Chapter 2
Equipment Arrangement Planning of a Fuel Cell Energy Network Optimized for Cost Minimization

2.1 Introduction

In recent years, uses of the distribution of fuel cells have been studied [9, 10]. Furthermore, fuel cell systems are connected by a network and the micro-grid of the electrical power operated in cooperation under the objective function given beforehand is investigated [11–13]. Moreover, compound utilization of green energy equipment is considered to have little environmental impact although it is unstable, and stable power-generator equipment is investigated by the electrical power grid of small energy equipment [11]. Construction of an electrical power micro-grid may to develop competition with the existing energy infrastructure other than in short-term utilization, such as a backup power supply at the time of disaster. Installation of both a micro-grid of solid polymer membrane-type fuel cells and a hot water piping network used to supply fuel cell exhaust heats to each building is anticipated to cause a large reduction in environmental impact [9, 10]. In order to achieve the energy network of electrical power and heat described above, cooperative control of the distributed energy equipment according to the objective function given beforehand, operation planning, the arrangement design of equipment, and capacity design of equipment are required. The fuel cell energy network (FEN) investigated in this paper examines the micro-grid (FMG) used for an electric power supply, and the hot water piping network (HWN) that uses the exhaust heat of equipment for supply or collection from each house. In small-scale FEN, since the power transmission length is short, the energy loss of electric power transmission is small, and the loss of exhaust heat transport can also be maintained at low levels. When loss of electric power transmission is improved rather than heat transport due to the difference in energy unit price, the total energy cost is generally low. However, in cold regions, houses, apartment houses, office buildings, hospitals, etc., have a great annual heat demand. It is expected that the heat transport loss of FEN in buildings with high heat demand has a large influence on the efficiency of the system. Therefore, when transporting a lot of heat using HWN, route planning of piping considering the heat release loss of HWN and an arrangement plan of equipment are required; these aspects depend on the route planning of HWN, and the optimum arrangement plan of heat output equipment depends on the energy demand pattern of each building linked to FEN, and the position of each house. The heat medium (hot water) temperature that flows through the inside of the HWN in a house outlet is decided by the heat supply and demand of each house, and the heat release of HWN is dependent on the hot water temperature and the piping length. Thus, in this paper, a plan is made to optimize the equipment arrangement of the fuel cell, reformer, and boiler, and an FEN with high energy efficiency and cheap facility cost is planned by optimizing the route of HWN used for supplying the exhaust heat of a fuel cell and a reformer to each house. If the scale of FEN is large, the total length of HWN will increase and heat release will also increase. From this, it is expected that the increase in the scale of FEN will lead to a decline in the energy efficiency of the system. However, compared with FEN that is not optimized, the cost and efficiency of the system may be improved by optimizing the equipment arrangement of each building linked to FEN, and the route of HWN. That is, compared with FEN that is not optimized, the same facility cost as FEN that has an optimized equipment, arrangement is expected and a HWN route whose scale (the number of houses linked to FEN) can be extended. In this paper, the arrangement plan of FEN that differs in the number of houses, and the route plan of HWN are conducted using a genetic algorithm [14–19]. From this analysis, the operation cost of the system, facility cost, and the installation cost of a facility are investigated, and the cost per house connected by FEN is investigated.

2.2 System Scheme

2.2.1 The Energy Network

The model of the fuel cell energy network (FEN) assumed in this paper is shown in Fig. 2.1. Each building is connected with the micro-grid (FMG) of electrical power, and the hot water piping network (HWN) used for waste heat recovery and heat supply. A fuel cell assumes a solid polymer membrane model, and a reformer assumes the steam reforming of city gas. Each facility of the fuel cell, the reformer, and the boiler is capacity free in each building, and it is assumed that it can be installed freely. It is necessary to optimize and perform design arrangement and capacity planning of this equipment based on the objective function given beforehand for the system. Houses in which fuel cells are installed, and the houses in which the installed reformers are connected with a reformed gas piping network are shown in Fig. 2.1. Supposing a gas piping network reformed from an existing city gas piping network is used, FMG decides to use the existing commercial electrical power network more. Therefore, in the analysis of cost in this paper, equip-

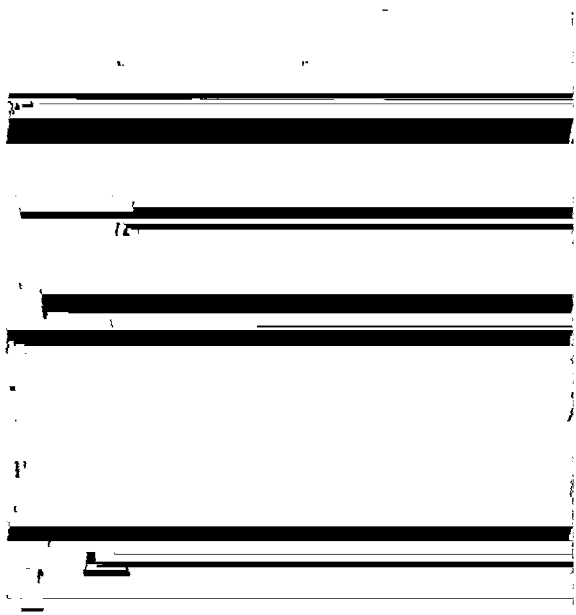

Fig. 2.1 Fuel cell network model with eight houses

ment cost of a reformed gas piping network and FMG is not taken into consideration. Since the route of HWN is planned considering the heat release in HWN that connects each house, they differ depending on outside air temperature. The outside air temperature of a representative day differs in different seasons, so the heat release of HWN is calculated using an outside air temperature model in summer (August), winter (February), and mid-term (May), and the optimal route is explored.

2.2.2 Fuel Cell System

Figure 2.2 shows a model in which a fuel cell is installed in house S_x. The reformed gas produced by the reformer is supplied to the fuel cells through a reformed gas network (town gas piping network). The power generated by the fuel cells is supplied to FMG through a DC–AC converter, an inverter, and an interconnection device, and supplies the load in each house. As shown in Fig. 2.2, the exhaust heat of a fuel cell is supplied to the heat load of house S_x, but when heat remains, heat is supplied to other houses through HWN. On the other hand, when heat is insufficient, heat is obtained and supplied by the HWN.

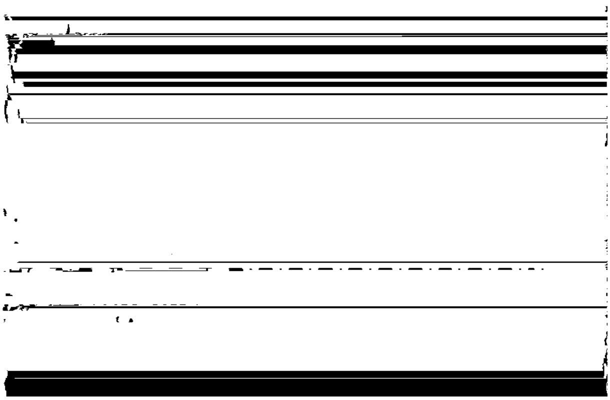

Fig. 2.2 Fuel cell introduced into a house

2.2.3 Heat Source Use Order

The heat source that supplies the heat demand in each house gives priority to the exhaust heat of the fuel cell and the reformer installed in the same house. When such exhaust heat is insufficient for the heat amount demanded, heat is obtained from HWN. Although a heat storage tank is installed in HWN, it stores the heat when the heat that flows through HWN remains. The stored heat can be used by conducting a time shift. A boiler is operated when heat runs short, even if it supplies the heat obtained from HWN to a house.

2.2.4 City Gas Reformer

Figure 2.3 shows the model of installing a reformer in house S_y. Although city gas is supplied to the reformer, in order to remove the carbon monoxide and water in the reformed gas, carbon monoxide oxidation equipment and a dryer are installed. The exhaust heat of the reformer can be supplied to each house through HWN.

