

STUDY ON IMPROVEMENT IN EFFICIENCY OF PARTIAL LOAD DRIVING OF INSTALLING FUEL CELL NETWORK WITH GEOTHERMAL HEAT PUMP

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ABSTRACT

Hydrogen piping, the electric power line, and exhaust heat recovery piping of the distributed fuel cells are connected with network, and operational planning is carried out. Reduction of the efficiency in partial load is improved by operation of the geo-thermal heat pump linked to the fuel cell network. The energy demand pattern of the individual house in Sapporo was introduced. And the analysis method aiming at minimization of the fuel rate by the genetic algorithm was described. The fuel cell network system of an analysis example assumed connecting the fuel cell co-generation of five houses. When geo-thermal heat pump was introduced into fuel cell network system stated in this paper, fuel consumption was reduced 6% rather than the conventional method.

Key Words: *fuel cell, heat pump, energy network system, partial load operation.*

1 INTRODUCTION

The analysis which distributes small-scale fuel cell cogeneration in a house is performed even in Japan (Hirata 2001 and Hamada et al 2003). When introducing the system into cold region houses, a back-up heat device other than fuel cell exhaust heat is required. Considering the betterment of an environmental problem which is the objective of fuel cell cogeneration, it is necessary to consider introduction of an electric heat pump system. However, in order to operate heat pump with the electric power generated with the fuel cell, the electric-power-generation capacity of several kilowatts is required. With the fuel cell of the large power generation capacity, if load following operation is performed, the partial load operation of low effectiveness will appear frequently. So, in this paper, the operating point of a fuel cell is shifted to a high efficiency point by operating heat pump, when the operational condition of a fuel cell is a partial load with low efficiency. Thermal storage of the heat outputted by heat pump is carried out, and time is shifted and outputted. Moreover, it is difficult from a point of cost to install energy devices, such as fuel cell cogeneration, heat pump, and a heat storage tank, into one house. In order to reduce equipment cost, it examines connecting by network and using the fuel cell cogeneration introduced into two or more individual houses. Heat pump, a heat storage tank, and a city-gas reformer are installed in the machinery room of the arbitrary houses on a network. Moreover, the hydrogen fuel system and output power system of fuel cell cogeneration (an electric power line and hot-water piping) to distribute are connected with the fuel-cell-network. Cooperation operation of the equipments linked to a network is carried out under the objective function given beforehand. Furthermore, as an analysis example, the fuel cell network system is applied to five individual houses of the cold-region city in Japan, and an operation plan is analyzed.

2 THE FUEL CELL CGS NETWORK MODEL, AND ENERGY AND SUBSTANCE BALANCE

2.1 The Network Model

The network model of the fuel cell CGS installed in individual houses, as assumed in this paper, is shown in Figure 1. The fuel cell CGS installed in each house is connected with hydrogen gas system piping, oxygen gas system piping, an electric system power line, and hot water piping of an exhaust heat system. The generation of hydrogen gas by water electrolysis and oxygen gas is possible for all fuel cells linked to the network. The hot water system performs heat recovery from fuel cells and supplies thermal energy to each house. Hot water flows in the one direction, as shown by the arrows in Figure 1. The

