Feasibility Study on Power Interchange Operation of Multiple Household Gas Engine Cogeneration Units by an Optimization Approach*

Tetsuya WAKUI**, Ryohei YOKOYAMA**, Itaru TAMURA*** and Akeshi KEGASA***

** Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
E-mail: wakui@ese.me.osakafu-u.ac.jp
***Energy Technology Laboratories, Osaka Gas Co., Ltd., 6-19-9 Torishima, Konohana-ku, Osaka 554-0051, Japan

Abstract
Household cogeneration systems have been increasingly utilized for energy saving; however, their energy-saving effect in Japan is not necessarily sufficient due to their operational restriction that electricity generated by them cannot be transmitted to commercial electric power systems due to the regulation. To relax the restriction, the authors propose power interchange operation of multiple household gas engine cogeneration units and investigate its feasibility from the energy-saving viewpoint by an optimization approach. In this power interchange operation, a micro-grid using the units is constructed in a housing complex; electricity generated by them is shared among households without transmitting to a commercial electric power system outside the housing complex so that the operating time of these units may increase. To evaluate the energy-saving effect of the power interchange operation, a numerical analysis of operational strategies by the mixed-integer linear programming is conducted for ten households and three types of household energy supply configurations: the power interchange operation of the gas engine cogeneration units, a stand-alone operation of each gas engine cogeneration unit, and conventional energy supply system without the gas engine cogeneration unit. A computational result clarifies the advantage of the power interchange operation from the energy-saving viewpoint over the other energy supply configurations.

Key words: Cogeneration, Gas Engine, Waste Heat Recovery, Thermal Storage, Power Interchange, Operational Planning, Optimization

1. Introduction

Cogeneration systems have been increasingly utilized for industrial and commercial applications because of their high energy-saving and economic efficiencies. Recently, their application has been extended to households because small-scale prime movers with high performance, including gas engines, fuel cells, and stirling engines, have been developed(1). Most of operating household cogeneration units adopt gas engines owing to their low cost and high reliability.

The energy-saving and CO₂ reduction effects by utilizing household gas engine cogeneration unit (H-GCGU) have been studied. Paepe et al. reported the energy-saving effect of 4.7 and 5.5 kW H-GCGUs that are operated at a detached house and terraced family house in Belgium(2). Cockroft and Kelly reported that an H-GCGU meeting the maximum heat demand in a household needs to operate with overall efficiency of more than 80% for

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energy saving\(^{(3)}\). Furthermore, Hawkes and Leach reported the CO\(_2\) reduction effect through an analysis of optimal operational strategy of a 2kW H-GCGU\(^{(4)}\). In these studies, the H-GCGUs can transmit surplus electricity to commercial electric power systems; thus, the H-GCGUs can operate to meet heat demand variations and do not need storage tanks. However, in Japan, electricity generated by household cogeneration units cannot be transmitted to commercial electric power systems by the regulation. Therefore, H-GCGUs for Japanese household are downsized and generate electricity at a rating of approximately 1 kW\(^{(5)}\), \(^{(6)}\). Nevertheless, these units can operate only when the electricity demand of each household exceeds the generated electricity at the rating because they must adopt on-off operation that implies either rated load operation or shutdown due to the inefficiency of their partial load operations\(^{(7)}\). Moreover, a storage tank must be installed for intermittent hot water supply under this operational restriction; however, heat loss from the storage tank is considerable when the operating period of the H-GCGU is much different from the high demand period of hot water. Therefore, its actual energy-saving effect in Japan is considered to underachieve. To overcome this problem, the capacity of the gas engine can be further reduced; however, this is not effective because generating efficiency of a smaller scale gas engine markedly decreases.

Based on this background, the authors propose power interchange operation of multiple H-GCGUs in a housing complex. In this operation, a power network by the H-GCGUs is considered as a micro-grid; that is, electricity generated by the H-GCGUs is shared among households in the housing complex without transmitting to an external electric power system. Because the surplus electricity generated at a household with little electricity demand can be transmitted to other households that have much electricity demand, the aforementioned operational restriction is relaxed. In addition, there is hardly any electric transmission loss due to the micro-grid system in the housing complex. Furthermore, each H-GCGU can also operate flexibly so that the heat loss from the storage tank may be decreased. Consequently, the power interchange operation is expected to increase their operating time and energy-saving effect.

