Energy 33 (2008) 1320–1330

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case

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ARTICLE INFO

Article history:
Received 17 June 2006

Keywords:
Economic analysis
Plant utilities estimation
Simulation modeling
System dynamics
Carbon tax
Sensitivity analysis

ABSTRACT

Economic growth is main cause of environmental pollution and has been identified as a big threat to sustainable development. Considering the enormous role of electricity in the national economy, it is essential to study the effect of environmental regulations on the electricity sector. This paper aims at making an economic analysis of Korea's power plant utilities by comparing electricity generation costs from coal-fired power plants and liquefied natural gas (LNG) combined cycle power plants with environmental consideration. In this study, the levelized generation cost method (LGCM) is used for comparing economic analysis of power plant utilities. Among the many pollutants discharged during electricity generation, this study principally deals with control costs related only to CO_2 and NO_2, since the control costs of SO_2 and total suspended particulates (TSP) are already included in the construction cost of utilities. The cost of generating electricity in a coal-fired power plant is compared with such cost in a LNG combined cycle power plant. Moreover, a sensitivity analysis with computer simulation is performed according to fuel price, interest rates and carbon tax. In each case, these results can help in deciding which utility is economically justified in the circumstances of environmental regulations.

1. Introduction

With the turn of the 21st century, fossil fuels are still the predominant source of energy in most economic sectors worldwide, particularly in the electric power sector. Fossil fuels are generally composed of aliphatic hydrocarbons with impurities such sulfur, water and other chemicals. The combustion of these chemicals results in the formulation of effluents such as sulfur dioxide and oxides of nitrogen as well as carbon dioxide and other effluents [1].

Along with rapid economic growth, increasing population, and advances in technology, the consumption of electricity is continuously increasing in developed and developing countries [2–4]. The role of power plant is also expanding. Unfortunately, emissions of environmental pollutants from these power plants have led to increase in stack emissions that are causing air quality degradation [3–5]. Environmental pollution has emerged as an overall global concern, directly related to the quality of life. There is a call for strengthening regulations on emissions of environmental pollutants worldwide. The issue of global warming emerged following the United Nations Framework Convention on Climate Change (UNFCCC), leading to tighter restrictions on CO_2 emission, and it is, therefore, necessary to evaluate the economical efficiency per generation by calculating generation costs by the effects on the environment [5,6]. When calculating the production costs of items causing environmental pollution, a price based on private costs disregarding environmental costs cannot work as an index in representing the exact generation cost.

Electric power plants are globally regarded as a major contributor to the local air quality degradation and global environmental impacts such as the greenhouse phenomenon. When various investment alternatives for power plant utilities that affect the environment are considered, the cost necessary for each alternative to generate electricity can make a real difference to private costs disregarding the social costs [7–9]. From this perspective, there is an urgent need to expand the definition of production costs in the power plant sector into social costs, which include environmental costs. The total cost of the energy consumption process consists not only of a conventional private cost, but also the external cost imposed on the society. Some studies have been undertaken on economic analysis by specifying a cost for emission of environment pollutants under the power generation facilities [10–12].

Jeffrey and Yanjia [13] compared the cost of electricity from new coal-fired and gas-fired power plants in China under various assumptions about fuel cost, exchange rates, carbon dioxide

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doi:10.1016/j.energy.2008.02.014

Nomenclature

A_p	internal consumption rate of power plant (%)
C_f	power plant utilization (%)
COM	capital rate (%)
CRF	capital recovery factor
C_t	carbon tax ($/kW h)
D	depreciation rate
f_p	unit cost of heat ($/J)
FC	fuel cost ($)
EP	fuel price ($/kg)
GC	generation cost ($/kW h)
F_x	fixed rate (%)
g	increasing rate (%)
G	annual generation (kW h)
$GGSF$	geometric gradient series factor
G_n	generating capacity (MW)
H	generation hours (h)
H_r	average heat efficiency (J/kW h)
HV	heating value (kJ/kg)
i	interest rate (%)
I	total investment cost ($)
In	initial investment cost ($)
n	power plant life span (year)
OM	operation and maintenance rate (%)
OMC	actual operation and maintenance cost ($)
AVR	asset value (investment cost) of reference power plant
T'	fixed rate of corporation tax

changes and application of carbon sequestration technology. Jerasorn et al. [14] estimated the potential of biomass power generation and its impact on power generation expansion planning as well as mitigating carbon dioxide emission from the power sector. Borchiellini et al. performed the environmental analyses and optimization of three existing plants: steam cycle, combined cycle and cogeneration gas turbine cycle. The effects of the abatement devices of NO_x and SO_x emissions on the cost of electricity were also evaluated [15].

In the existing long-term economic efficiency assessment method of power generation facilities, system cost analysis method (SCAM) was used. However, this study employs levelized generation cost method (LGCM) which makes the assessment of each power source possible and which can be utilized for economic efficiency analysis during build-transfer lease (BTL) construction [8,16]. In order to minimize the differences of data, when analyzing economic efficiency, we selected the standard power plant which is expected to be built among other power plants with different generation capacity and facilities but running on the same fuel. Moreover, by including atmosphere which is one of the environmental factors while conducting the assessment, we plan to present a developmental model which makes the internalization of environmental effects possible when calculating future generation costs and evaluating economic efficiency. More social costs will be added to the existing evaluation method, therefore, when assessing economic efficiency for constructing an additional power plant, all kinds of evaluations including environmental costs will be possible.

This paper consists of the following sections: Section 1 gives an overview and introduction to the study. Section 2 explains the selection of power plants subject to comparative analysis; the composed factors of power plant costs and the application of carbon tax in the economic analysis process. Section 3 describes a power cost computing models using system dynamics (SD) simulation method. Section 4 shows results of sensitivity analysis concerning the changing forms of coal-fired and liquefied natural gas (LNG) generation cost according to plant utilization factors, carbon tax change rates, and fuel price fluctuation rates. Finally, conclusions are drawn and further studies are presented in Section 5.

2. Economic analysis

Most economic efficiency assessment methods of environment values are based on benefit-cost analysis, and these are the travel cost method (TCM), the hedonic price method (HPM), and the contingent valuation method (CVM). Such methods are not adequate enough to solve all the external problems. However, CVM is widely utilized nowadays and regarded as the most advanced method in theory, but has shortcomings such as it does not use environment services those are excluded from the survey population, only the supplier side is highlighted, and the accuracy willingness-to-pay (WTP) statistics may not always be exact.

