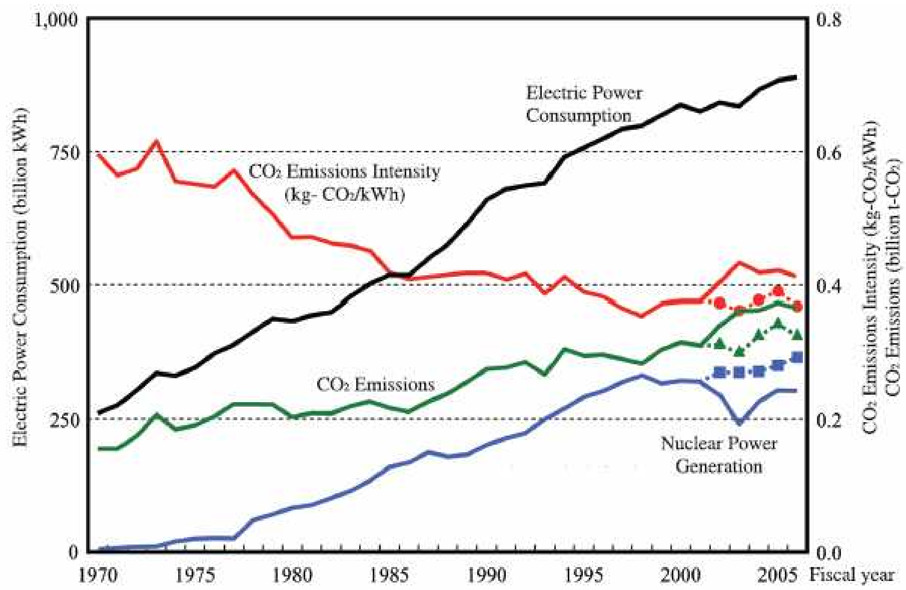


Fig. 1-9 CO_2 emissions by electric utility [7]

Notice: The marked dotted lines indicate estimates supposing no impact was exerted by the long-term shutdown of nuclear power plants in fiscal year 2002 through fiscal year 2006

1-2 Purpose of this paper and Research overview

Japan committed herself to 6% greenhouse gas (GHG) emissions reduction with the Kyoto Protocol in 2008-2012. Power generation mitigations are critical to the achievement of this target. Yet, the profound impacts of electricity supply to other industries and to the residential sector require that environmental regulations of this sector must be designed with special cares. If the mitigation target is set too strict, power generation mitigation technologies with high cost have to be taken and it is very likely that the increased cost will be passed to customers from both industry and residential sectors. As a result, the nation’s whole economy will be suffered. However, lease regulation will not result effective mitigations. Therefore, how to balance the mitigation effectiveness and mitigation cost becomes the point.

The restructuring of the electricity power industry has changed the previous paradigm of *electric assets planning* based on least cost and central decision process. A useful tool to model the competitive market is the Agent Based Simulation (ABS). ABS offers the potential of assigning different behavior to each participant in the market and, therefore, studying phenomena of exercising market power. Moreover, through simulations, the market outcome can be predicted for different pricing rules and arrangements, and new designs can be tested [8]. Researches on using multi-agent model simulating the deregulated electric power market have been studied in precedent works [9] [10]. However, these studies did not cover the influences of environmental policies.

In this paper, we will discuss the impacts of several environmental policies on the electric power market in Japan. Two kinds of cost-effective environmental policies, the Carbon Tax policy and the Emission Trading policy are evaluated in this paper. We introduce environmental cost to the supplier agent’s bidding function. By analysing simulation results we find out the changes of suppliers’ behaviors and how these changes are reflected to the market prices. We also assess the effectiveness of these policies on CO_2 emissions reduction.

Besides the above two kinds of environmental policies, we also build a multi-agent based model to assess the CO_2 free electricity trading policy. We compare the conventional power exchange market and the new CO_2 free market and simulate how the suppliers and demander reacte to the new CO_2 free market. The CO_2 emissions reduction result of this policy is also studied.

Chapter 2 Model description

2-1 Multi-agent model

In the traditional electricity market, power companies usually made their plans based on least-cost planning subject to reliability and some other constraints. However, the interactions and influences among the participants in a liberalized market are not reflected in the least-cost planning approach. Competitive markets are always investigated using the approaches that based on game theory. The task of these methods is to find the theoretical equilibrium points. The problem is that if the players enter the market repeatedly and are self-adaptive it is very difficult to find the equilibrium point

As an alternative to the equilibrium approaches, the multi-agent based simulation comes forth as being particularly well fitted to analyze dynamic and adaptive systems with complex interactions among constituents [11]. Agents make their decisions based on the partial knowledge of the environment and of other agents. They are self-adaptive in the simulation, which makes it possible to converge to the equilibrium points. However, the task of the multi-agent model is to understand complex system's behaviors rather than to work out the equilibrium points explicitly.

In our simulation, the physical bodies from which the artificial agents are immersed are the participants of the competitive electricity market, i.e. the electric power suppliers and demanders. We introduce a set of supplier agents $G=\{A_{gi} : i=1,\ldots,n\}$ to our model. And we assume there is only one demander agent $D=\{A_{dj} : j=1\}$. The supplier agents are clustered in terms of the primary energy sources they use to generate electricity. In our model there are five kinds of power generation plants (1, Hydro; 2, Nuclear; 3, Coal; 4, LNG; 5, Oil). To simplify calculation we assume each supplier agent generates electricity from one and only one kind of source.

The suppliers and the demander bid for the market to sell or buy electricity. The mechanism of market auction will be introduced in section 2-2. Each supplier is modeled as an autonomous adaptive agent capable of developing its own bidding strategy using Reinforcement Learning algorithm (section 2-3.2). The bidding strategy of the demander agent is not considered.

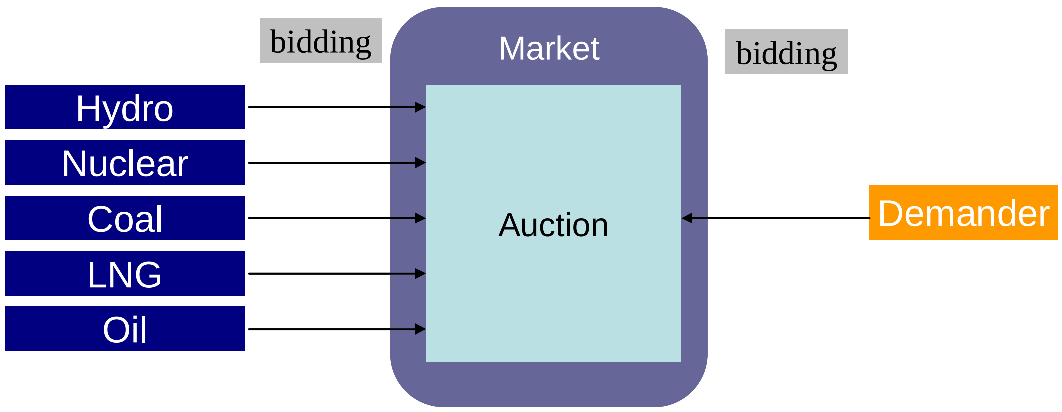


Fig. 2-1 Model framework

2-2 Markets

In a deregulated electricity market suppliers and demanders sell and buy electricity through auction. Two pricing rules for electricity auction are implemented in real markets: the uniform and pay-as-bid. Under uniform pricing, market players with winning bid are paid or pay at the market clearing price. On the other hand under the pay-as-bid pricing, a supplier and a demander with winning bid is paid or pays at his asking or bidding price.

Electricity auction in Japan is based on the uniform pricing system. In our model the Power Exchange (PX) market (Fig. 2-2) is a day-ahead market.

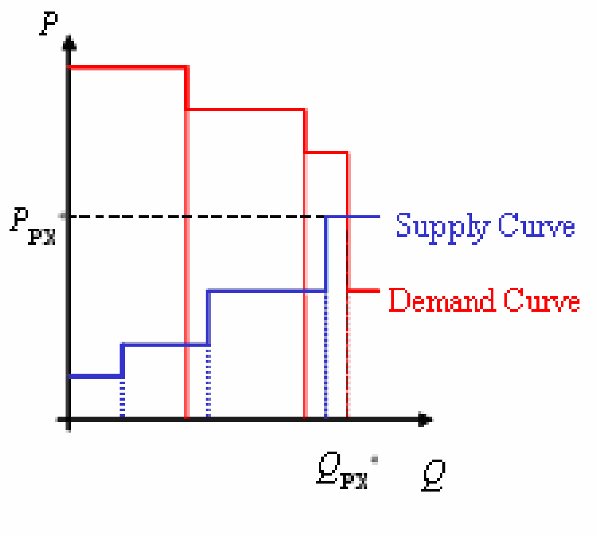


Fig. 2-2 Power Exchage (PX) electricity market

2-3 Model for supplier agents

2-3.1 Bidding function and cost function

The cost function and marginal cost function of supplier agents are given as follows.

Cost function:

$$C_i(q) = VC_{gi}(q) + c_{gi} = a_{gi}q^2 + b_{gi}q + c_{gi} \tag{2-1}$$

Marginal function:

$$\frac{dC_i(q)}{dq} \equiv MC_i(q) = 2a_{gi}q + b_{gi} \tag{2-2}$$

Where,

$VC_{gi}(q) = a_{gi}q^2 + b_{gi}q$: function of variable cost.

c_{gi} : indicator of fixed cost.

In our model we assume constant variable cost so the value of a_{gi} equals to zero. Therefore, the variable cost is decided by b_{gi}. In the BAU (Business As Usual) case b_{gi} equals to the unit fuel cost P_{fg} [JPY/kWh] [3].

The yearly fixed cost FC_i comes from plant cost and is calculated by equation (2-3).

$$FC_{gi} = g_{gi} \times P_{pg} \times Capa_i \tag{2-3}$$

Where,

P_{pg} : unit plant cost [JPY/kW]

$Capa_i$: plant capacity [kW]

g_{gi} : annual expense rate

The bidding function for supplier agents which is expressed by equation (2-4) is based on the marginal cost function.

$$P_{gi}(q) = MC_i(q) + \alpha_{gi} = 2a_{gi}q + b_{gi} + \alpha_{gi} \tag{2-4}$$

Where, α_{gi} is the bias value. Supplier agent A_{gi} decides its bidding curve by adjusting α_{gi}. The bidding curve for supplier agents is shown in Fig. 2-3 [12]. The bidding strategy of the supplier agent is to select a optimal α_{gi}, which leads to maximum reward.

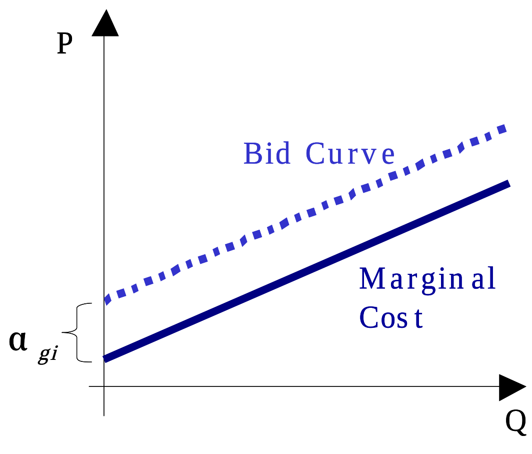


Fig. 2-3 Bidding curve of supplier agent

2-3.2 Reinforcement learning

Suppliers are modeled as adaptive agents capable of learning through the interaction with their environment following a Reinforcement Learning (RL) algorithm. Reinforcement Learning studies the learning process through interaction; it focuses on the effect of rewards (positive payoffs) and punishments (negative payoffs) on subjects' choices in their attempt to achieve a goal [8].

[3] JPY: Japanese Yen, 1JPY≒0.01 US dollar

The basic elements of RL theory are:

• the learner, who is called the *agent*, and

• everything it interacts with, which is called *environment*.

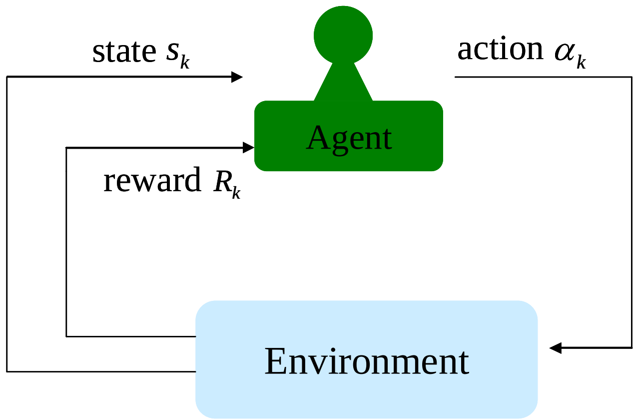


Fig. 2-4 Learning process of agent

As we have stated in the reinforcement learning theory, every agent can learn how to make the best policy by observing the result of its own behavior. This sequential behavior is called episode.In each episode *k*, the agent first perceive the state s_k. Then the agent tries several actions α_k and based on the perception of state s_k the agent gets a scalar evaluation (which can indicate reward R_k) of each action. The agent will take the action that results maximum reward R_k.

In our model we use one of the most commonly used RL algorithms, the Q-learning algorithm. In a certain episode *k*, we define that $Q_k(s,\alpha)$ is the expected action-value function when state s is a perceivable state. The agent will obtain reward R_k when one episode is finished. The relationship between $Q_k(s,\alpha)$ and R_k. can be understood from the following illustrations.

The iterating pattern of the action-value function *Q* can be expressed by equation (2-5).

$$Q_{k+1}(s,\alpha)=Q_k(s,\alpha)+l\left[R_k+\gamma\max_{a'}Q_{k+1}(s',\alpha')-Q_k(s,\alpha)\right] \quad (2\text{-}5)$$

Where *l* is the learning factor and γ is the weight factor.

We make two assumptions here:

Q is convergent perfectly $\quad Q_{k+1}(s,\alpha)=Q_k(s,\alpha)$

γ is equal to zero $\quad \gamma=0$

With these two assumptions we yields:

$$R_k=Q_k(s,\alpha) \quad (2\text{-}6)$$

The task for the agent is to select the optimal action α to maximize the reward R_k. Therefore, an agent expecting the highest reward is tying to select the optimal action α which makes *Q* value of each episode the maximum.

