The Effects of Fuel Price and System Efficiency on Cost and Energy Savings in a Distributed Energy System

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Abstract
This paper presents a simple model of a distributed energy system, which was introduced in the Kitakyushu Science and Research Park, in order to evaluate the energy saving and operating characteristics of the distributed generation system. We analyzed the effects of fuel price and equipment efficiency on the operating time, running cost and energy saving. The increase of electricity price and decrease of gas price will enhance the attractiveness of the distributed energy resource. According to the load function of the system, energy-saving and environmental improvement will have a maximum value at its optimal operating time. Compared with heat recovery efficiency, power generation efficiency has more influence on energy saving and CO\(_2\) reduction when total efficiency of the system is assured.

Keywords: distributed energy system; fuel price; system efficiency; energy saving; GAMS

1. Introduction
In recent years, as a supplement to conventional large-scale power, distributed energy resources (DER) have gained more attention. This interest is based on the vision that future electric power systems will not be built solely as centralized systems as they are today. DER can also reduce transmission losses and grid investments. One possible alternative to the traditional paradigm is the microgrid (μGrid)\(^1\), a local network of DER matched to local energy requirements. This framework could provide a more hospitable environment for DER, such as renewables (wind, solar) and co-generation, also known as combined heat and power (CHP) than that offered by traditional centralized power systems.

In previous research, Marnay (2000)\(^1\) developed the Distributed Energy Resources Customer Adoption Model (DER-CAM) to minimize the cost of supplying energy services to a customer by optimizing the installation of distributed generation and the self-generation of part or all of its electricity. At the same time, Lasseter (2002)\(^2\) introduced the microgrid concept proposed by the Consortium for Electric Reliability Technology Solutions (CERTS), which serves as an alternative approach to integrating small scale distributed energy resources (DER of < 500 kW) into electricity distribution systems. Zhou (2004)\(^3\), GAO (2004)\(^4\) reported the possibility of introducing DER technology in various buildings in Japan by using the DER-CAM model. Demonstration of the microgrid concept started in 2004 when the New Energy and Industrial Technology Development Organization (NEDO) introduced a small-scale DER at the 2005 World Exposition, Aichi and at Hachinohe City\(^5\).

In order to promote the application of DER, it is necessary to make clear what the benefits of DER are under certain fuel price systems and how the efficiency of distributed energy technology affects cost and energy saving. Yanagi (2002)\(^6\) studied the effects of energy demand characteristics of a building on the scale and operation of a cogeneration system. Wei (2002)\(^7\) tried an optimization of the heat supply system in the new heat supply area of the Tokyo station area.

In this paper, we present a simple model for the distributed energy system which was introduced in Kitakyushu Science and Research Park (KSRP). We use the General Algebraic Modeling System (GAMS)\(^8\) to find the optimal solution to a distributed energy system. For a GAMS outline, please refer to Note 1.

As shown in Fig.1., the energy center at KSRP contains a fuel cell, a gas engine and a PV system; all were installed in 2001. In this study, we analyze the effects of fuel price and equipment efficiency on operating time, the operating cost, and energy savings.

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2. Optimal Model of Distributed Energy Resource

2.1 Outline of the system

In this paper, the energy center at KSRP is assessed and its energy supply system is shown in Fig.1. A fuel cell (200kW), gas engine (160kW) and PV (153kW) system have been installed to supply the electricity for end-use at KSRP, while the insufficient electricity was provided by the utility electricity. The energy system not only supplies electricity, but can also recover exhaust heat by heat exchanger and supplying an absorption chiller.

Table 1 shows details of the nominal power generation and heat recovery efficiencies of the fuel cell and gas engine. Gas engine capacity is 160kW with a nominal generating electricity efficiency of 28.7% and a heat recovery efficiency of 47.7% for one circuit with a high temperature of 90°C. Fuel cell capacity is 200kW with a nominal electrical power production efficiency of 40% and a heat recovery efficiency of 20% for both circuits, one at a high temperature of 90°C and another at 50°C. The fuel cell ran for 24 hours except for some special periods, such as maintenance and repair of equipment or national holidays. The gas engine was designed to run from 8 am to 10 pm generally, but changed with the demand of electricity consumption.