Hence, this paper discusses the feasibility of the power interchange operation from the energy-saving viewpoint. To clarify theoretical limit of the energy-saving effect, operational strategies of multiple H-GCGUs are numerically analyzed by an optimization approach based on the mixed-integer linear programming. This feasibility study is conducted for ten households and three types of household energy supply configurations: the aforementioned power interchange operation of the H-GCGUs, stand-alone operation of each H-GCGU, which is only its operation permitted in Japan, and conventional energy supply system without the H-GCGU. This paper first presents the three types of household energy supply configurations. Then, a formulation for the optimal operational planning problem is described. Finally, through a numerical analysis of the operational strategies, the feasibility of the power interchange operation from the energy-saving viewpoint is clarified.

### 2. System Configurations

Figure 1(a) shows a schematic diagram of power interchange operation of H-GCGUs (IC). Each household in a housing complex installs a H-GCGU, a storage tank, and a gas-fired water heater. The solid, dash-dotted, and dotted lines in this figure show the flows of hot water, electricity, and natural gas, respectively. In this paper, electricity and hot water are considered as energy demands of the households because space cooling and heating are supplied by electric air conditioners installed in each household.

Electricity generated by each H-GCGU is synchronized with a grid through an inverter for voltage and phase conditioning. Thus, electricity is supplied to meet the electric demands of the households by operating the H-GCGUs and by purchasing electricity in bulk from an electric power company. Generated electricity is also provided to drive the auxiliary machine...
of the H-GCGU. In IC, electricity generated by the H-GCGUs is shared among the households in the housing complex so that their operating time may increase. However, the generated electricity is not transmitted to an electric power system outside the housing complex. Exhaust heat from both jacket cooling water and exhaust gas of the gas engine is recovered as hot water and stored in the storage tank. Hot water in the storage tank is not shared among the households and is independently supplied to each household. The H-GCGUs are not operated with a heat disposal from the energy-saving viewpoint. The shortage of hot water from the storage tank is supplemented by the gas-fired water heater.

This study also considers two other types of household energy supply configurations to evaluate the feasibility of IC. As shown in Fig.1(b), one is the stand-alone operation of each H-GCGU without the power interchange (SA). This is the only operation method of the H-GCGU permitted in Japan. The other is the conventional energy supply system without the H-GCGU (CO), as shown in Fig.1(c): electricity is supplied only by purchased one from an electric power company, and hot water is supplied only by the gas-fired water heater.

![Fig.1 Schematic diagram of three types of household energy supply configurations](image-url)
3. Optimal operational planning problem

The feasibility of IC from the energy-saving viewpoint is evaluated using an optimization approach based on the mixed-integer linear programming. That is, the operational strategies of the three types of household energy supply configurations including on-off and rated-partial load status of the operation of the system components, energy flow rates, and stored heat are determined in order to minimize primary energy consumption subject to the satisfaction of energy demand requirements.

3.1 Mathematical formulation

The housing complex investigated in this study has \(N\) households, and the index for the households is designated by \(n\), i.e., \(n = 1, 2, \ldots, N\). Moreover, to consider seasonal and hourly changes in the energy demands, a typical year is divided into \(M\) representative days with average and peak energy demands. The index for the representative days is designated by \(m\), i.e., \(m = 1, 2, \ldots, M\). Furthermore, each representative day is divided into \(K\) sampling times with a period of \(\Delta t\), i.e., \(\Delta t = 24/K\). The index for the sampling times is designated by \(k\), i.e., \(k = 1, 2, \ldots, K\). The operational strategy of a cogeneration system with a storage tank cannot be determined independently for each sampling time. Thus, the daily cyclic operation, which assumes that energy demands change cyclically with a period of 24 h on each representative day, is considered.