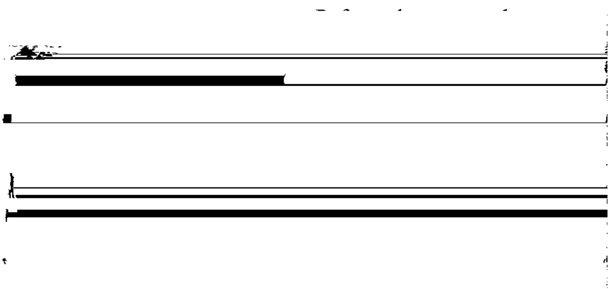

Fig. 2.3 Reformer and cylinder is installed in a house

2.2.5 Operation Model of the System

Figure 2.4 shows a model of equipment arrangement planning at the time of connecting the distributed fuel cell with an energy network. As shown in Fig. 2.4(a), in order to fulfill the demand of the electric power and the heat of six houses (from S_A to S_F), a reformer is installed in houses S_B and S_F, and a boiler is installed in houses S_A, S_C, and S_D for a fuel cell at houses S_A, S_C, and S_E.

Each house is connected with HWN and can transport the exhaust heat of the fuel cells and reformers, and the heat output of the heat storage tank and boilers with the heat medium (hot water) that flows through the inside of the piping. Here, the demand model of the electric power and the heat of each house is made to have the

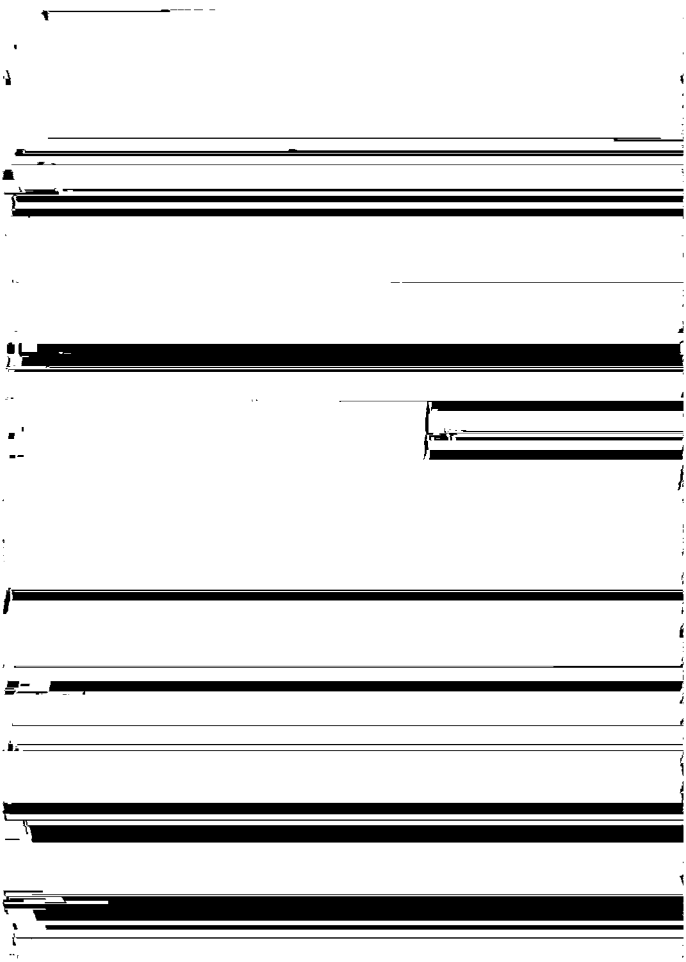

Fig. 2.4 Arrangement plan of the distributed fuel cells

characteristics shown in Fig. 2.4(b) and (c), respectively. As shown in Fig. 2.4(e), the exhaust heat output in each fuel cell in this case depends on the production of electricity (Fig. 2.4(d)) of the fuel cell. Moreover, Fig. 2.4(f) shows a model of the exhaust heat output of a reformer, and Fig. 2.4(g) shows a model of the heat output of a boiler. The hot water quantity of heat that flows through the inside of HWN is decided from the heat demand model shown in Fig. 2.4(c), and the model of the heat output in each piece of equipment is shown in Fig. 2.4(g) from Fig. 2.4(e). The heat release of HWN equipped with thermal insulation is dependent on the difference in temperature between the hot water and the atmospheric air. Figure 2.4(h) shows a model of the heat release of HWN that connects each house. Therefore, the amount of heat release in HWN differ depending on which equipment is installed in the house linked to a network, and the route of HWN.

2.3 Amount of Heat Release of the Hot Water Piping Network (HWN)

Figure 2.5(a) shows the model of incomings and outgoings of the heat of HWN that connects house S_i, S_{i+1}, and S_{i+2}. As shown in Fig. 2.5(b), the hot water of temperature $T_{in,S_i,t}$ and the quantity of heat $H_{in,S_i,t}$ inputs into S_i through HWN. The exhaust heat output of a fuel cell when generating the fuel cell installed in S_i is determined so that the amount $E_{need,S_i,t}$ of the electricity demand of sampling time t that can be supplied is $H_{fc,S_i,t}$. Moreover, $H_{need,S_i,t}$ is the heat amount demanded in S_i. The hot water quantity of heat ($H_{out,S_i,t}$) outputted from S_i is $H_{in,S_i,t} + H_{fc,S_i,t} - H_{need,S_i,t}$. The cost of fuel cell exhaust heat $H_{fc,S_i,t}$ differs according to the production of electricity $E_{fc,S_i,t}$ of a fuel cell; the following section describes the details of these relations. Although the temperature of the hot water outputted from S_i is $T_{out,S_i,t}$, there is heat release of $H_{w,S_{i-(i+1)},t}$ for the piping as it arrives in S_{i+1} from S_i. Therefore, with the hot water inputted into S_{i+1}, the temperature falls to $T_{in,S_{i+1},t}$, and the quantity of heat is $H_{in,S_{i+1},t} = (H_{out,S_i,t} - H_{w,S_{i-(i+1)},t})$. Furthermore, in house S_{i+1}, the exhaust heat $H_{fc,S_{i+1},t}$ is outputted by the generation operation of the fuel cell. The analysis of "the hot water quantity of heat that sets the heat amount demanded in S_{i+1} to $H_{need,S_{i+1},t}$, and is outputted from S_{i+1} is $H_{out,S_{i+1},t} = H_{in,S_{i+1},t} + H_{fc,S_{i+1},t} - H_{need,S_{i+1},t}$" is calculated for all the houses. Figure 2.5(c) shows a model of HWN that connects S_i and S_{i+1}. The inside diameter of the hot water piping is set to $D_{i,S_{i-(i+1)}}$, the outside diameter is set to $D_{o,S_{i-(i+1)}}$, and the outside diameter of the heat insulating material with which the piping is equipped is expressed as $D_{c,S_{i-(i+1)}}$. When the heat conductivity of the piping material and the thermal insulation is set to k_p and k_c, respectively, the coefficient of the overall heat transmission ($K_{S_{i-(i+1)}}$) of the hot water and the surface of the heat insulating materials is expressed by the following equation.

