Shin'ya Obara

Distributed Energy Systems

Novinka

DISTRIBUTED ENERGY SYSTEMS

SHIN'YA OBARA

Nova Science Publishers, Inc.
New York

For permission to use material from this book please contact us:
Telephone 631-231-7269; Fax 631-231-8175
Web Site: http://www.novapublishers.com

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

ISBN: 978-1-60692-543-0

Available upon request

Published by Nova Science Publishers, Inc. New York

DISTRIBUTED ENERGY SYSTEMS

SHIN'YA OBARA

Nova Science Publishers, Inc.
New York

CONTENTS

Chapter 1

OPERATION PLAN OF A COMBINED FUEL CELL COGENERATION USING GENETIC ALGORITHM

INTRODUCTION

From deregulation of energy business, and an environmental problem, the installation spread of the small-scale distribution power due to a fuel cell and a heat engine is expected. Under the objective function set up by the designer or the user, optimization planning that controls small-scale distribution power is required. In dynamic operation planning of the energy plant, the analysis method using mixed integer linear programming is developed [1, 2]. For the compound energy systems of solar modules and fuel cell cogeneration, there have been no reports of the optimization of operation planning. Therefore, there are no results showing the relationship between the objective function given to the combined system and operation planning. Such as a solar modules or wind power, green-energy equipment is accompanied by the fluctuation of an output in many cases. Almost all green energy equipment requires backup by commercial power, fuel cells, heat engines, etc. Operation planning of the system that utilizes renewable energy differs by the objective function and power and heat load pattern. Thus, this chapter investigates the operation planning of the compound energy system composed of proton exchange membrane fuel cell cogeneration with methanol steam-reforming equipment, a solar module, geo-thermal heat pump, heat storage, water electrolysis equipment, commercial power, and a kerosene boiler. In such a complex energy system, facility cost is expensive. However, in this chapter, it investigates as a case of the independent power source for backlands with renewable energy. This chapter considers the operation planning of a system, and the optimization of equipment capacity. The Genetic Algorithm (hereafter described as GA) applicable to a nonlinear problem with many variables is installed into the optimization calculation of the operation planning of the system [3]. In the operation analysis of a complex energy system, Mixed Integer Programming (MIP) other than GA can be used. Because the nonlinear analysis using MIP is made to approximate using a linear expression of relations, it is considered that an error is large. On the other hand, GA is applicable to the analysis of the nonlinear problem of many variables. The range of the analysis accuracy obtained by calculation with GA is understood that it can use industrially. In GA, the design variable of energy equipment is shown with many gene models. In this chapter, the objective functions given to the system were set up as (1) Minimization of error in demand-and-supply balance, (2) Minimization of the operation cost (fuel consumption) of energy equipment, (3) Minimization of the carbon dioxide gas emission accompanying operation, and (4) Minimization of the three objective functions described above. The load pattern in winter (February) and summer (August) of the average individual house in Sapporo, Japan, is used for the energy demand model shown with a case study [4]. This chapter described the operation plan of the independence energy system when installing a methanol steam-reforming type fuel cell and renewable energy into a cold region house. Such complex operation optimization of the energy system did not have a report until now. Consequently, the method of installing and analyzing the GA apply to the nonlinear problem of many variables was proposed. In points of equipment cost, it is difficult for a proposed system to spread generally. However, the installation to the area where the commercial power is not fixed is possible.

FUEL CELL, SOLAR MODULES, AND GEO-THERMAL HEAT PUMP COMBINED SYSTEM

Scheme of Combined System

Figure 1 shows the energy system scheme examined in this chapter. A combined system consists of a solar module (18), PEMFC-CGS (PEMFC: proton exchange membrane, fuel cell CGS: co-generation, the fuel cell is (1), the reforming equipment is (2)-(5) and (12), geo-thermal heat pump, (17), boiler, (8), commercial electric power, heat storage tank (10), and the water electrolysis equipment is (13)-(15)). Water electrolysis equipment is used to store electrical power with hydrogen and oxygen. The arrowhead in this figure shows the substance or direction of energy flux. Each system of solar module, commercial electrical power, and PEMFC-CGS is changed with a changeover switch (6), and electrical power is supplied to the consumer. However, electrical power is not at once supplied to the demand side from two or more power systems.