3.1.1 Decision variables

Decision variables are composed of binary and continuous variables. The binary variables express the on-off status of the operation of the H-GCGU of the \(n\)th household at the \(k\)th sampling time on the \(m\)th representative day. The continuous variables express the flow rates of the input and output energies of the system components and the stored heat in the storage tank in the same condition as that of the binary variables.

3.1.2 Objective function

The objective function to be minimized in this optimization problem is the total daily primary energy consumption of the intended households on each representative day from the energy-saving viewpoint. The definition of the total daily primary energy consumption depends on the household energy supply configurations. First, for IC, the objective function \(J_{IC}\) on the \(m\)th representative day is expressed by the following equation:

\[
J_{IC}(m) = \varphi_G \sum_{k=1}^{K} \left( \sum_{n=1}^{N} F_{GE}(n,k,m) \right) \Delta t + \varphi_E \sum_{k=1}^{K} \sum_{n=1}^{N} F_{GW}(n,k,m) \Delta t \\
(m = 1, 2, \ldots, M)
\]

where \(\varphi_G\) and \(\varphi_E\) denote the conversion factors for the primary energy consumption of natural gas and electricity, respectively; \(F_{GE}\) and \(F_{GW}\) denote the natural gas consumption of the H-GCGU and gas-fired water heater, respectively; and \(E_{P}^{I}\) denotes the electricity purchased in bulk. For SA, the objective function \(J_{SA}\) is expressed by the following equation:

\[
J_{SA}(m) = \varphi_G \sum_{k=1}^{K} \left( \sum_{n=1}^{N} F_{GE}(n,k,m) \right) \Delta t + \varphi_E \sum_{k=1}^{K} \sum_{n=1}^{N} E_{P}^{I}(n,k,m) \Delta t \\
(m = 1, 2, \ldots, M)
\]

where \(E_{P}^{I}\) denotes the electricity purchased individually at each household. For CO, the objective function \(J_{CO}\) is expressed by the following equation:

\[
J_{CO}(m) = \varphi_G \sum_{k=1}^{K} \sum_{n=1}^{N} F_{GW}(n,k,m) \Delta t + \varphi_E \sum_{k=1}^{K} \sum_{n=1}^{N} E_{P}^{I}(n,k,m) \Delta t \\
(m = 1, 2, \ldots, M)
\]
3.1.3 Constraints

The constraints in this optimization problem are the performance characteristics of the system components and energy balance and supply-demand relationships.

3.1.3.1 Performance characteristics of system components

As the first constraint equations, the performance characteristics of the system components are formulated as a relationship between the input and output energy flow rates.

(a) Gas engine cogeneration unit (H-GCGU)

The H-GCGUs adopt the on-off operation, which implies either rated load operation or shutdown\(^2\), \(^7\); this is attributed to the characteristic that the partial load operations of the small-scale gas engines are inefficient. Thus, the generated electricity \(E_{GE}\), heat flow rate of recovered hot water \(Q_{GE}\), natural gas consumption \(F_{GE}\), and electricity consumed by the auxiliary machine \(E_{aGE}\) are expressed as follows:

\[
\begin{align*}
E_{GE}(n,k,m) & = p_{GE}\delta_{GE}(n,k,m) \\
Q_{GE}(n,k,m) & = q_{GE}\delta_{GE}(n,k,m) \\
F_{GE}(n,k,m) & = r_{GE}\delta_{GE}(n,k,m) \\
E_{aGE}(n,k,m) & = s_{GE}\delta_{GE}(n,k,m) \\
\delta_{GE}(n,k,m) & \in \{0,1\}
\end{align*}
\]

where \(\delta_{GE}\) denotes the binary variable expressing the on-off status of the operation of the H-GCGU; the coefficients \(p_{GE}\), \(q_{GE}\), \(r_{GE}\), and \(s_{GE}\) denote the performance characteristic values.

