A STUDY ON FEASIBILITY EVALUATION OF A GAS COGENERATION SYSTEM CONSIDERING DEMAND FLUCTUATION RISK

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***ABSTRACT*:** Natural gas is highly demanded in various industries due to low emission of CO2 compared with the other fossil fuels. Natural gas cogeneration system which provides inhabitants living in an area with electricity and heat energy has high energy conversion efficiency. One of the challenges of the natural gas cogeneration system under the present situation where some counter measures against environmental issue are urgently required is its promotion. The natural gas cogeneration system is regarded as a good system to cope with environmental issues, however, the profitability of the system may prevent the promotion. In this study, a project scheme for the natural gas cogeneration system is developed, and an economical analysis method developed based on the scheme is also proposed. The stake holders addressed in the present study are project company, financial institution, gas supply company, local authority, and inhabitants of the district. The project company operates the cogeneration system without seeking a profit. The financial institution supplies funds to the project company with an interest rate. The gas supply company provides the project company with natural gas, and invests in the project. It is assumed that the local authority guarantees the debt of the project company, and that the guarantee of the debt by the local authority enables lower interest rate from the banking institution. Among the stake holders, a cooperative behavior is assumed. Accordingly, the behavior by the stake holders is not to maximize their own benefits by the project but to maximize the total benefit subject to the constraint where no stake holder has debt by the project. Distributions on costs and benefits among the stake holders were clarified by an analysis carried out by assuming that the natural gas cogeneration system was introduced to downtown Sapporo. All of the stakeholders received positive net benefit form the project.

KEYWORDS: gas cogeneration system, economical analysis, cost distribution

1. INTRODUCTION

Since natural gas has lower CO2 emission compared with the other fossil fuels, its demand has been increased. A natural gas cogeneration system, which is to be referred to as a gas cogeneration system, which provides both heat energy and electricity has high conversion efficiency. Diffusion of the gas cogeneration system has not been progressed due to its profitability. The diffusion of the gas cogeneration system is a problem under the situation where some counter measures against deterioration of environment are required. However, the gas cogeneration system is a good system to cope with the environmental issues, unless the profitability of the system is not solved it may be difficult for the gas cogeneration system to get in operation.

A project scheme for the gas cogeneration system is proposed and feasibility of gas cogeneration system is examined in terms of economical viewpoint. The stakeholders appeared in the scheme are project company, gas supply company, local authority, inhabitants of the district where heat and electricity are provided, and financial institution. The distributions of the cost and the profit among the stakeholders, which make it possible to get the gas cogeneration system in operation, will be examined. We do not assume the benefit or profit maximization behavior which is usually assumed in an economical analysis as a stakeholder's behavior. The behavior assumed in the analysis is a maximization of total benefit subject to positive benefit brought to each stakeholder.

2. COSTS IN THE PRJECT

2.1 Assumptions

We assume a project which provides heat and cold energies, and electricity by the gas cogeneration system to the inhabitants of the district. Not only electricity generated by a gas engine but also waste heat generated in the process of the electricity generation are provided to the inhabitants of the district. A road heating by the waste heat is also introduced to the district. If the electricity or heat demands exceed the gas engine capacity, we assumed that the project company purchases electricity from a power company or generate heat by a boiler installed in the system respectively, and provide them to the habitants in the district.

2.2 Trade-off in the gas engine power and the excess demand cost

The set of hosts to which heat and electricity are provided is:

$$P = \{f, h, c, o, h, rh\}$$

where *f* is household, *h* is hotel, *c* is commercial sector, *o* is office, *h* is hospital, and *rh* is road heating. Let ep_p^m denote the electricity which host $p \in P$ demands in the month *m* (=1,…, 12）. Total electricity demanded in the district ep^m is then:

$$ep^m = \sum_{p \in P} ep_p^m \ . \tag{1}$$

Let $ep_{\max}$ denote the monthly maximum output of electricity by the cogeneration system. As explained in the later section, we assumed that the $ep_{\max}$ follows Weibull distribution with a mean $EP_{\max}$ and a variance. The construction cost and its maintenance cost can be given respectively by:

$$CC = CC(EP_{\max}, p_b, s_{rh}), \tag{2}$$

$$MC = MC(EP_{\max}, p_b, s_{rh}, emp), \tag{3}$$

where p_b is price of the boiler, s_{rh} is the area for the road heating, and emp is the employment cost in the project. The electricity demanded in the district can be different to each month. As explained earlier, if the demand exceed the capacity $ep_{\max}$, the project company has to purchase the electricity from the power company and provide it to the district. In this case, the difference between the prices by the project company and the power company will be debt of the project company since the price by the project company is less than that of the power company which is implicitly assumed in the present study. We assumed that ep^m and $ep_{\max}$ follow the independent and identically distributed Weibull distribution and their means are given by EP^m and $EP_{\max}$, respectively. This assumption may be realistic since the electricity demand is determined by the weather, temperature and so on, which have uncertainty, and the maximum electricity has to follow the demand which is not given in advance. The expected dept observed in the *m*th month $L^m = L^m(EP_{\max}, EP_m)$ is then:

$$\begin{aligned}
L^m &= \delta p \cdot \Pr\left(ep^m \geq ep_{\max}\right) \\
&= \delta p \int_{-\infty}^{-g} (s+g) \cdot \frac{\exp(\theta \cdot s)}{(1+\exp(\theta \cdot s))^2} ds \\
&= \delta p \int_{-\infty}^{-g} \left(s \cdot \frac{\exp(\theta \cdot s)}{(1+\exp(\theta \cdot s))^2} + g \frac{\exp(\theta \cdot s)}{(1+\exp(\theta \cdot s))^2} \right) ds \\
&= \delta p \left(-g \frac{\exp(-g)}{1+\exp(-g)} + (g-1) \cdot \ln(1+\exp(-g)) \right)
\end{aligned} \tag{4}$$

where $g \equiv EP_{\max} - EP_m$; θ is a dispersion parameter for Weibull distribution which is assumed to one in the present study; δp is the unit price difference per unit electricity; and Pr. is the probability. The annual expected debt for the project company due to the electricity capacity $L = L(EP_{\max}, EP_m)$ is:

$$L = \sum_{m=1}^{12} L^m \ . \tag{5}$$

The expected annual debt for the project company is dependent on $EP_{\max}$ and $EP_m \left(m = 1,..,12\right)$.

2.3 Relationship between demands for heat and electricity and gas supply

In this section, we will consider the relationship between demands for heat and electricity and gas supply by using Fig.1. Let dEP and $dCAL_c$ denote the electricity supply and the heat energy supply which are generated by unit gas supply by using the gas engine. The maximal amount of gas supply per a month can be formulated as $G_{\max} = G_{\max}\left(EP_{\max}\right)$. The maximal amount of heat per a month by the cogeneration system can be formulated as $CAL_{\max} = CAL_{\max}\left(EP_{\max}\right)$.Then, the following two relationships hold.

$$dEP = EP_{\max} / G_{\max} \tag{6}$$

$$dCAL_c = CAL_{\max} / G_{\max} \tag{7}$$

On the other hand, let $dCAL_b$ denote the heat supply generated by unit gas supply by using the boiler. Then, the total demands for electricity and heat in the district in the *m*th month are respectively given by ep^m and $cal^m = \sum_{p \in P} cal_p^m$, where cal_p^m is the heat demand by host $p \in P$ including cold energy which is converted into heat energy. We assumed further that cal^m follows the independent and identically distributed Weibull distribution with mean CAL^m based on the idea applied to the electricity demand. The heat demand for the road heating in the *m*th month can be formulated as $cal_{rh}^m = cal_{rh}^m\left(s_{rh}\right)$. The expected gas supply for providing ep^m and cal^m is then:

$$\begin{aligned} &G^m\left(EP_{\max} \mid EP^m, CAL^m\right) \\ &= E\left[\min\left(ep^m, ep_{\max}\right)\right] / dEP \\ &+ \max\left(0, \left(\begin{array}{l} CAL^m - \\ E\left[\min\left(ep^m, ep_{\max}\right)\right] / dEP \end{array}\right) \cdot dCAL_c\right) \Big/ dCAL_b \end{aligned} \tag{8}$$

where

$$\begin{aligned} &E\left[\min\left(ep^m, ep_{\max}\right)\right] \\ &= -\frac{1}{\theta} \ln\left(\exp\left(-\theta \cdot EP^m\right) + \exp\left(-\theta \cdot EP_{\max}\right)\right) \end{aligned} . \tag{9}$$

