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OPTIMAL PLANNING AND ECONOMIC EVALUATION OF SMALL SCALE COGENERATION SYSTEM

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ABSTRACT

Cogeneration plants, which simultaneously produce electricity and heat energy have been introduced increasingly for commercial and domestic applications in Korea because of their energy efficiency. The optimal plant configuration of a specific commercial building can be determined by selecting the size and the number of cogeneration systems, auxiliary equipment based on the annual demands of electricity, heating and cooling. In this study, a mixed-integer, linear programming, utilizing the branch and bound algorithm was used to obtain optimal solution. Both the optimal configuration system equipment and the optimal operational mode were determined based on the annual cost method for installation of a cogeneration system to a hospital and a group of apartments in Seoul, Korea. In addition, the economic evaluation for the optimal cogeneration system depending on the fuel tariff system was calculated. A short payback period and a high internal rate of return on the initial investment were found to be essential for the adoption of cogeneration plants to hospitals and apartments.

NOMENCLATURES

C	unit cost of fuel or electricity ($/MW)
I	initial equipment cost
J	total number of RF units
K	total number of RS units
L	total number of AUXB units
M	total number of representative energy demand patterns
N	total number of GT/WHB units
Q_D	cooling demand
r	annual interest rate
R	rate of return
T	annual operational hours
x	fuel consumption
y	heat output (MW)
Y_D	heat demand (MW)
w_G	power output (MW)
w_P	purchased power (MW)
W_D	power demand (MW)
Z_f	annual fixed cost ($/yr)
Z_r	annual variable cost ($/yr)

Greek Letters

γ	ratio of an annual maintenance cost of the initial equipment cost
ρ	remainder rate of the equipment at the end of expected life
τ	expected life of equipment

Subscripts

A	AUXB unit
G	GT or GT/WHB unit
j	j^{th} RF unit
k	k^{th} RS unit
l	l^{th} AUXB unit
n	n^{th} GT/WHB unit
RE	turbo chiller unit
RF	gas directly-fired system
RS	gas absorption chiller

Superscripts

m	m^{th} energy demand pattern

INTRODUCTION

Cogeneration is a thermal system that produces electrical and heat energy simultaneously from a single source of fuel (Baughn and Kerwin, 1987). For industrial and domestic applications where both kinds of energy are required, this system is very energy efficient (Lundberg, 1991), and its application has undergone strong growth for commercial and public purposes in Korea. Even though, cogeneration system can return fossil fuel energy saving of up to 30 % compared with conventional systems, overall profit can still be elusive.

To determine the optimal configuration of the gas engine cogeneration plant to a specific commercial building such as a hospital or a group of apartments, firstly, the size and the number of cogeneration plant and auxiliary equipments are selected based on the data of the annual demand for electricity, heat, and cooling (Horii et al., 1987; Kwon et al., 1995; Yokoyama et al., 1996). Next, an evaluation is performed into whether or not the optimal plant chosen can be operated at higher load conditions. The optimal planning method employed in this study was to determine the optimal configuration of the system among every possible combination of the plant equipments and operational plans of the system given the representative energy demand patterns. Further, the payback period and the internal rate of return on the initial investment of the optimal plant were calculated to show that the introduction of the plant to the hospital or apartments is economically feasible.

Special attention was paid to selecting representative energy demand patterns from the actual measurement data in this study because the estimated energy demand patterns significantly affect the economic and energy saving characteristics of the cogeneration system (Yokoyama and Ito, 2002). In fact, a few energy demand pattern only cannot be applied to obtain an optimum sizing and optimal operational strategy for the cogeneration system (Horii et al., 1987; Yokoyama et al., 1994). However, although not impossible, it is certainly time-consuming to use hourly energy demand data for a one-year period in the optimization problem.

Various methods have been proposed to evaluate the cogeneration system properly with the finite amount of energy demand data. Takahashi and Ishizaka (1998) proposed a method to prioritize energy demand parameters from the actual data with aid of the information theory. Yokoyama and Ito (2002) proposed a robust optimal design method under uncertain energy demand to obtain the unit sizing of the energy supply systems. An optimal unit sizing method for cogeneration systems was proposed by Gamou et al. (2002) by treating the energy demands as continuous random variables.

The object of present study is to suggest a more reliable method to evaluate the economics of adopting a cogeneration plant by extending the optimal planning method by Horii et al. (1987) and Yokoyama et al. (1996; 1994) with proper treatment of energy demand data. The basic design concept of the plant is the cascade use of energy to minimize the operational costs and thereby save energy by efficient utilization of resources. A mixed-integer, linear programming utilizing the branch and bound algorithm was used to obtain the optimal solution. Evolutionary programming (Tsay and Lin, 2000) and multi-objective approach (Tsay, 2003) were proven to be also useful for operation strategy of cogeneration system. However, the branch and bound algorithm was efficient in the computer simulation for the case of involving the presence of various constraints in the performance for the components. Selling electricity produced in the system, which yields a quite different operational strategy for the cogeneration system (Tsay and Lin, 2000) was not considered in this study.