(b) Storage tank

For the storage tanks, the heat balance relationship is considered by the following difference equation:

\[
\begin{align*}
\frac{S_{ST}(n,k,m) - S_{ST}(n,k-1,m)}{\Delta t} & = Q^{in}_{ST}(n,k,m) - Q^{out}_{ST}(n,k,m) - \eta_{L}\Delta t S_{ST}(n,k-1,m) \\
& \quad (n = 1,2,\cdots,N; \ k = 1,2,\cdots,K; \ m = 1,2,\cdots,M)
\end{align*}
\]

where \(S_{ST}\) denotes the heat stored in the storage tank; \(Q^{in}_{ST}\) and \(Q^{out}_{ST}\) denote the heat flow rates of hot water stored into and supplied from the storage tank, respectively; and \(\eta_{L}\) denotes the heat loss rate of the storage tank. Moreover, the heat stored in the storage tank is limited by its capacity \(\bar{S}_{ST}\) as follows:

\[
0 \leq S_{ST}(n,k,m) \leq \bar{S}_{ST} \\
\quad (n = 1,2,\cdots,N; \ k = 0,1,\cdots,K; \ m = 1,2,\cdots,M)
\]

Under the assumption that the storage tank is used cyclically with a period of 24 h, the heat stored at the initial state is equal to that at the terminal state at each household on each representative day\(^8\).

\[
S_{ST}(n,0,m) = S_{ST}(n,K,m) \quad (n = 1,2,\cdots,N; \ m = 1,2,\cdots,M)
\]

The heat stored at the initial and terminal states is determined from this constraint so that the sum of the daily hot water supply from the storage tank to the demand and the daily heat loss is equal to the daily hot water supply from the H-GCGU to the storage tank.

(c) Gas-fired water heater

For the gas-fired water heaters, the relationship between the heat flow rate of supplied hot water \(Q_{GW}\) and the natural gas consumption \(F_{GW}\) is expressed by the following equations:

\[
\begin{align*}
Q_{GW}(n,k,m) & = p_{GW}F_{GW}(n,k,m) \\
0 & \leq F_{GW}(n,k,m)
\end{align*}
\]

where the coefficient \(p_{GW}\) denotes the performance characteristic value.
3.1.3.2 Energy balance and supply-demand relationships

As the second constraint equations, the energy balance and supply-demand relationships are formulated with the energy flow rates illustrated in Fig.1. The hot water balance and supply-demand relationship are considered at each household. Thus, for IC and SA, the following equation is derived:

$$Q_{SW}^{\text{in}}(n,k,m) + Q_{GW}(n,k,m) = Q_{D}(n,k,m)$$

$$\quad (n = 1,2,\cdots,N; k = 1,2,\cdots,K; m = 1,2,\cdots,M)$$  \hspace{1cm} (9)

where $Q_{D}$ denotes the hot water demand at each household. For CO, the following equation is derived:

$$Q_{GW}(n,k,m) = Q_{D}(n,k,m)$$

$$\quad (n = 1,2,\cdots,N; k = 1,2,\cdots,K; m = 1,2,\cdots,M)$$  \hspace{1cm} (10)

The electricity balance and supply-demand relationship also depend on the household energy supply configurations. First, for IC, the electricity balance and supply-demand relationship are considered in the housing complex as follows:

$$E_{B}^{\text{in}}(k,m) + \sum_{n=1}^{N} E_{GE}(n,k,m) = \sum_{n=1}^{N} E_{D}(n,k,m) + \sum_{n=1}^{N} E_{GE}^{+}(n,k,m)$$

$$\quad 0 \leq E_{p}(k,m)$$

$$\quad \left( k = 1,2,\cdots,K; m = 1,2,\cdots,M \right)$$  \hspace{1cm} (11)

where $E_{D}$ denotes the electricity demand at each household. Second, for SA, the electricity balance and supply-demand relationship are considered at each household as follows:

$$E_{B}^{\text{in}}(n,k,m) + E_{GE}(n,k,m) = E_{D}(n,k,m) + E_{GE}^{+}(n,k,m)$$

$$\quad 0 \leq E_{p}(n,k,m)$$

$$\quad \left( n = 1,2,\cdots,N; k = 1,2,\cdots,K; m = 1,2,\cdots,M \right)$$  \hspace{1cm} (12)

Finally, for CO, the following equations are obtained:

$$E_{B}^{\text{in}}(n,k,m) = E_{D}(n,k,m)$$

$$\quad 0 \leq E_{p}(n,k,m)$$

$$\quad \left( n = 1,2,\cdots,N; k = 1,2,\cdots,K; m = 1,2,\cdots,M \right)$$  \hspace{1cm} (13)

3.2 Solution method

The problem formulated in the previous section results in a mixed-integer linear programming problem. This is solved by the GAMS (General Algebraic Modeling System)/CPLEX solver, which is a general solver that combines the branch and bound method with the simplex one\(^9\).