The first term of the right hand side of Eq.(8) expresses the expected gas supply for generating the electricity of $E\left[\min\left(ep^m, ep_{\max}\right)\right]$ which can be generated by the gas engine. The second term expresses the expected gas supply to the boiler which is required for generating the excess heat demand which can not be provided by the gas engine. Since G^m is regarded as a function of $EP_{\max}$ for given EP_m and CAL^m, the expected annual gas supply to the cogeneration system is:

$$\begin{aligned} G &= G\left(EP_{\max} \mid EP^m, CAL^m\right) \\ &= \sum_m G^m\left(EP_{\max} \mid EP^m, CAL^m\right). \end{aligned} \tag{10}$$

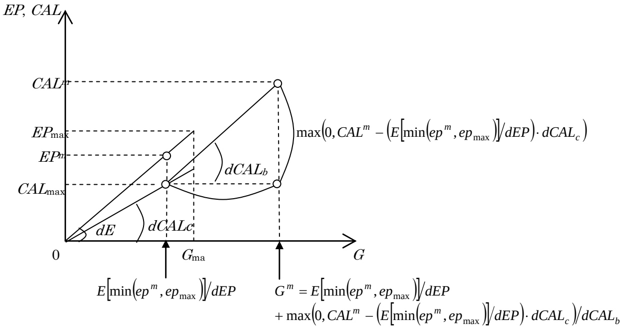

Figure 1. Relationship between heat and electricity demands and gas supply

3. CASH FLOWS AND BENEFIT FLOWS

3.1 behavior of the stakeholders

Fig.2 illustrates cash flows and benefit flows in the project scheme. The role of each stakeholder in the project scheme will be explained in the next sections.

3.1.1 The project company

The project company will collect construction cost as investments (I) from the gas supply company and loan from the financial institution (D). The gas cogeneration system will be built by using the construction cost $CC = I + D$. The project company will purchase gas form the gas supply company and supply heat and electricity to the district by the gas cogeneration system. The project company supply heat for the road heating as well. We assumed that the project company does not pursue the profit of the project.

3.1.2 The local authority

The local authority will receive the benefit from reduction of snow removal cost. In addition that, since the gas cogeneration system is a low environment load system, the local authority will subsidize the project company as the results of these two effects. On the other hand, we assumed that the local authority will guarantees the debt of the project company which is loaned from the financial institution. As a result, the project company can pay back the debt with a risk-free interest rate.

3.1.3 The gas supply company

The gas supply company will invest a part of the construction cost. The investments will be pay back by the principal and interest equal repayment through an operating period. The gas company will receive dividend in the last year of the operating period. On the other hand, the gas supply company will supply gas to the project company and receive profit from it. The benefits which the gas supply company receives are the dividend and the profit from the gas supply.

3.1.4 The inhabitants of the district

However, the inhabitants of the district does not have to pay energy bill which the habitants used to pay, the habitants has to pay for usage fee to the project company. If the usage fee is less than the energy bill, the difference between amounts of money can be regarded as benefit for the inhabitants. In addition, the inhabitants of the district will receive the benefits of traveling time reduction, traveling cost reduction, traffic accident reduction by the road heating in winter. However, all of these benefits do not come down to the inhabitants, we assumed that the benefits come down to the inhabitants for the sake of the simplicity.

3.1.5 The financial institution

The financial institution will loan the project company. As explained earlier, the loan will be pay back by the principal and interest equal repayment with the risk-free interest rate.