DESCRIPTION OF PLANT

Plant Structure

Figure 1 shows a cogeneration plant structure of gas engine and waste heat boiler (GE/WHB) unit with auxiliary equipment. In this figure, the abbreviation AUXB, RE, RS and RF stand for the auxiliary boiler, turbo chiller, gas absorption chiller and gas directed-fired system, respectively. The auxiliary boilers are installed to supply heat to the plant when the operation of the GE/WHB unit is stopped or when more heat is required than that can be supplied from WHBs. Turbo chillers are operated by the power generated from the gas turbine and/or purchased electricity. Gas-fired absorption chillers are operated by the steam produced by GE/WHB units and/or by the auxiliary boilers. The gas directly-fired system is operated when more cold water for space cooling is demanded. In Fig. 1, the dotted line, the solid line, the dot-dashed line and the two dots-dashed lines indicate the flow of fuel, electricity, steam and cold water, respectively.

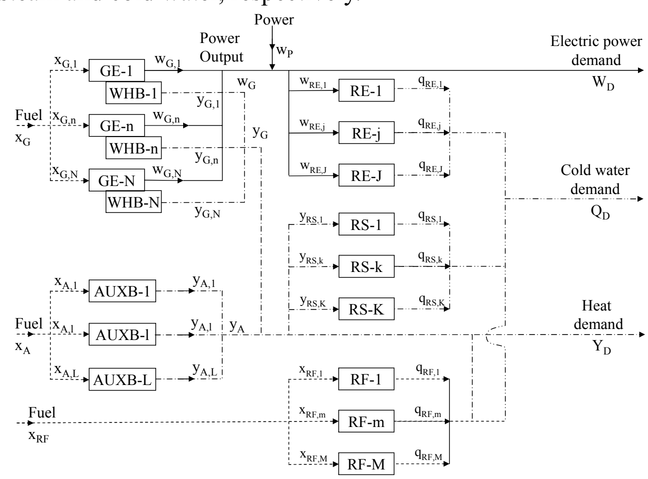

Fig. 1 Schematic diagram of the cogeneration system

Performance Characteristics of Plant Component

Generally, the performance characteristics of each component in the plant can be approximately represented by the following linear equation (Horii et al, 1986)

$$y = ax + b\delta \tag{1}$$

and

$$\underline{X}\delta \le x \le \overline{X}\delta \tag{2}$$

where x is the input variable, y is product, δ is the 0-1 integer variable to express the on/off condition of each component and $\underline{X}$ and $\overline{X}$ are the lower and upper bound for the input variables, respectively. The linear relationship between the product and the input fuel has proven to be good approximation for a 1,000 kW gas turbine (Oh et al., 1996) and for boilers (Tsay and Lin, 2000). Figure 2 illustrates typical examples of the curves of fuel consumptions versus power and heat output for actual GE/WHB units. Detailed expressions for the performance characteristics of each component follow below.

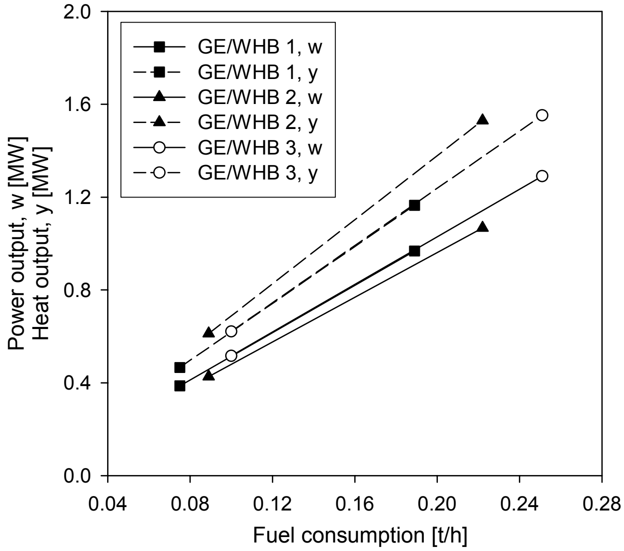

Fig. 2 Performance curves of the GE/WHB units

GE/WHB unit

This unit has two products, electricity (w) and steam (y) due to the consumption of fuel (x). The amount of electricity and steam produced depending on the amount of input fuel and can be approximated by the following equations.

$$w_{G,n}^{m} = a_{G,n} x_{G,n}^{m} + b_{G,n} \delta_{n}^{m}, \tag{3}$$

$$y_{G,n}^{m} = \alpha_{G,n} x_{G,n}^{m} + \beta_{G,n} \delta_{n}^{m}, \tag{4}$$

and

$$\underline{X}_{G,n}^{m} \delta_{n}^{m} \le x_{G,n}^{m} \le \overline{X}_{G,n} \delta_{n}^{m} \tag{5}$$