4. Numerical study

A numerical study on the feasibility of IC is conducted using the aforementioned optimization model. First, the input data for this optimization problem are described; then, the feasibility of IC is discussed through a numerical analysis of operational strategies.

4.1 Input data

The input data for this optimization problem are composed of the performance characteristics of the system components, household energy demands, and conversion factors for primary energy consumption.

The performance characteristic values of the system components are listed in Table 1. This study focuses on the commercial H-GCGU with the emphasis on practicality of this power interchange operation. Thus, these values are derived from Refs. (7) and (10) on the
commercial H-GCGU and our actual operating performance. The net generating efficiency and heat recovery efficiency of the H-GCGU and the water heater efficiency calculated using the higher heating value of natural gas are approximately 18%, 67%, and 80%, respectively. The H-GCGU must operate for approximately 2.3 h in order to fill the storage tank with hot water from the cold water state.

<table>
<thead>
<tr>
<th>Component</th>
<th>Performance characteristic value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas engine cogeneration unit</td>
<td>$p_{GE} = 1.0$ kWh/h</td>
</tr>
<tr>
<td></td>
<td>$q_{GE} = 3.7$ kWh/h</td>
</tr>
<tr>
<td></td>
<td>$r_{GE} = 0.443$ m$^3$/h</td>
</tr>
<tr>
<td></td>
<td>$s_{GE} = 0.075$ kWh/h</td>
</tr>
<tr>
<td>Storage tank</td>
<td>$S_{ST} = 8.36$ kWh</td>
</tr>
<tr>
<td></td>
<td>$\eta_s = 1.0$ %/h</td>
</tr>
<tr>
<td>Gas-fired water heater</td>
<td>$p_{GW} = 10.0$ kWh/(m$^3$/h)</td>
</tr>
</tbody>
</table>

The housing complex investigated in this study has ten households. The energy demands at the ten households are estimated at 24 sampling times for three representative days as shown in Table 2, i.e., $M = 3$, $K = 24$, and $\Delta t = 1$ h. The sampling period $\Delta t$ is specified based on the searching ability of the solver. However, it has a significant influence on the energy-saving effect of H-GCGUs obtained from the optimization model because household energy demands generally have fluctuations with short periods due to the use of appliances. Hawkes and Leach reported that CO$_2$ reduction effect of household cogeneration systems in SA is overestimated by analyses conducted using the sampling period of 1 h$^{(11)}$. Thus, the energy-saving effect of SA in this study may be also overestimated; however, it is considered that the overestimation of the energy-saving effect of IC is smaller than that of SA. This is because the fluctuation of electricity demand in each household is smoothed by evaluating the total electricity demand of the intended household, which becomes the electricity demand to each H-GCGU in IC. Hence, the energy-saving effect from IC to SA may be increased if the analysis conducted using a sufficient sampling period to evaluate the fluctuations is possible.

Fig.2  Energy demand characteristics of intended households
Table 2  Definition of representative days

<table>
<thead>
<tr>
<th>Day number $m$</th>
<th>Name of season</th>
<th>Estimated month</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Summer</td>
<td>August</td>
</tr>
<tr>
<td>2</td>
<td>Autumn</td>
<td>October</td>
</tr>
<tr>
<td>3</td>
<td>Winter</td>
<td>December</td>
</tr>
</tbody>
</table>

Table 3  Conversion factors for primary energy consumption

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>$\phi_E = 9.83$ MJ/kWh</td>
</tr>
<tr>
<td>Natural gas</td>
<td>$\phi_G = 45.0$ MJ/m$^3$</td>
</tr>
</tbody>
</table>

The electricity and hot water demands at the ten households have been measured by Tsuji et al.(12). The daily electricity and hot water demands and the heat to power demand ratio, which is defined as the ratio of the daily hot water demand to the daily electricity demand, are shown in Fig.2. Their demand characteristics are summarized as follows(13): the hourly electricity demands differ widely among the ten households on any representative day, and the period when the electricity demand exceeds the net generated electricity of the H-GCGU is limited at any household on any representative day; the hourly hot water demands are concentrated in the nighttime at any household on any representative day.