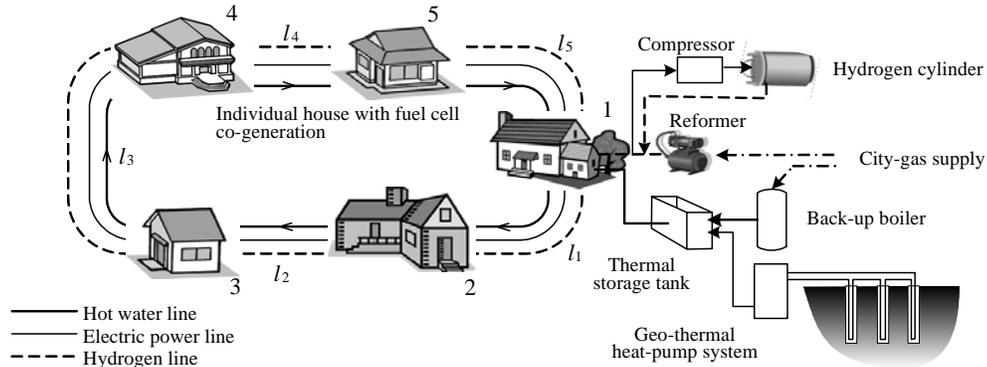


Figure 1 Fuel cell network system model

cylinders which store hydrogen gas and oxygen gas are installed in the machinery room of house 1, and both gases are generated when carrying out water electrolysis operation of the fuel cells linked to the network. Both gases are assumed to be pressurized to 1.0MPa with compressors and then stored in the cylinders. The city gas reformer is also installed in the machinery room, and hydrogen gas can be supplied to the network at arbitrary times. On the other hand, it is necessary to synchronize the operation of a fuel cell and a reformer for a system that combines a single fuel cell and a single reformer, as in a conventional system. Moreover, the standby time taken up by the reformer prior to starting and stopping, and the poor follow-up characteristics at the time of a load change, are problems. The network system has a specific method of storage of the hydrogen gas and the oxygen gas, and for connecting the fuel cells to the reformer through the network. Therefore, the fuel cells and the reformer can be independently employed. A thermal storage tank, a geo-thermal heat pump, and a back-up boiler can also be installed in the machinery room, and heat can be supplied to each house at arbitrary times through the hot water system network.

2.2 The Improvement-in-Efficiency Measure of Partial Load

Figure 2 shows the network models for the electric power line and the hot water line. The variables, which indicate the efficiency of each electric power and thermal energy device, are described in Figure 2. The power generation efficiency $\phi_{Conv,t}$ of the conventional system (combination of single fuel cell and single reformer) in the sampling time t ($= 0, 1, 2, \dots, R$, operation period of the system which determined R beforehand) is the product of the power generation efficiency $\phi_{f,m,t}$ of the fuel cell and the efficiency $\phi_{r,t}$ of the reformer which supplies hydrogen gas and air. Since the reformed gas produced by the reformer is pressurized with a compressor and it stores in a cylinder, the electric power consumption in a compressor is taken into consideration. The heat storage tank is prepared in the hot-water system of the fuel-cell-network, when heat balance is negative, heat is outputted from a heat storage tank, and in being excessive, it carries out thermal storage ($H_{s,t'}$). Here, subscript t' expresses the arbitrary time containing

the sampling time t . If heat balance is negative even if it supplies the thermal output in a heat storage tank to a network, heat supply by geo-thermal heat pump will be performed at thermal efficiency $\phi_{g,t}$. On the other hand, the thermal output in the back-up boiler by efficiency $\phi_{b,t}$ can also be chosen. This is the case where the operation methods in $\phi_{Net,t}$ exceeding $\phi_{Conv,t}$ exists, when the value of $\phi_{Conv,t}$ falls by partial load operation.