where n denotes the n^th GE/WHB unit installed ($1 \le n \le N$), m indicates the m^th ($1 \le m \le M$) energy demand pattern, and $a_{G,n}$, $b_{G,n}$, $\alpha_{G,n}$ and $\beta_{G,n}$ are constants determined by the performance characteristics of n^th GE/WHB unit. In Eq. (5), $\overline{X}_{G,n}^{m}$ and $\underline{X}_{G,n}^{m}$ are the upper and lower bounds, respectively, of the fuel consumption of the n^th GE/WHB unit for the operation of the m^th energy demand pattern. The same notations were used for the upper and lower bounds of the fuel consumption for the AUXB unit denoted with the subscript A and the RF unit denoted with the subscript RF. The symbol δ_{n}^{m} denotes the 0-1 integer variable to express the on/off condition of the n^th GE/WHB unit for the m^th energy demand pattern. The number of the representative energy demand pattern M was carefully chosen from the actual measurement data for the annual energy demand in existing hospital and apartments. One day may be chosen to represent the energy demand pattern for a month. However, the number of representative days for a specific month may depend on local weather conditions. In the optimization simulation, calculation was done on hourly basis for the daily energy demand patterns chosen. With the energy demand patterns from 1 to M and the corresponding annual operational hours T_{b}^{m}, the calculated total power demand W_D and the heat demand Y_D were in agreement within ±2 % and ±5 %, respectively, to the corresponding observed values for the hotel and the apartments.

AUXB unit

This unit supplies steam when the operation of the GE/WHB unit is stopped or generates insufficient steam to cover the steam demand. This performance curve is approximated by the following linear equations.

$$y_{A,l}^{m} = \alpha_{A,l} x_{A,l}^{m} + \beta_{A,l} \delta_{l}^{m} \tag{6}$$

and

$$\underline{X}_{A,l}^{m} \delta_{l}^{m} \le x_{A,l}^{m} \le \overline{X}_{A,l}^{m} \delta_{l}^{m} \tag{7}$$

where l is the l^{th} AUXB unit installed ($1 \le l \le L$) and $\alpha_{A,l}$ and $\beta_{A,l}$ are the constants determined by the performance characteristics of the l^{th} AUXB unit.

RE unit

The turbo chiller (RE) provides cooling water for space cooling by consuming the electricity from the GE/WHB unit and/or purchasing power.

RS unit

The gas absorption chiller (RS) provides cold water for space cooling. This unit may be operated in summer when there is a large demand for interior cooling. The refrigeration capacity obtained from this unit may be approximated by the following linear equation.

$$q_{RS,k}^{m} = \gamma_{RS,k} y_{RS,k}^{m} + \eta_{RS,k} \delta_{k}^{m} \tag{8}$$

and

$$\underline{Y}_{RS,k}^{m} \le y_{RS,k}^{m} \le \overline{Y}_{RS,k}^{m} \tag{9}$$

where k is the k^{th} RS unit installed ($1 \le k \le K$) and $\gamma_{RS,k}$ and $\eta_{RS,k}$ are the constants determined by the performance characteristics of k^{th} RS unit, respectively, and $\overline{Y}_{RS,k}^{m}$ and

$\underline{Y}^m_{RS,k}$ are the upper and lower bounds, respectively, of the steam consumption of the k^{th} RS unit.

RF unit

The gas directly-fired system unit supplies either cold water or steam depending on the shortage of cooling or heating demand, respectively. However, this unit cannot supply cold water and steam simultaneously. The refrigeration capacity or the steam obtained from this system may also be approximated by the following linear equations.

$$q^m_{RF,j} = \gamma_{RF,j} x^m_{RFc,j} + \eta_{RF,j}\delta^m_j \tag{10}$$

$$\underline{X}^m_{RFc,j} \le x^m_{RFc,j} \le \overline{X}^m_{RFc,j} \tag{11}$$

or

$$y^m_{RF,j} = \alpha_{RF,j} x^m_{RFh,j} + \beta_{RF,j}\delta^m_j \tag{12}$$

$$\underline{X}^m_{RFh,j} \le x^m_{RFh,j} \le \overline{X}^m_{RFh,j} \tag{13}$$

where j is the j^{th} RF unit installed ($1 \le j \le J$) and $\gamma_{RF,j}$, $\eta_{RF,j}$, $\alpha_{RF,j}$ and $\beta_{RF,j}$ are constants obtained from the performance characteristics of the j^{th} RF unit.

OPTIMIZATION PLANNING

It is well known that the operation cost of the power plant depends largely on the planning method and operational policy of the plant. In the optimal planning of the plant considered in this study, it is assumed that the annual demands of electricity and heat are given a priori. That is, for the mth energy demand pattern, the electricity demand is given by $W^m_D(MW)$, the heat demand by $Y^m_D(MW)$ and the cooling demand by $Q^m_D(MW)$ with the annual operational hours T^m_D. It is also assumed that the electricity will be purchased within the value of the maximum contract of power, $\overline{w}_p$. However, no excess electricity from GE/WHB units can be sold. The resulting energy supply-demand relation for the mth energy demand pattern is given by the following equations;

$$\sum_{n=1}^{N} w^m_{G,n} + w^m_p = W^m_D \tag{14}$$

$$\sum_{n=1}^{N} y^m_{G,n} + \sum_{l=1}^{L} y^m_{A,l} - \sum_{k=1}^{K} y^m_{RS,k} + \sum_{j=1}^{J} y^m_{RF,j} \ge Y^m_D \tag{15}$$