2.2 Hypothesis of system

Several hypotheses follow.

1) The primary benefit of DER comes from reduced electricity and gas consumption.
2) Because electricity demand is larger than the capacity of the distributed KSRP system, no electricity is sold back to the grid.
3) The total power generated by DER supplies KSRP consumers only.
4) When demand exceeds supply, more power is purchased from the power company.
5) Price and function of equipment are based on the data that manufacturers provide. Installation and other cost are not considered in the investment.
6) The supply reliability, quality, and the scale merit of running cost due to the capacity difference of the same equipments are not considered in the economic analysis.

2.3 Objective Function

In this paper, optimality is based on minimizing the DER system operation cost. DER cost during the life cycle includes investment, maintenance cost, running cost, and fuel cost of DER. Referring to Fig.2., the total cost can be expressed by the following formula:

Expression 1 is objective function, which can minimize cost. The item of this expression is composed of the following four factors: 1) initial investment 2) labor costs and cost of operation 3) cost of purchased power (basic charge and unit rate) 4) cost of purchased gas (basic charge, unit rate and contract rate). The character of i and m represent the day and the month, and j is the time. The other parameters are explained in Table 2.
2.4 Constraint conditions

The objective function must satisfy the following constraints such as the balance of heating supply and need.

\[
\sum_{t} E_{\text{load}}(i,t) \leq \sum_{t} E_{\text{max}}(i,t) + \sum_{t} Q_{\text{ge}}(i,t) \times \eta_{\text{ge}}^c + \sum_{t} Q_{\text{xc}}(i,t) \times \eta_{\text{xc}}^c
\]

\[
\sum_{t} H_{\text{load}}(i,t) \leq \sum_{t} Q_{\text{ge}}(i,t) \times \eta_{\text{ge}}^p + \sum_{t} Q_{\text{xc}}(i,t) \times \eta_{\text{xc}}^p
\]

\[
E_{\text{load}}^\text{MAX} \leq E_{\text{GE}}^\text{MAX} + E_{\text{FC}}^\text{MAX} + E_{\text{PV}}^\text{MAX} + E_{\text{RYE}}
\]

Expression 2 shows the balance in the power demand and supply, and the expression 3 shows the balance in the heat demand and supply. Expression 4 means the demand must be less than the supply in the current model.

3. Case Description and Setting of Database

3.1 Case description

In this paper, three cases for the energy center of KSRP were discussed:

Case 1: The change of fuel prices (gas and power). In this case, we investigated the effect of fuel prices on the operating schedule and found out when the system reaches its optimal economical point.

Case 2: The change of operating schedule of the distributed system. In this case, we tried to clarify the effect of running time on the cost and energy saving.

Case 3: Change of energy efficiency. In this case, we analyzed how efficiency affects cost and energy saving.

For purposes of comparison, a conventional energy-supply system is shown in Fig.3. In the conventional system, a boiler is used to supply heating energy and a steam absorption chiller is used to supply cooling energy by a district heating/cooling system. The basic parameters of the equipment and the emission of CO₂ are assumed as shown in Table 3.

3.2 Setting of demand and system

In this study, hourly electricity and heat load for 8,760 hours of the year 2003 were used.