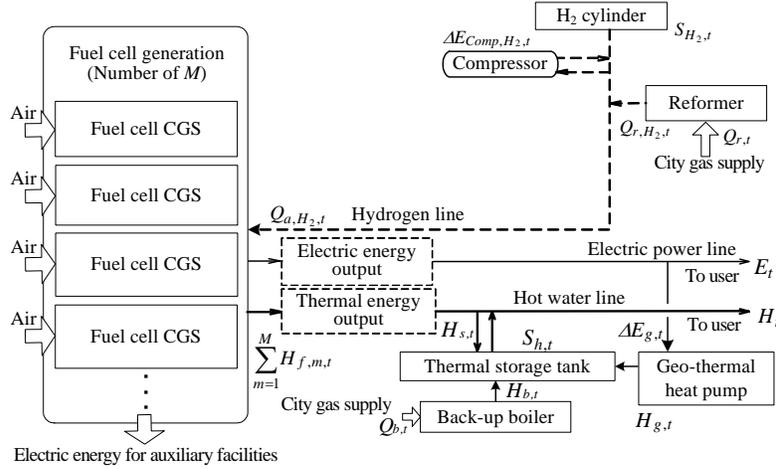


Figure 2 Energy flow

2.3 Energy and Substance Balance

The electric power balance in the sampling time t is shown by the following equation of the fuel cell CGS network system, constituted from fuel cells which perform M sets of power generation.

$$\sum_{m=1}^M E_{f,m,t} = E_t + \Delta E_{g,t} + \sum_{q=1}^V \Delta E_{sub,q,t} \quad (1)$$

The left side of this equation expresses the gross total power output of the DC-AC converter, of M sets of fuel cells which carry out the power generation operation. The 1st term of the right-hand side is the supply to houses through the network based on demand, the 2nd term represents the power consumption for the operation of the geo-thermal heat pump are performed, and the 3rd term expresses the power consumption of V sets of the auxiliary machines (pump in the hot-water system network, compressors of hydrogen and oxygen gases, etc.) for maintaining the network.

Furthermore, the heat balance of the system can be shown to be the following equation.

$$\sum_{m=1}^M H_{f,m,t} + H_{S,t} + H_{g,t} + H_{b,t} = H_t + \sum_{i=1}^M \Delta H_{f,i,t} \quad (2)$$

The left side is the overall heat output of the system. The 1st term expresses the heat output by M sets of fuel cell CGS, the 2nd term expresses the heat output of the thermal storage tank, and the 3rd and 4th term expresses the heat output of the geo-thermal heat pump and backed boiler. The right-hand side expresses consumption of heat, wherein the 1st term is the heat output supplied to a house based on demand through the heat system network, and the 2nd term expresses heat loss from the heat system network (i.e. the hot-water piping). This quantity is proportional to the distance l_{i-k} from the house (number i) which carries a heat output to the house (number k) which receives a supply of heat from the network, and is defined by equation (3) shown below.

$$\sum_{i=1}^M \Delta H_{f,i,t} = \varepsilon \cdot H_{f,i,t} \cdot l_{i-k} \quad (3)$$

ε in this equation is a coefficient based on the quantity of heat loss per unit length of hot water piping which, in the case study in section 5, assumes that thermal insulation material is used for keeping the general piping warm, and a temperature difference between hot water and outside air is assumed to be 330K and ε is given by 15 W/m.

Equation (4) shows the hydrogen balance in the system. The 1st term on the left side is the quantity of hydrogen gas flow supplied by the cylinder, and the 2nd term expresses the quantity of hydrogen gas generation of the reformer. The right-hand side expresses the amount of hydrogen gas consumed by M sets of the fuel cells which carry out power generation. The equation for oxygen gas balance in the system is very similar to equation. (4).

$$Q_{a,H_2,t} + Q_{r,H_2,t} = \sum_{m=1}^M Q_{f,m,H_2,t} \quad (4)$$

The total quantity of the city gas $Q_{c,t}$ supplied to $t+1$ from the sampling time t in the system is shown in equation (5). The quantity of city gas consumed by the reformer and the backed boiler ($Q_{r,t}$ and $Q_{b,t}$, respectively) are added, and $Q_{c,t}$ is estimated.

$$Q_{c,t} = Q_{r,t} + Q_{b,t} \quad (5)$$

2.4 The Objective Function of the System, and Calculation of the Fitness Value

The objective of the analysis is to search for an operation pattern with minimum city gas consumption of the system for an operational period from $t=0$ to R . Therefore, the operational planning represented by the value in the parenthesis of equation (6) should be smaller for a better solution. The genetic algorithm which is one of the optimization techniques is introduced, and an operational planning is performed. The optimization analysis in the genetic algorithm described in section 4 is also a solution with a high degree of the fitness value of the genetic algorithm.