In our simulation, the market represents the environment. When bidding for the market, the supplier agent can choose his bidding price and the quantity of electricity he wants to sell. Here we assume that the supplier agent bids at his maximum capacity. Therefore, the supplier agent's actions are limited to select bidding price. As stated in the former section, the supplier agent changes his bidding price by adjusting the bias value α_{gi}, which means that the in our model the action of the supplier agent is to take different α_{gi} s. The market price describes the state of the environment. The reward R_k can be perceived as the profit of the supplier agent.

In our model the supplier agent A_{gi} chooses the optimal bias value α_{gi} by using Boltzmann distribution function expressed in equation (2-7).

$$\pi(s,\alpha_{gi}) = \frac{\exp\left[\dfrac{Q(s,\alpha_{gi})}{T}\right]}{\sum_{j=1}^{N}\exp\left[\dfrac{Q(s,\alpha_{gj})}{T}\right]} \tag{2-7}$$

Where,

$\pi(s,\alpha_{gi})$: probability to select bias value α_{gi} when the state is *s*

N : number of options for bias values

T : Boltzmann temperature (constant). The function will become more selective with a lower *T*

According to the property of Boltzmann distribution function, the probability $\pi(s,\alpha_{gi})$ will go higher with a larger $Q(s, \alpha_{gi})$. Therefore, the optimal bias value α_{gi} that results the maximum $Q(s, \alpha_{gi})$ has the highest probability to be chosen. The upper limit value of bias value is 80[JPY/kWh] and the lower limit is 0. Between the limits the distribution of α is:

$$\alpha_j = 0.2 \times j^2 \qquad j = 0,1,2\ldots 20 \tag{2-8}$$

Within the episode *k*, the supplier agent:

i Get the market clearing price cp_k;

ii Calculate reward R_k based on cp_k;

iii Substitute R_k and $\alpha_j (j = 0,...,20)$ to equation (2-5) to update Q;

iv Select optimal bias value α_{gi} based on Boltzmann distribution function;

v Bidding for the *k+1* episode with the opitmal bidding price calculated from equation (2-4).

Fig. 2-5 shows how the agent learns to change its asking price as the number of episode increases.

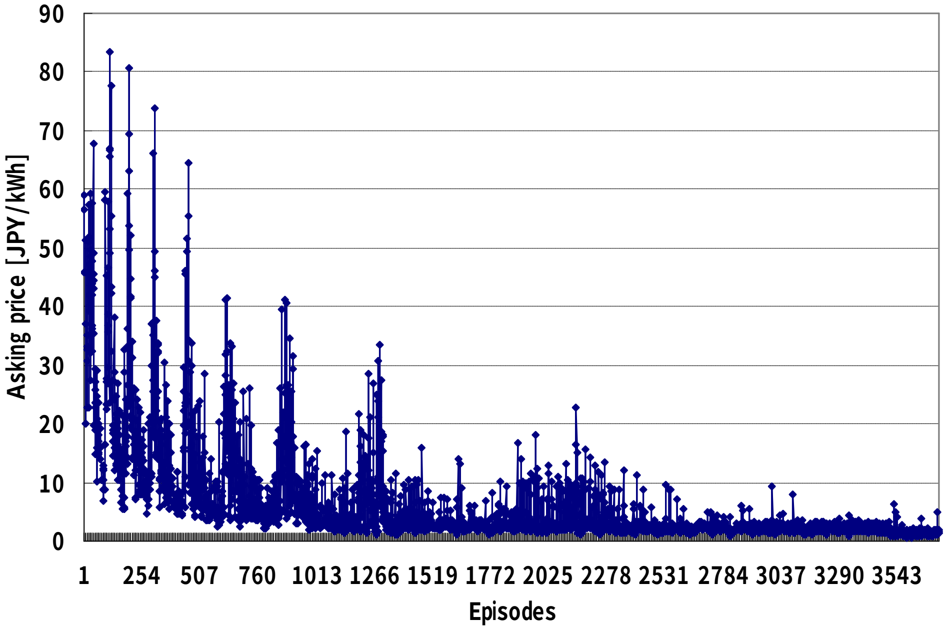


Fig. 2-5 Change of bidding price based on the different bias values

2-4 Model for demander agent

The marginal utility function of the demander can be obtained from the electricity price elasticity η (equation (2-9)). We assume that the electricity price elasticity η for demander is -0.05 [12].

$$\eta = \frac{dq/q}{dp/p} \tag{2-9}$$

From equation (2-9) we get :

$$p = C \cdot q^{1/\eta} \tag{2-10}$$

If the curve of equation (2-10) pass the reference point (Q_0, P_0), we yield:

$$p = \frac{P_0}{Q_0^{1/\eta}} q^{1/\eta} \tag{2-11}$$

The curve of equation (2-11) is shown in Fig. 2-6. Here the reference point (Q_0, P_0) = (100000MWh, 5

JPY/kWh). In the model in Chapter 3, the reference demand Q_0 of each hour in one day follows the daily load pattern shown in Fig. 2-7[4]. The reference price P_0 is 5 JPY/kWh.

In the function when the demand q is close to zero the corresponding price p will go infinite. To avoid this we set a cap for the market price (85JPY/kWh) for the demander. The demander will bid for the market below this price cap.

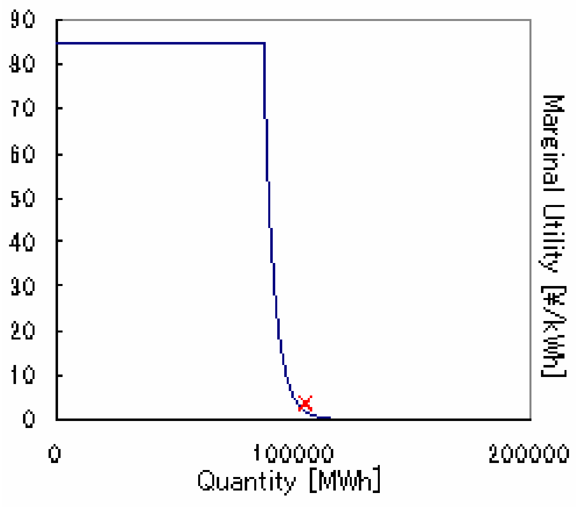


Fig. 2-6 Marginal utility function of demander

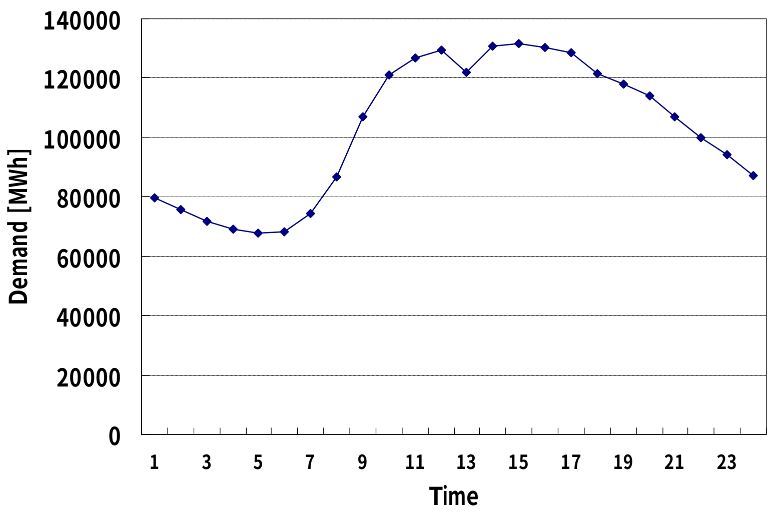


Fig. 2-7 Reference demand Q_0

2-5 Competition principle

In a deregulated electric power market suppliers compete to sell their electricity. We introduce competition principles to the market. Supplier agents will increase output capacity when they can get sufficient profit

[4] Here, the Q_0 is based on the average daily demand of Japan (except Okinawa). In Chapter 4 the Q_0 will be changed.

and will decrease output capacity in a deficit condition. The conditions for capacity adjusting is shown in Fig. 2-8.

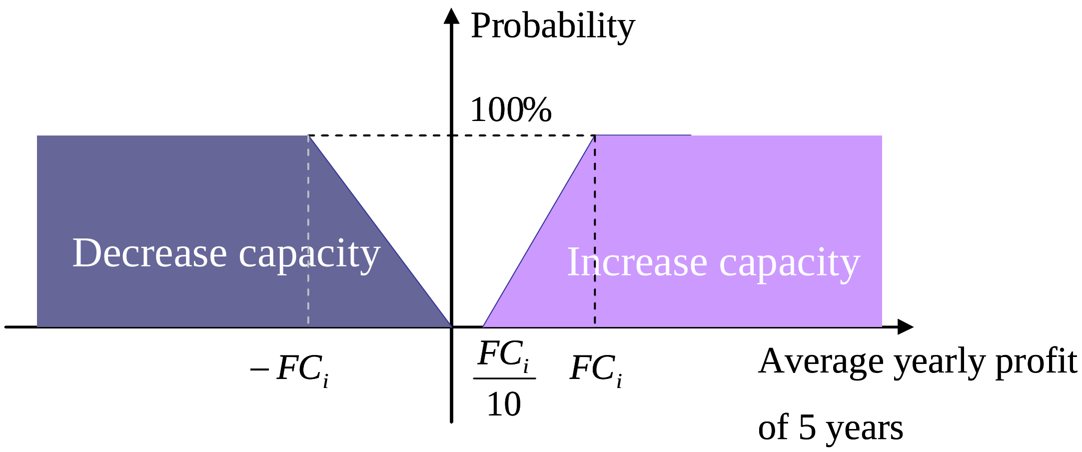


Fig. 2-8 Conditions for increasing or decreasing capacity [10]

The supplier agent has 5% chance to

Increase capacity if :

The point decided by (average yearly profit of 5 years, probability) is within the 'Increase capacity' region

Decrease capacity if :

The point decided by (average yearly profit of 5 years[5], probability) is within the 'Decrease capacity' region.

In our model, we assume that the hydro and nuclear plants will keep the same output capacity whatever the situation is (in Chapter 4 only the hydro power plants keep the same output capacity). We start simulation with all the supplier agents have the same capacity.

The calculation of yearly profit follows:

$$Yprofit_{gi} = Ysales_{gi} - YVC_{gi} - FC_{gi} \tag{2-12}$$

Where,

$Yprofit_{gi}$: Yearly profit of supplier angent *i*

$Ysales_{gi}$: Yearly sales

YVC_{gi} : Yearly variable cost

FC_{gi} : Yearly fixed cost

The yearly sales and variable cost are the sum of the each hour's accounting results. The calculation of the yearly fixed cost has been stated in Section 2-4.1.

5 In this case it is the lost

$$Ysales_{gi} = \sum_{d=1}^{365}\sum_{h=1}^{24}(cp_{d,h} \times cq_{i,d,h}) \quad (2\text{-}13)$$

$$YVC_{gi} = \sum_{d=1}^{365}\sum_{h=1}^{24}(a_{gi} \times cq_{i,d,h}^{2} + b_{gi} \times cq_{i,d,h}) \quad (2\text{-}14)$$

$$FC_{gi} = g_{gi} \times P_{pg} \times Capa_{i}$$

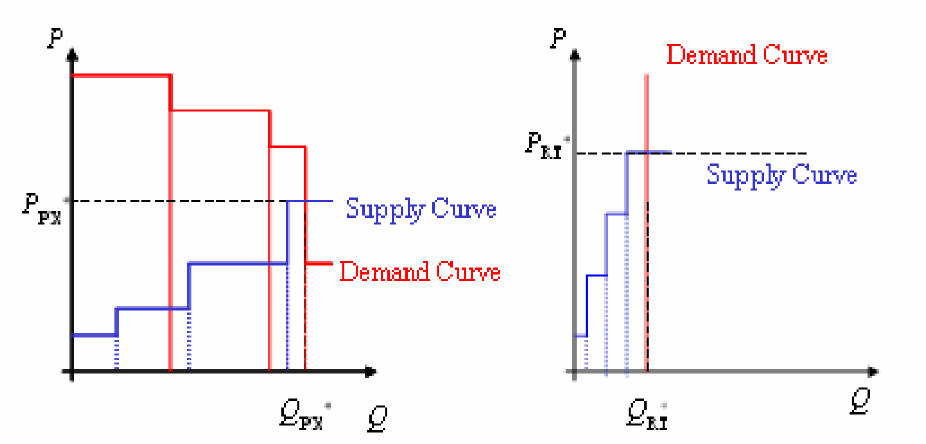
Chapter 3 Carbon Tax and Emission Trading

The Carbon Tax policy and the Emission Trading policy are two commonly used indirect environmental regulation measures. These kinds of environmental policies are supposed to be cost-effective. Market power plays an important role in achieving CO_2 emisions reduction under these environmental means. In this chapter we will discuss changes of market performe under these policies and the CO_2 emissions reduction achievement resulted from the changes.

3-1 Preconditions

3-1.1 Introduce of Real-Time market

To take into account the real-time demand, we also introduce a Real-Time trading market (Fig. 3-1-(b)) following the PX market. For the Real-Time market we assume logarithmic normal distributed stochastic electricity demands of which the average magnitude is 5% of the reference demand of each corresponding time [9].



(a) Power Exchange market (b) Real-Time market

Fig. 3-1 PX market and RT market mechanism

The electricity price elasticity for the demander in the RT market is zero. To prevent the market price to go infinite when an unbalance of supply and demand happens, we introduce VOLL (Value Of Lost Load) pricing to the RT market. The mechanism of VOLL pricing is shown in Fig. 3-2 [10]. We set a cap for the market price. If there is more demand than supply, the market price will equal to the cap instead of rising higher.

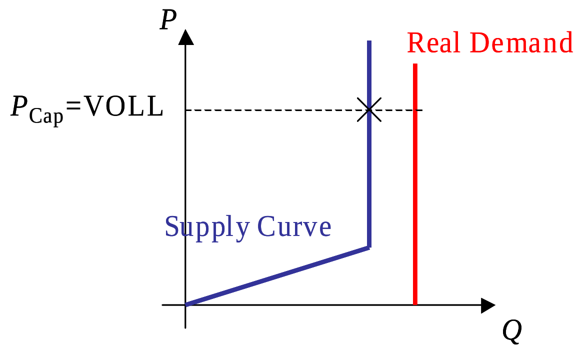


Fig. 3-2 Mechanism of VOLL pricing

The following figure shows the framework of the model used in this chapter. The supplier agents with nuclear or coal plants do not attending the RT market considering their load following properties.