The conversion factors for primary energy consumption of electricity and natural gas are listed in Table 3. For electricity, the thermal power average conversion factor defined in the Act Concerning the Rational Use of Energy of Japan is introduced; this is calculated by considering thermal power generations as the power regulator to load variations.

4.2 Results and discussion

4.2.1 Effect of power interchange operation for three households

Typical operational strategies obtained by the aforementioned optimization model that well show the energy-saving effect by IC is discussed. First, the energy-saving effect of IC for three of intended ten households, which are called as House-1 to -3 for convenience, i.e., $N = 3$, is investigated.

![Fig.3 Typical optimal operational strategy for electricity supply in winter](image)

![Fig.4 Typical optimal operational strategy for hot water supply in winter](image)
Figures 3 and 4 show the optimal operational strategies for the electricity and hot water supply in winter, respectively; those in IC and SA are compared. The operational strategy for the electricity supply in IC shows the total electricity supply to the three households, and the other operational strategies show the energy supply only to House-3, which has the least daily electricity demand in the intended households, though the daily heat to power demand ratio is high. As shown in Fig.3(b), the H-GCGU at House-3 cannot be operated in SA because the electricity demand at House-3 is less than the net generated electricity of the H-GCGU throughout the day. Therefore, all hot water is supplied by the gas-fired water heater. On the other hand, the H-GCGU at House-3 in IC can operate for 4 h as shown in Fig.3(a) because IC relaxes the operational restriction of the H-GCGU in SA. In this case, most of hot water is supplied from the storage tank.

Figures 5, 6, and 7 show the optimal operational strategies for the electricity supply, hot water supply, and stored heat in the storage tank in autumn, respectively; those in IC and SA are compared. The operational strategy for the electricity supply using IC shows the total electricity supply to the three households, and the other operational strategies show the energy supply only to House-2, which has much electricity demand and little hot water demand. The H-GCGU at House-2 is operated for 1 h in either energy supply configuration due to little hot water demand. Thus, there is no difference in the daily purchased electricity. However, the operating period of the H-GCGU at House-2 significantly varies depending on the energy supply configurations. In SA, the H-GCGU at House-2 operates in the morning, which is the only period when the electricity demand exceeds the net generated electricity of the
H-GCGU. Since the hot water demand at House-2 is concentrated in the nighttime, much hot water is retained in the storage tank during the daytime. This causes much heat loss from the storage tank, which is proportional to the stored heat as shown in Eq. (5). Further, the hot water supply from the gas-fired water heater increases due to this heat loss. On the other hand, in IC, the storage tank retains the hot water only at the nighttime because of the shift of the operating period of the H-GCGU; thus, the heat loss from the storage tank in IC is less than that in SA. These operational strategies show that the daily natural gas consumptions at House-2 in IC and SA are 0.534 and 0.571 m$^3$/d, respectively. Hence, the difference in the operating period of the H-GCGU results in the reduction of the natural gas consumption for the gas-fired water heater in IC.

These operational strategies show that the introduction of IC can result in an increase in the operating time of the H-GCGUs and a decrease in the natural gas consumption for the gas-fired water heater compared to SA. Since energy demand patterns differ widely in households, the actual energy-saving by IC is achieved by intricately combining these two effects. Table 4 lists the computational result of the daily electricity purchased in bulk, and the total daily natural gas and primary energy consumptions of the three households on the three representative days for the three types of household energy supply configurations. By the introduction of the H-GCGUs (IC, SA), the total daily natural gas consumption of the three households increases on any representative day, whereas the daily electricity purchased in bulk decreases because of electricity generated by the H-GCGUs. As a result, the total daily primary energy consumptions in IC and SA are less than that in CO. Furthermore, the total daily primary energy consumption in IC is lower than that in SA owing to the aforementioned two effects.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Purchased electricity in bulk and total natural gas and primary energy consumptions at three households on representative days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>Energy supply configuration</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>IC</td>
</tr>
<tr>
<td></td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>CO</td>
</tr>
<tr>
<td>Summer</td>
<td>IC</td>
</tr>
<tr>
<td></td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>CO</td>
</tr>
<tr>
<td>Autumn</td>
<td>IC</td>
</tr>
<tr>
<td></td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>CO</td>
</tr>
</tbody>
</table>