$$\text{minimize} \left(\sum_{t=0}^R Q_{c,t} \right) \quad (6)$$

3 DEVICE CHARACTERISTICS AND RELATIONAL EXPRESSION

3.1 The output characteristics of the fuel cell CGS

Figure 3 shows the results of performance measurement of the test fuel cell. The electrode surface product of a fuel cell shall be set to 6m^2 , and maximum power output shall be 6.2kW. Figures 5(a) show the relationship between the rate of load and power generation gross efficiency when supplying air and oxygen gas.

3.2 The Output Characteristics of the City Gas Reformer

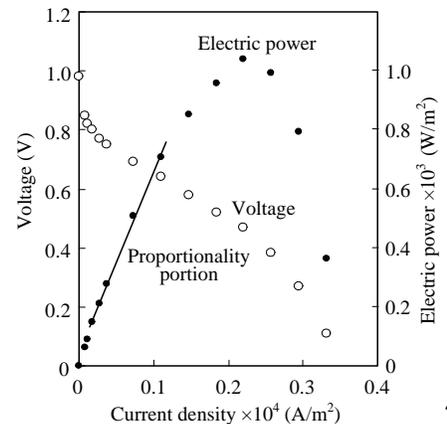


Figure 3 Cell performance

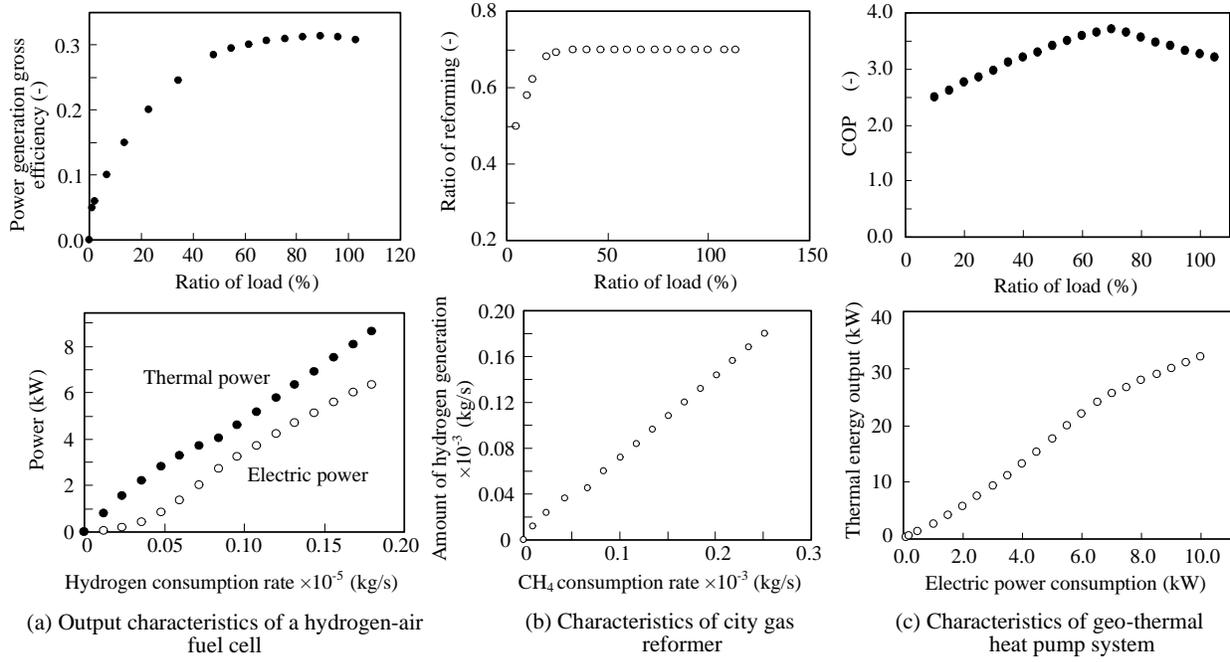


Figure 4 Characteristics of equipments performance

The output characteristics of the city gas reformer under development are shown in Figure 4(b). The upper plot in Figure 4(b) shows the relationship between the ratio of load and ratio of reforming. The rate of load efficiency of the reformer is low due to partial loading at about 25% or less. On the other hand, the rate of load efficiency shows a stable rated output at 25% or more. The lower plot of Figure 4(b) is the relation between the quantity of consumption of the city gas (methane gas is assumed in this paper) and the quantity of hydrogen generation of the reformer (Lindstroem et al. 2003 and FISITA 2000).

3.3 The Characteristics of Storage of Hydrogen Gas and Oxygen Gas

Hydrogen and oxygen gases generated during the water electrolysis operation of the fuel cells, and the hydrogen gas generated by the reformer are pressurized and stored in cylinders. The work of the compressor in this case is assumed to be compressive work using an ideal gas, and is calculated by equation (8). Here, ϕ_c expresses the whole compressor efficiency including inverter controller loss, the power consumption in an electric motor, power transfer loss, loss with insufficient air leaks, cooling loss, and other machine losses. In the case study in section 5, the value of ϕ_c is given as 0.5. Moreover, both hydrogen and oxygen gases are pressurized and stored to $U_{Comp} = 1.0MPa$ using compressors.