An electric heater (9) is installed inside the heat storage tank, and electric power is changed into heat and can be stored. Hydrogen and oxygen can be produced if electric power is supplied to an electrolysis tank (13). Hydrogen and oxygen are stored in tanks (14) and (15), respectively, and these are supplied to PEMFC and can be generated at an arbitrary time. When the heat produced by the geo-thermal heat pump exceeds the quantity demanded, surplus heat is stored in the heat storage tank. Although the exhaust heat of PEMFC and the methanol steam-reforming equipment is also supplied to the heat storage tank, when the total amount of heat exceeds the heat storage capacity, heat is radiated with a radiator (7). Tap water has heat exchanged for the heat transfer medium inside the heat storage tank, and moreover controls the temperature of this tap water by the boiler, and supplies hot water to the consumer.

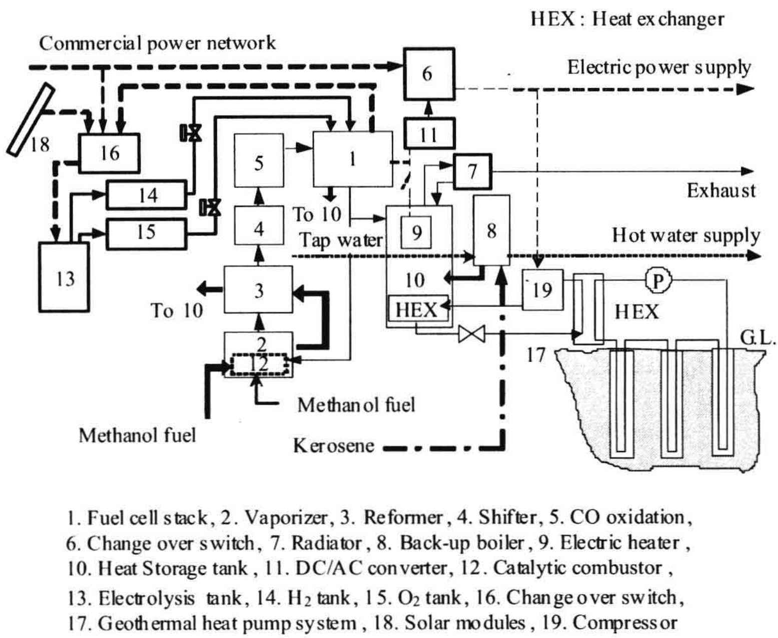

Figure 1. PEMFC-CGS, Heat-pump and solar module combined system for houses.