Table 2. List of Parameters

| Title          | Item                  | Units |
|----------------|-----------------------|-------|
| H_{\text{load}} | Heat load             | kW    |
| E_{\text{load}} | Electricity load      | kW    |
| Q_{\text{ge}}  | Fuel consumption of gas engine | kW   |
| \eta_{\text{ge}} | Generating efficiency of gas engine | %    |
| \eta_{\text{xc}} | Heat recovery efficiency of gas engine | %    |
| Q_{\text{pc}}  | Fuel consumption of fuel cell | kW |
| \eta_{\text{pc}} | Generating efficiency of fuel cell | % |
| \eta_{\text{bc}} | Heat recovery efficiency of fuel cell | % |
| Q_{\text{bc}}  | Fuel consumption of boiler | kW |
| \eta_{\text{bc}} | Heat efficiency of boiler | % |
| E_{\text{grid}} | Power purchased from the grid | kW |
| E_{\text{PV}}  | Power generated by PV  | kW |
| E_{\text{contract}} | Contracted power with the grid | kW |
| E_{\text{max}} | Maximum of electricity load | kW |
| E_{\text{PC}}  | Power capacity of PV   | kW |
| E_{\text{PC}}  | Power capacity of fuel cell | kW |
| E_{\text{max}} | Power capacity of gas engine | kW |
| C_{\text{base}} | Monthly base fee of electricity | Yen/kW |
| C_{\text{elec}} | Volumetric fee of electricity | Yen/kWh |
| C_{\text{gas}}  | Contracted quantity of gas | m³ |
| C_{\text{base}} | Natural gas basic service fee | Yen/m³ |
| C_{\text{base}} | Monthly basic fee of natural gas | Yen |
| C_{\text{base}} | Volumetric fee of natural gas | Yen/m³ |
| C_{\text{base}} | Natural gas heat rate | kWh/m³ |
| SerCost        | Administrative and maintenance fee | Yen |
| InMe           | Initial Investment | Yen |
| InMeRate       | interest rate | % |
| life           | Life cycle year of equipment | Year |

Table 3. Basic Parameters of the Equipment

| Equipment of the utility generating electricity | Gas boiler | Absorption chiller | Electricity for the utility(KWh-C/kWh) | Natural gas(Kg-C/kWh) |
|------------------------------------------------|------------|-------------------|--------------------------------------|----------------------|
| Efficiency                                      |            |                   | 0.104                                | 0.584                |

The fuel cell runs at 200kW for 24 hours because restarting would take a long time and waste energy. Power generated by the fuel cell can be treated as a constant. The power produced by PV varies with the solar radiation. In this study, we used the actual values of PV generation in 2003.

3.3 Setting of fuel price and technology efficiency

In this study, the electricity price was taken from Kyushu Electric Power Company tariffs shown in Fig.4. Electricity price consists of a basic charge, a daytime volumetric rate, a night volumetric rate and a peak volumetric charge. In this research we mainly analyze the effect of electricity price when the volumetric rate of electricity changes.

Fig.5 shows the system of gas prices in Japan. Generally, a basic charge is made up of a gas service fee, fixed fee and maximum season basic charge. As in the electricity price, we mainly analyze...
the effect of gas price when the volumetric rate of gas changes.

In the case of gas engine efficiency, we set the power generation efficiency and heat recovery efficiency change in the range of 30% to 45%.

4. Analysis of Simulation Results

4.1 Effects of fuel prices

In this section, we changed the gas and electricity prices to investigate the effects on the DER operation through solving expression 1 with the constraint condition by GAMS.

Case 1 is the effects of fuel price on the operating condition of the DER system when gas and electricity price were changed respectively. In this distributed generation system, as assumed, the fuel cell operates for 24 hours every day at 200kW. Therefore, only the gas engine follows load.

Based on a simulation of minimizing the cost of running a DER system, Fig.6 shows the relationship between the electricity price and operating time of a gas engine. It can be found that with the gradual rise of electricity price, the operating time of a gas engine increases from 0 hour to 8,760 hours for one year. At the present price (shown in Fig.4.), the optimal operating time is about 4,132 hours for one year, which is close to the current operating time (4,745 hours). This can be attributed to the structure of electricity price. Electricity price in the night-time is half that of the daytime. On the other hand, the gas price does not vary in one day. Therefore, it would be economical to stop the gas engine from 10 pm to 8 am while we can use the cheap electricity from the grid during that time.

From the economic point of view, we can see the optimal operating time for a gas engine should be from 8 am to 10 pm every day. As the electricity price increases, the competitiveness of DER technologies becomes stronger. For instance, operating time of the gas engine will reach 5,801 hours, when the electricity price is increased by 5% compared with the present price. Also, if the electricity price is increased by 20%, the operating time will grow to 6,774 hours. In contrast, it is difficult to introduce DER economically when the electricity price is at a lower level.