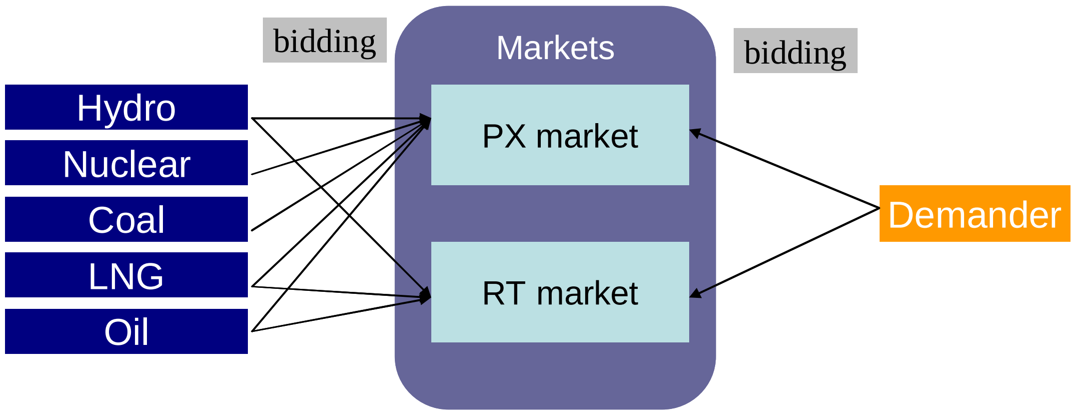


Fig. 3-3 Model for market simulation under CT and ET policies

3-1.2 Calculation flow

In our simulation, the suppliers and the demander bid for the market hourly. Whithin one bidding cycle, they first bid for the PX market, and then the demander checks whether more demand is needed or not. The suppliers and the demander will bid for the RT market if there is realtime demand. After the two biddings are finished, the supplier agent calculates his reward which is substituted to the Q value updating function (equation (2-5)) and then by using Boltzmann distribution selects the optimal bias value for the bidding of the next hour. The supplier agents do annually accounting after 24×365=8760 times of bidding cycles.

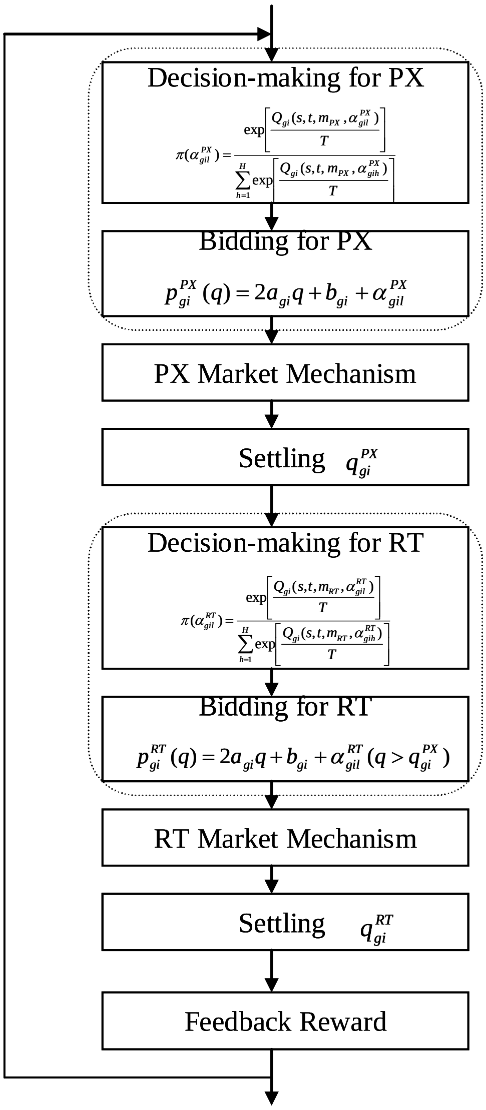


Fig. 3-4 Calculation flow within one bidding cycle

3-1.3 Basic parameters

Our simulation is for short-term, in which we assume the parameters do not change with time.

At the beginning of the simulation, each supplier agent has the same output capacity. Except the agents with hydro and nuclear power plants, the supplier agents adjust their capacity following the competition principle (Section 2-5) according to the yearly profit.

Table 3-1 Basic parameters of plants

	Hydro	Nuclear	Coal	LNG	Oil
Unit plant cost[1][1000JPY/kW]	732	279	272	164	269
Depreciation period[1][year]	40	16	15	15	15
Annual expense rate[%]	5.052	8.582	9	9	9
Fuel cost[2][JPY/kWh]	0	1.58	1.74	5.79	7.6
Emission rate e_i[3][e-6 t-CO_2/kWh]	0	0	887	478	704

Source: 1) The Federation of Electric Power Companies of Japan [14];

2) Based on IEA "WORLD ENERGY OUTLOOK 2004" [15];

3) Center Research Institute of Electric Power Industry [16]

Table 3-2 Other parameters for the simulation of CT & ET

	Supplier agents	Demander agent
Number of agents	20*5=100	1
Bidding block	200 [MWh]	
Price cap (PX & RT markets)	85 [JPY/kWh]	
Market capacity	131497 [MWh]	
Initial capacity $Capa_i$	1400 [MWh]	

3-2 Carbon Tax Policy

3-2.1 Introduce environmental cost to the model

Under the carbon tax policy, tax is paid for each unit of CO_2 emissions. In the power generation sector, the CO_2 emissions are mainly from the combusion of fossil fuels and a small part are due to other factors like the operation of machines, the transport of fuels, and so on. Here we assume that combustion of fossil fuels is the only source of CO_2 emissions. Therefore, supplier agents with hydro and nuclear power generation plants are carbon free. On the other hand, supplier agents with fossil fuel (coal, LNG, oil) power plants have to pay carbon tax for their CO_2 emissions and thus add cost to their generations. Carbon tax is added to the variable cost of the supplier agent. The multipulator of the variable cost b_{gi} (Section 2-4.1) is rewritten as:

$$b_{gi} = P_{fg} + e_g \times P_{ct} \tag{3-1}$$

Where,

e_g : emission rate of agent A_{gi} with the type g power plant [t-CO_2/kWh], g=3,4,5

P_{ct} : carbon tax rate [JPY/t-CO_2]

A propriately designed tax rate is critical to the success of the carbon tax policy. We simulate the cases that the tax rate ranges from 1000[JPY/t-CO_2] to 8000[JPY/t-CO_2] as well as the BAU case. Marginal costs of each kind of power plants under different carbon tax rates are concluded in Table 3-2. The change of market share of each kind of plants, daily average PX market prices and RT market prices and the CO_2 emissions will be discussed in the following section. Here we focus on the trends rather than accurate quantities of the change and all the results are the average values of one day.

Table 3-3 Marginal cost of each kind of plants under different carbon tax rates

Carbon Tax Rate [JPY/t-CO2]	Hydro [JPY/kWh]	Nuclear [JPY/kWh]	Coal [JPY/kWh]	LNG [JPY/kWh]	Oil [JPY/kWh]
BAU	0	1.58	1.74	5.79	7.6
CTR1000	0	1.58	2.627	6.268	8.304
CTR2000	0	1.58	3.514	6.746	9.008
CTR3000	0	1.58	4.401	7.224	9.712
CTR4000	0	1.58	5.288	7.702	10.416
CTR5000	0	1.58	6.175	8.18	11.12
CTR6000	0	1.58	7.062	8.658	11.824
CTR7000	0	1.58	7.949	9.136	12.528
CTR8000	0	1.58	8.836	9.614	13.232

3-2.2 Results

The changing pattern of daily average power source mix is shown in Fig. 3-5. From equation (3-1) we know that as carbon tax rate rises, the increasing environmental cost (except for hydro and nuclear) weights more in coefficient b_{gi}. Recalling the cost function expressed by equation (2-1), b_{gi} is the multipulator of the variable cost. Therefore, when the carbon tax rises supplier agents with thermal power plants will pay more for the same amount of generation. The supplier with higher emission rate undergoes heavier environmental cost.

Among the fossil fuel power plants coal has the lowest fuel cost but highest emission rate. As the environmental cost goes higher, supplier agents with coal power plants will lose their cost advantage to the suppliers with LNG power plants (LNG has the lowest emission rate). Finally the increasing environmental cost provides enough incentives to cause a switching from coal to LNG (Fig. 3-5). We assume there are enough LNG power plants not generating in the power system. These LNG plants can replace coal plants. Attentions should be paid to that in the simulation we do not consider the change of primary energy prices, which may have a large impact on the fuel switching point [17].

When Fig. 3-5 and Fig. 3-7 are put together we discover that large progress on CO_2 emissions reduction will be achieved as a result of the fuel switching. On the other hand, there is also a not slightly but large rising of the average PX market price when the fuel switching happens (Fig. 3-6). It means that the cost of

CO_2 emissions reduction will finally be paid or partly be paid by the customers. However, the changing pattern of RT market price has not been found. The details of the changing mechanisms of the PX and the RT market price will be given in Section 3-4.

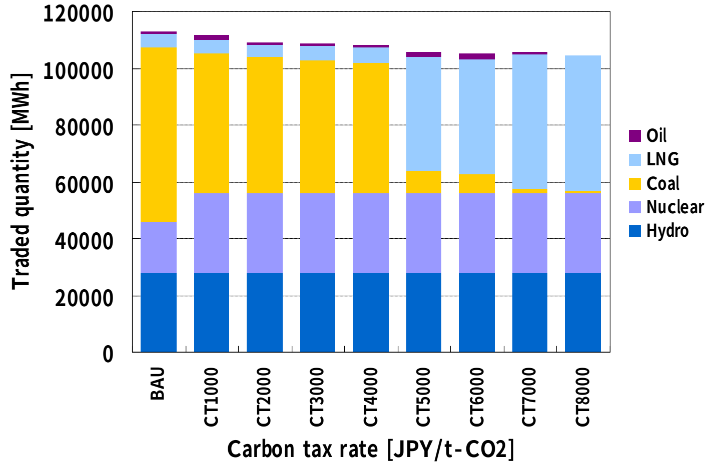


Fig. 3-5 Market share of each kind of plants in the CT case

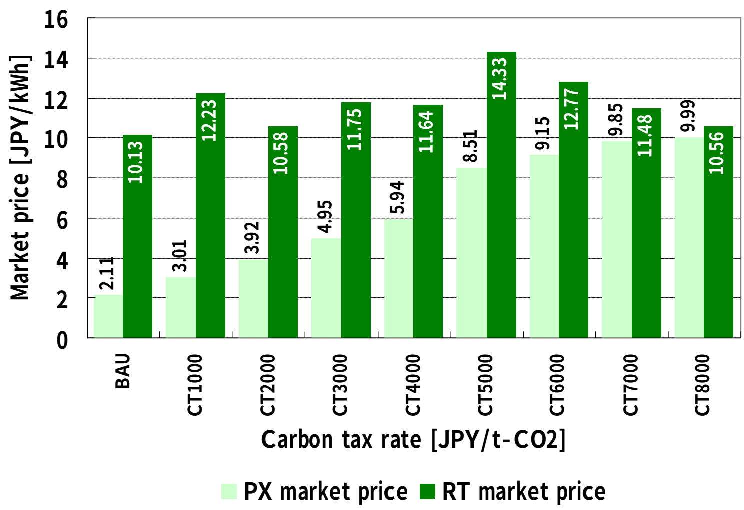


Fig. 3-6 Average market prices in the CT case

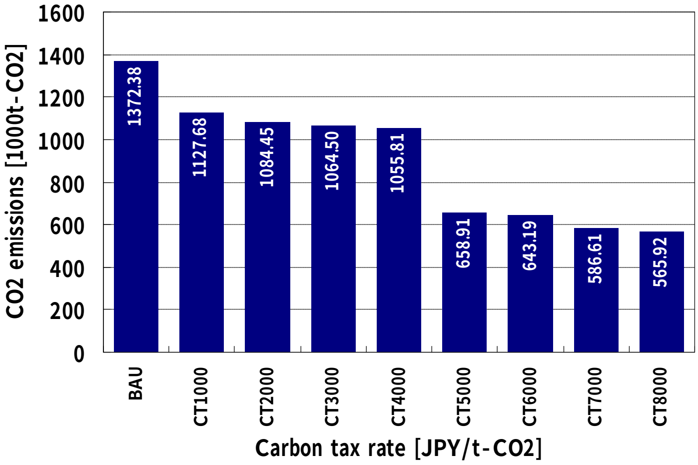


Fig. 3-7 CO_2 emissions in the CT case

3-3 Emission trading

3-3.1 Introduce environmental cost to the model

Under the Emission Trading policy, we set a cap e_{cap} for the emission rate. Supplier agents with emission rates higher than e_{cap} have to buy CDM credits (Certified Emission Reductions: CERs) to offset the excessive part. Supplier agents with emission rate below the e_{cap} are allocated CERs which can be sold in the secondary market. Under the ET policy b_{gi} is rewritten as:

If $e_g > e_{cap}$:

$$b_{gi} = P_{fg} + (e_g - e_{cap}) \times P_{et} \tag{3-2}$$

If $e_g \le e_{cap}$:

$$b_{gi} = P_{fg} - (e_{cap} - e_g) \times P_{et} \tag{3-3}$$

Where, P_{et} : the price of CDM creditin the secondary market [JPY/t-CO_2]

To ensure the effectiveness of the emission trading policy, the e_{cap} need to be set carefully. However, in this paper, instead of discussing how to design a propriate e_{cap} we focus on the market behaviors under different e_{cap}s with the increasing of CERs price.

We choose three e_{cap}s to do the simulations. The lowest e_{cap} is 340e-6 [t-CO_2/kWh] which is the CO_2 emissions suppression goal of the electric utility industry set by themselves; the highest e_{cap} is 550e-6 [t-CO_2/kWh], which is the default emission rate set by the Ministry of the Environment of the Japanese government. The names of electric power companies or PPSs with the emission rate below this default rate will be published. And we also choose one between the two e_{cap}s: 450e-6 [t-CO_2/kWh].

Similar with the CT case, under each e_{cap} we simulate the cases of CER price ranging from 1000[JPY/t-CO_2] to 8000[JPY/t-CO_2] (Fig.23~Fig. 28). Marginal costs of each case are concluded in Table3-3 (340e-6 [t-CO_2/kWh]), Table 3-4 (450e-6 [t-CO_2/kWh]) and Table 3-5 (550e-6 [t-CO_2/kWh]).