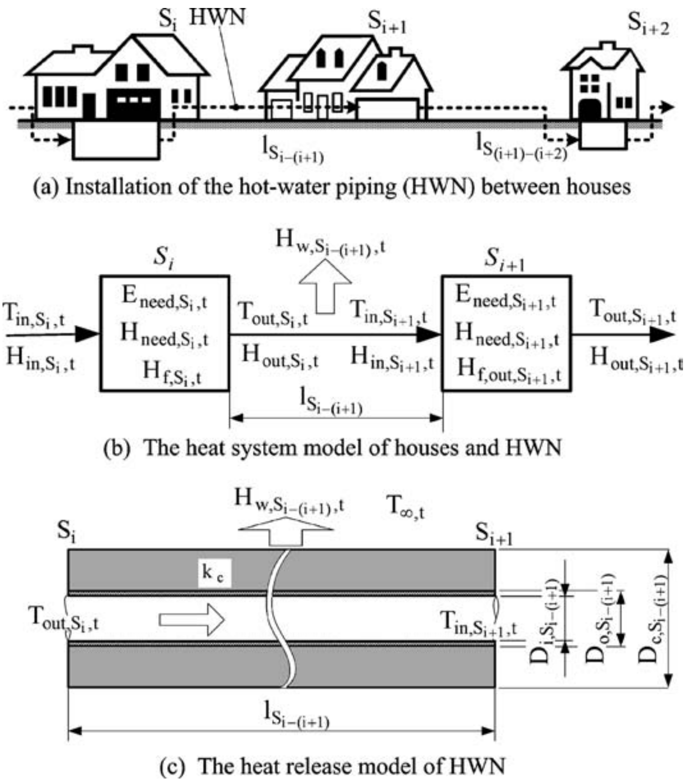

Fig. 2.5 Heat model for the hot water piping network

$$K_{S_{i-(i+1)}} = 1 \Big/ \left\{ \frac{1}{h_{w,S_{i-(i+1)}} \cdot D_{i,S_{i-(i+1)}}} + \frac{1}{2 \cdot k_p} \ln \frac{D_{o,S_{i-(i+1)}}}{D_{i,S_{i-(i+1)}}} + \frac{1}{2 \cdot k_c} \ln \frac{D_{c,S_{i-(i+1)}}}{D_{o,S_{i-(i+1)}}} + \frac{1}{h_{\infty,S_{i-(i+1)}} \cdot D_{c,S_{i-(i+1)}}} \right\} \tag{2.1}$$

Moreover, the outside air temperature of time t is set to $T_{\infty,t}$ for the outlet hot water temperature ($T_{out,S_i,t}$) of a house by S_i, and the heat release ($H_{w,S_{i-(i+1)},t}$) in piping of length $l_{S_{i-(i+1)}}$ that connects S_i and S_{i+1} is calculated by the following equation. However, the exhaust heat temperature of the fuel cell is set to 353 K (80°C) in the analysis example described later.

$$H_{w,S_{i-(i+1)},t} = K_{S_{i-(i+1)}} \cdot D_{o,S_{i-(i+1)}} \cdot \pi \cdot l_{S_{i-(i+1)}} \cdot \left(T_{out,S_i,t} - T_{\infty,t} \right) \tag{2.2}$$

2.4 Energy Balance

The number of the houses linked to a fuel cell network shown in Fig. 2.1 is set to N_{bd} . Each number is set to N_{fc} , N_{rm} , and N_{bo} , although a fuel cell, a reformer, and a boiler are installed in any of the houses. In the lower part of the figure, the energy balance of the power and the heat of the system in sampling time t is described.

2.4.1 The Balance of Power

Equation (2.3) is a balance equation of power. The left-hand side of Eq. (2.3) expresses the power outputted to FMG from the fuel cell of the number N_{fc} that is generated. On the other hand, the first term on the right-hand side of Eq. (2.3) expresses the power consumption in the number of the houses N_{bd} linked to a network. The second term on the right-hand side of Eq. (2.3) expresses the power consumed with the circulating pump supplying hot water to HWN. In the analysis example of following section, the power of a hot water circulating pump is calculated as consumption according to a hot water quantity of flow.

$$\sum_{i=1}^{N_{fc}} E_{fc,i,t} = \sum_{j=1}^{N_{bd}} E_{need,j,t} + E_{pump,t} \tag{2.3}$$

2.4.2 The Balance of Heat

Equation (2.4) is a balance equation of heat. The left-hand side of Eq. (2.4) expresses the exhaust heat of a fuel cell, the exhaust heat of a reformer, the heat output of a boiler, and the heat output of a heat storage tank, respectively. On the other hand, the right-hand side expresses heat consumption with the number of houses N_{bd} linked to a network, and the heat release in hot water piping that connects each house.

$$\sum_{i=1}^{N_{fc}} H_{fc,i,t} + \sum_{j=1}^{N_{rm}} H_{rm,j,t} + \sum_{l=1}^{N_{bo}} H_{bo,l,t} + H_{st,t} = \sum_{m=1}^{N_{bd}} H_{need,m,t} + \sum_{n=1}^{N_{bd}} H_{w,n,t} \tag{2.4}$$

2.5 Cost Calculation and Objective Function

2.5.1 Cost Calculation

(1) Operation Cost

Equation (2.5) expresses the operation cost of a system required between Δt from sampling time t. The first term in the right-hand bracket of Eq. (2.5) expresses the operation cost of reformers. The operation cost of reformers is calculated by multiplying by the amount of city gas consumed by the reformers (the number is N_{rm}), and the unit price $J_{s,rm}$ of city gas. The second term in the right-hand bracket of Eq. (2.5) expresses the operation cost of the circulating pump used for a hot water network. The operation cost is calculated by multiplying by the power consumption and the power unit price. The third term in the right-hand bracket of Eq. (2.5) expresses the operation cost of boilers.

$$Y_{d,t} = \left(\sum_{i=1}^{N_{rm}} Q_{rm,i,t}\, J_{s,rm} + E_{pump,t} \cdot J_{s,pump} + \sum_{k=1}^{N_{st}} Q_{bo,k,t} \cdot J_{s,bo} \right) \cdot \Delta t \tag{2.5}$$

(2) Equipment Cost

Equation (2.6) calculates equipment cost from the installed capacity and the capacity unit price. The right-hand side of Eq. (2.6) expresses the equipment cost of fuel cells, reformers, boilers, heat storage tanks, HWN, and hot water circulating pumps, respectively.

$$\begin{aligned} Y_c &= \sum_{i=1}^{N_{fc}} U_{fc,i} \cdot J_{c,fc} + \sum_{j=1}^{N_{rm}} U_{rm,j} \cdot J_{c,rm} + \sum_{k=1}^{N_{bo}} U_{bo,k} \cdot J_{c,bo} + U_{st} \cdot J_{c,st} \\ &+ \sum_{m=1}^{N_{bd}} U_{pih,m} \cdot J_{cl,pih} + U_{pump} \cdot J_{c,pump} \end{aligned} \tag{2.6}$$

(3) Equipment Installation Cost

Equation (2.7) is a formula for the installation cost of equipment. In this paper, cost is taken into consideration for the installation of the fuel cell, the reformer, the boiler, and the heat storage tank, which are shown on the right-hand side of Eq. (2.7). However, it assumes that the other equipment shown in Fig. 2.2 is included in the installation cost of a fuel cell, and all the equipment shown in Fig. 2.3 is included in the installation cost of a reformer.

$$Y_f = \sum_{n=1}^{N_{fc}} J_{f,fc,n} + \sum_{j=1}^{N_{rm}} J_{f,rm,j} + \sum_{k=1}^{N_{bo}} J_{f,bo,k} + J_{f,st} \tag{2.7}$$

2.5.2 Objective Function

The objective function of the system is calculated by Eq. (2.8) using the value of the cost of Eqs. (2.5), (2.6), and (2.7). The minimum arrangement planning of the equipment, capacity planning, and operation plan in the case objective function F is investigated. g_c, g_y, and g_d in Eq. (2.8) express the weight of equipment cost, the weight of the installation cost of equipment, and the weight of operation cost, respectively. When any of the terms on the right-hand side of Eq. (30) is much larger than the other terms, it is necessary to determine a weight so that the objective function does not depend on the term too heavily. However, in the analysis of following section, all g_c, g_y, and g_d are calculated as 1.0.

$$F_O = g_c \cdot Y_c + g_y \cdot Y_f + g_d \cdot \sum_{t=0}^{Day} Y_{d,t} \tag{2.8}$$

The third term on the right-hand side of Eq. (2.8) expresses the operation cost of the system on a representative day. In the analysis, an operation plan in the case of the value of Eq. (2.8) being the minimum is decided as the optimal solution. Since calculation of optimization of this paper is non-linear with many variables, it uses a genetic algorithm (GA) [14–19] for optimization calculation. The chromosome model showing the operating method of the system using GA decides that it is “a solution with high fitness value” as an individual with a small value of the objective function of Eq. (2.8).