Fig.7 shows the relationship between the gas price and operating time of the gas engine. Compared with the price of electricity, influence of the gas price will show a reverse result. When gas price rises, the DER will lose its attractiveness based on the economic consideration. On the other hand, decrease in gas price will increase the operation time of the gas engine. There is a turning point to reach at the optimal. For example, when the gas price changes from 0% to 40%, there is no change in the operation time, which implies that if gas companies increase the price to some extent, the DER still makes sense.

4.2 Effects of operating time

Fig.8 shows the relationship between gas engine operating time and energy-savings for the current fuel price systems. With the increase of operating time, the energy-savings, compared to conventional energy system, are increased and reach a maximum value. After the point of maximum value, the energy saving will decrease with an increase in the operating time. This is probably because the recovered heat has not been utilized completely, which is decided by the load function of the demand site. From the point of view of energy-saving, Fig.8 shows that the best operation time is about 4,333 hours. Compared to the conventional energy system, in which there is no distributed generation system, the DER system can gain about 6.46% energy saving at its maximum in the KSRP case.
As for environmental impact, Fig. 9. shows the relationship between gas engine operating time and CO$_2$ reduction. It is almost the same as the energy-saving shown in Fig. 8. Compared to the conventional energy system, the DER system reduces CO$_2$ up to a maximum of 3.99% at its optimal running time, but CO$_2$ will increase when the operating time is more than about 7,000 hours. The reason is that waste heat has not been utilized and as a result, total efficiency will be lower than the average of power plants in Japan.

The profile of economic efficiency is also the same as energy-saving, just as Fig. 10. shows, the best operating time is approximately 4,500 hours and compared with the conventional system, has a maximum of 1.88%. It is not economical when the gas engine runs for the whole year.

### 4.3 Effects of the efficiency of the gas engine

Case 3 concerns the effects of energy-saving and environmental improvement when efficiency of the gas engine changes. Gas engine efficiency includes power generation efficiency and exhaust heat efficiency. Generally, with the increase of efficiency, the rate of energy saving will be increased at the same time, as shown in Fig. 11.

Compared with heat recovery efficiency, power generation efficiency has more influence on energy saving. For example, if the system has a total efficiency of 80%, energy saving in the case with power generation efficiency of 45% and heat recovery efficiency of 35% is larger than that of the case with power generation efficiency of 30% and exhaust heat efficiency of 50%. In Fig. 10., the dotted line shows this result.

Fig. 12. shows the relationship between efficiency of the gas engine and CO$_2$ decrease. Although the profile is almost the same as Fig. 10., the discharge amount of CO$_2$ will increase if the power generation efficiency is lower than 30%.

### 5. Conclusion

This paper presents a simple model for the distributed energy system introduced in Kitakyushu Science and Research Park in order to evaluate the energy saving and running characteristics of a distributed generation system. We analyzed the effects of fuel price and equipment efficiency on the operation time, running cost and energy saving.

The results can be summarized as follows:

1) For the current system, optimal operating time of the gas engine is about 4,132 hours for one year, and the gas engine should run from 8 am to 10 pm.
2) We quantitatively investigated the effects of the fuel price on the operating time. The increase of electricity price and decrease of gas price will increase the attractiveness of distributed energy resource.

3) According to the load function of the system, energy-saving and environmental improvement will have a maximum value at its optimal operating time.

4) Compared with heat recovery efficiency, power generation efficiency has more influence on energy saving and CO$_2$ reduction in cases in which total efficiency of the system is assured.

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Note 1 Outline of GAMS

Generally speaking, GAMS is a high-level modeling system for mathematical programming and optimization. The actual mathematical program is modeled via user-defined algebraic equation. GAMS then compiles them and applies standard solvers to the resulting problem. The features can be mainly described as follows:

1) GAMS lets the user concentrate on modeling. By eliminating the need to think about purely technical machine-specific problems such as address calculations, storage assignments, subroutine linkage, and input-output and flow control, GAMS increases the time available for conceptualizing and running the model, and analyzing the results.

2) Using GAMS, data are entered only once in familiar list and table form. Models are described in concise algebraic statements which are easy for both humans and machines to read.