Table 3-4 Marginal cost of each kind of plant under e_{cap} = 340e-6 [t-CO_2/kWh]

Ecap=340e-6 [t-CO2/kWh]	Hydro [JPY/kWh]	Nuclear [JPY/kWh]	Coal [JPY/kWh]	LNG [JPY/kWh]	Oil [JPY/kWh]
BAU	0	1.58	1.74	5.79	7.6
CER1000	0	1.58	2.287	5.928	7.964
CER2000	0	1.58	2.834	6.066	8.328
CER3000	0	1.58	3.381	6.204	8.692
CER4000	0	1.58	3.928	6.342	9.056
CER5000	0	1.58	4.475	6.48	9.42
CER6000	0	1.58	5.022	6.618	9.784
CER7000	0	1.58	5.569	6.756	10.148
CER8000	0	1.58	6.116	6.894	10.512

Table 3-5 Marginal cost of each kind of plant under e_{cap} = 450e-6 [t-CO_2/kWh]

Ecap=450e-6 [t-CO2/kWh]	Hydro [JPY/kWh]	Nuclear [JPY/kWh]	Coal [JPY/kWh]	LNG [JPY/kWh]	Oil [JPY/kWh]
BAU	0	1.58	1.74	5.79	7.6
CER1000	0	1.58	2.177	5.818	7.854
CER2000	0	1.58	2.614	5.846	8.108
CER3000	0	1.58	3.051	5.874	8.362
CER4000	0	1.58	3.488	5.902	8.616
CER5000	0	1.58	3.925	5.98	8.87
CER6000	0	1.58	4.362	5.958	9.124
CER7000	0	1.58	4.799	5.986	9.378
CER8000	0	1.58	5.236	6.014	9.632

Table 3-6 Marginal cost of each kind of plant under e_{cap} = 550e-6 [t-CO_2/kWh]

Ecap=550e-6 [t-CO2/kWh]	Hydro [JPY/kWh]	Nuclear [JPY/kWh]	Coal [JPY/kWh]	LNG [JPY/kWh]	Oil [JPY/kWh]
BAU	0	1.58	1.74	5.79	7.6
CER1000	0	1.58	2.077	5.718	7.754
CER2000	0	1.58	2.414	5.646	7.908
CER3000	0	1.58	2.751	5.574	8.062
CER4000	0	1.58	3.088	5.502	8.216
CER5000	0	1.58	3.425	5.43	8.37
CER6000	0	1.58	3.762	5.358	8.524
CER7000	0	1.58	4.099	5.286	8.678
CER8000	0	1.58	4.436	5.214	8.832

3-3.2 Results

Daily average market power source mix

Similar with the CT policy, under the ET policy with the increasing of CERs price, the LNG power plants with lower emission rate acquire cost advantage over the coal power plants though the fuel cost of coal is cheaper. As a result, fuel switching from coal to LNG will happen.

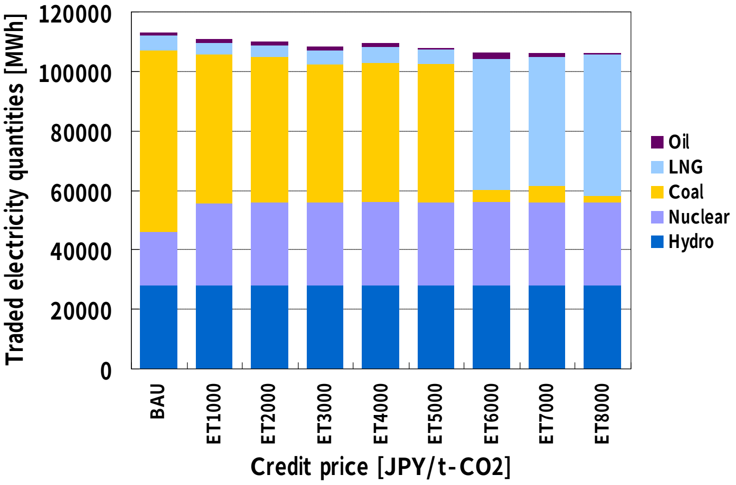


Fig. 3-8 Power source mix under e_{cap}=340e-6 [t-CO_2/kWh]

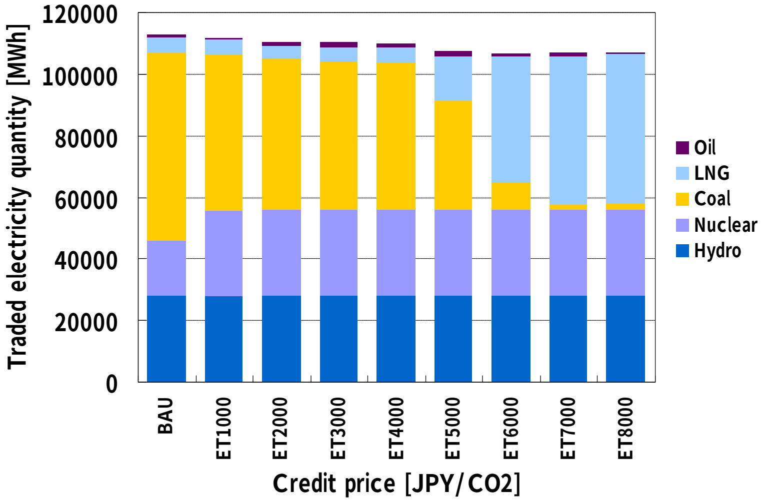


Fig. 3-9 Power source mix under e_{cap}=450e-6 [t-CO_2/kWh]

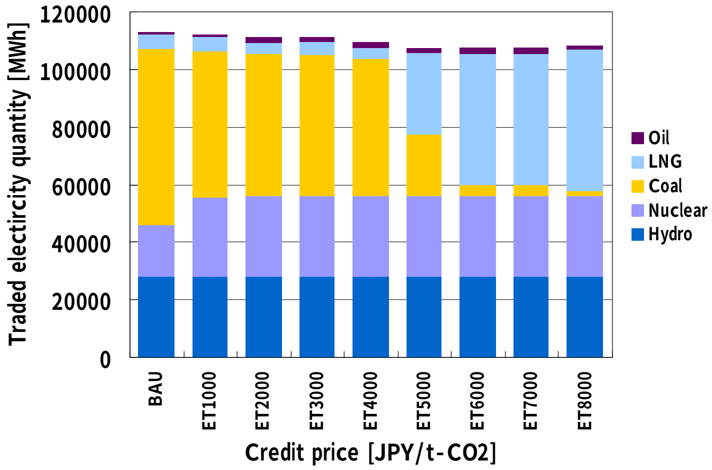


Fig. 3-10 Power source mix under e_{cap}=550e-6 [t-CO_2/kWh]

Daily average PX market and RT market prices

The changing pattern of market prices under ET policy is similar with that under the CT policy. The average daily PX market prices increase with the CER price. While there is not a fixed changing pattern for the daily average RT prices. The details of the changing mechanism of the market prices will be given in Section 3-4.

Attentions should be paid to the case when e_{cap}=550e-6 [t-CO_2/kWh]. In this case, the cap is set higher than the emission rate of the LNG power plants, which means that suppliers with LNG plants are given CERs. Additional revenues are made by selling the CERs to the secondary marekt, which has the same meaning as cost reduction. Further more, from Fig. 3-16 we learn that after the fuel switching the market as a whole do not need to pay for CERs and there are additional CERs in the market. It means that the cost of the whole market is reduced. That is why after the fuel switching the PX market price has a trend of going down.

However, because the expantion space for the LNG power plants is limited (limitation of capacity of power plants and/or the limitation of the feedstock of LNG, and the limitation of market capacity), the market price will stop going down when the LNG capacity get to its upper limit.

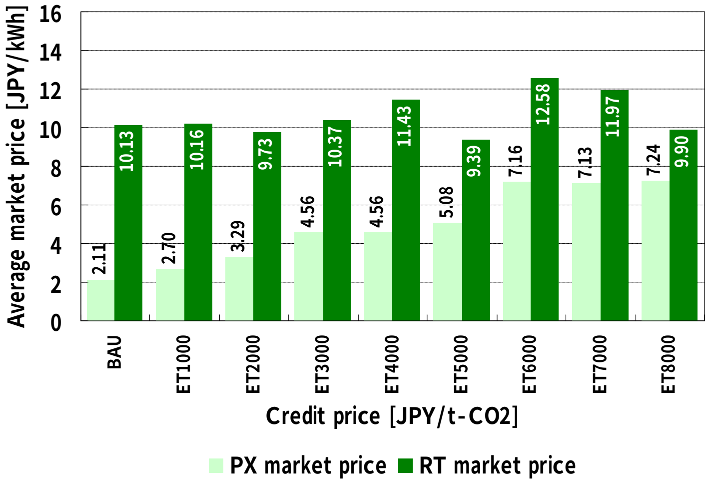


Fig. 3-11 Daily average market prices under e_{cap}=340e-6 [t-CO_2/kWh]

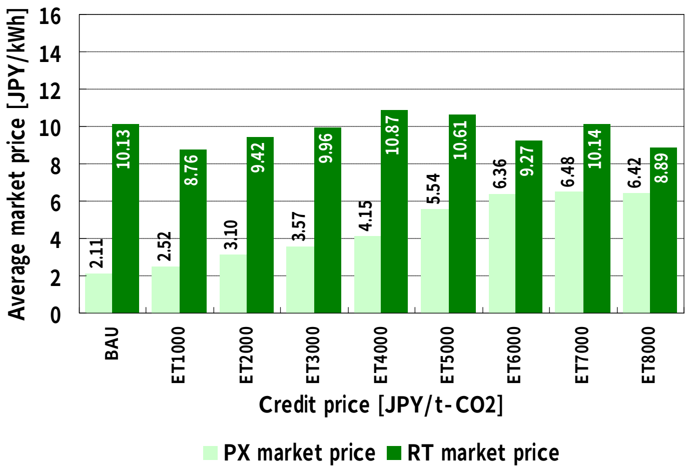


Fig. 3-12 Daily average market prices under e_{cap}=450e-6 [t-CO_2/kWh]

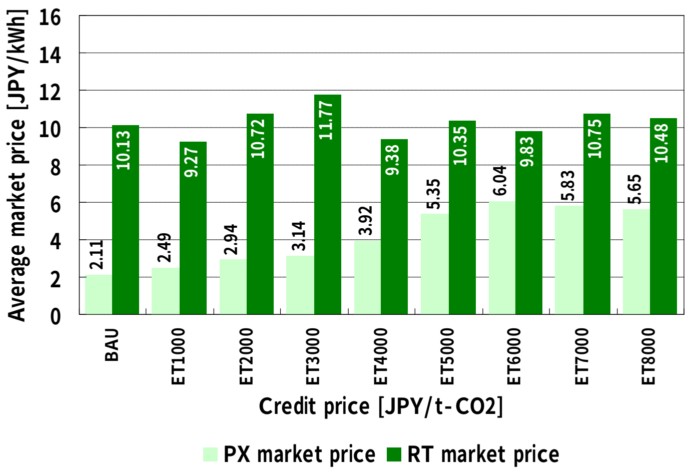


Fig. 3-13 Daily average market prices under e_{cap}=550e-6 [t-CO_2/kWh]

Daily average CO_2 emissions and needed CERs

The ET policy is also effective on CO_2 emissions reduction by triggering the fuel switching. In a study of the EU ETS (EU Emission Trading Schima) they comment that the short term reduction of CO_2 emissions partly will have to result from a switch from coal-fired electricity generation to gas-fired electricity generation (in Japan mainly the LNG power generation) [18]. However, from the figures (including Fig. 3-7) we discover that after the fuel switching, further CO_2 emissions reduction is difficult.

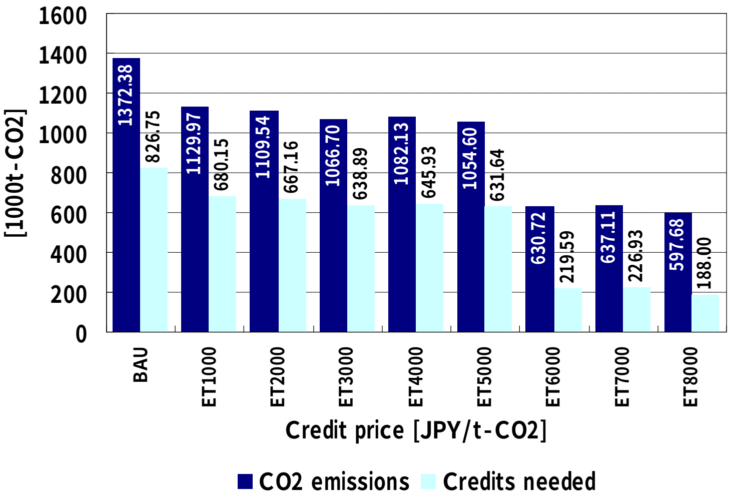


Fig. 3-14 Daily average CO_2 emissions and CERs required under e_{cap}=340e-6 [t-CO_2/kWh]

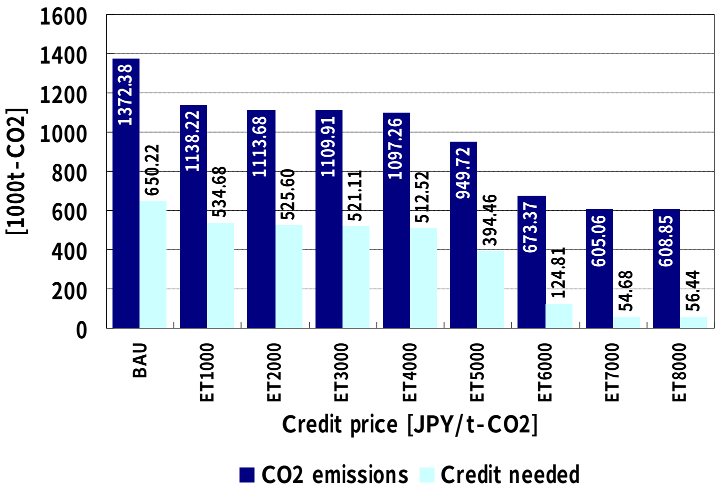


Fig. 3-15 Daily average CO_2 emissions and CERs required under e_{cap}=450e-6 [t-CO_2/kWh]

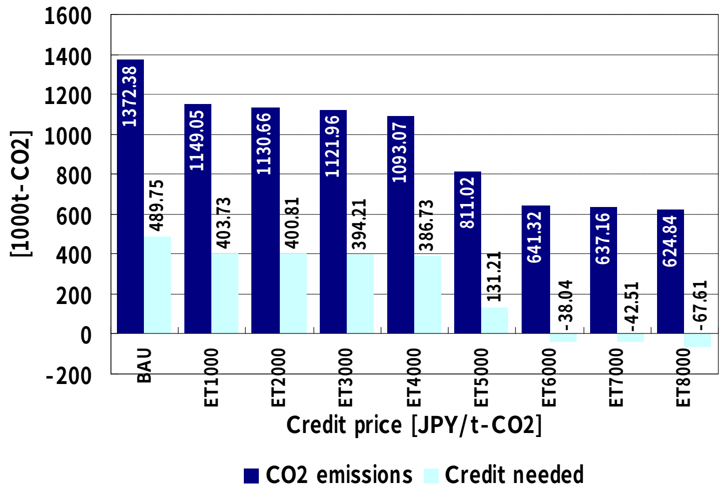


Fig. 3-16 Daily average CO_2 emissions and CERs required under e_{cap}=550e-6 [t-CO_2/kWh]

3-4 Analysis of market price

As carbon tax rate or the CERs price rises, the increasing environmental cost weights more in the whole cost and will cause a switching from coal to LNG. Large progress on CO_2 emissions reduction will be achieved with the fuel switching. Yet another fact is that there is also a sudden rising of the average PX market price when the fuel switching happens. The cost of CO_2 emissions reduction will finally be passed to the customers.