2.6 Analysis Method and Case Study

2.6.1 Optimization Using a Genetic Algorithm

(1) Chromosome Model

Figure 2.6 shows the chromosome model used in the optimization analysis of GA. The chromosome model composes gene models, and a gene model expresses the arrangement and the output of fuel cells and reformers, and the route of HWN. In the analysis example described later, the number of houses is set at 4–9, and the installation of a fuel cell and a reformer is determined at random using a gene model for each house. Furthermore, the output of a fuel cell and a reformer is also decided at random, and is expressed by the gene model.

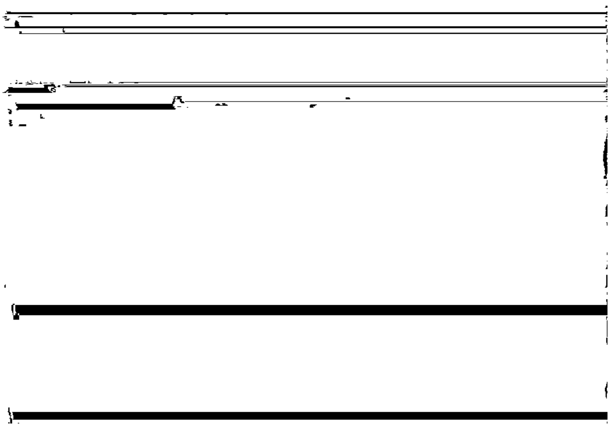

Fig. 2.6 The chromosome model used for the genetic algorithm

(2) Expression of Hot Water Piping Route

As the section “Operation Model of the System” describes, according to the route of HWN, the amount of heat release of the whole system differs, and the efficiency of the system is affected. Therefore, the arrangement planning of equipment and the route plan of HWN are predicted to affect cost. In this paper, the path-planning program of HWN is developed using the idea of the traveling salesman problem (TSP) [19]. Herein, the view of the order expression of route by Dewdney is installed into TSP. According to this view, it is managed by a symmetrical number that is different from the housing number in the gene indicating the route of HWN. By this method, when gene manipulation such as cross-over and mutation is added to a chromosome model, models that show unachievable routes do not appear. From this, the analysis efficiency improves sharply.

2.6.2 Equipment Characteristics Model

(1) Operation of a Fuel Cell

The production of electricity $E_{fc,i,t}$ $(i = 1,2,..., N_{fc})$ of the fuel cell installed in any house at sampling time t determines the amount of power demanded $\sum_{j=1}^{N_{bd}} E_{need,j,t}$ in time t by random distribution. The gene model group of (a) of the chromosome models shown in Fig. 2.6 shows the number of installations of fuel cells N_{fc}, and the houses in which they are installed. Moreover, although the group of the gene model of (d) expresses the generation rate in each fuel cell, the production of elec-

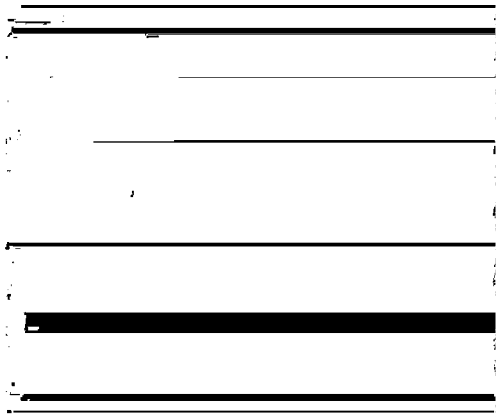

Fig. 2.7 Fuel cell performance

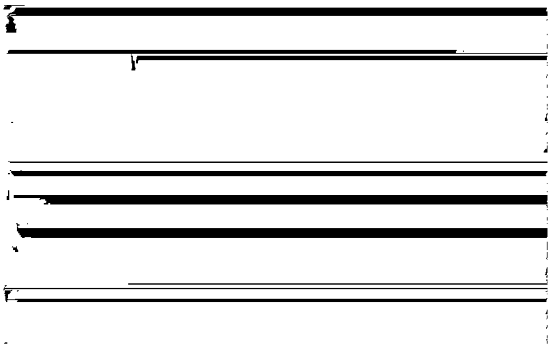

Fig. 2.8 Output characteristics of a hydrogen-air fuel cell

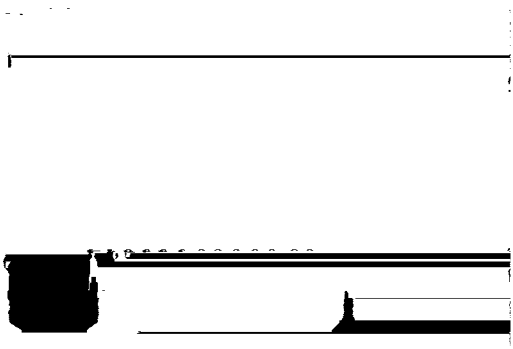

Fig. 2.9 Characteristics of the ratio of reformation

tricity $E_{fc,i,t}$ (however, $i = 1,2,...,N_{fc}$) of each fuel cell is decided from these values. The exhaust heat output of each fuel cell $H_{fc,i,t}$ (however, $i = 1,2,...,N_{fc}$) is decided by the characteristic model of the electric power and the exhaust heat output of the fuel cell shown in Fig. 2.7. The characteristics of the electric power and the heat output of a fuel cell shown in Fig. 2.7 were obtained by the experimental results of the fuel cell manufactured as an experiment.

(2) Operation of a Reformer

When the production of electricity of each fuel cell is determined, the quantity of reformed gas required for generation will be determined from the characteristic model of the production of electricity and the consumption of reformed gas of the fuel cell shown in Fig. 2.8. A characteristic of the reformer of Fig. 2.8 is the model created from the output characteristics of a fuel cell and a reformer manufactured as an experiment. By the reformer installed in each house, the quantity of reformed gas produced is decoded and determines the value of the gene model of (b) and (e) of the chromosome model shown in Fig. 2.6. If the amount of reformed gas production of each reformer is decided; the exhaust heat output $H_{rm,S_x,t}$ (however, $x = 1, 2, ..., N_{rm}$) will be decided from the relation of the ratio of load and the ratio of reformation of Fig. 2.9.

2.6.3 Operation of the Heat Storage Tank and Boiler

The heat of $(H_{fc,total,t} + H_{rm,total,t} - H_{need,total,t})$ is stored when the value to which is added exhaust heat $H_{fc,total,t} = \sum_{i=1}^{N_{fc}} H_{fc,i,t}$ of the fuel cell and exhaust heat $H_{rm,total,t} = \sum_{j=1}^{N_{rm}} H_{rm,j,t}$ of the reformer compared with the heat demand $H_{need,total,t} = \sum_{k=1}^{N_{bd}} H_{need,k,t}$ of all the houses linked to FEN at sampling time t is exceeded. On the other hand, when $H_{fc,total,t} + H_{rm,total,t} + H_{st,t}$ is less than $H_{need,total,t}$, the heat of $(H_{need,total,t} - H_{fc,total,t} - H_{rm,total,t} - H_{st,t}) = \sum_{l=1}^{N_{bo}} H_{bo,l,t}$ is outputted to HWN from the boiler. On installing a boiler in all the houses, the heat output of each boiler is determined so that the heat balance in each house does not become negative. The city gas consumption of a boiler is calculated to a boiler efficiency of 85%.