The CVM attempts to internalize the environment cost concerning the CO_2 regulations of an international issue, and therefore, it is difficult to selectively invest in a development sector by evaluating the aforementioned existing environment values. This is due to the fact that the problem of CO_2 regulations is an international matter rather than domestic one. Even though we assess the environmental costs in the economic efficiency evaluation of the development sector, economic efficiency of the development sector can vary due to other external factors. As solutions to external effects and internalization, methods of direct regulations and market incentives regulations are often cited, and examples of the latter include carbon tax and an emission trading system. This paper furthermore conducts the economic efficiency assessment in terms of carbon tax, which is the focus of a heated debate nowadays.

The economic analysis procedure of this study is detailed in the following steps and shown in Fig. 1.

Step 1: Choose similar power plants according to the exact selection criteria.
Step 2: Calculate the construction cost, which is the total capital cost during the construction period necessary for commercial work.
Step 3: Calculate the generation cost from construction costs, operation costs, and fuel costs.
Step 4: Analyze the generation cost including the carbon tax using the LGCM.

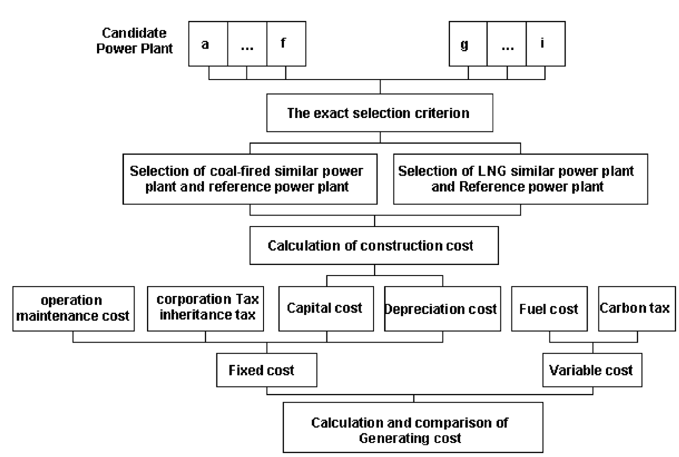

Fig. 1. The procedure of economic analysis.

2.1. Selection of similar power plants

Among the major domestic resources such as nuclear power, coal, and LNG generation, the nuclear energy which emits little CO_2, was excluded as a subject of analysis from this study. Coal-fired and LNG generations were compared through economic analysis.

The most common coal-fired power plant is the steam power plant with pulverized coal combustion at atmospheric pressure. The power plant consists of equipments such as coal supply, pulverizer, boiler, stack, generator, and transformer. The coal is processed and delivered by a conveyor belt to the generating plant. The coal is pulverized to a fine powder, mixed with air and blown into the boiler, or furnace for combustion at pulverizer. Burning coal produces carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Exhaust gases emitted through the stack. Electricity is delivered to substations in cities and towns, the voltage flowing into the distribution lines is reduced, and then reduced again to distribute electricity to customers. In generally, limited efficiency of coal-fired power plant is known as approximate 43%. Compositions of LNG combined cycle power plant are similar coal-fired power plant. It is known as 43–55%.

For comparison, similar power plants should be selected in order to calculate the generation cost of new power plants. The selection criteria for selecting similar power plants are as shown in Table 1.

According to the calculation methods, we have selected the examined power plants from the existing power plants or the one under construction and evaluated results according to the selection criteria. In other word, the power plant with the highest score was selected as the standard similar power plant. Where it was difficult to acquire data of similar power plants under construction, alternative power plants were used as reference power plants. The analysis results according to the selection criteria (of the examined power plants in order to select similar coal-fired and LNG combined cycle power plants) are presented in Tables 2 and 3.

By using the analysis results, Hadong #1 (500 MW coal-fired power plant) and Seoincheon #1 (400 MW LNG combined cycle power plant) were selected as subjects of comparison analysis in this paper. Technical information on the two types of power plants, coal-fired and LNG is shown in Table 4. Note that we assume no particular change in fuel efficiency and economies of scale in fuel use for each power system since there is not enough empirical data. This study, however, can systematically include technological innovation or autonomous energy efficiency improvement (AEEI) in power generation and economies of scale in using fuel on availability of relevant data.

Table 1
Selection criteria of similar power plant

Selection criteria	Mark distribution	
	Coal-fired	LNG
Similarity in capacity	20	20
Similarity in fuel resources	20	20
Similarity in utilities	10	10
Similarity in construction lead time	10	10
Utility in accessing information	10	10
Reasonableness in calculating construction cost	10	10
Applicability of new technology	5	10
Applicability of construction standardization	5	10
Rationality of the site	10	10

Sources: Business process planning of the civil generation, Korea Electronic Power Corporation [18].

2.2. Variables for economic analysis

The major economic variables affecting the economic analysis can be divided into technological and artificial factors. The results differ according to selection criteria as and applied variables of these factors. Therefore, the application of these variables must be considered with prudence. In this study, the applied economic variables are as follows:

(1) Standard time of price: As of January 1, 2002.
(2) *Economic lifetimes*: Coal and LNG plants are amortized over their likely physical lifetimes of 25 and 20 years, respectively.
(3) Depreciation method: straight line.
(4) *Interest rate*: Interest rates must be calculated reflecting future economic prospects at the point of evaluation, thus it needs to be modified to the current economic climate. In this study, interest rates of 13%, 10%, 8.5%, and 8% are variously applied.
(5) *Inflation rate and exchange rate*: Inflation rates and exchange rates are based on the National Statistical Office data. As for inflation rates, 2.7% (2002), and USD/KRW = 1251 was applied as exchange rate (2002).
(6) Utilization degree of power plant.

The utilization of the different generating capacity for these four utilities in 2000 is shown in Table 5. Nuclear and coal generation units are the most intensively used, followed by the LNG units, and oil-fired units. Since we do not have the actual data to identify the capacity factor for LNG1 (simple cycle) and LNG2 (combined cycle) considered in this paper, we assume that the LNG2 is used more intensively than LNG1 because of its greater efficiency, and we assign LNG2 a uniform capacity factor of 60% of all utilities having LNG2 capacity and calculate LNG1 Utilization as a residual given this assumption and the observed 2000 use of LNG by the utility.

