Economic Evaluation of A CGS with Energy Storage Systems

Yoshihide Kojima* and Masakazu Kato†

Abstract - Problems such as global warming and resource depletion are becoming more and more serious. End consumers are required to reduce CO2 emissions and to make effective use of energy. As measures, cogeneration systems (CGSs) and energy storage systems including heat storage and battery are considered. In this paper, optimum facility planning and economy evaluation has been performed by linear programming for a CGS with energy storage systems.

Keywords: Cogeneration system, Energy storage, Optimum operation, Optimum planning, Linear programming

1. Introduction

Problems such as global warming and resource depletion are becoming more and more serious. End consumers are required to reduce CO2 emissions and to make effective use of energy. As measures, cogeneration systems and energy storage systems including heat storage and battery are considered. A cogeneration system (CGS) which can supply both heat and power on-site is one possible solution to improve energy usage efficiently. A battery charges electricity during midnight and discharges it during peak period. Therefore, the load curve leveling can be realized. A heat storage system can be expected more effective heat use. Therefore, they are paid much attention in recent years. It aims at economy optimization to the customer with these equipment. In this paper, optimum facility planning method is proposed, and the advantage has been made clear.

2. Study System

2.1 CGS Introduction System

Fig. 1 shows the CGS introduction system. An energy storage system is assumed only hot water storage that can effectively use exhaust heat of CGS. Electric power is supplied by a CGS and a power grid. Cooling demand is supplied by a turbo refrigerator and an absorption refrigerator. Heating demand is supplied by exhaust heat of a CGS, a boiler, hot water storage, and a heat pump.

2.2 Energy Storage System

Fig. 2 shows the energy storage system as a comparison system. Electric power is supplied only by a power grid. Electric demand is supplied by a battery and the grid. Cooling demand is supplied by a turbo refrigerator and an ice storage. Heating demand is supplied by a heat pump and a hot water storage.

3. Modeling and formulation

3.1 Equipment Modeling

(a) CGS

The fuel consumption characteristic of a CGS is generally shown as follows as quadratic function of the electric output.

\[ F_{CGS} = a \times P_{CGS}^2 + b \times P_{CGS} + c \]  

\[ P_{CGS}: \text{Electric power of CGS [kW]}, \]
\[ F_{CGS}: \text{Amount of fuel for CGS [kW/h]} \]

Because the value of “a” is generally very small, in this paper it is approximated as the linear function of Eq. (2).

\[ F_{CGS} = \alpha \times P_{CGS} + \beta \]

\[ P_{min} \leq P_{CGS} \leq P_{max} \]

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\[ F_{CGS} = \alpha \times P_{CGS} + \beta \]  

\[ P_{min} \leq P_{CGS} \leq P_{max} \]
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Fig. 2. Energy storage system.

(b) Battery

Modeling of a battery is expressed as Eq. (3) per one hour with a time constraint. As for the battery, the loss of energy by time passage is not taken into account. Only input/output loss is considered.

\[ E'_{\text{battery}} = \alpha_b E_{\text{battery, in}} + \beta_b E_{\text{battery, out}} - \gamma_b E_{\text{battery, sat}} \]  

\[ E_{\text{battery}}: \text{Storage energy [kWh]}, \quad E_{\text{battery, in}}: \text{Input energy [kWh]}, \quad E_{\text{battery, out}}: \text{Output energy [kWh]}, \quad \alpha_b, \beta_b, \text{and} \gamma_b: \text{Cycle efficiency} \]

(c) Thermal storage system

Thermal storage systems have similar modeling for an ice storage and a hot water storage. For example, the hot water storage is expressed as Eq. (4) with a time constraint. Because energy loss generally occurs when heat is carried forward to the next time period, the thermal storage system is expressed as Eq.(4) per one hour.

\[ E'_{\text{wat, in}} = \alpha_w E_{\text{wat, in}} + \beta_w E_{\text{wat, out}} - \gamma_w E_{\text{wat, sat}} \]

\[ E'_{\text{wat, in}}: \text{Storage heating energy [kWh]}, \quad E_{\text{wat, in}}: \text{Input heating energy [kWh]}, \quad E_{\text{wat, out}}: \text{Output heating energy [kWh]}, \quad \alpha_w, \beta_w, \text{and} \gamma_w: \text{Cycle efficiency} \]

3.2 System Formulation

The objective function is a total cost beared by the customer, including electricity charge, gas charge, electric demand charge and annual cost of introduced facility. It is expressed as Eq. (5).