2.6.4 Specification of Hot Water Piping and a Hot Water Circulating Pump

As shown in Table 2.1, the hot water piping uses a coat of polyethylene tube with an inside diameter of 28 mm, and a wall thickness of 10 mm. The heat transfer coefficients between the piping inner wall and the hot water is 2500 W/m^2K, the

Table 2.1 Specification of hot water piping

[illegible]

heat transfer coefficient between the outer surface of the piping and the atmospheric air is 20 W/m^{2}K, and the heat conductivity of the piping is 0.043 W/mK. The overall heat transfer coefficient between the hot water and the atmospheric air is calculated using the value described above. Heat release $H_{w,n,t}$ (however, $n = 1, 2, ..., N_{bd}$) of the hot water is calculated by multiplying the overall heat transfer coefficient by the piping length and the difference between the temperature of the hot water and the open air. The power of hot water circulating pump P_{pump} is calculated by Eq. (2.9). In the analyses of this paper, the water head W_p shall be 7 m considering pipeline friction.

$$P_{pump} = \rho_w \cdot g \cdot q_w \cdot W_p \tag{2.9}$$

2.6.5 Analysis Flow

The flow of the analysis program of arrangement planning optimization of FEN developed in this paper is shown in Fig. 2.10. The initial data of the energy need pattern of each house, the position of the house, the outside air temperature, the overall heat transfer coefficient of the hot water piping, etc., the generation number, the selectivity probability, the number of individuals of a chromosome, mutation probability, and the cross-over probability that are the GA's solution parameters are first inputted into the analysis program. The GA's parameters are determined by applying a trial-and-error method to find the best accuracy and effectiveness of analysis. Next, the number that gave the chromosome model shown in Fig. 2.6 before is prepared at random. If the first generation's chromosome model group is set, each term under balance equation (2.3) of electric power and heat balance equation (2.4) will be determined in the procedure of the sections "Equipment Characteristics Model" and "Operation of the Heat Storage Tank and Boiler". If a chromosome model is decoded and the operating conditions of each piece of equipment are set, cost can be calculated using Eqs. (2.5)–(2.7). From the result of the cost calculation, the fitness value of each chromosome model is calculated using Eq. (2.8). In a chromosome model group, the top 60% of individuals with a high fitness value is extracted, other models are discarded, and the new chromosome models determined at random are added. Intersection and mutation are added to the high chromosome model of the fitness value, and the newly created chromosome model by probability is first given to the program. Cross-over and mutation are added to the chromosome models of the high fitness value described above, and the newly prepared chromosome model by probability is first

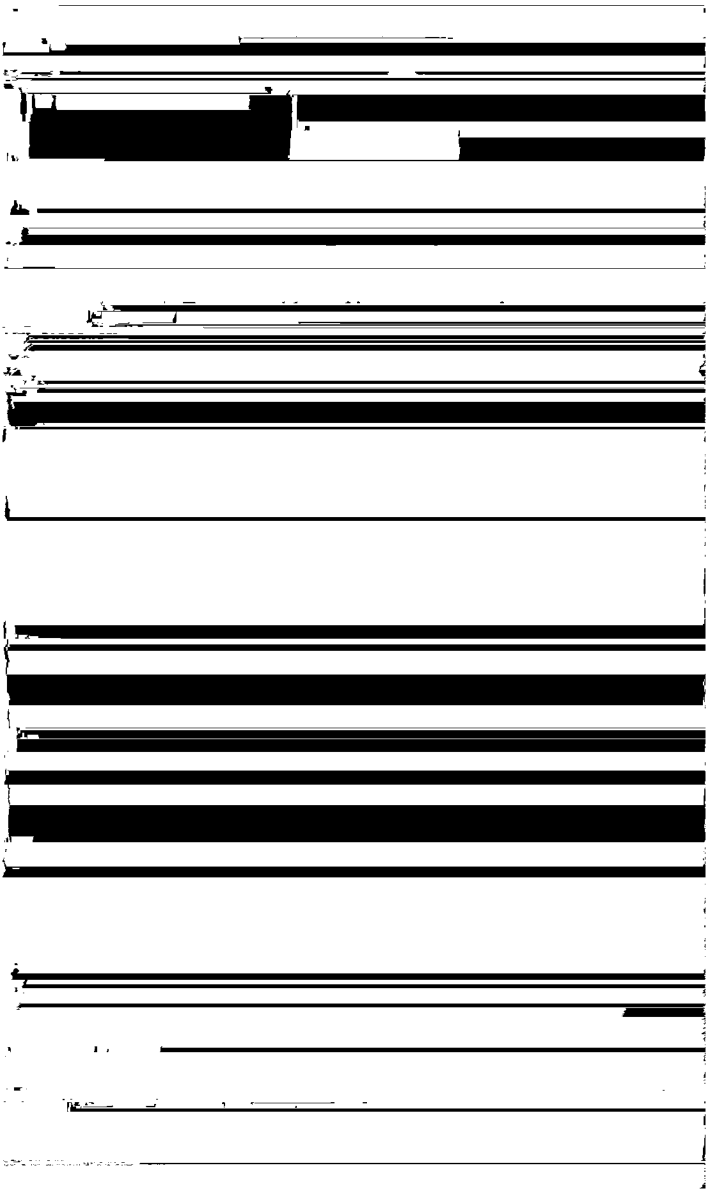

Fig. 2.10 The chromosome model used in the genetic algorithm

given to the program. For the chromosome model to which gene manipulation is added, the fitness value of each model is re-calculated. Individuals with a low fitness value in a chromosome model are discarded, and a chromosome model that is newly determined is supplied at random. This calculation is iterated with the generation number first given to the program. Among the last generation's chromosome models, the highest model of fitness value is decided as a temporary optimal solution. In the temporary optimal solution, which is obtained from the analysis of Fig. 2.10 having been repeated at least 20 times, a solution with the highest fitness value is determined as the optimal solution. In the analysis of the following section, it is considered to be 5000 chromosome models, and the generation number is set at 10–20. Moreover, mutation probability and cross-over probability are set at 0.01.

2.6.6 Analysis Conditions

The city area model assumed in the analysis of this paper is shown in Fig. 2.11. FEN to four buildings of houses S_A, S_C, S_E, and S_G of Fig. 2.11 is called the four-houses model, and FEN to five buildings S_B, S_D, S_F, S_H, and S_I is called the five-houses model. Moreover, FEN to nine buildings S_A to S_I is called the nine-houses model. Although the energy demand of each house shown in Fig. 2.11 differs due to the number of residents, composition age, lifestyle, etc., it is analyzed by giving the simplest possible energy demand pattern to an analysis program in this analysis. Then, the average energy demand pattern of a 3–4 person household in Sapporo [8] that shows the energy demand pattern of each house in Fig. 2.12 is used. The power load pattern of Fig. 2.12(a) is consumption by household electric appliances and lighting, and electric air-conditioning equipment is not used throughout the year. For this reason, as shown in Fig. 2.12(a), there is not a large difference in the electricity demand pattern of each month. On the other hand, the items of heat load are hot water supply, baths, and space heating. Moreover, the outside air temperature model of Sapporo used for calculating the heat release in HWN is shown in Fig. 2.13 [20]. For Sapporo, a cold, snowy area, the annual average temperature is 288 K, and the mean temperature in February and August is 269 K and 294 K, respectively. The equipment efficiency, the energy cost, the cost of equipment, and the installation cost of equipment are used for cost

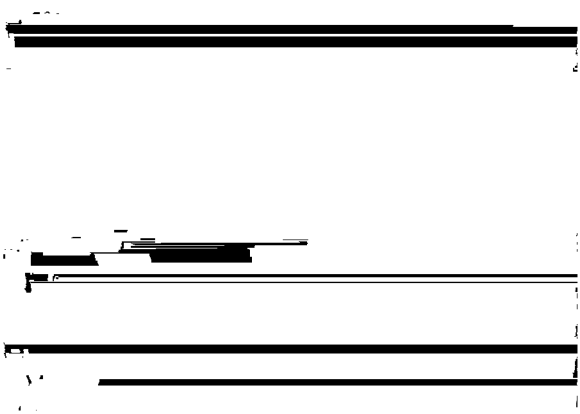

Fig. 2.11 The arrangement model of houses

analysis are shown in Table 2.2. The fuel cell and the reformer are calculated to be 2500 dollars/kW and 1500 dollars/kW, respectively. It is expected that these cost values will be attained within several years. The equipment costs of other boilers, heat storage tanks, and hot water circulating pumps are decided by a product catalog as reference. For equipment installation costs, such as for a fuel cell or a boiler, the installation cost of a common home boiler or a hot water supply system was assumed.