Table 2
Selection evaluation results of coal-fired similar power plants

Selection criteria	Mark distribution	Boryeong #1	Hadong #1	Boryeong #3	Samchunpo #1	Samchunpo #3	Dangjin #1
Similarity in capacity	20	20	20	18	5	5	20
Similarity in fuel resources	20	20	20	20	10	10	10
Similarity in utilities	10	0	10	10	0	0	6
Similarity in construction lead time	10	3	8	3	3	3	8
Utility in accessing information	10	10	8	10	10	10	8
Reasonableness in construction cost	10	0	10	5	0	5	0
Applicability of new technology	5	0	5	0	0	0	0
Applicability of construction standardization	5	0	5	5	0	0	0
Newness of the site	10	10	10	5	10	5	5
Total	100	63	96	76	38	43	57
Overall ranking		3	1	2	6	5	4

Table 3
Selection evaluation results of LNG similar power plants

Selection criteria	Mark distribution	Seoincheon #1	Pyeongtaek	Seoincheon #3
Similarity in capacity	20	10	10	0
Similarity in fuel resources	20	20	20	20
Similarity in utilities	10	10	10	10
Similarity in construction lead time	10	5	8	10
Utility in accessing information	10	10	10	3
Reasonableness in calculating construction cost	10	10	10	10
Applicability of new technology	10	0	0	10
Applicability of construction standardization	10	10	5	5
Total	100	75	73	68
Overall ranking		1	2	3

Table 4
Technical information of the considered power plant

Power plant	Generating capacity (kW)	Gross generation (MW h)	Average load (kW)	Peak load (kW)	Load factor (%)	Plant factor (%)	Auxiliary use (MW h)	Aux. use factor (%)	Net generation (MW h)
Coal-fired	500,000	3,784,732	432,047	528,000	81.8	86.41	177,669	4.69	3,607,063
LNG-combined	400,000	1,962,060	223,979	488,000	45.9	55.99	22,833	1.16	1,939,227

Table 5
Utilization of the different generating capacity (% of 8760 h, 2000)

Power plant	*A*	*B*	*C*	*D*
Oil	37	28	16	–
Coal-fired	72	80	74	71
LNG 1	46	41	42	–
LNG 2	60	60	60	–
Nuclear	80	83	84	–

Sources: Electric Utility Handbook, Korea Electric Power Corporation, September 2002.

We use 2000 data because it was the latest year for which complete data were available when this study was initiated. Also, we utilize 80% which is the maximum utilization between coal-fired and LNG2 to the real attainable limits of the utilization degree.

2.3. Generation cost components

The generation cost is the cost of the electric power being connected to the power system and generally includes construction costs, operation costs, and fuel cost. It can be divided into fixed unit costs and variable unit costs according to classification methods.

Fixed unit costs occur regardless of production and they can be divided into capital, depreciation rate, insurance, corporation tax, and other taxes which concern the payback of the initial investment such as construction costs. The variable unit costs are divided into operation costs and fuel costs.

2.3.1. Fixed cost

Fixed unit cost is a fixed recurring cost according to the total investment of the power plants and is composed of capital costs, depreciation costs, prime, inheritance, and gift taxes.

As for capital costs, if the total construction cost is expected to be recovered through the power plant lifespan, it can be calculated by capital recovery factor (CRF), a factor converting the current value into annual equivalence plus the depreciation rate, which is a loss cost of assets without cash payment. Moreover, the CRF can be calculated through the power plant's total lifetime and interest rate (Eq. (1)).

$$CRF = \frac{(1+i)^n \times i}{(1+i)^n - 1}. \quad (1)$$

The rate of depreciation (D) is shown by the straight-line method as mentioned above (Eq. (2)).

$$D = \frac{1}{n}. \quad (2)$$

The capital rate can be represented as the depreciation rate subtracted from the CRF and therefore, can be equated as below (Eq. (3)).

$$COM = CRF - D. \quad (3)$$

When the interest rate is 8.5%, the capital rate and the depreciation rate are as indicated in Table 6.

2.3.2. Operation costs

Generally, the operation cost is calculated on the basis of actual results or budgets. When calculating utilization through construction costs, it uses a sample power plant due to obtain accurate results. For calculating operation cost, power plant a as coal-fired reference power plant and power plant h as LNG generation are selected in Tables 2 and 3. Thus, the utilization is calculated by dividing the price index applied to operation cost results by the asset value of reference power plant (Eq. (4)). Boryeong #1 (500 MW coal-fired power plant) and Seoincheon #3 (400 MW LNG combined cycle power plant) were selected as reference power plants of calculation for operation costs. The data for the fuel cost calculation is shown in Table 7.

$$OM\,(\%) = \frac{OMC}{AVR} \times 100. \quad (4)$$

2.3.3. Fuel cost

There are two main methods of calculating fuel costs. First, the actual measuring method where the fuel usage is measured and then multiplied by the fuel unit cost. Second, the heat consumption curve usage method where the fuel usage is not measured but instead the heat unit cost is multiplied by the average heat unit

Table 6
Capital rate and depreciation rate

Power plant	*CRF*	*D*	*COM*
Coal-fired (lifetimes: 25 years)	0.0977	0.04	0.0577
LNG-combined (lifetimes: 20 years)	0.1057	0.05	0.0557

Table 7
Data for operation cost calculation of the reference power plants

	Reference power plant of coal-fired (Boryeong #1)	Reference power plant of LNG-combined (Seoincheon #3)
OMC ($)	32,023,181	18,758,593
AVR ($/kW)	713	599,840
OM (%)	4.5	3.16
I_n ($)	948,822,542	239,971,223

Sources: Korea Electric Power Corporation [19].

Table 8
Data for fuel cost calculation

	Coal-fired	LNG-combined
HV (kJ/kg)	26,334	54,340
FP ($/kg)	0.03	0.177
f_p ($/kJ)	25,247.2	71,101.8
H_r (kJ/kW h)	9087.2	7273.2

Sources: Korea Electric Power Corporation [19].

cost by using the heat consumption curve. The heat consumption curve method is used in this study (Eq. (5)). The data for the fuel cost calculation is shown in Table 8.

$$FC\ (\$) = H_r \times G \times f_p. \tag{5}$$

2.3.4. Total cost

The electricity generation cost consists of the fixed cost and variable cost. The fixed cost is calculated by fixed rates to the total construction cost, and the operation cost is calculated from the utilization to the total investment. The variable cost, a fuel cost, is calculated by multiplying the generation amount of electricity by rate of heat generation and the heat unit cost. Moreover, the electricity generation is calculated by multiplying the capacity of plant utilities without the consumption rate within power plant by the utilization and annual generating hours.