4.2.2 Effect of increasing number of intended households

On the basis of the results for the three households, the energy-saving effect of increasing the number of intended households in IC is investigated.

Figure 8 shows the optimal operational strategy for the total electricity supply in winter using IC at five, seven, and ten households. For any number of intended households, i.e., $N = 3 - 10$, the operation of the H-GCGUs is concentrated in the nighttime when the hot water demands increase. Moreover, by analyzing the operational strategies for the hot water supply, it is confirmed that most of hot water is supplied from the storage tank at any household. Although the operation of the H-GCGUs is also restricted by the capacity of the storage tank, there is no operational strategy where the heat in the storage tank reached its capacity both in SA and in IC.
To evaluate the energy-saving effect of IC, Table 5 shows the reduction rates of the total daily primary energy consumption from CO to IC $\alpha_{IC/CO}$, that from SA to IC $\alpha_{IC/SA}$, and that from CO to SA $\alpha_{SA/CO}$ for four cases of the number of intended households. $\alpha_{IC/CO}$, $\alpha_{IC/SA}$ and $\alpha_{SA/CO}$ on the $m$th representative day are defined as follows:

$$\alpha_{IC/CO}(m) = \frac{J_{CO}(m) - J_{IC}(m)}{J_{CO}(m)} \times 100 \quad (m = 1, 2, \cdots, M) \quad (14)$$

$$\alpha_{IC/SA}(m) = \frac{J_{SA}(m) - J_{IC}(m)}{J_{SA}(m)} \times 100 \quad (m = 1, 2, \cdots, M) \quad (15)$$

$$\alpha_{SA/CO}(m) = \frac{J_{CO}(m) - J_{SA}(m)}{J_{CO}(m)} \times 100 \quad (m = 1, 2, \cdots, M) \quad (16)$$

Obviously, IC has a higher energy-saving effect than SA and CO on any representative day for any number of the intended households. The increase of $\alpha_{IC/CO}$ is outstanding in winter where the operating time of the H-GCGUs increases strikingly owing to much hot water demand, while $\alpha_{IC/SA}$ increases in autumn and winter. However, $\alpha_{SA/CO}$ is hardly influenced by the seasonal change in the energy demands. This is because the operating time of the H-GCGUs in SA does not increase even in winter with much hot water due to the aforementioned operational restriction. Furthermore, there is no definite correlation between the three types of the reduction rates and the number of the intended households. The

<table>
<thead>
<tr>
<th>Season</th>
<th>Reduction rate of total daily primary energy consumption $\alpha$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
</tr>
<tr>
<td>Comparative configuration</td>
<td>IC/CO</td>
</tr>
<tr>
<td>3 households</td>
<td>3.92</td>
</tr>
<tr>
<td>5 households</td>
<td>3.32</td>
</tr>
<tr>
<td>7 households</td>
<td>3.38</td>
</tr>
<tr>
<td>10 households</td>
<td>2.60</td>
</tr>
</tbody>
</table>

Fig.8  Optimal operational strategy for total electricity supply using IC in winter
aforementioned result of the operational strategy for the three households indicates that the energy saving by IC results from the increases in the operating time and flexibility of the operation of the H-GCGUs due to the relaxation of the operational restriction. Thus, this energy-saving effect is not affected by the number of the intended households but by the energy demand patterns of the intended households.