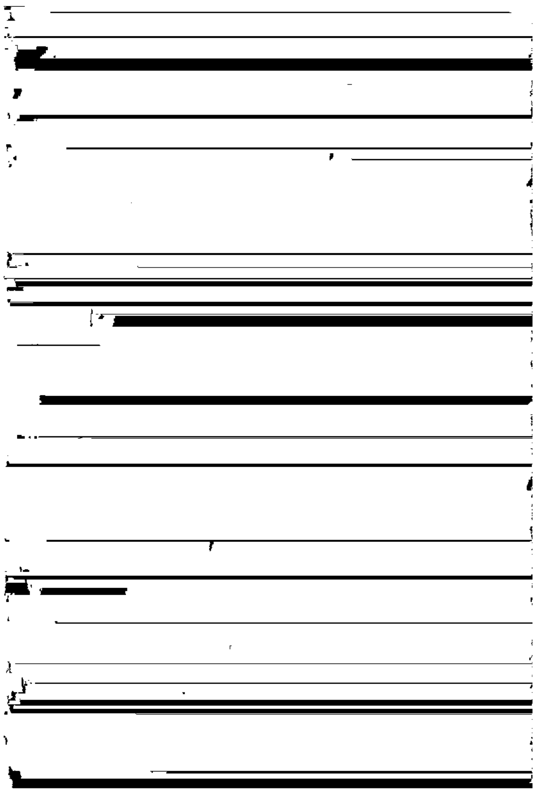

Fig. 2.12 The average energy demand pattern of family households of 3–4 persons in Sapporo

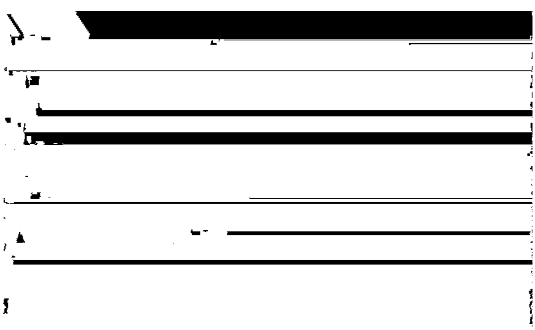

Fig. 2.13 Outside air temperature model in Sapporo

Table 2.2 Analysis conditions of the case study

[illegible]

2.7 Analysis Result

2.7.1 Operation Plan of the Fuel Cell and the Reformer

Figure 2.14 shows the analysis result of the electric power of a fuel cell, and the exhaust heat output and the analysis result of the reformed gas output of a reformer when installing a fuel cell network into the four-houses model.

Table 2.3 is the result of analysis using an energy demand pattern and the outside air temperature data of a representative day in February, May, and August, and is a result of the capacity of a fuel cell, a reformer, and a boiler and the installation location of the four-houses and the five-houses models. In the analysis result of the four-houses model shown in Fig. 2.14, although a fuel cell is installed in two houses, S_C and S_G, for all months, a reformer is scheduled to be installed in one house. The electric power and the heat output of fuel cells are different in their output characteristics of two sets to other months, although the two sets of outputs will be almost the same in February. The reason for this is explained in detail in the section “Quantity of Flow of a Hot Water Circulating Pump”, and it is because heat release by HWN is large, and a plan is made for representative days in February so that the heat transport using HWN can decrease. That is, although a fuel cell of the same capacity will be installed in a symmetrical position on a representative day in February, and exhaust heat is supplied to the house with the equipment installed and a nearby house, heat is not supplied to distant houses. Furthermore,

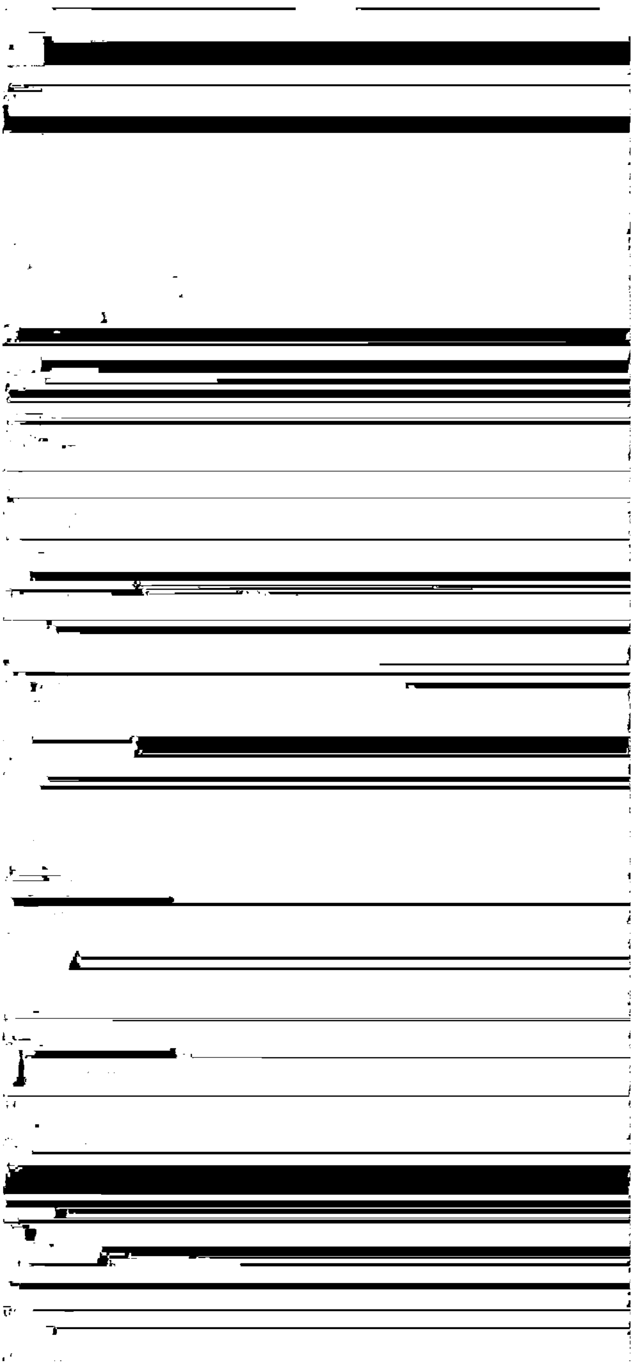

Fig. 2.14 Analysis results of the operational schedule of the fuel cells and reformers installed in the four-houses model

Table 2.3 Results of the arrangement plan and equipment capacity for FEN

[redacted]

although a reformer is scheduled to be installed in house S_E on a representative day in February, this result does not overlap with the houses in which fuel cells are installed in order to effectively use the exhaust heat output of the reformer.

2.7.2 Amount of Hot Water Heat Release and the Hot Water Piping Route

Figure 2.15 shows the analysis results of the route plan of the hot water piping of the four-building model and the five-building model, and the flow direction of hot water. The route plan of hot water piping, the house used as the starting point of HWN, and the flow direction of hot water show the same results every month in the four-building model. On the other hand, although the route result of the hot water piping of a five-building model is the shortest route by which each house is connected in any month, each result of the house used as the starting point of HWN, and the flow direction of hot water differs every month. However, since the energy demand pattern of each house is the same, the house used as the starting point of HWN and the flow direction of the heat medium do not affect the objective function equation (2.8). Figure 2.16 shows the analysis result of the time change of the hot water piping heat release every month. Since it is dependent on the difference in temperature of a medium and the outside air temperature, there will be great heat release of HWN in February. Especially on representative days in February, there is great heat release in a time zone with little heat demanded. The heat release at each time in August is characterized by many upward slants to the right. This is because there is little heat demanded by each house, so the heat transported by HWN increases, and as a result, the hot water temperature rises and the heat release increases.