$$\sum_{n=1}^{N} y^m_{G,n} + \sum_{l=1}^{L} y^m_{A,l} \le H/C \tag{16}$$

$$\sum_{n=1}^{N} y^m_{G,n} + \sum_{l=1}^{L} y^m_{A,l} - \sum_{k=1}^{K} y^m_{RS,k} \ge 0 \tag{17}$$

$$\sum_{k=1}^{K} q^m_{RS,k} + \sum_{j=1}^{J} q^m_{RF,j} = Q^m_D \tag{18}$$

where H/C is the capacity of the heat exchanger. Substituting Eq. (3) into Eq. (14),

$$\sum_{n=1}^{N}\left(a_{G,n} x^m_{G,n} + b_{G,n}\delta^m_n\right) + w^m_p = W^m_D \tag{19}$$

Substituting Eqs. (4), (6) and (12) into Eq. (15),

$$\begin{aligned}\sum_{n=1}^{N}\left(a_{G,n} x^m_{G,n} + b_{G,n}\delta^m_n\right) + \sum_{l=1}^{L}\left(\alpha_{A,l} x^m_{A,l} + \beta_{A,l}\delta^m_l\right) \\ - \sum_{k=1}^{K} y^m_{RS,k} + \sum_{j=1}^{J}\left(\alpha_{RF,j} x^m_{RF,j} + \beta_{RF,j}\delta^m_j\right) \ge Y^m_D\end{aligned} \tag{20}$$

Finally, the cooling demand can be obtained by substituting Eqs. (8) and (10) into Eq. (18).

$$\begin{aligned}\sum_{k=1}^{K}\left(\gamma_{RS,k} y^m_{RS,k} + \eta_{RS,k}\delta^m_k\right) \\ + \sum_{j=1}^{J}\left(\gamma_{RF} x^m_{RFc,j} + \eta_{RF,j}\delta^m_j\right) = Q^m_D\end{aligned} \tag{21}$$

The annual variable cost of the plant Z_r may be expressed by the following equation (Horii et al., 1987)

$$Z_r = \sum_{m=1}^{M}\left(c_G \sum_{n=1}^{N} x^m_{G,n} + c_A \sum_{l=1}^{L} x_{A,l} + c_p w^m_p\right) T^m_D + \overline{c}_p \overline{w}_p \tag{22}$$

By substituting Eq. (19) into the above equation, the annual variable cost can be written as

$$Z_r = \sum_{m=1}^{M}\left[c_G \sum_{n=1}^{N} x_{G,n}^{m} + c_A \sum_{l=1}^{L} x_{A,l}^{m} + c_D W_D^m - c_p \sum \left(a_{G,n} x_{G,n}^{m} + b_{G,n}\delta_n^m\right)\right] T_D^m + \bar{c}_p \bar{w}_p \tag{23}$$

Based on the annual cost method, the annual fixed cost of the plant, Z_f is given by (Horii et al., 1987)

$$Z_f = \sum_{n=1}^{N} R_G I_{G,n} + \sum_{l=1}^{L} R_A I_{A,l} + \sum_{j=1}^{J} R_{RE} I_{RE,j} + \sum_{k=1}^{K} R_{RS} I_{RS,k} + \sum_{j=1}^{J} R_{RF} I_{RF,j} + \sum_{n=1}^{N} \gamma_G I_{G,n} + \sum_{l=1}^{L} \gamma_A I_{A,l} + \sum_{j=1}^{I} \gamma_{RE} I_{RE,j} + \sum_{k=1}^{K} \gamma_{RS} I_{RS,k} + \sum_{j=1}^{J} \gamma_{\mathrm{RF}} I_{RF,j} \tag{24}$$

where I denotes for the initial equipment cost and γ is the ratio for the annual maintenance cost to the initial equipment cost. In the above equation, the rate of return for the GE/WHB unit, e.g. R_G is given by

$$R_G = r\left[1 - \rho(1+r)^{-\tau_G}\right] / \left[1 - (1+r)^{-\tau_G}\right] \tag{25}$$

where r is the annual interest rate, ρ is the remainder rate of the equipment at the end of expected life and τ is the expected life of equipment. The same equation was used to obtain the value of R for other equipment. By adding the annual variable cost of equation (23) to the annual fixed cost of equation (24), the total annual cost of the plant Z is given by

$$Z = Z_r + Z_f \tag{26}$$

which is the objective function to be minimized under constraints of equations (5), (7), (14), (15), (16) and (17) for the optimal planning.

A mixed-integer, linear programming utilizing the branch and bound algorithm based on the method developed by Land and Doig (1960) and Kuester and Mize (1973) was adopted in the present study to obtain the optimal solution. The effectiveness of the branch and bound algorithm depends on the proper selection of a branching variable as well as a branching node, which can be found in any linear programming textbook (Gass, 1994). The branching variables allow the set of feasible solutions to be divided into several subsets based on the values of the integer variables. The selection of the proper branching node allows the optimal solution to be obtained quickly. The detailed procedure to determine the optimal configuration and operational policy for the cogeneration plant is shown in Fig. 3.