The bidding parterns of the PX market before the switching and after the switching are shown in Fig. 3-17 and Fig. 3-18. The horizon axis indicates quantity and the vertical axis is the price. The bidding blocks of the suppliers are ordered in terms of their asking price (from low to high) while the demander arranges his bidding blocks from a high to low price order. The market clearing point is decided not only by the bidding price of each player but also their bidding quantities.

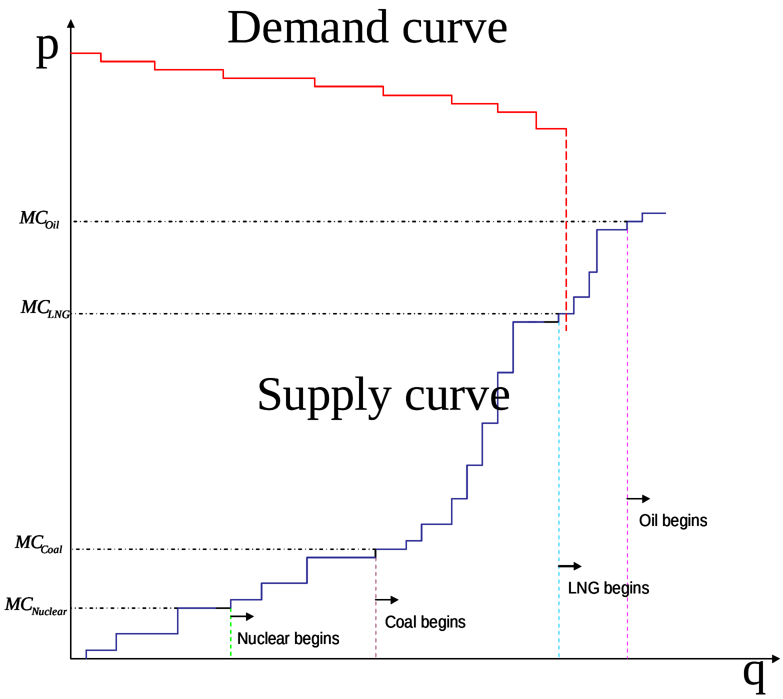


Fig. 3-17 PX market bidding process before fuel switching

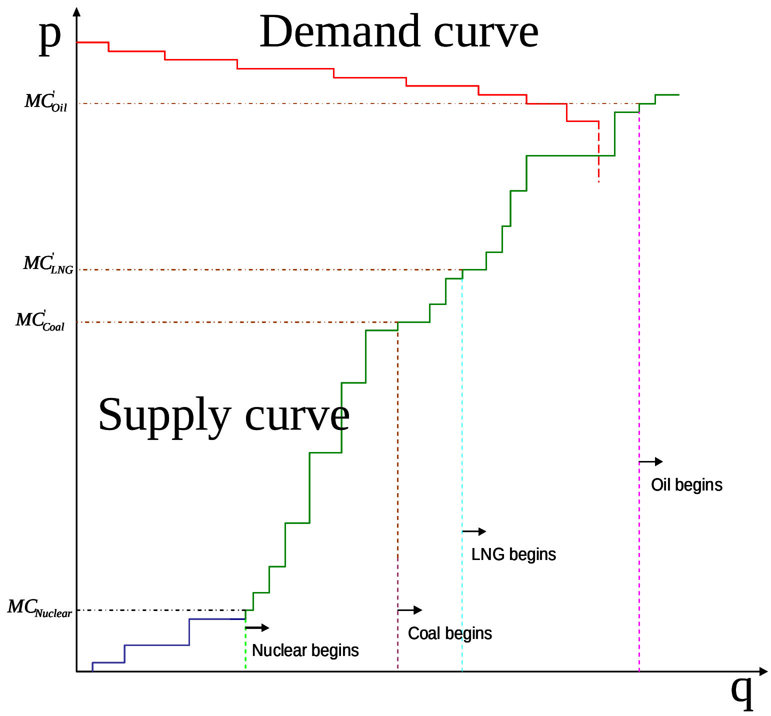


Fig. 3-18 PX market bidding process after fuel switching

Here the bidding function for the supplier agents (Equation (2-4)) can be rewriten as follows:

$$P_{gi}(q) = MC_i(q) + \alpha_{gi} = 2a_{gi}q + b_{gi} + \alpha_{gi} \tag{3-4}$$

$$= b_{gi} + \alpha_{gi} = (P_{fg} + e_g \times P_{ct}) + 0.2 \times j^2 \quad \text{under the CT policy}$$

Or

$$= b_{gi} + \alpha_{gi} = (P_{fg} + (e_g - e_{cap}) \times P_{et}) + 0.2 \times j^2 \quad \text{under the ET policy}$$

For each supplier agent, the asking price is the sum of the marginal cost and the bias value α_{gi}. Supplier agents with the high marginal cost tend to bid at a higher price level. However, the asking price of each bidding is finally decided by the optimal bias value α_{gi}, which is chosen from $\alpha_j = 0.2 \times j^2$ ($j = 0,1,2...20$) (Section 2-4.2) to maximize profit. Certainly, supplier agents will have no chance to win the bid if their marginal costs are higher than the clearing price of the market.

Before the fuel switching, according to the competition principle, the cheap fuel cost makes coal generation the most profitable compared with the other two kinds of thermal power plants in our model. The profit of the coal plants is high enough to spur the agents to enlarge their capacities. Therefore, the most part of the market is taken by supplier agents with coal power plants and the market price is dominated by the asking price of the coal agents. Most of the cases the market clearing price is lower than the asking price of the LNG and oil power plants. However, supplier agents with coal power plants afford the highest environmenal cost due to their high emission rate. As the environmental cost increaseing and weighting more in the whole cost, by self learning more and more coal agents find themselves have to ask at a higher price to guarentee the profit. Finally coal plants lose their cost advantadge and the market shares to LNG plants. After the switching, the market's clearing price will be dominated by the asking price of the supplier agents with LNG power plants, which results to a higher market price.

However, the story in the RT market is quite different. The environmental cost seems to have little impact on the RT market price. As we have stated, considering the load following propertities, the supplier agents with nuclear power plants or coal power plants do not bid for the RT market. Amonge the remaining three kinds of power plants, because there is an upper limit for the capacity of hydro plants, only the LNG and oil plants bid for the RT market after the PX market.

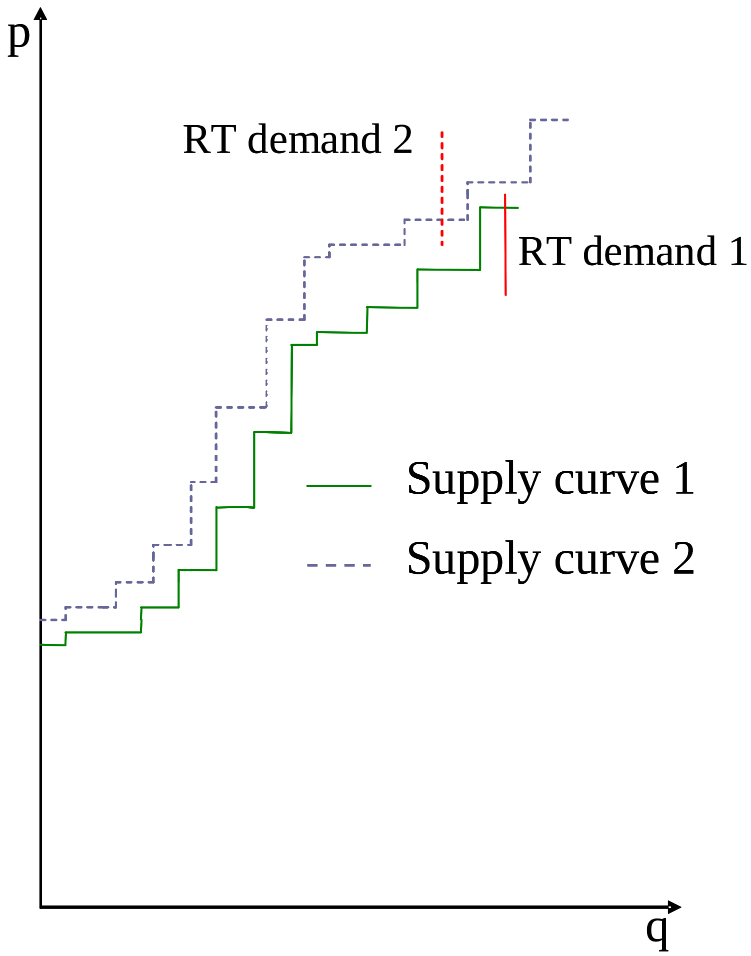


Fig. 3-19 RT market bidding process

The bidding pattern of the RT market is shown in Fig. 3-19. Here we consider two cases. In case 2 (purple dotted line) the environmental cost is more than that in case 1(green line), so the bidding curves of the suppliers is lifted. However, the clearing point of the market is not only decided by the bidding prices but also by the bidding quantity. Therefore, if the demand in case 2 (red dotted line) is smaller than that in case 1(red line) , the clearing price in case 2 may be lower that in case 1. As we have stated the demand in the RT market is quite random, so the price change may not follow a fixed pattern.

3-5 Conclusions of this chapter

In this chapter we discussed how the power souce mix of the market and the market prices react to the Carbon Tax policy and the Emission Trading policy. We have also checked the effectivness of the two policies on CO_2 emissions reduction.

Because we have not applied the competition principle (Section 2-5) to the hydro and the nuclear power plants, the power source mix figures actually showed the changes of the combination of the thermal power plants with the rising of environmental cost. According to our simulation results, we found out that there was a trend that coal plants with the highest emission rate be replaced by the LNG plants which have a lower emission rate. The increasing environmental cost would weight more in the total cost and finally provided enough incentives to trigger the fuel switching.

The change of market structure was reflected in the market prices by the rising of PX market price. It means that the increased environmental costs were tend to be passed to the customers. On the other hand, the RT demand was pretty random, which resulted that the changing pattern of RT market prices with the rising of invironmental cost was difficult to find. In section 3-4 we discussed the details of the mechanism of the bidding process and why the fuel switching caused the sudden increase of PX market prices.

The fuel switching would lead to an large progress on CO_2 emissions reduction. But we also noticed that after the fuel switching further CO_2 emissions reductions were difficult. On other words, the effectiveness of CO_2 mitigation solely by fuel switching was limited.

We did not consider CO_2 mitigation approaches such as improving generation efficiency of thermal power plants, introducing new clean resources like hydro, nuclear (the capacity of hydro and nuclear power plants were fixed), and renewable energy, and technologies like the CCS and so on. Therefore, fuel switching was the only choice to reduce CO_2 emissions when the envirionmental regulations became stricter.

Chapter 4　CO$_2$ free electricity trading

4-1 Overview of CO$_2$ free electricity trading

The Japan Electric Power Exchange (JEPX) is expected to function more in promoting competition of the electric power market as well as to contribute to mitigating CO_2 emissions from the power generation sector. The CO_2 free electricity trading is an answer to the expectation. The purpose of this policy is to lower the average emission rate of the JEPX, make CO_2 emissions of the participants more transparent as well as to promote renewable energies.

The image of how CO_2 free electricity trading works can be understood from Fig. 4-1.

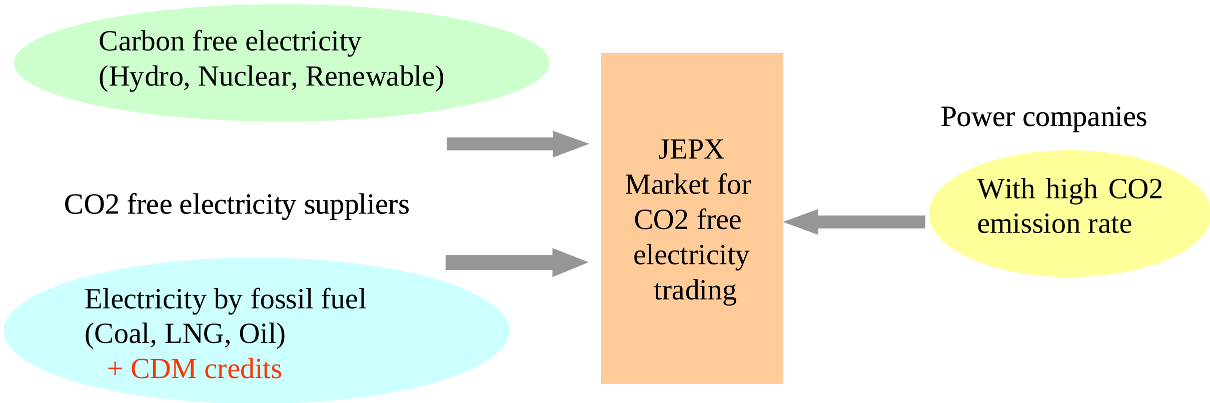


Fig. 4-1 Mechanism of CO_2 free electricity trading

There are two kinds of CO_2 free electricity. One is the electricity from clean sources without CO_2 emissions such as electricity generated by hydro, nuclear or renewable energies. If the electricity is from fossil fuels (coal, LNG and oil) it has to be traded with CDM credits (CERs) which can offset the CO_2 emissions. The suppliers of CO_2 free electricity are supposed to be power companies with hydro, nuclear or renewable energy power plants, trading companies or financial companies who have stored CDM credits and at the same time own power generation plants. The demanders of CO_2 free electricity are always the power companies with high CO_2 emission rates.