$$L_{c,H_2,t} = \phi_c \cdot P_\infty \cdot U_{\infty,t} \cdot \ln(U_{Comp,H_2}/U_\infty) \quad (8)$$

3.4 The Characteristics of Geo-thermal Heat Pump System

The upper plot in Figure 4(c) is the relationship between the ratio of load and COP of the geo-thermal heat pump, and the lower plot shows the relationship between electricity consumption of heat pump and thermal output. The refrigerant of the assumed heat pump is HC-12a, the low temperature side heat source of heating period is 278K, and the hot-water outlet temperature of the condenser is 333K. The geo-thermal heat pump assumed in this paper installs heat exchangers in the earth, and obtain low-temperature heat source (HC-TECH Inc 1997).

4 THE ANALYSIS METHOD OF THE OPERATIONAL PLANNING

The network is constituted from fuel cell CGS which can choose between operations of power generation or water electrolysis, and the operational planning of this energy system is analyzed by the genetic algorithm. Figure 5 is the chromosome model introduced into the genetic algorithm, which performs group division of the gene model of a chromosome model, and expresses the operation of all fuel cells and the reformer. The following information from the sampling time t to $t+1$ is expressed with the gene model: the information on fuel cells that generate power and information on the quantity of geo-thermal heat pump generation. The chromosome model of Figure 5 expresses the operation patterns of all fuel cells and the geo-thermal heat pump connected to the network in the time interval of $t+1$ from t . All the operational patterns of the operation period R are decided by creating such chromosome models with respect to each sampling time to $t=0,1,2,\dots,R$. The chromosome models of all such operation periods R of the system are called an "individual." This individual is generated in large numbers at random, gene operations (the reproduction, the selection, the crossover, the mutation) are added under the objective function shown in equation (6), and it searches for the optimal operational pattern with changing generations.