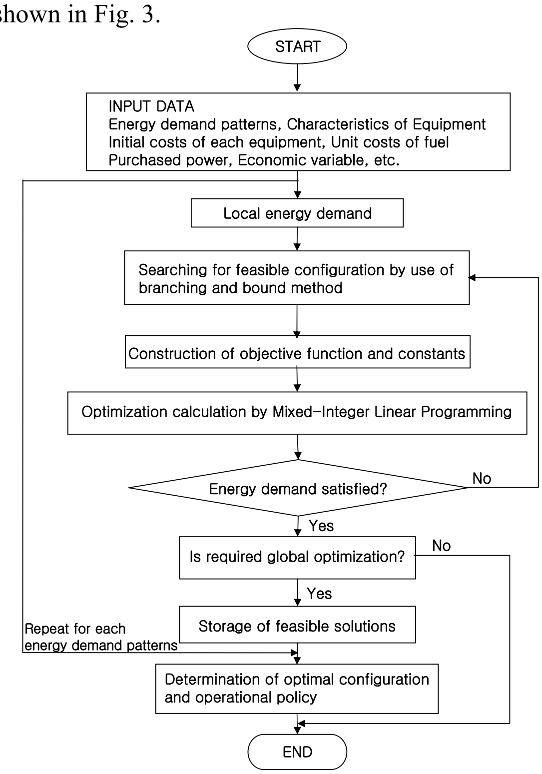

Fig. 3 A procedure to determine the optimal configuration and operational policy for the cogeneration plant.

CALCULATION RESULTS AND DISCUSSION

A hospital and a group of apartments in Seoul, Korea were chosen for this study to determine whether the adoption of the cogeneration plant is economically viable. Figure 4 shows the energy demand data in which each day represent one month for the hospital. Usually, hospitals and apartments have a large heat demand in winter and a large cooling demand in summer. It is this demand pattern which determines the configuration of the cogeneration system installed and the operation mode of the optimal cogeneration plant.

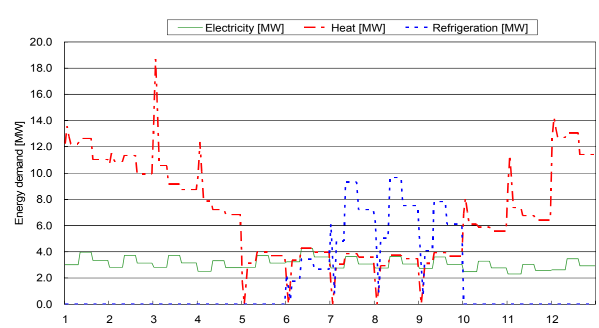

Fig. 4 Energy demand pattern of the hospital

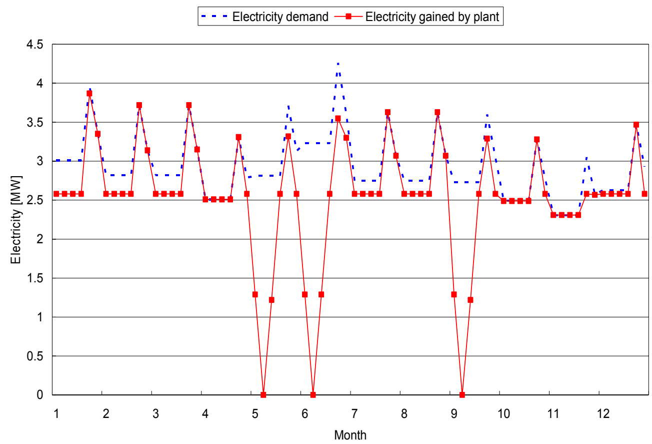

Fig. 5 Electricity demand and the electricity generated by the optimal cogeneration plant

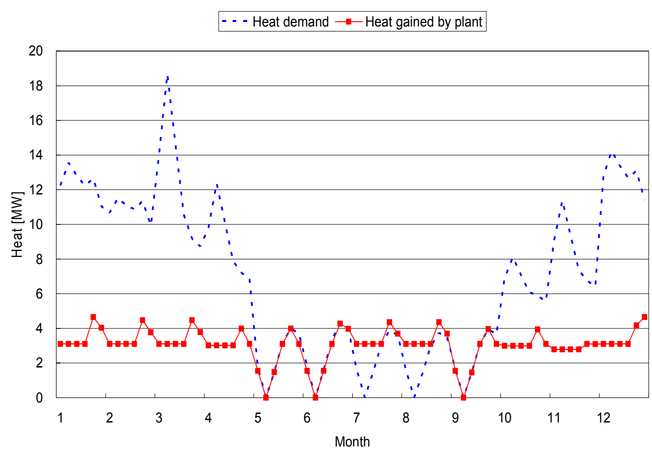

Fig. 6 Heat demand and the heat generated by the optimal cogeneration plant

For the hospital, the maximum electricity, heat, and refrigeration demands were 4.26 MW, 18.68 MW and 9.68 MW (2,500RT), respectively. The maximum outputs corresponding to fuel, power, or steam consumption and the initial equipment costs of each component considered in the optimal planning of the plant for the hospital are shown in Table 1. The tariffs of electricity and fuel, along with the annual fixed costs used in the calculation are shown in Table 2, and 3 respectively. The fuel tariff, shown in Table 3 can be applied only to the hospital where the cogeneration plant is installed. The unit cost of hot water was taken as 12 $/GJ in this study.