The pilot trading of CO_2 free electricity has been started in JEPX from 17th 11, 2008.

4-2 Model for CO_2 free electricity trading

4-2.1 Model framework

The model in this chapter is developed from the multi-agent model proposed in Chapter 2. The framework of the model for CO_2 free electricity trading is shown in Fig. 4-2.

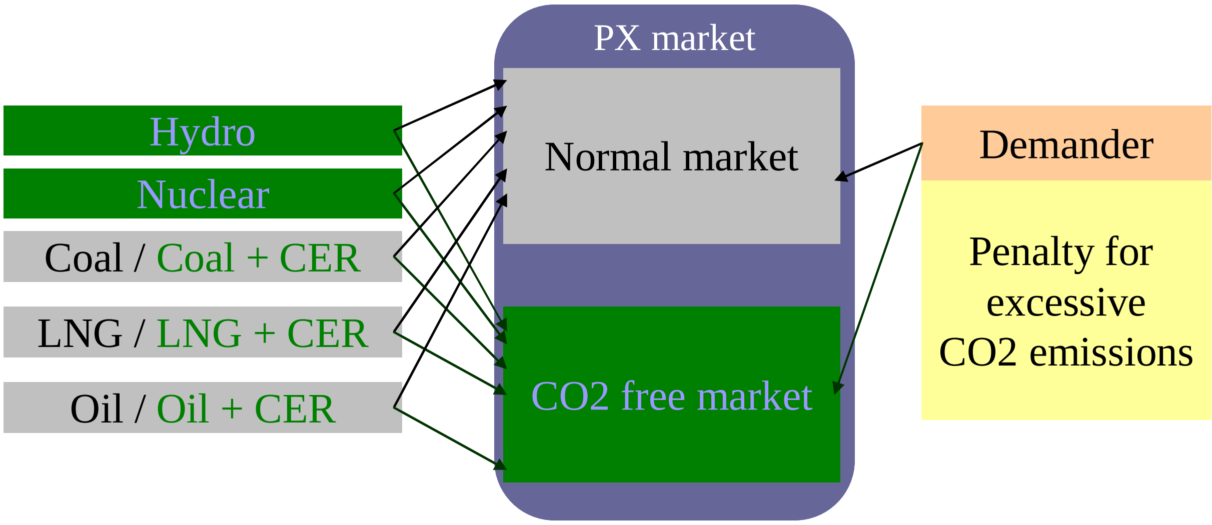


Fig. 4-2 Framework of model for CO_2 free electricity trading

In our model, a market for CO_2 free electricity trading is hold within the Power Exchange market. Supplier agents with hydro and nuclear plants will bid for the CO_2 free market based on the same bidding function as for the normal market. However, if supplier agents with thermal power plants bid for the CO_2 free market, the CERs that offset the CO_2 emissions coming from the fossil fuel combustion for power generation must be traded at the same. It is to say that, within the bidding functions and the cost functions of thermal power supplier agents the cost of CERs is accounted in.

The normal and the CO_2 free market are all day-ahead markets. Biddings of the two markets are hold hourly at the same time. At the end of the bidding the clearing price and the clearing quantity for each marekt are decided.

As stated above, the demander of the CO_2 free electricity is supposed to be the power utilities with high emission rate. Here, we set a cap for the amount of the demander's daily CO_2 emissions. If the cap is exceeded high penalty for the excessive part of carbon emissions is charged.

Because the normal market and the CO_2 free market are hold at the same time, the supplier agents and the demander agent will do market selection. At the end of one bidding cycle, based on the outcomes of the two markets the supplier agents and the demander agent reallocate their bidding quantity for the two markets for the next bidding cycle. The supplier agents will increase the bidding capacity for the market from which they can get higher unit profit (profit for one kW) while decrease the bidding capacity for the other market. The demander agent will allocate more demand for the market that cost less.

4-2.2 Model for supplier agents

The bidding functions of supplier agents for the normal market and the CO_2 free market are expressed in equation (4-1) and equation (4-2).

$$P_{gi}^{nor}(q) = b_{gi}^{nor} + \alpha_{gi} = P_{fg} + \alpha_{gi} \tag{4-1}$$

$$P_{gi}^{cf}(q) = b_{gi}^{cf} + \alpha_{gi} = P_{fg} + (e_g \times P_{CER}) + \alpha_{gi} \tag{4-2}$$

Where,

P_{CER} : primary CER price [JPY/t-CO_2]

For suppliers in the normal market b_{gi} comprises the unit fuel cost P_{fg} and bias value α_{gi}. In the CO_2 free marekt b_{gi} also includes the cost of CERs (product of emission rate e_g ([t-CO_2/kWh] and P_{CER}).

At the beginning of the simulation, supplier agents bid for each market with the same capacity. When each hour's biddings of the two markets are finished, the supplier agents will do three things.

The first thing is the decision making of the optimal bias value α_{gi} for the next hour's bidding (Section 2-4.2).

The second thing is to reallocate bidding capacities for the two markets based on the results of the hourly accountings for each market. The supplier's unit profit UPR_{gi} ([JPY/kW], equation (4-3)) got from each market is calculated based on the market clearing price and the bidding quantity won in the market.

$$UPR_{gi} = (SL_{gi} - CO_{gi}) / Capa_i \tag{4-3}$$

Where,

SL_{gi} : hourly sales [JPY]

CO_{gi} : hourly cost {JPY}

$$SL_{gi} = cp_h \times cq_{gi,h} \tag{4-4}$$

$$CO_{gi} = b_{gi} \times cq_{gi,h} \tag{4-5}$$

Where,

cp_h : clearing price at hour *h* [JPY/kWh]

$cq_{gi,h}$: clearing quantity of supplier agent *i* at hour *h* [KWh]

The supplier agents will reallocate their bidding quantity according to the following principle:

Increase the bidding capacity for the normal market while decrease the same amount of the bidding capacity for the CO_2 free market if:

$$(UPR_{gi}^{nor} - UPR_{gi}^{cf}) / UPR_{gi}^{nor} \geq (1/s) \qquad s = 10 \tag{4-6}$$

Decrease the bidding capacity for the normal market while increase the same amount of the bidding capacity for the CO_2 free market if

$$(UPR_{gi}^{cf} - UPR_{gi}^{nor}) / UPR_{gi}^{cf} \geq (1/s) \qquad s = 10 \tag{4-7}$$

The last thing the supplier agents will do after one bidding is to decide whether to re-entry the market. The supplier will re-entry the normal market or the CO_2 free market if the following three conditions are all satisfied:

- The clearing price of this market is higher than the other market;
- The clearing price of this market is higher than the marginal cost of the supplier agent;
- The supplier's bidding capacity for this market is 0.

In the model for CO_2 free electricity trading, we assume the hydro power plants keep their output capacity the same. The supplier agents with other types of power plants will adjust their total capacity following the competition principle (Section 2-5) at the end of one year. But the supplier's capacity is upper limited.

4-2.3 Model for demander agent

The marginal utility function of the demander agent is not changed in the model for CO_2 free electricity trading.

$$P = \frac{P_0}{Q_0^{1/\eta}} q^{1/\eta}$$

As the CO_2 free electricity trading is hold in the JEPX, the reference demand Q_0 is based on the average daily transaction quantity of the JEPX market.

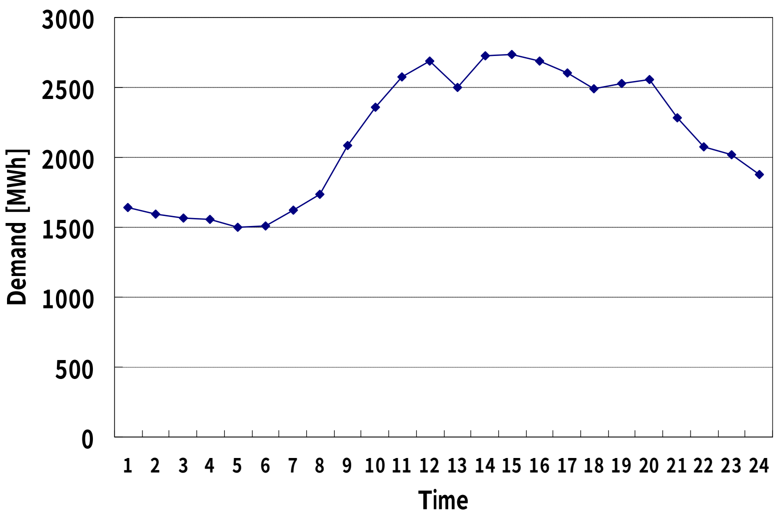


Fig. 4-3 Reference demand Q_0 in the model for CO_2 free electricity trading

After one hour's bidding, the demander agent reallocate his demand for the two markets in terms of the unit cost ([JPY/kWh]) of each market. The cost of the CO_2 free market is the market clearing price. On the other hand, because we assume that the CO_2 emissions of the demander come from the electricity bought from the normal, the penalty for excessive CO_2 emissions above the cap is counted in when calculating the unit cost of normal market. Because the cap is set for daily CO_2 emissions, we introduce the average daily penalty to the unit cost function.

In the normal market:

$$E_{power} = \sum_{h}^{24} \sum_{g=1}^{5} q_{g,h} \times e_g \tag{4-8}$$

Where,

E_{power} : daily CO_2 emissions from the electricity bought from the normal market [t-CO_2]

$q_{g,h}$: transacted quantity of the electricity generated by type *g* power plants [kWh]

If $E_{power} > E_{cap}$

$$P_{avepenalty} = P_{Penalty} \times E_{power} / DQ \tag{4-9}$$

Where,

$P_{avepenalty}$: daily average penalty [JPY/t-CO_2]

$P_{Penalty}$: penalty rate [JPY/t-CO_2]

DQ : daily traded electricity in normal market [kWh]

The unit cost is:

$$P_{nor} = cp_{nor,h} + P_{avepenalty} \tag{4-10}$$

Where,

P_{nor} : unit cost of the normal market [JPY/kWh]

$cp_{nor,h}$: clearing price of the normal market at hour *h* [JPY/kWh]

If $E_{power} \le E_{cap}$

$$P_{nor} = cp_{nor,h} \tag{4-11}$$

In the CO_2 free market:

$$P_{cf} = cp_{cf,h} \tag{4-12}$$

Where,

P_{cf} : unit cost of the CO_2 free market [JPY/kWh]

$cp_{cf,h}$: clearing price of the CO_2 free market at hour *h* [JPY/kWh]

The demander agent reallocates his demand for the two markets based on the following principle:

Decrease demand for the normal market while increase the same quaantity of demand for the CO_2 free market if:

$$(P_{nor} - P_{cf}) / P_{nor} \geq (1/s) \qquad s = 10 \tag{4-13}$$

Increase demand for the normal market while decrease the same quantity of demand for the CO_2 free market if:

$$(P_{cf} - P_{nor}) / P_{cf} \geq (1/s) \qquad s = 10 \tag{4-14}$$

4-2.4 Calculation flow

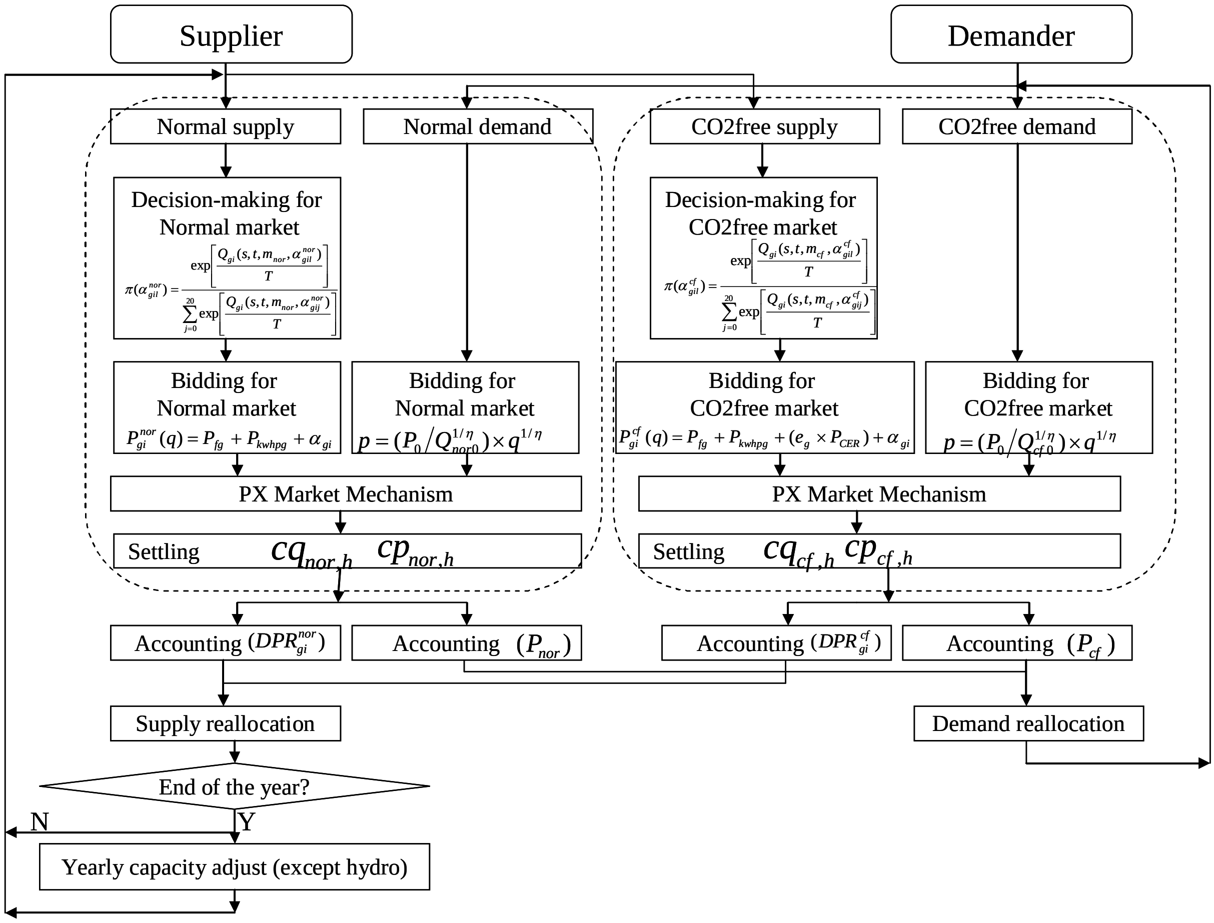


Fig. 4-4 Simulation flow for CO_2 electricity trading model

4-3 Parameters and simulation cases

The parameters of the power plants are almost the same as parameters used in Chapter 3. But here we assume hydro plants enjoy 30% policy subsidies, which is to say that the unit plant cost of the hydro plants used in the simulation is 70% of the value in Table 3-1.