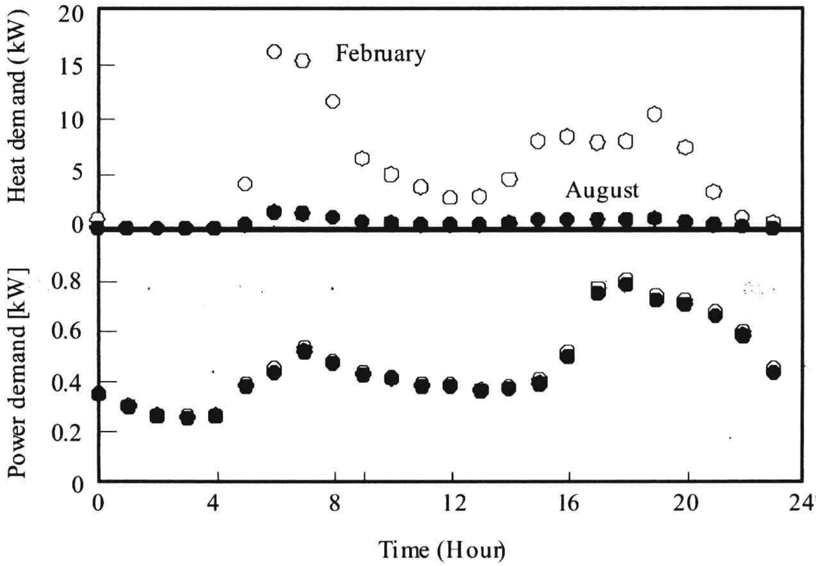

Figure 2. Energy demand of Sapporo-city (Narita *et al,* 1996).

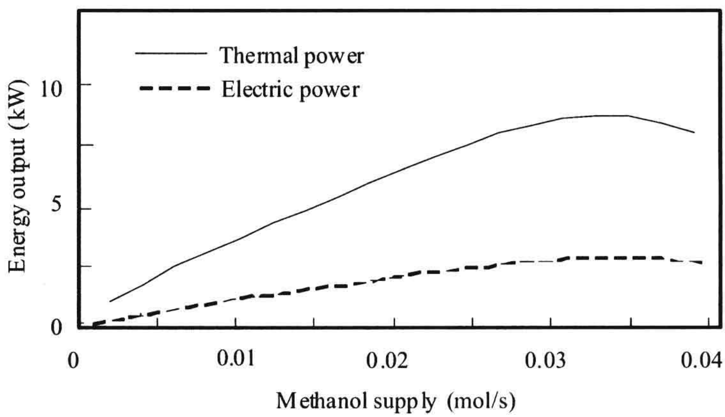

Figure 3. Characteristics of fuel cell stack with methanol steam reforming (Obara *et al.*, 2003).

Methanol fuel is supplied to the reformed gas system of the methanol steam-reforming equipment, and the catalytic-combustion equipment (12) installed in the evaporator (2). Kerosene fuel is supplied to the boiler (8). The energy demand pattern used for analysis is a model in February (winter) and August (summer) in the average individual house in Sapporo in Japan, and shows this in Figure 2. 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 operating period of a system is made into 23:00 from 0:00 of a representation day, and sampling time is expressed by t_k $(k = 0, 1, 2,....., 23)$. The initial values of the capacity of each energy device set up the value used for the usual individual house. The specifications of each energy device are shown in Table 1.

Table 1. Energy device specifications

Solar module	
Area	6.0 m^2
Electric energy output	3kW (Maximum)
Fuel cell	
Type	Proton-exchange membrane fuel cell
Fuel	Water/Methanol=1.4/1.0 (mole ratio)
Reforming type	Methanol steam reforming
Electric energy output	Maximum 3kW
Thermal energy output	9kW (Maximum)
Commercial power	5kW (Maximum)
Heat pump	
Type	Geothermal heat source
Energy source	Electricity
p-h diagram	See Fig.4
Thermal energy output	5kW (Maximum)
COP	3.0
Electrolysis device [8]	
Electrolysis efficient	0.85 (Constant)
Accumulation of electricity	180MJ
Backed boiler	
Fuel	Kerosene
Efficincy	0.85 (Constant)
Thermal energy output	40kW (Maximum)
Thermal storage tank	
Thermal storage capacity	180MJ
Heat medium temperature	353K (Maximum)
Thermal storage efficiency	0.95

Compared with the condition of the steady operation of the methanol reformer, the characteristics of a startup and a shutdown differ greatly. Cold start operation and shutdown operation require about 20 minutes, respectively. In the analysis of this section, it is assumed that the startup of the methanol reformer is always a hot start.