The electricity generation total cost, when not considering the carbon tax, is calculated by dividing the sum of the fixed cost, operation cost and fuel cost by the generation amount of electricity. If carbon tax is taken into account, carbon tax is added to the generation cost. Carbon tax does not include the consumption rate within the power plant (Eq. (6)).

$$\begin{aligned} GC\ (\$/\text{kWh}) &= (I \times F_x + I \times OM + H_r \times f_p \times G_n \\ &\quad \times H \times C_f \times (1 - A_p) + C_f \times G_n \times H \\ &\quad \times C_t)/(G_n \times H \times C_f \times (1 - A_p)) \\ &= (I \times F_x)/(G_n \times H \times C_f \times (1 - A_p)) \\ &\quad + (I \times OM)/(G_n \times H \times C_f \times (1 - A_p)) \\ &\quad + H_r \times f_p + C_t/(1 - A_p). \end{aligned} \tag{6}$$

2.4. Environmental factors

2.4.1. Pollution reduction facilities

The most serious pollutants concerning power plants using fossil fuels are CO_2 which increases global warming, SO_2 which is the main contributor to acid rain, NO_2, and dust. As for dust, electric dust collectors can eliminate all the dust from power plants, and the removal facility of SO_2 is included in the power plant utilities. Therefore, air pollutants focused on in this study are CO_2 and NO_2.

2.4.2. Carbon tax per fuel

America's Data Resources, Inc. (DRI) and related institutions conducted diverse researches on carbon tax, and DRI concluded that in order to stabilize CO_2 emissions, 100 dollars of tax must be imposed for 1 ton of carbon [17]. DRI analysis demonstrates that if current programs underway are combined with such carbon tax, then CO_2 emissions of the US by 2010 will be at the level of 1990. Carbon tax is highly likely to be international tax rather than domestic, therefore the study conducts sensitivity analysis based on carbon tax standard of $100 per DRI's ton, with the tax varying range from $0 to $200 [17]. In order to calculate the carbon tax ($100 per ton) for fuel, carbon tax per kW h is calculated with respect to fuel components, generated heat, and average heat rate as follows and represented in Table 9:

(1) Carbon emissions per 41,800 kJ

$$LNG:\ 0.756\,\text{kg C/kg L} \times \frac{41,800\,(\text{kJ})}{54,340\,(\text{kJ/kg})} = 0.582\,\text{kg C}/41,800\,\text{kJ}$$

$$\text{Coal-fired}:\ 0.69\,\text{kg C/kg F} \times \frac{41,800\,(\text{kJ})}{26,334\,(\text{kJ/kg})} = 1.095\,\text{kg C}/41,800\,\text{kJ}.$$

(2) Carbon emissions per kW h

$$LNG:\ 0.582\,\text{kg C}/41,800\,\text{kJ} \times 7273.2\,\text{kJ/kW h} = 0.101268\,\text{kg C/kW h}$$

$$\text{Coal-fired}:\ 1.095\,\text{kg C}/41,800\,\text{kJ} \times 9074.78\,\text{kJ/kW h} = 0.238053\,\text{kg C/kW h},.$$

Carbon taxes: $100 per ton-carbon

$$LNG:\ \$100/\text{ton C} \times 0.101268\,\text{kg C/kW h} = ¢1.012168/\text{kW h}$$

$$\text{Coal-fired}:\ \$100/\text{ton C} \times 0.238053\,\text{kg C/kW h} = ¢2.38053/\text{kW h},$$

where kg C, kg L, and kg F stand for a kilogram of carbon, LNG, and anthracite, respectively.

Table 9
Fuel components, generated heat, and average heat rate

Classification	Components (%)					*HV* (kJ/kg)	H_r (kJ/kW h)
	Carbon	Hydrogen	Sulfur	Nitrogen	Others		
LNG	75.6	24.4	–	–	–	54,340	7273.2
Coal-fired	69.0	4.3	0.8	1.4	15.8	26,334	9087.2

Sources: Korea Electric Power Corporation [19].

2.4.3. NO_2 emission

The selective non-catalytic reduction (SNCR) has been operated since 2000. The levelized cost of SNCR based on the Korea electric power corporation is 0.39 cents/kW h for coal-fired and 0.1 cents/kW h for LNG based power plant, respectively [18,22].

3. Methodology and model structure

3.1. System dynamics

SD dates back to the late 1950s and interest in the methodology grew rapidly during the 1960s and early 1970s. The initial focus was on the application of SD to management issues [19], but was soon extended to the analysis of environmental, social and macro-economic problems [20]. Since the mid-1980s, there has been renewed interest in applying SD to business policy and strategy problems. This interest has been facilitated by the availability of new, user friendly and high-level graphical simulation programs (such as Ithink, Stella, and Vensim). Easily accessible books describing the SD approach have also played a key role [21].

The SD methodology is consistent with traditional economic approaches towards modeling dynamics phenomena, but uses different conventions and terminology. The feedback structure of a system is described using causal loops. These are either balancing (capturing negative feedback) or reinforcing (capturing positive feedback) loop. A balancing loop exhibits goal seeking behavior; in which the system seeks to return to an equilibrium situation (conforming to the economic notion of a stable equilibrium) after a disturbance. In a reinforcing loop an initial disturbance leads to further change, suggesting the presence of an unstable equilibrium.

This structure is formalized via a simulation model consisting of two components: the stock and flow network, and the information network. Stocks capture the inertia of a system. They accumulate or deplete gradually and regulate by their in- and out-flows. Stocks can be 'hard' (tangible) concepts, such as physical capital, or 'soft' concepts, such as perceptions. The flow rates are determined by the information network and depend on the level of the various stocks in the system. These rates can be interpreted as the output of policies, or as decision-making processes.

Mathematically, of course, such relationships can be modeled using systems of ordinary differential or difference equations, as in conventional dynamic models. However, the rapid advances in software technology make it readily possible to construct such SD models, and to test out a variety of alternative specifications.