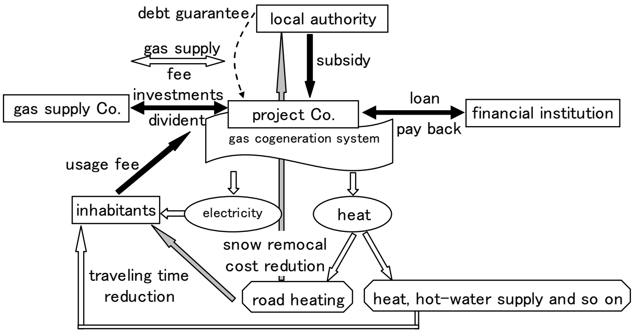

Figure2. The project scheme

3.2 Payment method of the debts

Fig. 3 illustrates the payment method of the debt for the gas cogeneration system. As explained earlier, the gas cogeneration system is constructed by money collected from the gas supply company and the financial institution. The project company will operate the gas cogeneration system and pay back the debt during the operating period (n years). We will formulate benefit flows and cash flows of the gas cogeneration project by five periods, i.e. the periods of A, B, C, D and E (Fig.3). During the A period, the project company does not pay back the debts. During the B period, the project company pays back the principle of the loan. During the C period, the project company pays back the principles of the loan and investment. During the D period, the project company pays back the principle of the investment only since pay back for the loan has been finished in this period. The E period is the last year of the operating period. Debt or profit can be observed in each year during the operating period. If the debts incurred, we assumed that the project company borrow money from the financial institution again which is to be pay back with the risk-free interest rate. Adversely, if profit is made, we assumed that the project company turns over it with the risk-free interest rate such as a national bond.

set up	operating period										
year 0	1	$\cdots$	n_0	$\cdots$	n_1	$\cdots$	n_2	$\cdots$	n_3	$\cdots$	n
			pay back of the loan								
					Pay back of the investments						dividend
period	A		B		C			D		A	E

Figure3. Payment method of the debts

3.3 Formulations of the benefit flows and the cash flows

In this section, we will formulate utility function for each stakeholder based on the benefit flows and the cash flows illustrated in Fig.2. Henceforth, we will call the benefit flows and the cash flows as benefit flows with no distinction since they are measured by currency value. The benefit flow for the project company in the *k*th year is:

$$f_k = x_k + y_k - H - MC - C_D^k - C_I^k - L(EP_{\max}) - i_k \tag{11}$$

where $f_k = 0$.

$$\Rightarrow i_k = x_k + y_k - H - MC - C_D^k - C_I^k - L(EP_{\max}) \tag{12}$$

x_k: the amount of subsidy from the local authority in the *k*th year.

y_k: total amount of usage fee from the inhabitants of the district in the *k*th year.

H: cost for gas supplied by the gas supply company $(H = G \cdot p_g)$ where p_g is a unit gas price.

MC: maintenance and operating cost for the gas cogeneration project including employment cost.

C_D^k: the amount of repaid during the periods of A and B for the loan D in the *k*th year ($n_0 \le k \le n_2$) which is calculated by assuming the present value of the loan of $D(1+r)^{n_0}$, the pay back period of $n_2 - n_0 + 1$, and the principal and interest equal repayment.

C_I^k: the amount of repaid during the periods of B and C for the investment I in the *k*th year ($n_1 \le k \le n_3$) which is calculated by assuming the present value of the investment of $I(1+r)^{n_1}$, the pay back period of $n_3 - n_1 + 1$, and the principal and interest equal repayment.

i_k: profit (or debt) in the *k*th year.

Note that, f_k is always zero since we assumed that the project company does not pursue the profit from the gas cogeneration project. This constraint means that the benefit of the project company is 0 throughout the operating period. So is the benefit of the financial institution because the loan is surely paid back. C_D^k and C_I^k are respectively given by:

$$C_D^k = \begin{cases} \dfrac{D(1+r)^{n_0} \cdot r(1+r)^{n_2 - n_0 + 1}}{(1+r)^{n_2 - n_0 + 1} - 1} & \text{if } n_0 \le k \le n_2 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$C_I^k = \begin{cases} \dfrac{I(1+r)^{n_1} r(1+r)^{n_3 - n_1 + 1}}{(1+r)^{n_3 - n_1 + 1} - 1} & \text{if } n_1 \le k \le n_3 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Since the benefits of the project company and the financial institution are zero, we have to consider the benefits of the local authority, the gas supply company and the inhabitants of the district. The benefits of these three stakeholders in the *k*th year are respectively given by:

$$u_1^k = B_s - x_k + \min(CD^k, 0) \tag{15}$$

$$u_2^k = H \cdot pr + C_I^k + \max(CD^k, 0) \tag{16}$$

$$u_3^k = B_a + B_t + B_h \tag{17}$$

where $B_s = B_s\left(s_{rh}\right)$ is the snow removal cost reduction benefit; H is the income by the gas supply; pr is the profit rate of the gas supply; $B_a = B_a\left(s_{rh}\right)$ is the traffic accident reduction benefit; $B_t = B_t\left(s_{rh}\right)$ is the traveling time reduction benefit; $B_h = EB - y_k$ is the energy bill reduction benefit; *EB* is energy bill which the inhabitants used to pay when the gas cogeneration system has not been introduced; and where CD^k is the dividend to the gas supply company if $CD^k > 0$, or the debt to the local authority if $CD^k < 0$, and is given as:

$$CD^k = \begin{cases} R^n & \text{if } k = n \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

where

$$R^k = \sum_{l=1}^{k} i_l (1+r)^{k-l} \ . \tag{19}$$

Eq.(19) is the accumulated profit or the accumulated debt till the *k*th year in which each year's profit or debt is transformed into the present value by using the risk-free interest.

3.4 The objective function of the stakeholders

The present value of the benefits of the local authority, the gas supply company and the inhabitants of the district are given respectively by:

$$U_1 = \sum_{k=1}^{n} \frac{u_1^k}{(1+r)^k} \ , \tag{20}$$

$$U_2 = \sum_{k=1}^{n} \frac{u_2^k}{(1+r)^k} - I \tag{21}$$

$$U_3 = \sum_{k=1}^{n} \frac{u_3^k}{(1+r)^k} \ . \tag{22}$$

Then, the objective function of the stakeholders can be formulated as:

$$\max Z = \sum_{i\in\{1,2,3\}} U_i - \sum_{i\in\{1,2,3\}} \delta(U_i)\, pnl - \delta(R^n)\, pnl \tag{23}$$

w.r.t.

$$x_k, y_k, I, D, EP_{\max,} s_{rh}$$

s.t.

$$f_k = 0 \ \ \forall k \tag{24}$$

$$D - \sum_{k'=n_0}^{n_2} \frac{C_D^{k'}}{(1+r)^{k'}} = 0 \tag{25}$$

$$I - \sum_{k'=n_1}^{n_3} \frac{C_I^{k'}}{(1+r)^{k'}} = 0 \tag{26}$$

$$CC = I + D \tag{27}$$

$$y_k \le EB \tag{28}$$

$\delta(x)$: variable which is equal to one if x is less than 0, and zero otherwise.

pnl : penalty value.

The control variables in the objective function are the amount of subsidy from the local authority, the total amount of usage fee, the investment from the gas supply company, the loan from the financial institution, the capacity of the gas engine, and the area for the road heating. As explained earlier, Eq.(24) means that the project company does not pursue the profit from the gas cogeneration project. Eq.(25) and Eq.(26) expresses the pay back constraints for the principles of the loan and the investments.

4. A CASE STUDY IN THE DOWNTOWN SAPPORO

We examined the feasibility of the gas cogeneration project by assuming that the project is introduced to a town block of the downtown Sapporo, Japan. We assumed that the construction cost excluding the costs for the road heating, the gas engine and the boiler is 1.36 billion JPY considering the area of the town block. The characteristics of the hosts of the gas cogeneration project are determined considering the actual situation of the town block which are summarized in Table 1.

Table 1. The characteristics of the hosts

hosts	total floor space / the number of households
hotel	18,000 m^2
commercial	18,000 m^2
office	18,000 m^2
hospital	4,250 m^2
household	235 households

Monthly demand for electricity and heat in each host which is provided by a gas supply company in Sapporo are used as data. They are summarized in the following figures. We assumed that the annual energy bill, before the introduction of the gas cogeneration project, for the household is 200 thousand JPY per year ($\mathrm{JPY}/year$). We assumed that the annual energy bill for other hosts is 3.0 thousand JPY per unit floor space per year ($\mathrm{JPY}/m^2/year$). We assumed that the operating period and the pay back period for the principal of the loan are 20 years ($n_0 = 1, n_2 = 20$), and that the pay back period for the principal of the investment is 15 years ($n_1 = 5, n_3 = 19$). The total construction cost and the operating and management cost are respectively assumed as:

$$CC = 1357000 + 32.5 \cdot s_{rh} + 2805 \cdot EP_{\max} + p_b \text{,} \quad (29)$$