Relational Expression

(1) Energy Output of PEMFC-CGS

3kW methanol steam reforming type PEMFC shown in Figure 3 is used for the output characteristic of the fuel cell introduced into analysis [5]. The horizontal axis of Figure 3 is divided into two or more zones, and the output characteristics are given by the analysis program by using the secondary least-squares method approximation for each range. The electric power output at the time of supplying and generating hydrogen and oxygen stored by water electrolysis to a fuel cell is expressed by Equation (1).

$$E_{FS,tk} = I_{c,tk} \cdot E_{V,tk} - \Delta W_{FS,tk} = \frac{Q_{f,tk} \cdot F_d}{E_c} \cdot E_{V,tk} - \Delta W_{FS,tk} \quad (1)$$

Here, $I_{c,tk}$, $E_{V,tk}$, $\Delta W_{FS,tk}$, $Q_{f,tk}$, F_d and E_c express current, voltage, power loss of a cell stack, hydrogen amount of supply, Faraday constant and chemical equivalent, respectively.

(2) Heat Output of Geo-thermal Heat Pump

Figure 4 is a *p-h* diagram of Refrigerant HC-12a [6], used by the geo-thermal heat pump [7, 8]. This refrigerant is a mixed refrigerant of propane, butane, and isobutene. Although the output characteristics of the heat pump were the analysis of soil temperature T_L and condensation temperature T_H exactly, coefficient of performance COP_{t_k} was set to 3.0 in this section.

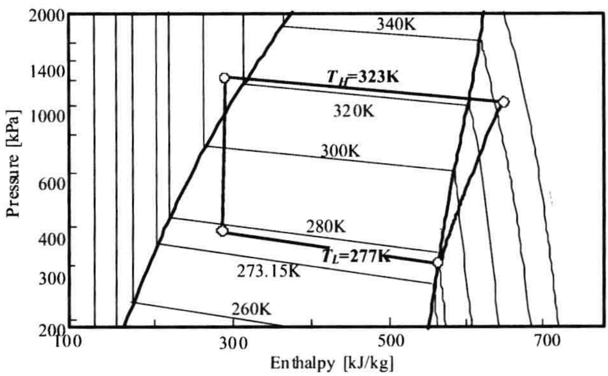

Figure 4. p-h diagram of Refrigerant AHC-12a (HC-TECH Inc., 1997).

(3) Characteristic Equation of Water Electrolysis Tank

From sampling time t_k to Δt, the electric power supplied to an electrolysis tank is expressed by $E_{EL,tk}$, and the efficiency of the electrolysis tank is expressed by ϕ_{EL}. In this case, hydrogen quantity $Q_{H_2,tk}$ to be produced is calculated by Equation (2). Moreover, the amount of production of oxygen is similarly calculated. The efficiency of water electrolyzer refers to the results of a study [9] that used the proton exchange membrane, and ϕ_{EL} is set as 0.85.

$$Q_{H_2,tk} = \frac{E_{EL,tk} \cdot E_c}{F_d \cdot E_V} \cdot \phi_{EL} \qquad (2)$$

In calculations for this case study, the hydrogen and oxygen are pressurized to 1.0 MPa, respectively. The work of the compressor is assumed to be compression work for an ideal gas. The whole compressor efficiency including an inverter controller loss and the power consumption in an electric motor, transfer loss of power, loss with insufficient air leak and cooling, and other machine losses is set up to 50%.

(4) Characteristic Equation of Heat Storage Tank and Boiler

The conditional expression showing heat storage characteristics is given by Equation (3) and Equation (4) using the amount of maximum heat storage $S_{St,\max}$, and maximum temperature $T_{St,\max}$ of the heat medium. The capacity and the specific heat of the heat storage medium are expressed by V and C_p, and outside air temperature is expressed by T_∞ (The heat medium is assumed to be calcium chloride). Moreover, the heat storage temperature at time t_k is calculated by $T_{St,tk} = S_{St,tk} / (\rho \cdot C_p \cdot V)$. Here, ρ express density of heat storage medium.

$$0 \le S_{St,tk} \le S_{St,\max} \qquad (3)$$

$$T_{\infty,tk} \le T_{St,tk} \le T_{St,\max} \qquad (4)$$

The characteristic equation of heat storage tank between time t_k and Δt is given by Equation (5).