3.2. Structure of model

We have designed the SD simulation model for analyzing of coal-fired and LNG combined power plants. The components of the generation cost and related factors for simulation experiments are indicated in Fig. 2.

Generation unit cost is calculated by dividing the generation cost by generation production. The generation cost consists of fixed costs, fuel costs, NO_2 costs and carbon tax cost.

(1) The fixed cost is calculated by interest rate and initial investment costs.
(2) Fuel cost translates into a geometric series. Thus, *g* (geometric series change rate) and *g_prime* (interest rate of geometric series) are necessary. This is calculated by interest rate and plant utilization.

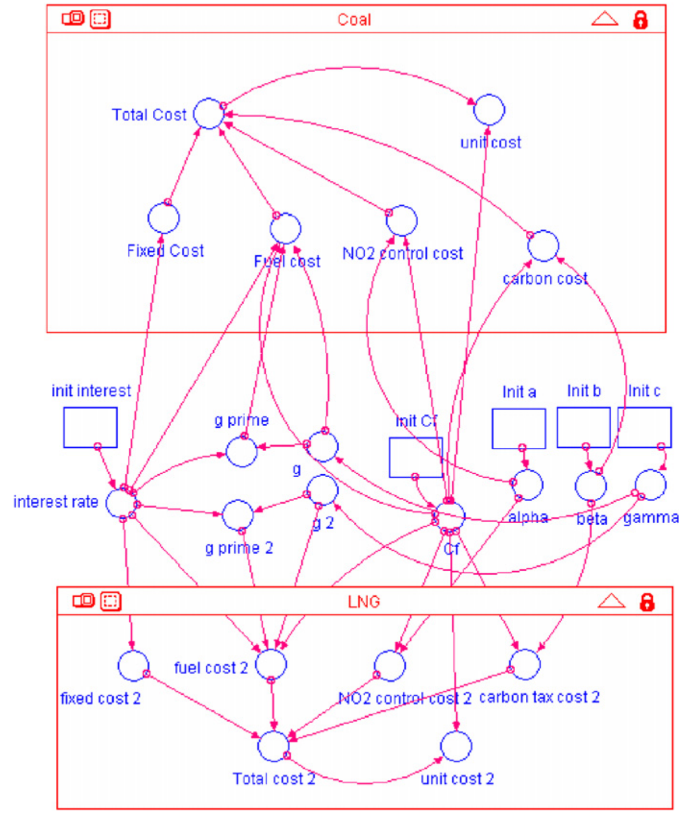

Fig. 2. Calculation model of generation cost using system dynamics.

(3) The NO_2 control cost is calculated by the rate of NO_2 control criteria costs and plant utilization.
(4) Carbon taxes are calculated by the rate of plant utilization to the carbon tax standard cost.

Initial values and variable of the generation unit cost calculation modeling are as follows:

init a = 1 (rate to NO_2 control criteria cost)
init b = 1.3 (the minimum carbon tax whose LNG generation cost dominates that of the coal-fired, unit \$100)
init c = 1 (standard rate to fuel price fluctuation ratio)
Init C_f = 0.5 (plant utilization)
init discount = 0.085 (interest rate)
g = 0.01 × *gamma* (geometric series change rate to 1% change of fuel price in coal-fired generation)
gamma = *init_c*
g_2 = 0.03 × *gamma* (geometric series change rate to 3% change of fuel price in LNG generation)
g_prime = (1+*discount_rate*)/(1+g)−1 (interest rate of geometric gradient series factor of coal-fired thermo electricity)
g_prime_2 = (1+*discount_rate*)/(1+g_2)−1 (interest rate of geometric gradient series factor of the LNG generation)

3.3. Formulation of model

Fixed costs, fuel costs, NO_2 control costs, carbon tax costs, total costs, and unit cost within the modeling can be calculated with the following modeling formulas.

Fixed rate is the sum of CRF and the fixed rate of corporation tax (Eq. (7)).

$$Fixed\_Cost = In \times (CRF + T' + OM). \quad (7)$$

Annual generation must be calculated excluding the consumption within power plants; therefore the generation is calculated as follows (Eq. (8)).

$$G = H \times G_n \times (1 - A_p) \times C_f. \tag{8}$$

Fuel cost can be calculated as follows (Eq. (9)).

$$Fuel\_Cost = f_P/(1+g) \times GGSF \times CRF \times H \times G. \tag{9}$$

NO_2 control costs must be calculated as the actual generation not including the consumption rate within power plants (Eq. (10)).

$$NO_2\_Control\_Cost = NO_2\_Cost \times G/(1 - A_P). \tag{10}$$

Carbon tax cost must be calculated by the actual generation (less consumption rate within power plants) as below (Eq. (11)).

$$Carbon\_Tax\_Cost = Carbon\_Tax \times G/(1 - A_P). \tag{11}$$

Total cost consists of fixed costs, fuel costs, NO_2 control costs, and carbon taxes. The total cost for coal-fired and LNG is calculated as follows (Eq. (12)).

$$Total\_Cost = Carbon\_Tax\_Cost + Fixed\_Cost + Fuel\_Cost + NO_2\_Control\_Cost. \tag{12}$$

Generation cost is calculated through dividing the generation cost by the generation amount of electricity (Eq. (13)).

$$Generation\_Cost = 1000 \times Total\_Cost/(G_n \times C_f \times H \times (1 - A_P)). \tag{13}$$

4. Results analysis

The power plant utilization shows severe fluctuations according to power demand, and economical efficiency of power plants differ according to the utilization. Therefore, power plants must be selected with prudence according to the scenario of carbon taxes and power plant utilizations. Moreover, it is necessary to find break-even points, where economical efficiency among power plants shifts due to fluctuating carbon taxes during the power plant selection processes.

In this study, the economic efficiency of power plants is evaluated through the sensitivity analysis of generation cost for the continuously changing intervals of each parameter according to fluctuations of plant utilization, carbon taxes, and fuel prices.

4.1. Analysis for changing of the plant utilization

Continuously changing intervals of the plant utilization are from 10% to 100%, and the results are presented below:

(1) *Generation costs comparison with the continuous changing power plant utilization*: When no carbon tax is charged (as power plant utilization changes 0% to the real attainable utilization limits) the compared results of coal-fired and LNG generation costs are as shown in Fig. 3. Since the plant utilization slightly exceeds 36% approximately, coal-fired generation would be more economic.