The expected life of each equipment was assumed to be $\tau_G = 15yr$ and the remainder rate was taken as $\rho = 0.1$. The possible annual operation time of the cogeneration plant was assigned as 8,760 hrs. The ratio of the annual maintenance cost including insurance to the initial investment was set as $\gamma = 0.035$, and the annual interest rate was $r = 0.12$.

Table 1 Maximum outputs, corresponding fuel consumption and initial equipment costs for GE/WHB, AUXB, RE, RS and RF units

Type of equipment	1	2	3
GE/WHB Power output (MW)	0.968	1.067	1.290
GE/WHB Heat output (MW)	1.165	1.530	1.552
Fuel consumption (Nm^3/hr)	228	268	303
Initial cost ($)	7,540,000	8,450,000	9,130,000
AUXB Heat output (MW)	4.0	6.0	9.6
Fuel consumption (Nm^3/hr)	426	639	1,023
Initial cost ($)	616,000	874,000	1,190,000
RE cooling load (RT)	1,045	1,500	-
Power consumption (MW)	7.26	9.0	
Initial cost ($)	1,890,000	2,500,000	-
RS cooling load (RT)	741	960	-
Steam consumption (ton/h)	3.87	5.06	
Initial cost ($)	2,500,00	2,900,00	-
RF Cooling load (RT)	1,000	1,400	-
RF Heat outputs (MW)	2.94	4.12	-
Fuel consumption (Nm^3/hr)	286	400	-
Initial cost ($)	2,560,000	3,390,000	-

Table 2 Tariff of electricity

Period	Summer	Spring/Fall	Winter
Tariff ($/kWh)	0.0926	0.0616	0.0656

Table 3 Tariff of fuel

	Unit cost ($/$Nm^3$/hr)
Heating (Spring, fall and winter rate)	0.382
Refrigeration (Summer rate, May-Sept.)	0.166

Previously, the optimal configuration of the cogeneration plant was determined with the assumption that the plant should cover the maximum demand of electric power. However, this was not the case for the cogeneration plant with profit. In this study, the payback period was calculated for the possible configurations of the cogeneration plant according to combinations of various scales of gas engine as shown in Table 1, to compare the economic merit of the possible plants. In Table 4, the annual fixed and variable costs, the profit produced in the electricity and heat by introducing the cogeneration plant, the operating rate of the plant and the payback period to the initial investment are given. When the scale of the cogeneration plant was increased, the payback period became longer because the operating rate is reduced for larger plant. Calculation showed that the cogeneration plant designed to cover 60 % of the electricity demand was the solution with the highest economic feasibility. The electricity demand and the electricity gained by the optimal cogeneration plant are shown in Fig. 5. The heat demand of the hospital and the heat gained by the optimal cogeneration plant are shown in Fig. 6.

Table 4 Economic evaluation for the possible configuration of the cogeneration plant

Covering percent-age for the electricity demand	Cogene-ration configu-ration (kW× set(s))	Operational cost ($)		Profit (operating rate)		Pay-back period (yr)
		Fixed cost	Variable cost	Electricity ($)	Heat ($)	
60	1,290×2	411,899	1,975,769	1,687,366 (97.9)	1,157,013 (97.4)	4.0
68	968×3	487,326	2,153,758	1,828,998 (92.8)	1,251,076 (93.6)	5.2
70	968×2 1,067×1	503,069	2,237,057	1,860,281 (91.3)	1,354,250 (91.7)	5.0
75	1,067 ×3	534,555	2,250,465	1,823,462 (85.3)	1,467,094 (83.5)	5.0
80	1,067 ×2 1,290 ×1	546,319	2,332,474	1,916,614 (83.8)	1,467,094 (81.4)	5.5
83	968 ×1 1,290×2	542,340	2,314,360	1,992,648 (82.7)	1,338,681 (82.0)	5.4
91	1,290×3	569,847	2,354,725	1,983,899 (76.7)	1,343,886 (75.5)	6.8

An optimal configuration of the cogeneration plant obtained for the hospital is given in Table 5. A reference energy system without the GE/WHB unit to supply heat and cooling demands for the hospital was chosen for economic evaluation of the optimal cogeneration plant, as is shown in Table 6. With the special tariff system for the fuel given in Table 3, the operational modes of the optimal cogeneration plant corresponding to the electricity, heat and cooling demands are shown in Figs. 7, 8, and 9, respectively. As shown in Fig. 7, the two GE/WHB units supplied electricity even when the electricity demand was less than the maximum electricity output from the GE/WHB units at full load condition due to the constant heat demand so that the GE/WHB units should supply the heat as shown in Fig. 8. Additional heat demand could be supplied by the two RF units and partly by the AUXB unit. Especially, the two RF units were operated to satisfy the cooling demand during summer, as shown in Fig. 9.