$$MC = emp + 0.012 \cdot CC \text{,} \quad (30)$$

where p_b is 48,000 (thousand JPY) and emp is 27,000 (thousand JPY/year). The benefits from the road heating are estimated by using the results reported in Kudoh et al., 2007 and kohata et al, 2004 as (thousand JPY):

$$B_a = 0.06 \cdot s_{rh} \text{,}$$

$$B_t = 2.0 \cdot s_{rh} \text{,}$$

$$B_s = 0.3 \cdot s_{rh} \text{.}$$

An algorithm developed based on GA (Genetic Algorithm) was applied for solving the optimization problem shown by Eqs. (23)-(28).

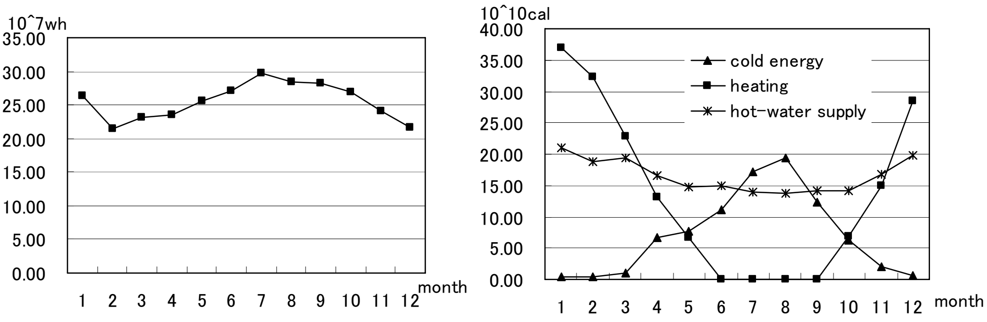

Figure 4. The demand of the hotel (right hand: electricity, left hand: heat)

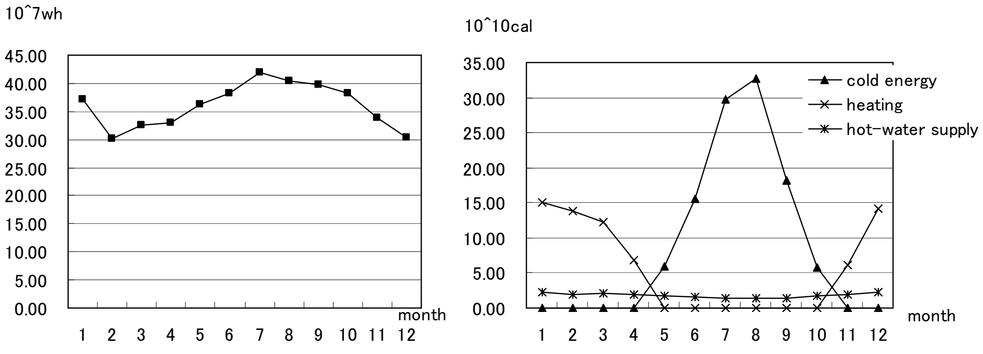

Figure 5. The demand of the commercial (right hand: electricity, left hand: heat)

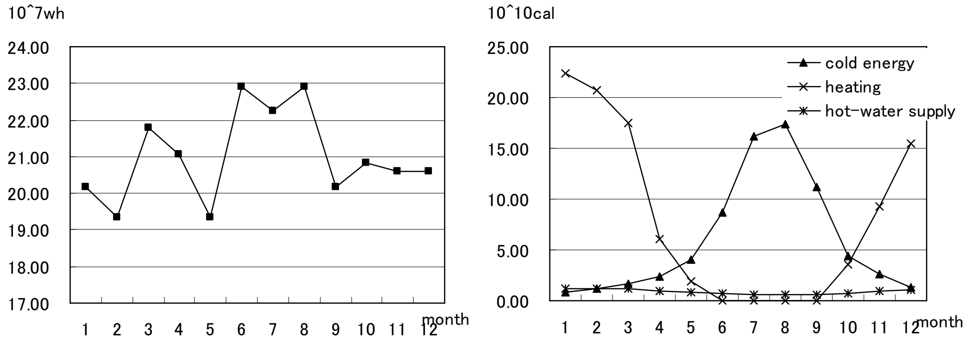

Figure 6. The demand of the office (right hand: electricity, left hand: heat)