As a result of increasing the carbon tax from $0, we can see that the LNG generation costs are less than the coal-fired generation costs in the given real attainable utilization limits. If carbon tax exceeds $136/ton C, the LNG generation costs become less than the coal-fired generation costs in whole plant utilization. The comparison of coal-fired and LNG generation costs, when charged at $136/ton C for carbon tax, is shown in Table 10.

(2) *Sensitivity analysis with carbon tax and utilization changes*: We perform the sensitivity analysis according to the carbon tax and plant utilization changes. The changing intervals of the carbon tax are from $0 to $200/ton C. As shown in Figs. 4 and 5, carbon tax changes much more at coal-fired power plants than at LNG-combined.

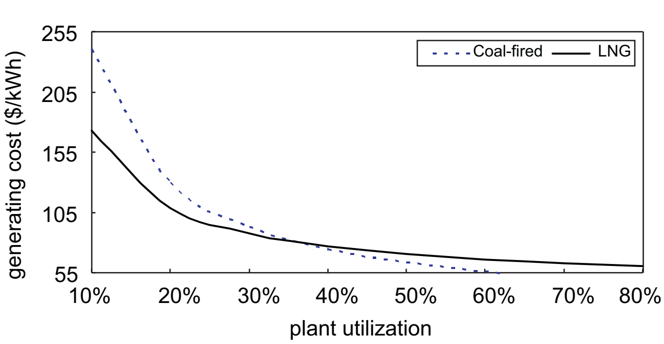

Fig. 3. The comparison between generation costs of coal-fired and LNG generation (no carbon tax levied).

Table 10
Generation unit cost according the utilization (when carbon tax is charged at $136)

GC ($/kW h)			*GC* ($/kW h)		
Utilization (%)	Coal-fired	LNG	Utilization (%)	Coal-fired	LNG
10	267.54	183.83	50	90.79	81.53
20	157.07	119.89	60	83.43	77.26
30	120.25	98.58	70	78.17	74.22
40	101.84	87.92	80	74.22	71.93

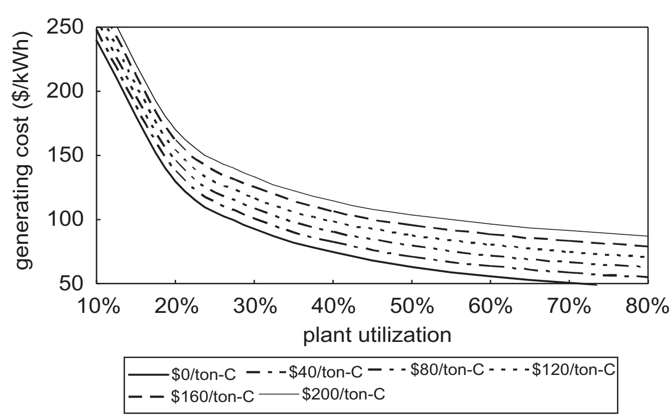

Fig. 4. Generation cost of coal-fired according to the carbon tax and utilization changes.

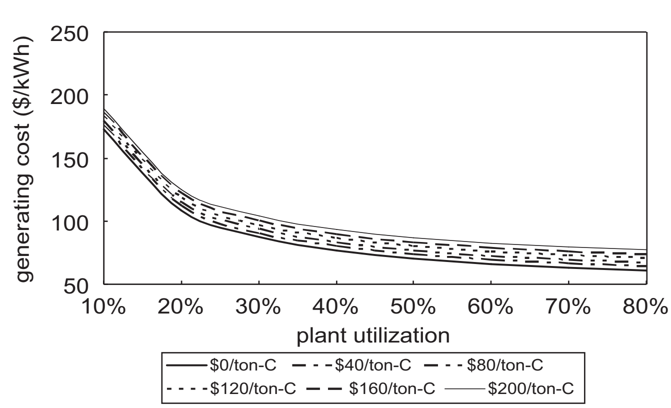

Fig. 5. Generation cost of LNG-combined according to the carbon tax and utilization changes.

Table 11
Equilibrium point of plant utilization according to the carbon tax changes

	Equilibrium point of utilization by each carbon tax ($/ton C)						
	0	21.4	42.9	64.3	85.7	107	129
Power plant utilization (%)	35.7	40.2	45.4	52.5	61.8	75.1	95.6

Table 12
The comparison of the generation costs between coal-fired and LNG combined according to the interest rate changes

GC ($/kW h)			*GC* ($/kW h)			*GC* ($/kW h)		
i (%)	Coal-fired	LNG	*i* (%)	Coal-fired	LNG	*i* (%)	Coal-fired	LNG
4	63.41	67.30	10	70.66	69.38	16	79.13	72.63
5	64.50	67.55	11	72.00	69.85	17	80.62	73.26
6	65.54	67.85	12	73.38	70.34	18	82.12	73.92
7	66.83	68.17	13	74.78	70.87	19	83.64	74.59
8	68.07	68.54	14	76.21	71.43	20	85.16	75.29
9	69.34	68.94	15	77.66	72.02			

When carbon tax is charged at more than $136/ton C, the generation cost of LNG is superior to that of coal-fired; therefore, an analysis is required when carbon tax is charged at less than $136/ton C. At this moment, the range of carbon tax is fixed from $0 to $135/ton C. The equilibrium point is a point when the differences of coal-fired and LNG generation costs become equal. The results of such equilibrium points between coal-fired and LNG-combined plant utilizations by each carbon tax are given in Table 11.

4.2. Analysis for changing of the interest rate

Continuously changing ranges of the interest rate are from 4% to 20%. The results are presented below:

(1) *Generation cost comparison according to the interest rate changes*: When given the imposed carbon tax of $136/ton C and 100% of plant utilization. We can compare the generation cost differences between coal-fired and LNG-combined within the changing rates of interest from 4% to 20%. The results are demonstrated in Table 12.
(2) *Sensitivity analysis with carbon tax and interest rate changes*: In order to compare the generation costs with the interest rate and the carbon tax changes, we perform the sensitivity analysis in the range of interest rates from 4% to 20% and with a carbon tax from $0/ton C to $200/ton C. As shown in Figs. 6 and 7, carbon tax is more sensitive at coal-fired power plants than LNG-combined plant.
(3) *Equilibrium analysis*: Table 13 shows the results that analyze the equilibrium point of the generation costs between coal-fired and LNG-combined power plants according to the interest rate and carbon tax changes. When carbon tax is charged at $90/ton C, LNG-combined is at more of an advantage and has a 6% or more interest rates.