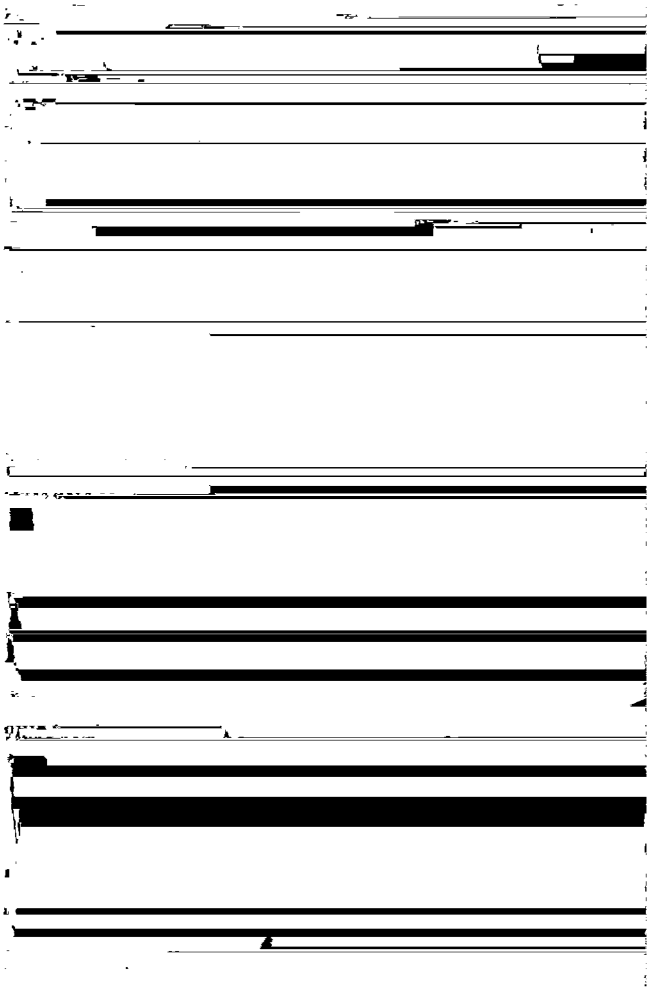

Fig. 2.15 The results of hot water supply planning of the four-houses model and the five-houses model

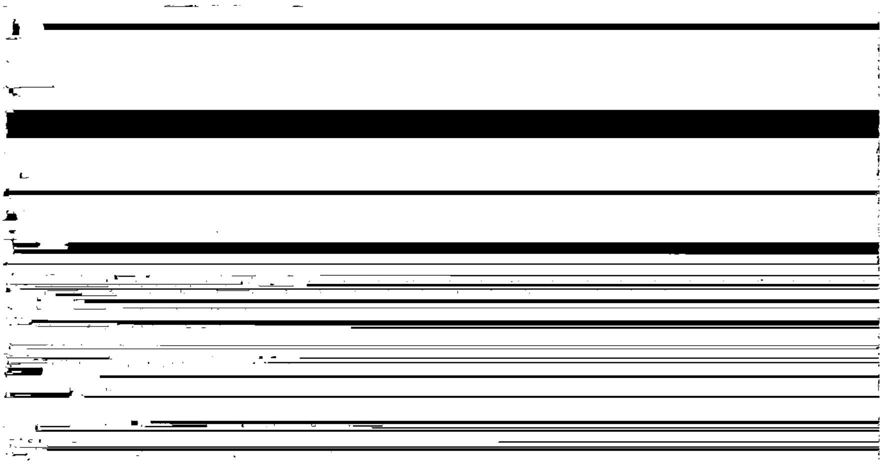

Fig. 2.16 Heat release of HWN for the four-houses model

2.7.3 *Quantity of Flow of the Hot Water Circulating Pump*

Figure 2.17 shows the analysis result of the heat-medium (physical properties using the value of water) quantity of flow that flows through the inside of HWN. The heat-medium quantity of flow (quantity of flow of a hot water circulating pump) determined that 363 K was not exceeded at any position of HWN. There is little heat-medium flow in the four-building model and the five-building model, and there will be little transportation of heat between each house in February. The difference in temperature of a heat medium and the open air is large, and the heat release will be large in February. Then, transportation of heat between each house through HWN is suppressed, and a plan is made so that the heat demand of each house may be supplied with the exhaust heat of the fuel cell installed in each house, the reformer, and the heat output of the boiler.

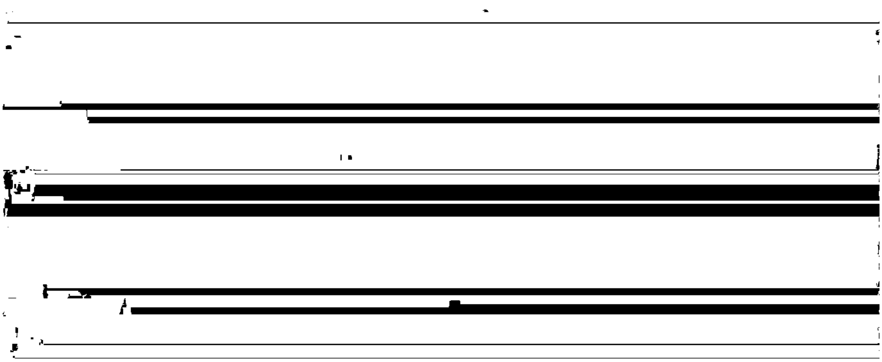

Fig. 2.17 Flow rate of the hot water circulating pump

2.7.4 Operation of the Heat Storage Tank and the Boiler

Figure 2.18 shows the analysis result of the amount of heat surplus that was set at the starting time of operation of the system as 0:00, and was calculated from the heat balance for every time. Since there is high heat demand at each time, there is little heat surplus in February compared with other months. From the characteristics of Fig. 2.18, the capacity and the operation plan of thermal storage can be designed considering the energy demand pattern of every month. Figure 2.19 shows the analysis result of the boiler output in each time of representative days in February. As Table 2.3 shows, on representative days in February, any model is planned so that a boiler can be installed in all the houses.