In the bidding functions of the supplier agents for the CO_2 free market, the cost for CERs is counted in. The calculation of CERs is based on the primary CERs price which is listed in Table 4-1. Here we choose $P_{CER} = 2362[JPY/t-CO2]$ (Max value of scenario d).

Table 4-1 Primary CER prices for each scenario[6]

	Scen.(a)	Scen.(b)	Scen.(c)	Scen.(d)
Max	1418	1733	2127	2363
Avg	997	1273	1754	1969
Min	551	866	1418	1733

The primary CER price is set according to "pCER Survey Results" published by IDEAcarbon [19]. In terms of risk features there are four different scenarios. The CER prices are increasing from scenario (a) to scenario (d). In each scenario there are the maximum, average and minimum value of the CER prices.

Table 4-2 Other parameters for the simulation of CO_2 free electricity trading

	Supplier agents	Demander agent
Number of agents	10*5=50	1
Bidding block	3 [MWh]	
Price cap (PX & RT markets)	85 [JPY/kWh]	
Market capacity	2734 [MWh]	
Initial capacity Capa/	60 [MWh]	

To understand the changes after the introduce of CO_2 free market, we also do a simulation of the conventional market without CO_2 free market. In the simulations for assessing the CO_2 free electricity trading we set the penalty to 50,000 [JPY/t-CO_2], and investigate the market performances under 2 different CO_2 emission caps. Moreover, we will also compare the differences between the results by using our model and by using the least-cost approach.

Table 4-3 Simulation cases

Multi-agent based model			
	Conventional market	case 1	
	With CO2free market	Ecap=5,000	Ecap=2,400
		case 2	case 3
Least-cost approach		Ecap=5,000	Ecap=2,400
		case 4	case 5

4-4 Simulation results

4-4.1 Demand allocations

In this section we will discuss how de demander agent allocates his demand to the two markets under

6 The values in this table are calculated based the exchange rate: 1 Euro =157.55 JPY (2008.3)

environmental regulations.

The demander tends to buy more electricity from the CO_2 free market when subjects to caps for CO_2 emissions. By comparing Fig. 4-5 to Fig. 4-6 we can know that when the Ecap becomes lower, the demander will increase his demand for the CO_2 free market.

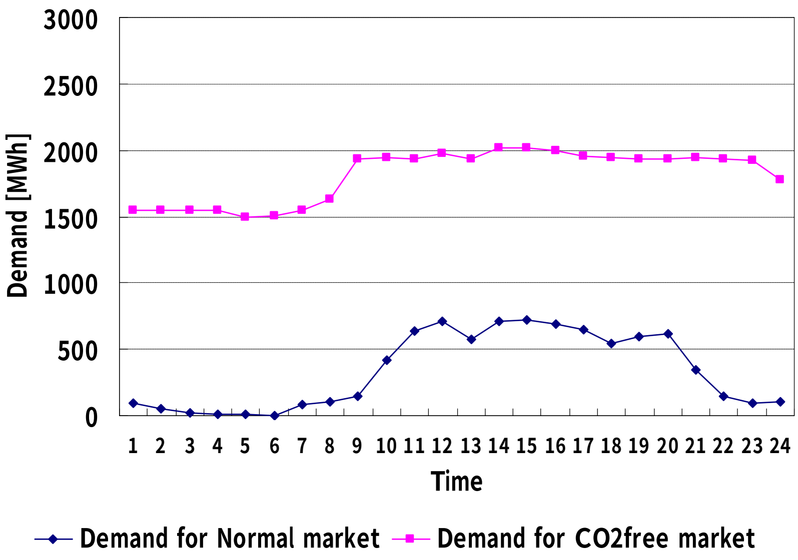


Fig. 4-5 Demand allocation under Ecap=5,000[t-CO_2/day]

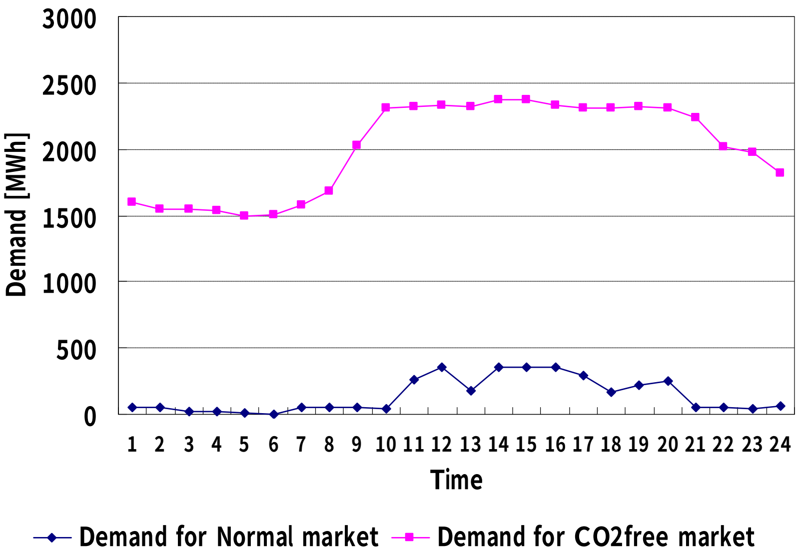


Fig. 4-6 Demand allocation under Ecap=2,400[t-CO_2/day]

Fig. 4-7 and Fig. 4-8 show the prices of the normal and the CO_2 free markets under each Ecap. From the figures we know that in both cases the CO_2 free market prices are higher than the normal market prices. This means that compared to paying penalty for the excessive CO_2 emissions the demander finds that buying more electricity from the CO_2 free market costs less though the price of this market is higher.

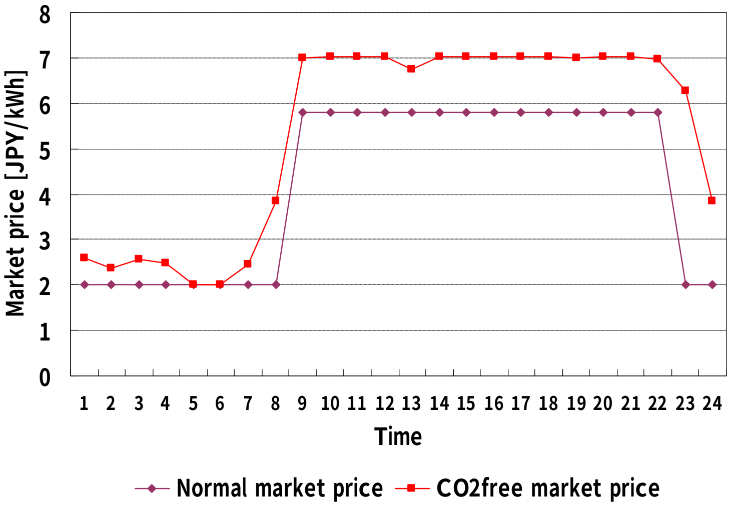


Fig. 4-7 Market prices under Ecap=5,000[t-CO_2/day]

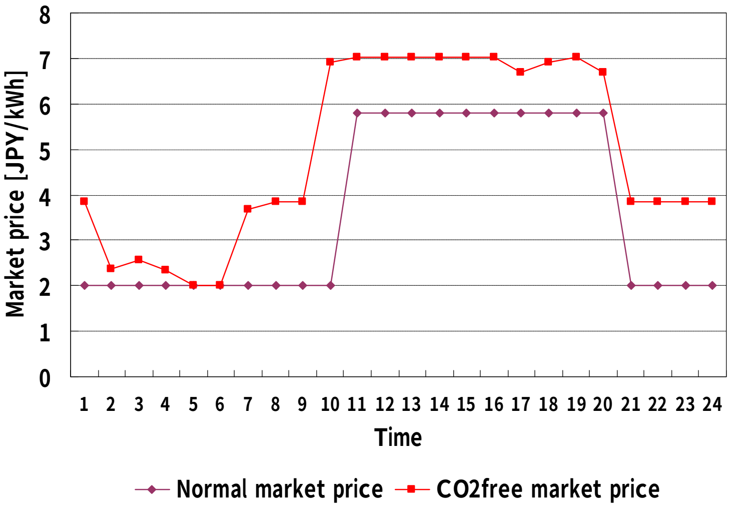


Fig. 4-8 Market prices under Ecap=2,400[t-CO_2/day]

4-4.2 Daily power mix

In this section we will see how the daily power mix changes before and after the introduce of the CO_2 free market. Fig. 4-9 shows the daily power mix without the CO_2 free market. Fig. 4-10 and Fig. 4-11 shows the daily power mix after the introduce of the CO_2 free market under each Ecap.

By comparing the figuers, we find out that after the introduce of the CO_2 free market the supplier agents with coal power plants will enter the CO_2 free market (selling their electricity with CERs). As we have stated above, when encironmental regulation becomes stricter the demand for CO_2 free market will increase. Because the capacities of hydro and nuclear power plants are limited, the coal power plants will sell more electricity in the CO_2 free market.

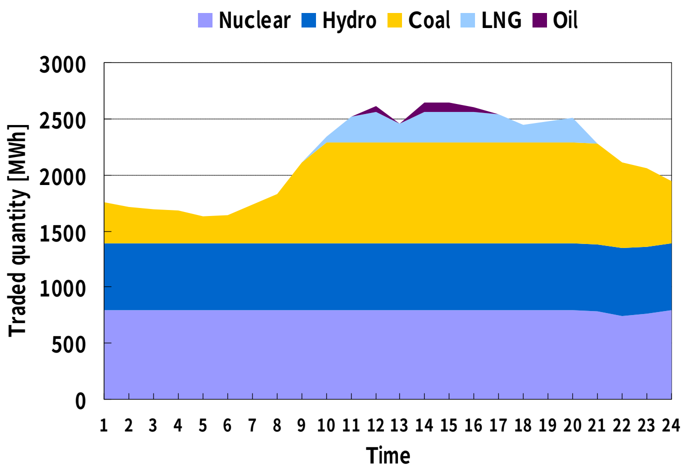


Fig. 4-9 Power mix without CO_2 free electricity market

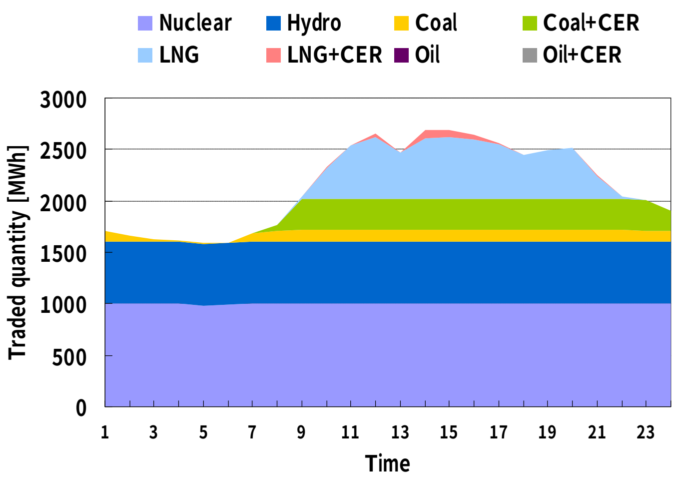


Fig. 4-10 Power mix under Ecap=5,000[t-CO_2/day]

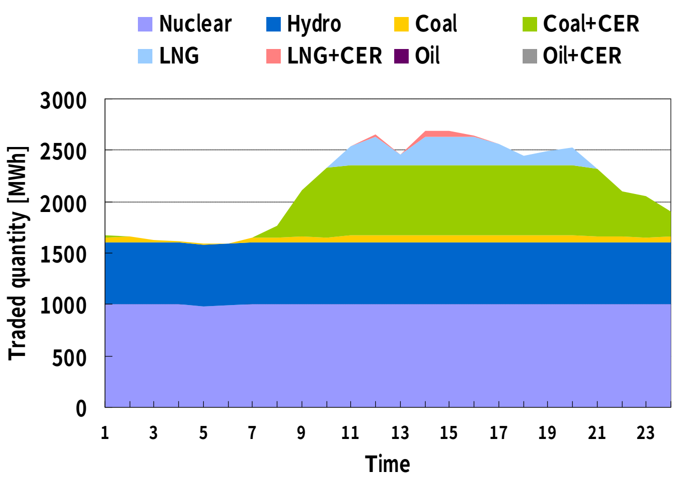
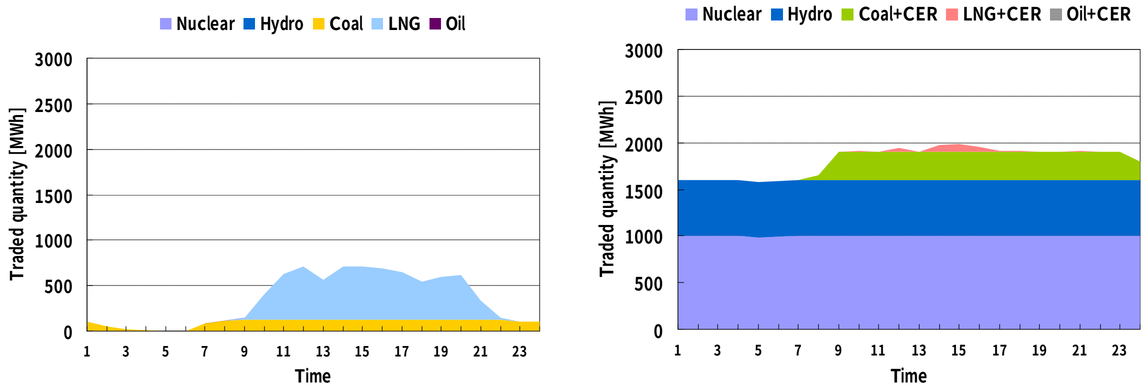