\[ \text{cost} = \sum \alpha \times P_{\text{buy}} + \beta \times P_{\text{max}} + \gamma \times (F_{\text{CGS}} + F_p) + \sum \delta \times C_{\text{CGS}} + \delta_b \times \text{Boiler}_{\text{max}} + \delta_s \times AR_{\text{max}} + \delta_h \times TR_{\text{max}} + \delta_{\text{hp}} \times HP_{\text{max}} + \delta_{\text{wat}} \times \text{wat, satu}_{\text{max}} \rightarrow \text{min} \]

\[ \alpha: \text{Electric power charge [yen/kWh]}, \quad P_{\text{buy}}: \text{Electric energy of purchase[kWh]}, \quad \beta: \text{Electric demand charge [yen/kW]}, \quad P_{\text{max}}: \text{Electric energy of the maximum purchase[kWh]}, \quad \gamma: \text{City gas charge [yen/kWh]}, \quad F_{\text{CGS}}: \text{Fuel consumption of CGS [kWh]}, \quad F_p: \text{Fuel consumption of boiler [kWh]}, \quad \delta: \text{Facility year of each equipment expenditure [yen/kW]}, \quad C_{\text{CGS}}: \text{CGS installed capacity[kW]}, \quad \text{Boiler}_{\text{max}}: \text{Installed capacity of boiler[kW]}, \quad AR_{\text{max}}: \text{Installed capacity of absorption refrigerator [kW]}, \quad TR_{\text{max}}: \text{Installed capacity of turbo refrigerator [kW]}, \quad HP_{\text{max}}: \text{Installed capacity of heat pump[kW]}, \quad \text{wat, satu}_{\text{max}}: \text{Hot water storage capacity[kW]} \]

The constraints includes as follows;

Electric power supply and demand balance:

\[ P_{\text{load}} = P_{\text{buy}} + P_{\text{CGS}} - P_{\text{hp}} - P_{\text{turbo}} \]  

Heating energy supply and demand balance:

\[ H_{\text{load}} \leq H_{\text{CGS}} + H_{\text{boiler}} + H_{\text{abs}} + H_{\text{wat, in}} + H_{\text{wat, out}} + H_{\text{hp}} \]  

Cooling energy supply and demand balance:

\[ C_{\text{load}} \leq C_{\text{abs}} + C_{\text{turbo}} \]

4. Simulation

4.1 Used Data

Optimum operation has been studied during three seasons, using heat and electric demand curves of a customer with during large heat demand. Table 1 shows each coefficient of the energy storage systems. Table 2 shows the efficiency of other equipment. Table 3 shows the facility introduction annual cost and the lifetime of other equipment.

All data are prepared based on publicly-available information. [3]-[5]

It has been assumed to introduce one CGS of the output 1000kW in this simulation.
Table 1. Coefficient of the energy storage systems

<table>
<thead>
<tr>
<th></th>
<th>Battery</th>
<th>Hot water storage</th>
<th>Ice thermal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1/0.85</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>COP</td>
<td>---</td>
<td>---</td>
<td>3.2</td>
</tr>
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</table>

Table 2. Efficiency of other equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>performance</th>
<th>COP</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo refrigerator</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption refrigerator</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat pump</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiler</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CGS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric power</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust heat</td>
<td>40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* COP: Coefficient Of Performance

Table 3. Facility introduction cost and lifetime of other equipment

<table>
<thead>
<tr>
<th>Facility</th>
<th>Facility introduction cost ($10^3$ yen /kW)</th>
<th>lifetime (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGS</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Boiler</td>
<td>0.8</td>
<td>15</td>
</tr>
<tr>
<td>Absorption refrigerator</td>
<td>3.41</td>
<td>15</td>
</tr>
<tr>
<td>Turbo refrigerator</td>
<td>2.63</td>
<td>15</td>
</tr>
<tr>
<td>Heat pump</td>
<td>3.3</td>
<td>15</td>
</tr>
<tr>
<td>Hot water storage tank</td>
<td>1.6</td>
<td>15</td>
</tr>
<tr>
<td>Ice storage tank</td>
<td>1.5</td>
<td>15</td>
</tr>
<tr>
<td>Battery</td>
<td>24</td>
<td>10</td>
</tr>
</tbody>
</table>

4.2 Simulation

Linear programming is applied to decide an optimum operation plan.

(a) Optimum operation planning method

In this research, the fuel cost of CGS always has constant $\beta$. Therefore, it always costs $\beta$ even for output 0. It is necessary to consider start/stop of a CGS. In the research, start/stop of a CGS has been determined from comparison of economy in each time period. However, because this study system has energy storage systems and facilities introduction cost is taken into account, it is impossible to determine a CGS’s start/stop (CGS unit commitment) in each time period alone.

Fig.3 shows optimum operation planning method based on heuristics.

First, assuming that a CGS operates all time period, the tentative operation plan is obtained which is called as “continuous operation case”.

Next, attention is paid to the time period when demand is the smallest, because the advantage of a CGS doesn't easily go out there. After stopping a CGS at this time period, the optimum operation plan is obtained again, and the total cost is calculated. This plan is a comparison one. The tentative plan and the comparison one are compared.

Here, when the cost decreases, a CGS stops at time period with next smallest demand, and the tentative plan is updated. The above-mentioned procedure is repeated until the cost increases, and the optimum operation plan is decided.

How to decide the operation plan is explained using a hospital as a customer. Fig.4 shows the continuous operation case. Pay attention at three o'clock when demand is the least. In the comparison plan, a CGS stops at three o'clock. Fig. 5(a) shows the cost comparison. In this example, the cost decreases when a CGS stops at three o'clock. So, a CGS stops at three o'clock. This plan is a new tentative one.