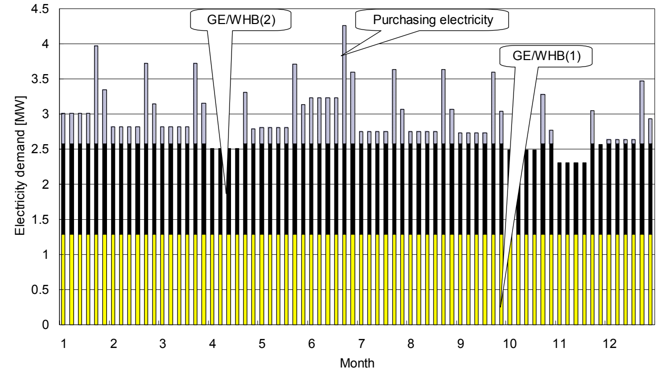

Fig. 7 Operation mode of the optimal cogeneration plant for the electricity demand

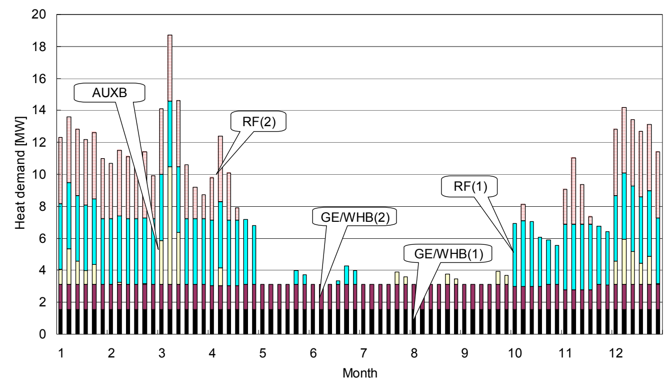

Fig. 8 Operation mode of the optimal cogeneration plant for the heat demand

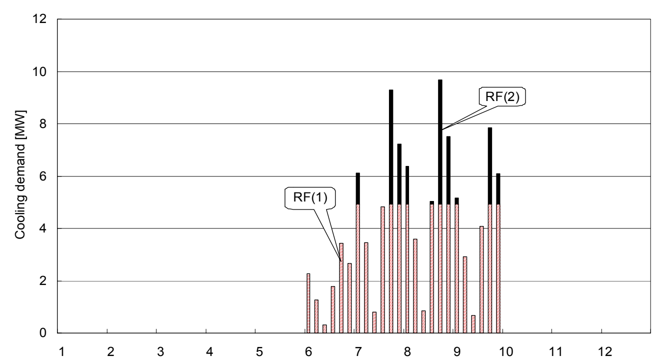

Fig. 9 Operation mode of the optimal cogeneration plant for the cooling demand

Table 5 Optimal configuration of the cogeneration plant for the hospital

Equipment	Scale of unit	Number of unit	Initial investment ($)
GE/WHB	1.290 MW	2	18,260,000
AUXB	9.6 MW	1	1,190,000
RF	1,400 RT	2	6,780,000
Total initial investment for plant			26,230,000

Table 6 A reference energy system for the hospital

Equipment	Scale of unit	Number of unit	Initial investment ($)
AUXB	6 MW	2	1,748,000
RF	1,400 RT	2	6,780,000
Total initial investment for system			8,528,000

Table 7 Monetary comparison of the optimal plant to the reference energy system for the hospital with tariff of the fuel of 0.382 $/Nm^3/hr$

	Optimal cogeneration plant (A)	Reference energy system (B)	Economic loss or gain (B-A)
Total investment	2,623,000	852,800	-1,770,200
Total annual cost	4,590,315	4,821,417	231,102
Annual fixed cost	538,315	192,120	-
Annual variable cost	4,052,000	4,629,297	-
Annual variable cost	4,052,000	4,629,297	-

Table 8 Monetary comparison of the optimal plant to the reference energy system for the hospital with special tariff of the fuel in Table 3 (unit is in $)

	Optimal cogeneration plant (A)	Reference energy system (B)	Economic loss or gain (B-A)
Total investment	2,623,000	852,800	-1,770,200
Total annual cost	3,990,315	192,120	831,102
Annual fixed cost	538,315	4,629,297	-
Annual variable cost	3,452,000	852,800	-

Table 7 shows the economic loss or gain achieved by introducing the cogeneration plant into the hospital and includes; the annual variable cost, the fixed cost for the cogeneration plant, and the reference energy system without the special tariff system for the fuel. With the fixed tariff of fuel of 0.382 $/Nm^3/hr$ for all years, the payback period and the internal rate of return (IRR) by introducing the optimal cogeneration unit to the hospital (calculated from the data in Table 7) were 7.7 years and 10 %, respectively. The additional investment cost (B-A in Table 7) could be recouped within the lifetime of the component. However, the IRR calculated was less than the annual interest rate of 12 % that was assumed in this study, indicating that the adoption of the cogeneration plant to the hospital was not profitable with the fuel tariff 0.382 $/Nm^3$. However, with the special fuel tariff system, the profit obtained by introducing the cogeneration plant increases considerably as shown in Table 8. The payback period and the internal rate of return (IRR) by introducing the cogeneration plant to the hospital, which were calculated from the data in Table 8 were 2.8 years and 47 %, respectively, confirming that, it was economically feasible for the hospital to adopt the cogeneration plant.