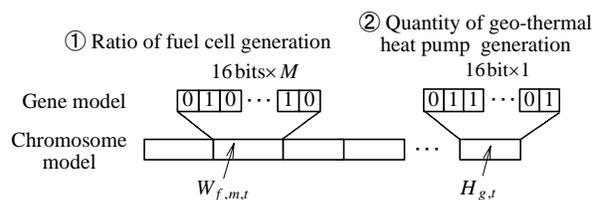


Figure 5 Chromosome model

The following information from the sampling time t to $t+1$ is expressed with the gene model: the information on fuel cells that generate power and information on the quantity of geo-thermal heat pump generation. The chromosome model of Figure 5 expresses the operation patterns of all fuel cells and the geo-thermal heat pump connected to the network in the time interval of $t+1$ from t . All the operational patterns of the operation period R are decided by creating such chromosome models with respect to each sampling time to $t=0,1,2,\dots,R$. The chromosome models of all such operation periods R of the system are called an "individual." This individual is generated in large numbers at random, gene operations (the reproduction, the selection, the crossover, the mutation) are added under the objective function shown in equation (6), and it searches for the optimal operational pattern with changing generations.

5 CASE STUDY

5.1 System Outline

The operational planning of the fuel cell network system for the five individual houses in Figure 1 is calculated using the energy demand model in the individual houses in Sapporo in Japan. The horizontal axis of the figures under Figures 4(a), 4(b) and 4(c) is divided into two or more domains, and the least-squares method approximation formulas to the 4th clause are generated for each domain, and the output characteristics of power generation operation are given. The horizontal axis of the figure under Figure 4(c) for the characteristics of the reformer was also divided into two or more domains, to generate least-squares method approximation equations. The output characteristics of the back-up boiler are not based on the quantity of the hot-water supply, but yield an efficiency of 0.75. The capacity of the thermal storage tank and the gas cylinders are considered to be unknown, and the hydrogen and the oxygen gases are considered to be pressurized to 1.0 MPa with compressors, and are stored in cylinders.

5.2 Energy Demand Patterns

In this case study analysis, the interval of sampling time was 1 hour, and R introduces the energy demand pattern of an individual house in Sapporo in every month for a representative day from 0 to 23 hours. However, if operational planning is performed at intervals of sampling time from several minutes to dozens of minutes, an analysis is possible by applying the energy demand pattern for short intervals. On the other hand, since changes in demand such as the inrush current for less than one second requires a special examination, it is not described in this paper.

The analysis example in this paper introduces two energy demand patterns shown in Figures 6(a) and 6(b). These demand patterns are for the state in which five houses were simply added and the energy demands of every house was synchronized with the electric power and the heat demand pattern of one individual house.

5.3 Analysis Parameters

In consideration of maintaining the diversity of an individual group, the number of individuals was 5500, the number of generations was 20, and intersection probability and mutation probability were set to 0.9, for the values of the parameters introduced into the genetic algorithm, respectively.