4.3. Analysis for changing of the carbon tax

The continuously changing ranges of the carbon tax are from $0/ton C to $200/ton C, and the results are presented below:

(1) *Generation costs comparison according to the carbon tax changes*: When carbon tax is not imposed, coal-fired is more favorable. However, when imposed at more than $58.3/ton C, there exists a break-even point which is more favorable for LNG as shown in Table 14. Thus, finding break-even points where the economical efficiency of power plants shifts with changing carbon taxes is required during the power plant selection procedure.
(2) *Sensitivity analysis of generation costs according to the carbon tax changes and fuel price increasing*: Fuel price increases caused a change in coal-fired plant from −1% to 5%, and in LNG plant from −3% to 15% during the continuously changing intervals of carbon tax. Figs. 8 and 9 show the results of the sensitivity analysis. The range of generation cost fluctuations appeared to be more sensitive in coal-fired than in LNG according to carbon tax changes.

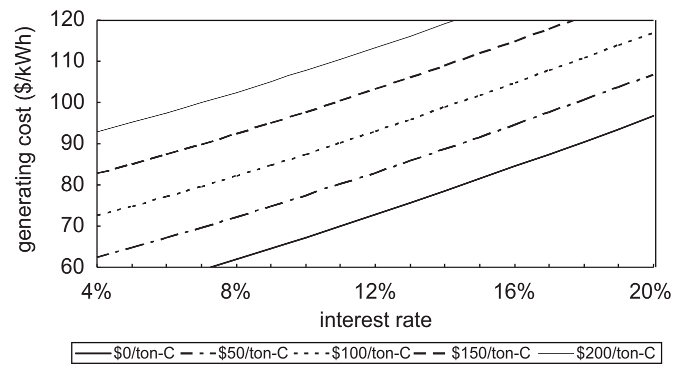

Fig. 6. Generation cost of coal-fired according to the interest rate and carbon tax changes.

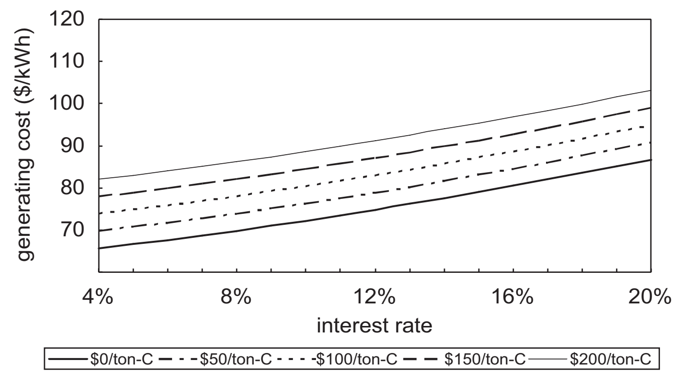

Fig. 7. Generation cost of LNG-combined according to the interest rate and carbon tax changes.

4.4. Analysis on the fuel cost changes

(1) *Generation cost according to the fuel price increasing*: When given the imposed carbon tax of $136/ton C and 50% of plant utilization, the generation costs are compared with an increase of fuel price. As seen in Table 15, if the fuel increases

Table 13
Equilibrium point according to the carbon tax and interest rate

$i(\%)$	Difference between generation unit cost by coal-fired (A) and by LPG-combined (B) (equilibrium point = A–B) ($/kW h)					
	C_t ($/ton C)					
	22.5	45	67.5	90.0	112.5	135.0
5	−9.35	−6.63	−3.91	−1.19	1.53	4.25
6	−7.99	−5.27	−2.55	0.17	2.89	5.61
7	−6.59	−3.87	−1.15	1.57	4.29	7.00
8	−5.17	−2.45	0.27	2.99	5.71	8.43
9	−3.72	−1.00	1.72	4.43	7.15	9.87
10	−2.26	0.46	3.18	5.90	8.62	11.34
11	−0.78	1.94	4.66	7.38	10.10	12.82
12	0.71	3.43	6.15	8.87	11.59	14.30
13	2.20	4.92	7.64	10.36	13.08	15.80
14	3.70	6.42	9.14	11.86	14.58	17.30
15	5.20	7.92	10.64	13.36	16.08	18.80
16	6.70	9.42	12.14	14.86	17.58	20.30
17	8.20	10.91	13.63	16.35	19.07	21.79
18	9.69	12.41	15.13	17.84	20.56	23.28
19	11.17	13.89	16.61	19.33	22.05	24.77
20	12.65	15.37	18.09	20.81	23.53	26.25

Table 14
The comparison between coal-fired and LNG-combined generation costs according to the carbon tax changes

GC ($/kW h)			GC ($/kW h)			GC ($/kW h)		
C_t ($/ton C)	Coal-fired	LNG	C_t ($/ton C)	Coal-fired	LNG	C_t ($/ton C)	Coal-fired	LNG
0	63.23	70.40	70	77.42	76.13	140	91.61	81.85
10	65.26	71.22	80	79.44	76.94	150	93.63	82.67
20	67.28	72.03	90	81.47	77.76	160	95.66	83.49
30	69.31	72.85	100	83.50	78.58	170	97.69	84.31
40	71.34	73.67	110	85.52	79.40	180	99.71	85.13
50	73.36	74.49	120	87.55	80.22	190	101.74	85.94
60	75.39	75.31	130	89.58	81.03	200	103.77	86.76

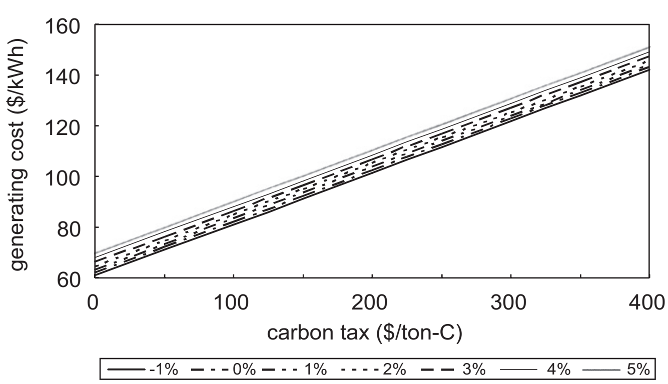

Fig. 8. Generation cost of coal-fired according to the fuel cost and carbon tax changes.