$$S_{St,tk} - S_{St,tk-1} = \{H_{St,in,tk} - H_{St,out,tk} - \phi_{St} \cdot \rho \cdot C_p \cdot V \cdot (T_{St,tk} - T_{\infty,tk})\} \cdot \Delta t \quad (5)$$

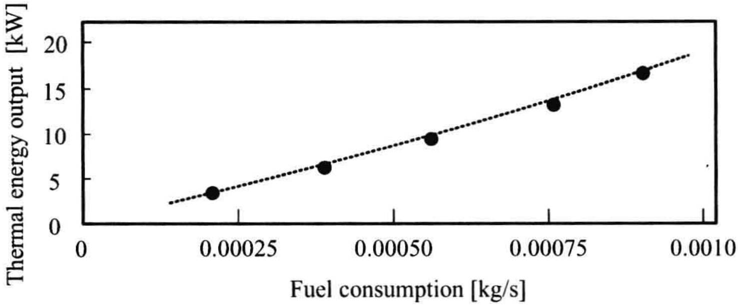

Figure 5. Thermal energy output of boiler.

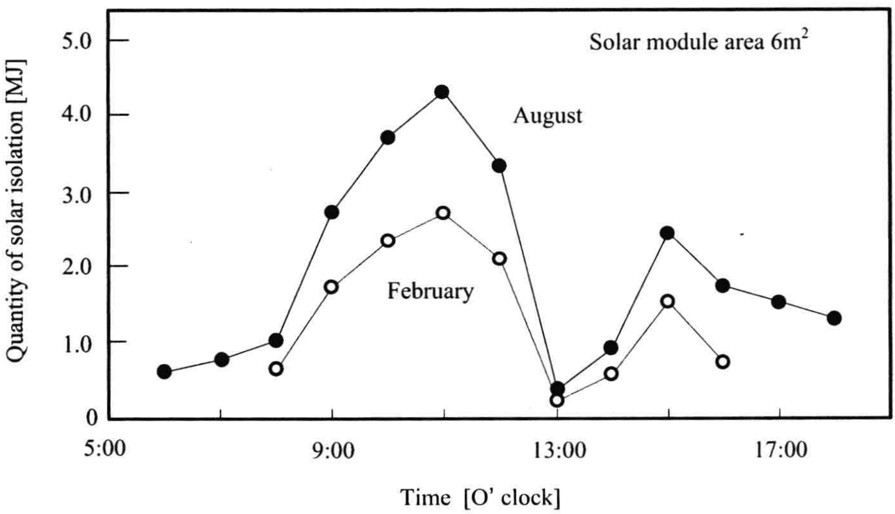

Figure 6. Time change of solar module output (Nagano et al., 2002).

$H_{St,in,tk}$ and $H_{St,out,tk}$ express the heat input and heat output of the heat storage tank, respectively. The third term in the right-hand bracket of Equation (5) includes outside air temperature $T_{\infty,tk}$ supposing heat storage loss is dependent on outside air temperature. However, in the analysis in this section, the efficiency of heat storage ϕ_{St} is set to 0.95, and change in outside air temperature is not taken into consideration. Figure 5 shows the relationship between the fuel consumption of a boiler and hot-water-supply output. It is expressed with the calorific value of the fuel being α_{Boiler}, the boiler efficiency being ϕ_{Boiler}, and the fuel-supply quantity of flow being $F_{Boiler,tk}$, and the characteristic equation of a boiler is given by the following equation.

$$H_{Boiler,tk} = \alpha_{Boiler} \cdot F_{Boiler,tk} \cdot \phi_{Boiler} \tag{6}$$