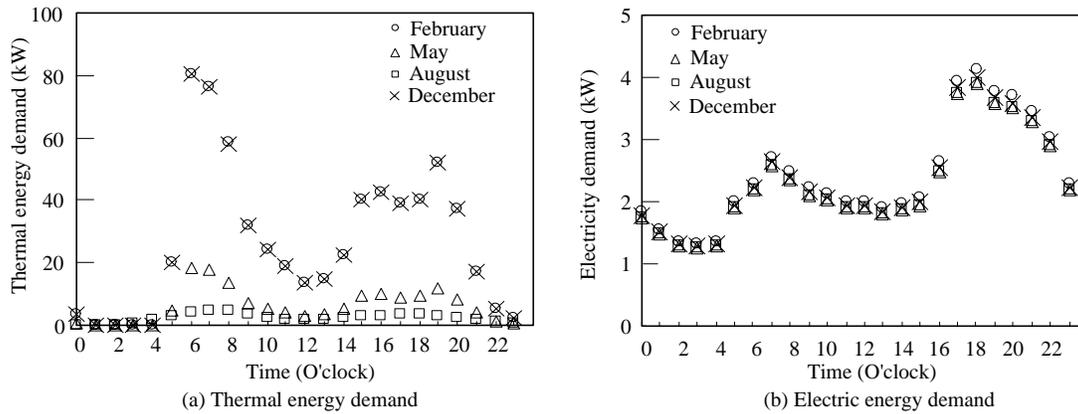


Figure 6 Energy demand patterns

5.4 The Result of the Operation Plan of the Geo-thermal Heat Pump

Figure 7 shows the analysis result about the efficiency of a system. The analysis results of the system described in this paper, not to perform thermal storage (Method 1), and the conventional method that fuel cell exhaust heat and a boiler perform heat supply (Method 2) and the capacity of the fuel cell and the reformer shall be about 1kW, and fuel cell exhaust heat and a boiler perform heat supply (Method 3) are shown in a figure. In the operation plan of the system in this paper, it operates at high efficiency in the time zone (from 0:00 to 5:00, and 9:00 to 13:00, and 21:00 to 23:00) of low effectiveness of Method 1. By the result of the operation plan of the system in this paper, it becomes efficient maneuvering in all the sampling time to Method 2. In Method 3, since the capacity of the fuel cell and the reformer was set as smaller 1kW, the ratio of load of each device improves and whole system thermal efficiency improves. However, Method 3 has small power capacity and not heat pump but a boiler must be operated in winter. As for the result of the efficiency of each system in January in Figure 7, the system of this paper is 17%, the Method1 is 13%, the Method2 is 4%, and the Method3 is 20%.

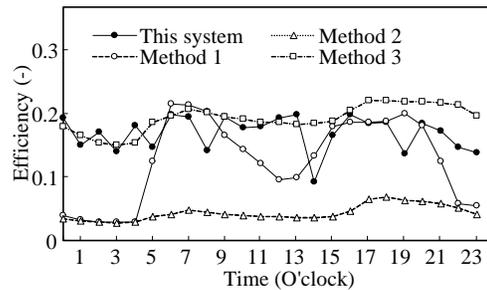


Figure 7 Results of efficiency

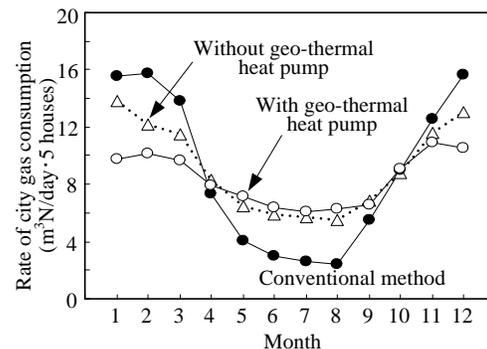


Figure 8 Comparison of operation cost

5.5 Results of the Geo-thermal Heat Pump Linked to the Fuel-cell-network.

Figure 9 shows the analysis result of the city gas consumption (five houses) of representation time

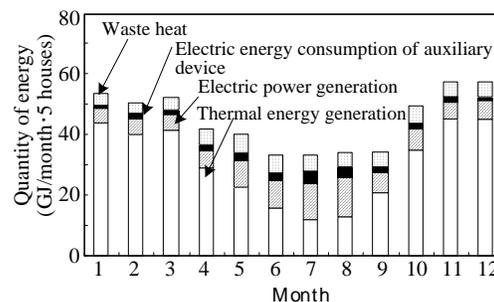


Figure 9 Items of energy

every month in the fuel-cell-network system in this paper. The analysis results of the system (conventional system) introduced into individual house by one set of the fuel cell and the reformer, and with/without connecting geo-thermal heat pump linked fuel-cell-network are shown in a Figure 8. The ratio of the city-gas consumption in every year is 0.91 to 1.0 by the existence of link to geo-thermal heat pump with a fuel cell network system. Therefore, introduction of heat pump is effective in the cutback of city-gas consumption. Figure 9 shows the breakdown of the energy output for every month in the fuel cell network system which connects the geo-thermal heat pump. From the result of Figure 8, city-gas consumption decreases rather than a conventional system in winter. This result is unrelated to connect of geo-thermal heat pump. However, city-gas consumption has less operation of a conventional system in mid-term to a summer (from April to October). The result related with city-gas consumption is decided by relation of the ratio of the power supply of every month to heat supply shown in Figure 9. By introducing the fuel-cell-network system, it becomes more advantageous than conventional system from November in March, and is this thermoelectricity ratio at the time of nearly 8.5 or more.