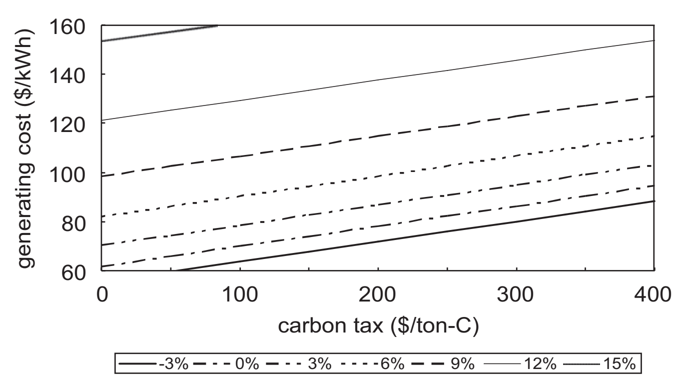

Fig. 9. Generation cost of LNG-combined according to the fuel cost and carbon tax changes.

by more than 1.8% for coal-fired and 5.4% for LNG-combined, break-even points for increase rates of fuel price occur, which are unfavorable for LNG-combined.

(2) *Sensitivity analysis of the generation cost according to fuel price fluctuation rates*: The results of analyzing the generation cost by changing carbon taxes by $50/ton C between the ranges of $0 to $200 are shown in the case of coal-fired in Fig. 10 and LNG generation in Fig. 11. The range of generation cost fluctuations according to fuel costs turns out to be more sensitive in the LNG-combined than in the coal-fired.

4.5. Carbon tax level according to the interest rate changes

Fig. 12 shows the results for the carbon tax level with LNG-combined showing more economical than coal-fired according to the interest rate changes.

Table 15
The comparison between coal-fired and LNG-combined according to the increasing rate of fuel cost

g (%)		GC ($/kW h)		g (%)		GC ($/kW h)	
Coal-fired	LNG	Coal-fired	LNG	Coal-fired	LNG	Coal-fired	LNG
−1	−3	88.51	66.63	2.5	7.5	92.93	100.75
−0.5	−1.5	89.03	69.56	3	9	93.74	109.55
0	0	89.58	72.96	3.5	10.5	94.60	119.95
0.5	1.5	90.17	76.91	4	12	95.53	132.25
1	3	90.79	81.53	4.5	13.5	96.51	146.82
1.5	4.5	91.46	86.93	5	15	97.57	164.10
2	6	92.17	93.28				

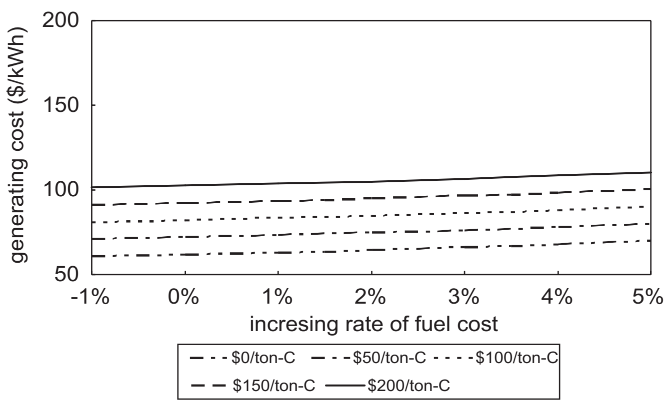

Fig. 10. Generation cost of coal-fired according to the fuel cost and carbon tax changes.

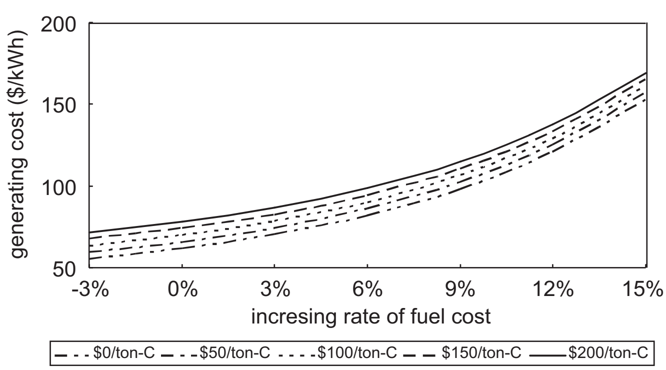

Fig. 11. Generation cost of LNG-combined according to the fuel cost and carbon tax changes.

5. Conclusion and future studies

In this study, the economic efficiency of coal-fired and LNG generations were analyzed through a LGCM. Furthermore, similar power plants and reference power plants were selected through criteria to minimize inaccuracies in the data. In order to evaluate power plants under environmental regulations, the generation costs of coal-fired and LNG were examined through a sensitivity analysis by computer simulation through economic comparison according to an increase in pollution reduction utility costs, carbon taxes, and fuel costs.

The purpose of this study was to provide reference criteria on economic efficiency and environmental impacts to be used for key

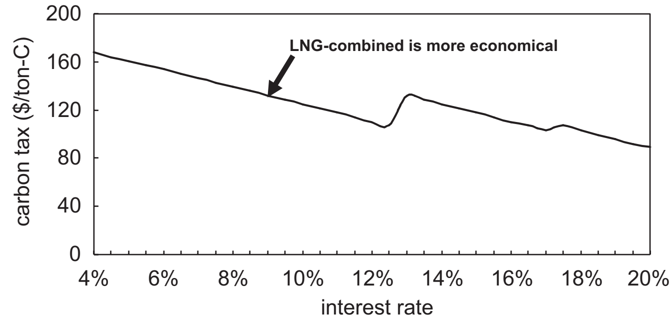

Fig. 12. Carbon tax level which LNG-combined is absolutely economical according to the interest rate changes.

decision makers in the power plant/environmental divisions of a government. Moreover, it helps to decide the right moment to introduce CO_2 reduction technology and carbon tax systems, in the interest of conflicting costs.

In this study, due to data limitations, only an economic analysis of the existing facilities was performed; however, long-term economic comparison of power plants including new ones is required. Moreover, we focused on air pollution by the power plants as the only environmental pollutant. However, further studies on the economic analysis of integral power plants considering the overall economic effects, including other types of environmental pollutant are needed.

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