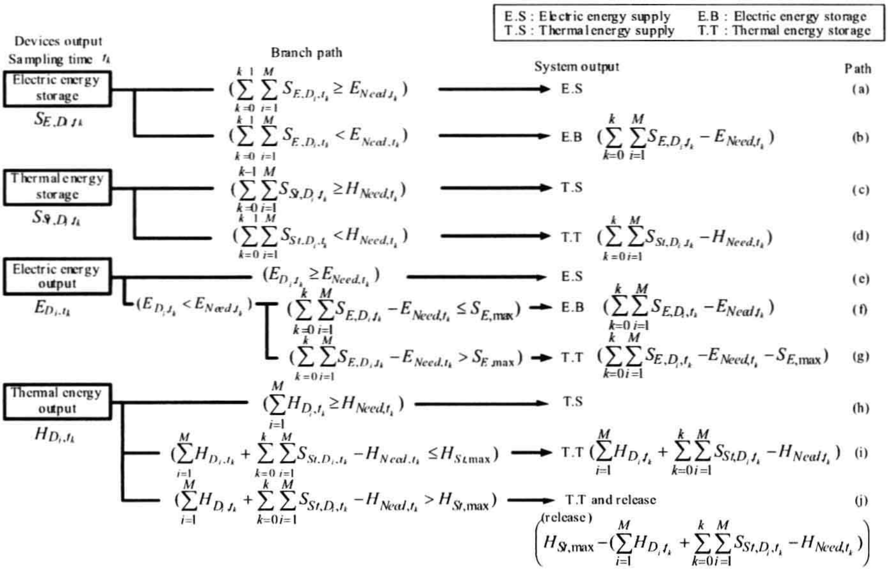

Figure 7. Energy supply path.

(5) Characteristic Equation of Solar Module

Figure 6 shows the results of measurement of the production of electricity of the solar module in February and August in Sapporo [10]. However, the panel was vertically installed so that this solar module would not be covered in snow in winter. Therefore, the production of electricity decreases as shown in the results of Figure 6 at 13:00.

Energy Supply Path

The energy equipment is expressed by D_i, and let subscript i ($i = 1, 2, 3, ..., M$, M are the number of pieces of equipment) be the equipment number. The electric power and heat that are outputted by energy device D_i

follow one path (a) to (j) as shown in Figure 7. When electric energy $E_{D_i,tk}$ generated by the system exceeds power demand $E_{Need,tk}$, hydrogen and oxygen are produced and stored by water electrolysis. Moreover, it is also possible to change electric power into heat with a heater, to shift time, and to supply the demand side.

ENERGY BALANCE AND OBJECTIVE FUNCTION

Objective Function of System

The objective function given to the system is given by (1) Minimization of error in demand-and-supply balance, (2) Minimization of the operation cost (fuel consumption) of the energy equipment, (3) Minimization of the carbon dioxide gas emission accompanying operation, and (4) Minimization of the three objective functions described above. Equation (7) and Equation (8) are energy balance equations of electric power and heat, respectively.

$$E_{FS,tk} + E_{Utility,tk} + E_{Stp,tk} = E_{System,tk} + \Delta E_{EL,tk} + \Delta E_{HP,tk} + \Delta E_{CPH,tk} + \Delta E_{CPO,tk} + E_{H,tk} \quad (7)$$

$$\alpha_{FS} \cdot F_{FS,tk} \cdot \phi_{FS} + \alpha_{Boiler} \cdot F_{Boiler,tk} \cdot \phi_{Boiler} + H_{HP,tk} + H_{St,tk} = H_{System,tk} + H_{Rad,tk} + \Delta H_{St,tk} \quad (8)$$