Fig. 4-11 Power mix under Ecap=2,400[t-CO_2/day]

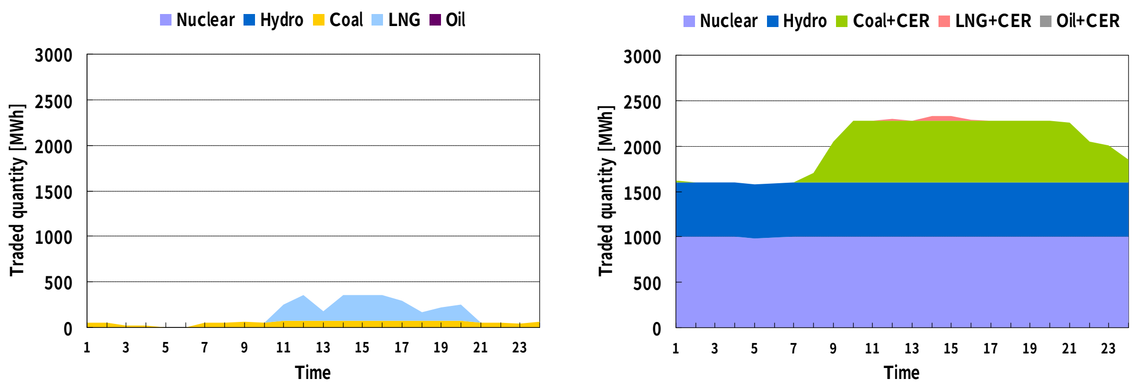
The distribution of power sources after the introduce of CO_2 free market can be understood more clearly if we show the power mix of the normal and the CO_2 free markets seperately under the two caps (Fig. 4-12, Fig. 4-13).

The supplier agents with nuclear or hydro power plants will bid for the CO_2 free market only for they can get more profit in this market. Because more coal power is sold in the CO_2 free market the demand in the normal market will be met mainly by LNG power.



(a) Normal market (b) CO_2 free market

Fig. 4-12 Power mix of each market under Ecap=5,000[t-CO_2/day]

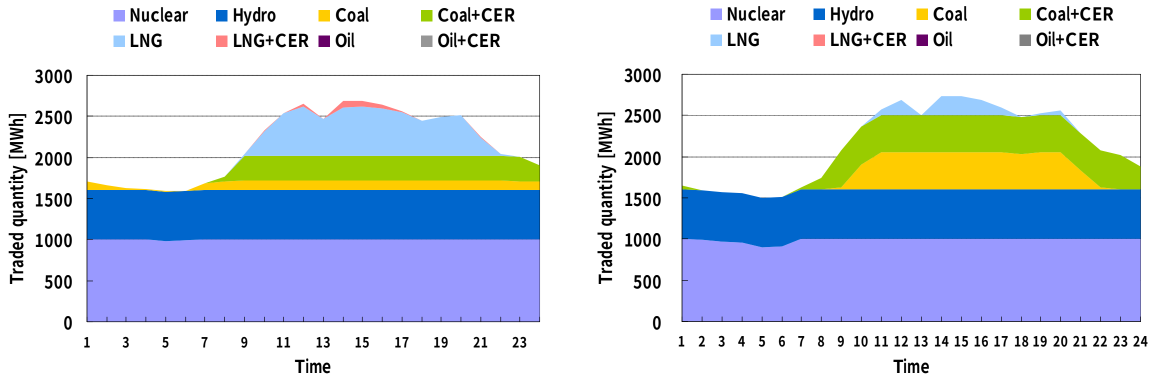


Normal market CO_2 free market

Fig. 4-13 Power mix of each market under Ecap=2,400[t-CO_2/day]

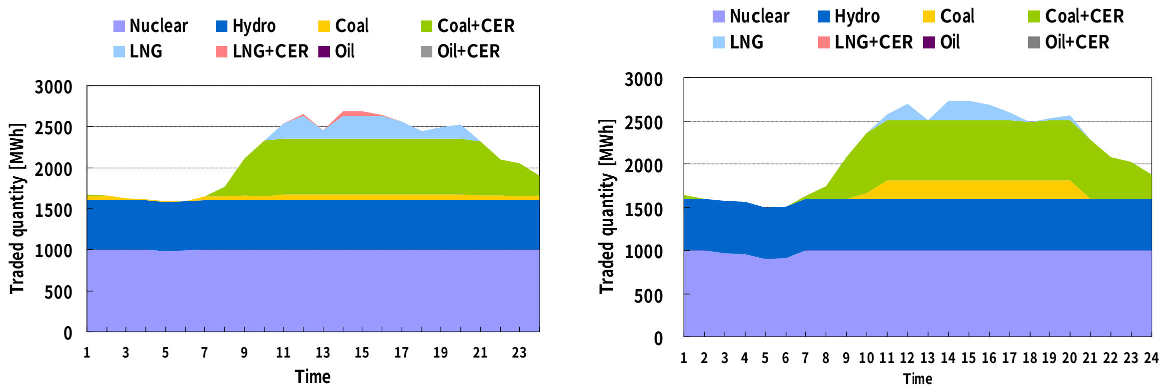
4-4.3 Multi-agent approach V.S. Least-cost approach

The idea of the least-cost approach is to find the optimal power mix which results to the minimum whole cost of the market while subject to reliability and some other constraints. The whole cost refers to the sum of each supplier's cost. In our model, the constraints include the reliability (supply is not less than demand) and the CO_2 emissions (not exceed the Ecap).



(a) Multi-agent approach (b) Least-cost approach

Fig. 4-14 Multi-agent approach V.S. Least-cost _Ecap=5,000[t-CO_2/day]



(a) Multi-agent approach (b) Least-cost approach

Fig. 4-15 Multi-agent approach V.S. Least-cost _Ecap=2,400[t-CO_2/day]

The power mix of the base loads of the two approaches are almost the same. There are some differences in the power mix from the media to the peak loads. We suppose that the differences are mainly due to the properties of the two approaches.

The objectives of these two approaches are different. The multi-agent model is developed from the game theory. In this approach the supplier agents aiming to maximize their profits while the demander agent tries to minimize his cost. On the other hand, the purpose of the least-cost approach is to make the total cost of the market the least. Moreover, in the multi-agent model the supplier agents act in a decentralized way and they interact with each other. Based on analyzing of the results of others' actions one agent will select the optimal strategy. For example, in the multi-agent model, if one participant finds himself in a deficit situation, he will leave the market. However, in the least-cost model, the planning is made centrally and the action of each participant is not considered.

The market design in our model may also have some influences on the results. However, considering the different characters of the two approaches the simulation results of our model are supposed to be acceptable.

4-4.4 Daily CO_2 emissions

The following figuer shows the daily CO_2 emissions before the introduce of the CO_2 free market and after the introduce of the CO_2 free market with different Ecaps for the demander. The daily total CO_2 emissions of each case are listed in table 4-3.

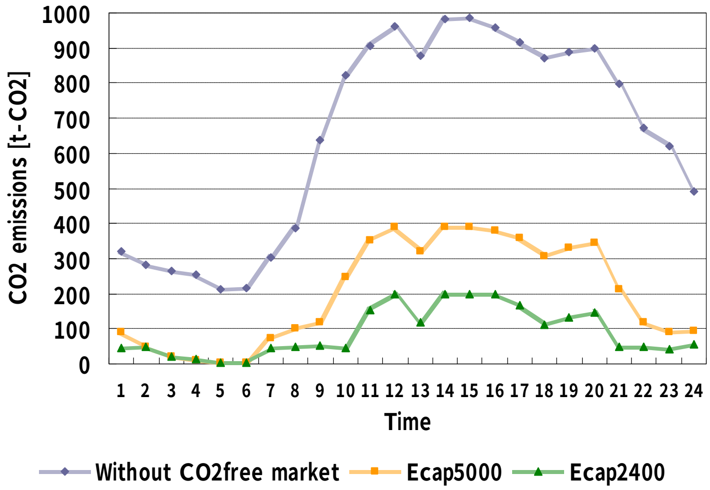


Fig. 4-16 Daily CO_2 emissions of each case

Table 4-4 Daily CO_2 emissions of each case

Cases	Without CO2 free market	Ecap=5000	Ecap=2400
Daily CO2 emissions [t-CO2]	15538	4790	2148

In the CO_2 free market CERs are traded with electricity. The CERs can offset the CO_2 emissions from the thermal power electricity. The demander agent under environmental regulation tend to buy CERs from the CO_2 free market.

The introduce of the CO_2 free market would also change the market structure (for example more electricity from LNG power plants are traded in the normal market), which was supposed to be another reason of CO_2 emissions reduction.

Therefore, compared to the traditional market in witch only the electricity is traded, the CO_2 free market functions on lowering the average emission rate of the whole market.

4-5 Conclusion of this chapter

In this chapter we developed a model for assessing the CO_2 free electricity trading policy. The key point of the model was that the supplier agents and the demander agent did market selection based on their profits or cost. By conducting simulation we evaluated the CO_2 free market from the following aspects:

First we investigated the demander agent's strategies. The CO_2 emissions of the demander agent was capped. Therefore, when calculating the cost in the normal market, the penalty was counted in. The results showed that, rather than pay penalty for the excessive CO_2 emissions, the demander would buy more electricity from the CO_2 free market despite of its higher price.

Then the market performances before and after the introduce of the CO_2 free market were studied. After the introduce of the CO_2 free market the suppliers with coal power plants tended to enter the new market (selling their electricity with CERs). The decreasing of the coal plants in the normal market resulted to that the demand in this market was met by LNG power plants. The nuclear and hydro power plants shift to the CO_2 free market totally.

We also compared the results got from the least-cost approach to our simulation results. Considering the different characters of these two approaches, though there were some differences of the results, we thought our results were reasonable.

The CO_2 free market provided a trading place not only for electricity but also for CERs. The demander agent under environmental regulation tend to buy CERs from the CO_2 free market which offsets the CO_2 emissions of the thermal power plants. The introduce of the CO_2 free market would also change the market structure, which was supposed to be another reason of CO_2 emissions reduction. Thus after the introduce of the CO_2 free market the emission rate of the whole marke would be lowered.

Chapter 5 Conclustions

5-1 Findings of this study

In this paper we built a multi-agent based model to analyze the effects of environmental regulations on the liberalized electricity power market.

In Chapter 1 based on the IPCC reports we introduced the approaches to reduce baseline GHG emissions of the global electricity sector, the mitigation potentials and the cost of these methods. Then we gave a brief introduction of the electricity market of Japan including the history of deregulation, the JEPX and the power source mix, the CO_2 emissions status and so on.

The second chapter was the description of the multi-agent model for the market, from which the assessment models of the environmental policies were developed. In the market, the suppliers were modeled as self-adaptive agents capable of learning through market feedback, following a Reinforcement Learning algorithm. However, the bidding strategy of the demander agent was not considered.

Based on the model introduced in the second chapter, in Chapter 3 we developed a model to analyze the Carbon Tax policy and the Emission Trading policy. The environmental cost was added to the marginal cost function of the supplier agents. And we also added a realtime market to the model considering the realtime demand. The simulation was based on the wholesale electricity market of Japan. From the simulation results we found out that the increasing environmental cost provided enough incentives for fuel switching from coal with high emission rate to LNG with lower emission rate. The fuel switching leaded to a large progress on CO_2 emissions reduction. However, further reductions after the fuel switching were difficult. We also found out that the burden of environmental cost tended to be passed to customers by the rising of PX market prices. But because the demand in the RT market was quite random, the influence of environmental regulations on this market has not been discovered in this paper.

In chapter 4 we focused on the CO_2 free electricity trading which has been started pilot trading in the JEPX. In the model for assessing this policy we assumed that the CO_2 free market and the normal market were hold at the same. Based on their profits or cost the supplier agents and the demander agent would do market selection. Because the CO_2 emissions of the demander was capped and the penalty is high, as a result of costs comparison, the demander agent found that buying more electricity from the CO_2 free market at a high price was more cost effective than buying more electricity from the normal market while paying penalty for the excessive CO_2 emissions. As the demand for the CO_2 free market increased, the supplier agents with coal power plants would shift to this market (selling their electricity with CERs) because compared to the normal market they could get more profit in this market. As a result the demand in the normal market was satisfied mainly by LNG plants. Because CERs were traded in the CO_2 free market, the emission rate of the whole market was lowered. We also discussed the differences of the multi-agent approach and the least-cost planning approach in this chapter.

5-2 Future works

The future works of this study are as follows:

Considering the influence of the primary enery supplies

In chapter 3 we have found out that the increasing of environmental cost would lead to a fuel switching from coal to LNG without considering the change of fuel costs. However, the trigering point (at how much environmental cost the switching will happen) of the fuel switching relies largely on the variation of the market prices of coal and LNG. By considering both the environmental regulations and the market price of primary energies, the simulation results will become more reasonable.

Introduce new technologies

Besides fuel switching, technologies like the IGCC (Integrated coal Gasification Combined Cycle) which can rise the generation efficiencies or the CCS (Carbon dioxide Capture and Storage) which is to reduce the CO_2 directly are also effective mitigation approaches for the power generation sector. Based on this study, the model for assessing the influences of the environmental policies on these mitigation technologies can be developed.

Introduce renewable energies to the model

One of the targets of the CO_2 free electricity trading policy is to promote the use of renewable energy. Therefore, it is necessary to update our model for analyzing the CO_2 free electricity trading by including the renewables. However, when introducing supplier agents with renewable power plants to the current model, attentions should be paid to the following two issues among others:

The physical limitation of the renewable power. The renewable power generations are always distributed, small-scale and the output of which is difficult to be controlled. As a result, the renewable agents may following different rules on strategy selection.

The combination of other policies. Several other policies for the promotion of renewables (like the RPS) has been exist. These policies are supposed to interact with the CO_2 free electricity trading policy. Therefore, how to reflect the influences of the other policies in the model has to be solved when considering the renewable energies.

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