To clarify a dominant parameter to characterize the energy-saving effect of IC, the total daily heat to power demand ratio of the intended households (THPR) is calculated: THPR on the \( m \)th representative day is defined as the ratio of the total daily hot water demand of the intended households to their total daily electricity demand as follows:

\[
THPR(m) = \frac{\sum_{k=1}^{N} \sum_{n=1}^{K} Q_D(n,k,m) \Delta t}{\sum_{k=1}^{N} \sum_{n=1}^{K} E_D(n,k,m) \Delta t} \quad (m = 1, 2, \cdots, M)
\]

The arranged result of THPR from the energy demands is listed in Table 6. THPR varies depending on the season and the number of the intended households. The relationship between the three types of the reduction rates and THPR on the representative days is shown in Fig.9. Although it is generally considered that the energy-saving effect of cogeneration systems in SA is associated with the heat to power demand ratio, there is no correlation between THPR and \( \alpha_{SA/CO} \). This result indicates that the energy-saving effect of the H-GCGU in SA is strongly impacted by the operational restriction due to the electricity demand. On the other hand, \( \alpha_{IC/CO} \) increases almost linearly with THPR; therefore, the energy-saving effect by introducing IC can be evaluated using THPR in the range of THPR lower than the heat to

<table>
<thead>
<tr>
<th>Total daily heat to power demand ratio THPR kWh/kWh</th>
</tr>
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<tbody>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>3 households</td>
</tr>
<tr>
<td>5 households</td>
</tr>
<tr>
<td>7 households</td>
</tr>
<tr>
<td>10 households</td>
</tr>
</tbody>
</table>

Fig.9  Relationship between reduction rates of primary energy consumption and total daily heat to power demand ratio of intended households
power supply ratio of the H-GCGU (3.7). It is considered that the hot water supply from the gas-fired water heater is increased in a demand with THPR higher than 3.7. $\alpha_{IC/SA}$ tends to increase with THPR; however, there is no clear correlation between $\alpha_{IC/SA}$ and THPR. Since the relaxation of the operational restriction by IC is affected by the energy demand patterns of the intended households, a detailed analysis of the energy demand patterns is required to investigate a dominant parameter to characterize $\alpha_{IC/SA}$ that is the criterion to determine the energy supply configuration using the H-GCGU.

5. Conclusions

The feasibility of a power interchange operation of multiple household gas engine cogeneration units in a housing complex from the energy-saving viewpoint has been investigated by an optimization approach. In the power interchange operation, electricity generated by the gas engine cogeneration units is shared among households in the housing complex without transmitting to an external electric power system. A numerical analysis of operational strategies by the mixed-integer linear programming has been conducted for ten households and three types of household energy supply configurations: the power interchange operation of the gas engine cogeneration units (IC), stand-alone operation of each gas engine cogeneration unit (SA), and conventional energy supply system without the gas engine cogeneration unit (CO). The results obtained in this study are summarized as follows:

- IC, which relaxes the operational restriction in SA due to the electricity demand of each household, increases the operating time of the gas engine cogeneration units and enables their operation so that the heat loss from the storage tank may be decreased.
- IC is the most effective in the energy saving among the three types of household energy supply configurations in any season for any number of the intended household.
- The energy-saving effect from CO to IC increases with the total heat to power demand ratio of the intended households in the range of the total heat to power demand ratio lower than the heat to power supply ratio of the gas engine cogeneration unit.
- The advantage of IC over SA from the energy-saving viewpoint is affected by the energy demand patterns of the intended households.

These results clarify the feasibility of the power interchange operation of the gas engine cogeneration units in the housing complex with high energy-saving effect in the area where electricity generated by household cogeneration units cannot be transmitted to commercial electric power systems. In the future, the authors will conduct a feasibility study for more intended households and investigate a dominant parameter to characterize the energy-saving effect of the power interchange operation against the stand-alone operation through a detailed analysis of the energy demand patterns of the intended households. Furthermore, the optimal capacity of the household gas engine cogeneration unit for SA and IC will also be investigated for higher energy-saving effect.

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Abbreviation

CO : Conventional energy supply system  
H-GCGU : Household gas engine cogeneration unit  
IC : Power interchange operation of household gas engine cogeneration units  
SA : Stand-alone operation of each household gas engine cogeneration unit  
THPR : Total daily heat to power demand ratio
References