The left-hand side in Equation (7) and Equation (8) is the amount of energy inputted into the system, and the right-hand side expresses the amount of energy outputted from the system. Here, $E_{FS,tk}$, $E_{Utility,tk}$, $E_{Stp,tk}$ and $E_{System,tk}$ express electric power of fuel cell stack, commercial power and power storage, respectively. $\Delta E_{EL,tk}$, $\Delta E_{HP,tk}$, $\Delta E_{CPH,tk}$, $\Delta E_{CPO,tk}$ and $E_{H,tk}$ express power consumption of electrolyzer, heat pump, hydrogen compressor, oxygen compressor and heater, respectively. α_{FS} and α_{Boiler} express calorific value of fuel of fuel cell stack and boiler. ϕ_{FS} and ϕ_{Boiler} express efficiency of fuel cell stack and boiler. $F_{FS,tk}$ and $F_{Boiler,tk}$ express fuel quantity of flow of fuel cell stack and boiler. $H_{HP,tk}$, $H_{St,tk}$, $H_{System,tk}$, $H_{Rad,tk}$ and $\Delta H_{St,tk}$ express heat of heat pump, heat storage tank, system, radiator and heat storage loss, respectively.

Objective function (1) described in Introduction is an operating pattern when the difference in input-output of energy balance Equation (7) and Equation (8) serves as the minimum. Objective function (2) is an operating pattern when fuel cost and commercial power cost serve as the minimum. The operation cost of equipment D_i between time t_k and Δt is calculated from fuel flow rate F_{D_i,t_k} and unit fuel price C_{fuel,D_i} that are supplied to the equipment. Therefore, the operation cost of the whole system is calculated by Equation (9). Here, $C_{Utility,t_k}$ express commercial power cost.

$$C_{System,t_k} = \sum_{i=1}^{M} \left(C_{fuel,D_i} \cdot F_{D_i,t_k} \cdot \Delta t \right) + C_{Utility,t_k} \tag{9}$$

Objective function (3) expresses the operation pattern whose amount of greenhouse gas discharge calculated from the fuel consumption is the minimum. Amount of emission W_{System,t_k} of greenhouse gases is calculated by Equation (10). However, the number of gas compositions that contribute to greenhouse gas discharged by equipment D_i is expressed by S.

$$W_{System,t_k} = \sum_{i=1}^{M} \sum_{j=1}^{S} \left(G_{D_i,EX_j} \cdot \varepsilon_{D_i,EX_j,t_k} \cdot F_{D_i,t_k} \cdot \Delta t \right) \tag{10}$$

Table 2. Energy cost and greenhouse-warming coefficient (Japanese Environment Agency, 2000)

Kerosene fuel	0.01097 Dollar/J
	3.099 kg?CO_2/kg
	2.026 kg/Dollar
Methanol fuel	0.01772 Dollar/J
	1.379 kg?CO_2/kg
Commercial power	0.0647 Dollar/J (9:00-21:00)
	0.01515 Dollar/J (22:00-8:00)
	0.000099167 kg?CO_2/kJ

Table 3. Calculation result of each purposes of February (Kerosene (kg))

Minimization of	operation cost	the error of demand-and -supply balance	greenhouse gas
Minimization of operation cost	**14.72** (15.36)	0.439	13.76 (13.35)
Minimization of the error of demand-and-supply balance	22.40	**0.0170**	18.82
Minimization of the amount of green-house gas discharge	15.66	0.426	**13.16**

Table 4. Calculation result of each purposes of August (Kerosene (kg))

	operation cost	the error of demand-and -supply balance	greenhouse gas discharge
Minimization of operation cost	**3.61** (4.28)	0.795	3.42 (2.60)
Minimization of the error of demand-and -supply balance	6.85	**0.0247**	4.174
Minimization of the amount of green-house gas discharge	5.27	0.199	**2.55**

Here, G_{D_i,EX_j} expresses a global-warming factor per unit weight of fuel, $\varepsilon_{D_i,EX_j,t_k}$ being the weight concentration of EX_j, and F_{D_i,t_k} being the amount of fuel supply to equipment D_i. Table 2 shows fuel cost and a global-warming factor [11], and is analyzed using these values in an analysis case.

Multi-objective Optimization

As shown in Equation (11), the operation pattern that minimizes the sum that multiplies each objective function by weight is a multiple-objective optimal solution.