Then, pay attention at two o'clock when demand is the second smallest. The new tentative plan in which a CGS stops at two o'clock. It is compared again. From the result, a CGS stops at two o'clock in this example. A similar procedure is repeated.

Fig. 5(b) shows the example when the procedure ends. The cost is higher when a CGS stops at 22 o'clock. Therefore, CGS operates at 22 o'clock. For this judgment, a CGS should operate when the demand is larger than that at 22 o'clock, and this procedure ends.

This resulting plan is assumed to be an optimum operation plan.

A similar operation is done at winter and the middle period, and the optimum operation plan was calculated.

(b) Optimality check of facility plan

It is necessary to judge whether it is optimum or not because proposed planning method is based on heuristics. The total cost obtained by 4.2(a) is compared with the lower bound obtained by the following method, and its validity is confirmed.

In this paper, the lower bound is calculated by changing the fuel consumption characteristic of a CGS. Fig. 6 shows the comparison of CGS fuel consumption characteristics. (a) is applied to this optimization simulation. Instead of (a), (b) that passes the origin is applied to obtain the lower bound. As a result, it always gives smaller value for the optimum plan. Moreover, as it passes the origin, the unit commitment doesn't need to be taken into account. Thus the
lower bound is calculated. Table 4 shows the total cost comparison among the lower bound, the continuous operation case, and the optimum operation case. Here, the lower bound is assumed to be 100. And, it is shown that the optimum solution is very close to the lower bound. From this result, the proposed method gives a very appropriate plan.

**Fig. 3.** Optimum operation planning method algorithm.

<table>
<thead>
<tr>
<th>Hospital</th>
<th>Lower bound</th>
<th>Continuous operation case</th>
<th>Optimal operation case</th>
</tr>
</thead>
<tbody>
<tr>
<td>hospital</td>
<td>100</td>
<td>101.76</td>
<td>100.02</td>
</tr>
</tbody>
</table>

**4.3 Simulation Results**

Fig. 7 shows optimum operation result of a hospital with a CGS in summer. A CGS should stop during midnight. Cooling energy is supplied during daytime by a CGS and a boiler through an absorption refrigerator.

Fig. 8 shows the optimum operation result with the energy storage equipment. Operation of the battery can not be seen from the result. The ice storage and the hot water storage are seen from the result. This is because low charge electricity during midnight is used.

Table 5 shows the running cost, the facility annual cost, and the total cost. For both the CGS case and the energy storage case, the facility annual cost increases more than the base case without a CGS nor energy storage systems. On the other hand, the running cost over the year decreases. Moreover, both the total cost decreases from the base case. The energy storage case gives the largest cost reduction. On the contrary, the CGS introduction case gives the lowest operational cost over the year.
5. Consideration

5.1 CGS Introduction System

CGS has the advantage according to the simultaneous supply of electricity and heat. CGS start-up cost has to be recovered from the energy supply cost.

The advantage of the hot water storage decreases by time passage because of energy storage loss. So, large volume of hot water storage using CGS exhaust heat at midnight when the power demand is small is not beneficial. The start-up cost cannot be recovered and a CGS stops at midnight.

The cooling energy supply in summer places more emphasis on the turbo refrigerator and less on the absorption refrigerator. This reason is related to the facilities cost of the absorption refrigerator and the turbo refrigerator, and the electric demand charge.

In general, the running cost of the turbo refrigerator is lower compared with the absorption refrigerator, because COP of the turbo refrigerator is higher. And, the facility introduction annual cost of the turbo refrigerator is also lower.

Suppose that output of each equipment increases in daytime. As for the absorption refrigerator, the running cost and the facility cost increase. As for the turbo refrigerator, the electric demand charge as well as the running cost and the facility cost increase. For this reason, operation of the absorption refrigerator during daytime leads to more economic operation even if its COP is lower.

5.2 Energy Storage System

Operation of the battery can not be seen from the result. It is because facility introduction annual cost is high.

Stored energy in the ice storage and the hot water storage is discharged in daytime for load leveling.

In addition, the hospital generally has abundant demand of hot water through year. Therefore, the introduction advantage of the hot water storage is quite large.

6. Consideration

In this paper, optimum facility planning method has been proposed. From numerical simulation, the advantage of a CGS and each energy storage system has been made clear.

In optimization included facilities cost, the equipment with expensive cost like the battery doesn't have any benefit because its introduction cost exceeds reduction of operation cost. However, if its introduction cost becomes cheaper, its benefit will be realized in the future.

The followings are future issues to be tackled.

(1) A detailed study is necessary for different type customers because introduction advantage of a CGS and the energy storage systems is changed according to their demand characteristics.

(2) Optimum facility planning method including optimum capacity of a CGS has to be developed.
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Fig. 8. Energy storage case (hospital, summer).

References


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Masakazu Kato obtained Bachelor, Master and Doctor degree in 1977, 1979 and 1982 all from the University of Tokyo. He is engaged in R&D on energy systems, especially, electric power systems planning. He is now a professor of Tokyo Denki University.