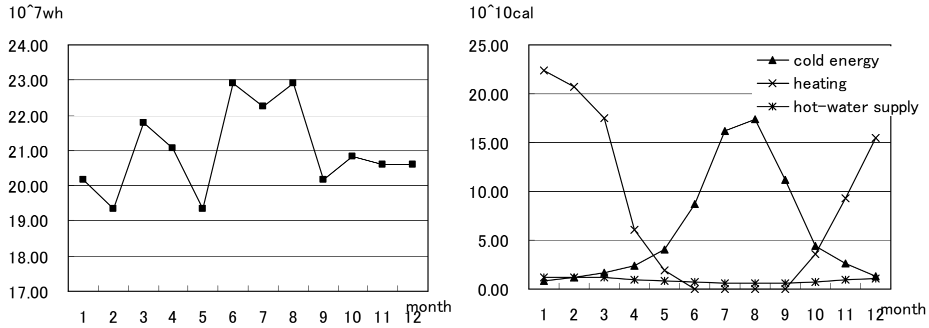

Figure 7. The demand of the households (right hand: electricity, left hand: heat)

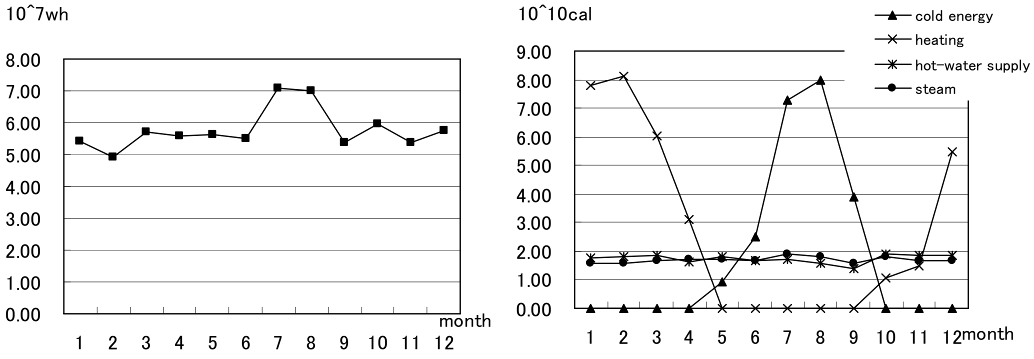

Figure 8. The demand of the hospital (right hand: electricity, left hand: heat)

Table 2 shows the optimal control variables for the problem. Table 2 shows the present value of benefit received by each stakeholder. The total construction cost including the gas engine, the boiler and the road heating is estimated as 1,800 million JPY. Almost 70 % of the total construction cost is collected from the gas supply company as the investment. The total present benefit from the gas cogeneration project is estimated as 1,950 million JPY and 75% of the total benefit is received by the gas supply company. There is a little benefit received by the local authority. This result means that the local authority subsidizes as much as the benefit from the reduction of snow removal cost.

Table 2. The optimized control variables

var.	x_k (thousand JPY/year)	y_k (thousand JPY/year)	I (thousand JPY)	D (thousand JPY)	$EP_{\max}$ (Mw/ month)	s_{rh} (m^2)
value	829	291,738	1,309,686	476,875	93	3,670

Table 3. The benefits (thousand JPY)

host	local authority	gas supply company	inhabitants
benefit	3,700	1,465,950	479,379

5. CONCLUDING REMARKS

In this study, an economical model for evaluating a feasibility of a gas cogeneration project is proposed. The stakeholders addressed in the present study are the project company, the gas supply company, the local authority, the inhabitants of the district, and the financial institution. In the model proposed, cooperative behavior among the stakeholders is assumed. Accordingly, the behavior among the stakeholders is not the maximization of their own benefits but the maximization of the total benefit subject to the constraint in which no stake holder has debt by the project. Distributions on the construction cost and the benefit among the stakeholders were clarified by the model analysis which was carried out by assuming that the natural gas cogeneration project was introduced to the downtown Sapporo, Japan. All of the stakeholders received positive net benefit from the project. Note that, if we assume that all of the stakeholders pursue their own benefit, the project may not be feasible in terms of profitability since some of stakeholders can receive debt.

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