Table 9 Energy demand, the power, load condition and operating rate of the gas engine and economic evaluation of the optimal cogeneration system for apartments in Seoul, Korea

APT No.	Energy demand			Optimal cogeneration system			Economic evaluation	
	Electricity (MWh)	Heat (Mcal)	Peak electricity (kW)	Engine power (kW)	Load condition (%)	Operating rate (%)	Payback period (yrs)	IRR (%)
1	738,300	7,363,794	130	26	91.5	91.5	2.9	36
2	802,200	7,418,906	140	26	91.5	91.5	2.7	37
3	1,063,000	11,304,354	180	26	91.5	91.5	2.5	39
4	1,237,300	8,931,861	210	119	90.0	91.5	3.1	32
5	2,169,300	1,251,464	370	26	91.5	91.5	3.1	32
6	2,581,079	23,631,972	450	119	91.5	91.5	2.0	50
7	3,060,800	8,611,019	530	119	91.5	91.5	2.1	49
Average	1,664,526	9,749,053	287	66	91.3	91.5	2.6	39

Table 10 Payback periods change as the fuel cost increases by 15 % or the electricity cost decreases by 15 % for the optimal cogeneration systems given in Table 9

Apartment No.	1	2	3	4	5	6	7
Fuel cost increase by 15 %	3.4	3.3	3.0	4.2	3.9	2.4	2.5
Electricity cost decrease by 15 %	3.7	3.6	3.3	4.5	4.4	2.6	2.8

Similar calculations were done for the various apartments having different annual demands of electricity and heat and the peak electricity demands, as shown in Table 9. The typical energy demand pattern for the apartment in Seoul is shown in Fig. 10. For each group of apartments, the power, load condition, and the operating rate of the gas engine chosen in the optimal cogeneration system are also given in Table 9. The operating rate and the load condition were greater than 90 %, which is reasonable for the operation of the cogeneration system. Furthermore, the average payback period and the IRR on the initial investment were 2.6 yrs and 39 % respectively. In addition, the payback periods increases by only one year when the fuel cost increased by 15 % or the electricity cost decreased by 15 %, as clearly confirmed in Table 10.

An optimal design for a cogeneration system may be obtained based on the average energy demand patterns of several demand patterns for several representative days by considering the uncertainty in the energy demand (Yokoyama and Ito, 2002). In addition, the cogeneration system may be successfully planned using the annual energy demand with some important demand indices (Takahashi and Ishizaka, 1998). However a more reasonable evaluation of the cogeneration system and the optimal design of the cogeneration system with the proper operation mode can be achieved by suitable selection of the energy demand patterns which can represent hourly and seasonal variation of the energy demand for the specific application. Our optimization method for the cogeneration system may be used as a tool to add or replace components in the energy supply system when the energy demands are changed.

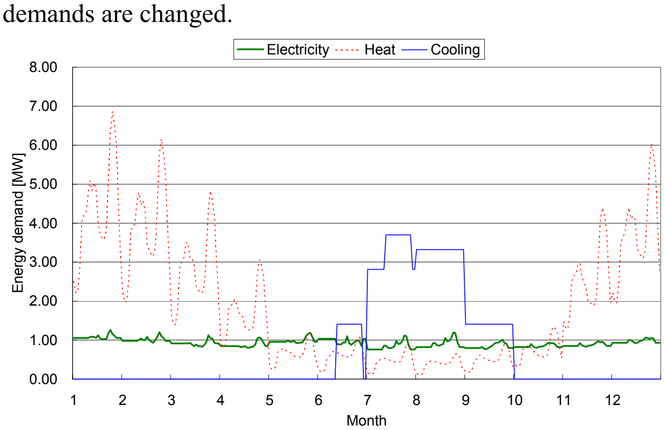

Fig. 10 A typical energy demand pattern for apartments in Seoul, Korea

CONCLUSION

A planning method to determine the optimal operational mode and the optimal configuration of a co-generation plant was applied to a hospital and a group of apartments in Seoul, Korea in order to evaluate whether or not the adoption of the cogeneration plant was profitable. The optimal configuration of the cogeneration plant was determined by considering the annual energy demand pattern of the hospital and the apartments, and this pattern was confirmed to be the crucial parameter determining the feasibility of the use of the cogeneration plant. When the cogeneration plant was introduce to a hospital, a special tariff system which decreases the cost of the fuel consumed for the cooling demand in summer should be chosen by the city government. The optimal configuration of the cogeneration plant may differ with different cogeneration systems and auxiliary systems. Furthermore, it was found that the payback period should be short and the internal rate of return of the plant chosen on the initial investment should be high. These two variables were relatively insensitive to increases in the fuel cost and decreases in electricity cost for reliable and profitable operation of the plant.

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