Figure 10 shows the energy consumption in every month for five individual houses calculated from the city gas consumption of conventional system and the fuel-cell-network system (When introducing or not introducing geo-thermal heat pump). The city-gas consumption of the fuel cell network system which connects geo-thermal heat pump serves as a 6% reduction at every year compared with a conventional system. On the other hand, in the network system which does not connect geo-thermal heat pump, every year comes 3% of excess.

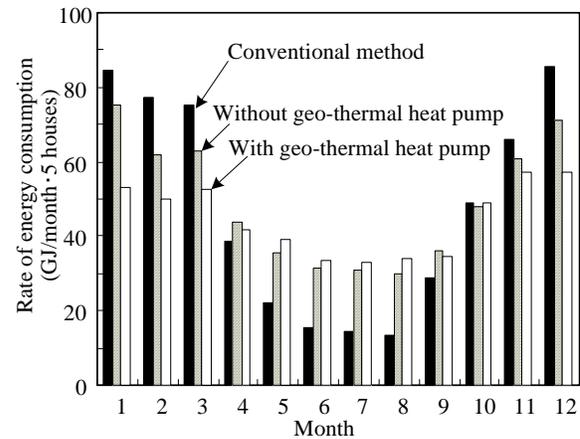


Figure 10 Result of energy consumption

6 CONCLUSIONS

Heat pump was connected to the fuel-cell-network, and when a fuel cell was in the condition of performing partial-load operation of low effectiveness, the system which produces heat was examined. In this system, when fuel cells perform partial load operation with low efficiency, operation operating point can be shifted to an efficient side. And the heat outputted by heat pump can be stored in a heat storage tank, and this heat can shift and use time. The operation plan at the time of forming a fuel cell network system in five individual houses under the energy-demand pattern of the individual house in Sapporo was performed.

(1) The energy cost of a fuel cell network system is more advantageous than a conventional system (System which performs energy supply in the combination of a fuel cell and a reformer) at more than thermoelectricity ratio 8.5.

(2) When geo-thermal heat pump is connected to the fuel cell network system proposed in this paper, compared with the city gas consumption of a conventional system, it is a 6% reduction in every year. This reason is the result of operation of the fuel cells shifting from partial load operation with low efficiency to efficient operation by operation of heat pump.

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NOMENCLATURE

| | | |
|------------|---|--|
| E | = | electric power (kW) |
| ΔE | = | electric power consumption (kW) |
| H | = | heat (kW) |
| ΔH | = | heat consumption (kW) |
| L | = | work (J) |
| l | = | distance (m) |
| M | = | Sets of the fuel cell which carries out power generation operation |
| P | = | pressure (Pa) |
| Q | = | quantity of flow (kg/s) |
| R | = | operation period of system (s) |
| S | = | quantity of storage (kg) |
| S_h | = | quantity of thermal storage (kJ) |
| T | = | temperature (K) |
| t | = | sampling time |
| U | = | volume rate of flow (m ³ /s) |
| V | = | the number of the auxiliary devices which consume electric power |

Greek Symbols

| | | |
|---------------|---|---|
| ε | = | the coefficient of the amount of heat loss per unit length of hot water piping (Eq.(3)) (W/m) |
| ϕ | = | efficiency (%) |

Subscripts

| | | |
|-----|---|--|
| a | = | gas cylinder |
| b | = | backed boiler |
| c | = | city gas |
| f | = | fuel cell |
| g | = | geo-thermal heat pump |
| m | = | the code of the fuel cell which carries out power generation operation |
| r | = | reformer |
| s | = | thermal storage tank |

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