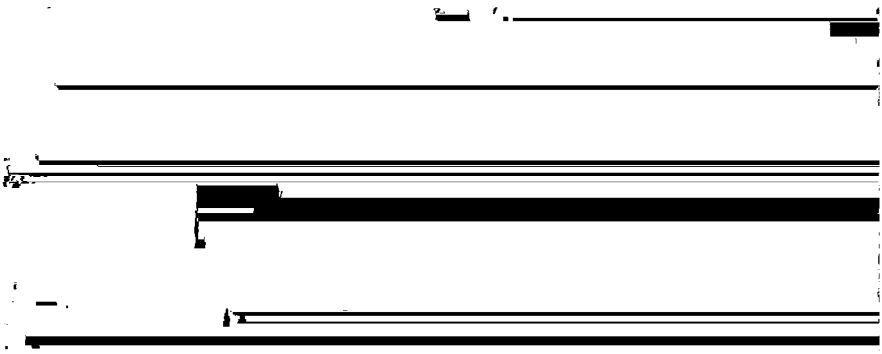

Fig. 2.18 The amount of heat surplus

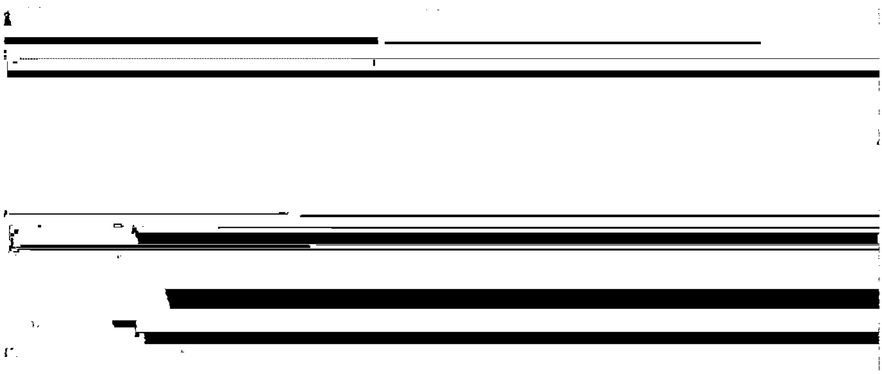

Fig. 2.19 Heat quantity of a boiler in February

2.7.5 Cost Analysis Results

Figure 2.20 shows the analysis results for cost operation (Fig. 2.20(a)) for every month, equipment cost (Fig. 2.20 (b)), and the installation cost (Fig. 2.20(c)) of equipment for the four-building model, the five-building model, and the nine-building model. Moreover, Fig. 2.20(d) shows the total cost as a result of Fig. 2.20(c) from Fig. 2.20(a). However, each result of Fig. 2.20 is arranged as cost per house. Furthermore, the cost of an independent system that installs a fuel cell, a reformer, a boiler, and a heat storage tank in an individual house, and that performs energy supply is shown in Figs. 2.20(b)–(d). The cost per house compared with an independent system decreases, so that the number of the houses connected to FEN from the result of Fig. 2.20(d) increases. In FEN planned using the energy demand pattern in February, 18%, 22%, and 25% of the total cost is reduced by the four-houses model, the five-houses model, and the nine-houses model compared with an independent system, respectively. When constructing FEN in the houses of four to nine buildings analyzed in this paper, the total cost per building can be reduced by optimizing the arrangement planning of the equipment as well as the system operation plan, so that there are many houses.

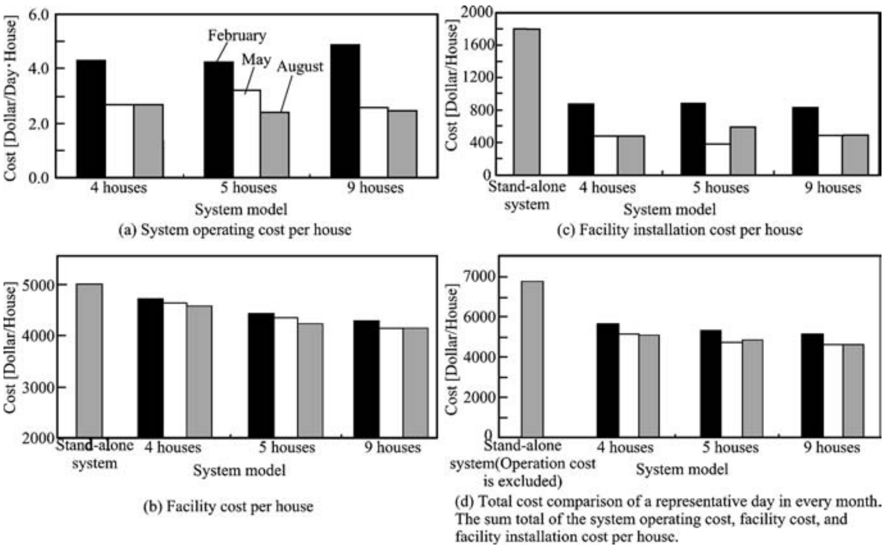

Fig. 2.20 Cost analysis results

2.7.6 Consideration of Analysis Accuracy

In order to investigate the difference in fitness values and the difference in operation plans, the solution (solution with a sufficient fitness value to the second term of Eq. (2.8)) of the second ranking of the four-building model is shown in Fig. 2.21 and Table 2.4. Figure 2.21 shows the cost analysis results of the optimal solution and the second ranking solution. Figure 2.21(a) expresses the analysis result of the operation cost of a representative day every month, Fig. 2.21(b) shows equipment cost, and Fig. 2.21(c) shows the result of the installation cost of

Table 2.4 The results of the arrangement plan of the FEN for the four-houses model. These analysis results are the optimal solutions of the second ranking

[redacted]

[redacted]

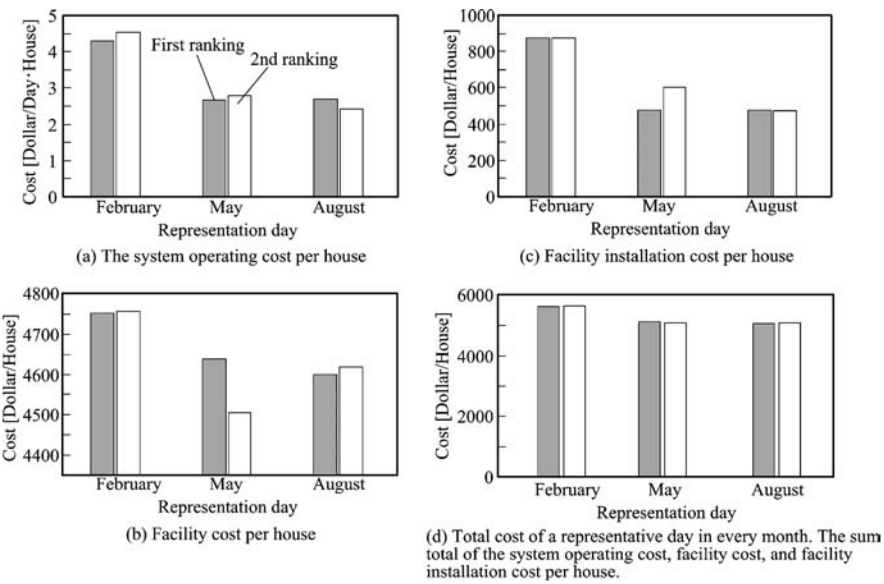

Fig. 2.21 Four-houses model cost comparison of a different fitness value analysis result

equipment. Figure 2.21(d) shows the total cost as a result of Fig. 2.21(c) from Fig. 2.21(a). The difference in the total cost of the optimal solution and the second ranking solution will be 0.1% in February and May, and will be 0.4% in August. When the results of Tables 2.3(a) and 2.4 are compared on a representative day, there will not be a big difference in the setting position or the output of the fuel cells, reformers, and boilers in February. However, on representative days of May and August, there will be a difference in the setting position and the output of the fuel cells and reformers. In the analysis of the operation plan using GA, when the difference in the value of the objective function is 0.4% or less, as shown in Tables 2.3(a) and 2.4, it differs.

2.8 Conclusions

A computer program that optimizes the equipment arrangement of each building linked to a fuel cell network, and the route of the hot water piping network for supplying the exhaust heat of a fuel cell and a reformer to each house under the cost minimization objective has been developed. As a result of analyzing and optimizing the fuel cell network of four to nine houses using the average energy demand pattern of Sapporo, compared with a system that is not optimized, it clearly showed lower equipment costs and installation costs of equipment. If it is analyzed using the energy demand pattern of a house in February and outside temperature data, there will be 18% to 25% cost reduction by optimization. The heat release in a hot water piping network decreases, and it is for this reason that the route of the hot water piping and the arrangement of equipment are planned. In this study, further, the capacity of a heat storage tank, the arrangement planning of a boiler and capacity, and the quantity of flow of the hot water circulating pump were investigated, and the operation plan of each piece of equipment was described. In this study, although the route plan of a hot water piping network and the arrangement planning of equipment were investigated for a representative day in February, May, and August, respectively, in order to actually install these plan results, it is necessary to select the appropriate plan. It is necessary to select the optimal plan from the result of the route of a hot water piping network, and the arrangement of equipment for every month, and to investigate the results when conducting system management through the year from now on.