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An Optimal Operation Model for Centralized Micro-Energy Network Considering Electric Heating

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Abstract

The interest in heat energy network as well as electri energy network has been growing. For this reason, it is required to develop the integration operation technique of electric and heat energy by using the combined heat and power (CHP) generation.Electric energy can be used for heat energy in order to improve the energy efficiency by the electric heater in the proposed centralized micro-energy network (μENet).This paper deals with an optimal operation model for centralized micro-energy network considering the electric heating. A mathematical model is established and the validation of proposed the model is shown through the simulation.

Keywords: *Micro-energy network, optimal operation, combined heat and power (CHP) system, heat trade, electric heating*

1. Introduction

In order to expand smart grid to application networks with various resources, total energy network including heat energy as well as electric energy has been studied recently. Especially, electric energy networks are studied in many applications such as smart-grid and microgrid but heat energy network is studied in the basic research phase although the heat energy takes up the most of the energy compsumtion with electric energy. Therefore, the development of network technologies based on heat trade has been required [1-4].

Meanwhile, building energy management systems (BEMSs) managing and operating the electric and heat energy at a building have been studying [5-7] and studies on the district heating and combined heat and power (CHP) generation for effective operation have being carried out [8, 9]. Especially, optimal operation technique of energy network using the CHP generation is key technique of combind electric and heat energy network because it can manage both of the electric and heat energies effectively.

This paper proposes an optimal operation model for centralized micro-energy network (μENet) which is a cooperative operation model composed of a group of buildings. the system can trade with power grid but the system is not connected with a district heat system for trading heat energy. In addition, electric heating can be used for heat loads by the electric heater. Optimal operation scheduling of μENet is performed by the μENet energy management system (μEMS). A mathematical model for optimal operation is established and is tested to show feasibility through the simulation.

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2. Micro-Energy Network

A micro-rnergy network(μENet) has an optimal operation model of electric energy and heat energy of a group of buildings as an energy community. Although various types of μENet can be existed according configurations, this paper deals with a μENet which has centralized operation model as shown in Figure 1. In the μENet, the electric energy network and the heat energy network are coupled at CHP generators in buildings because they produce electric and heat energies together. In addition, the heat energy can economically meet by using the cheap electric energy using the electric heater in buildings. In order to economically operate, μENet has a μENet energy management system(μEMS) which has a function of the optimal operation to manage total energy in the μENet.

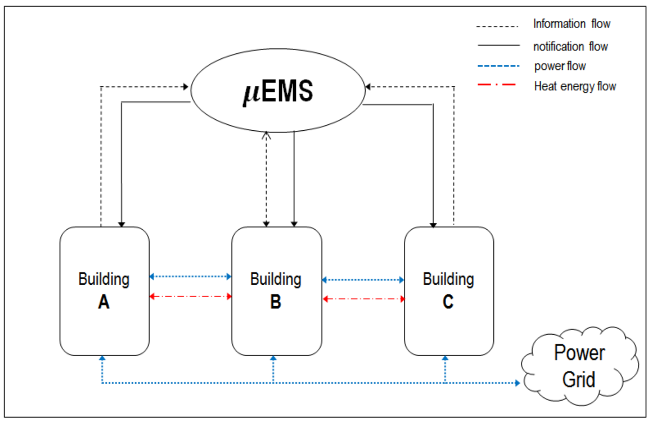


Figure 1. Information and energy flows in the centralized μENet

3. Mathematical Modeling of μENet Operation

In this section, the operation process of the μENet is mathematically modeled. Mathematical notations are first defined as shown in Section 3.1, and the mathematical model for operating the μENet is presented.

3.1 Nomeclature

t = the identifier of operation interval
T = the number of operation intervals
l = the identifier of buildings
L = the number of buildings
j = the identifier of heat only boiler (HOB)
J = the number of HOBs
e = the identifier of electric energy
h = the identifier of heat energy
η_{CHP_l}= the heat to power ratio of [%]
τ_{CH} = the charging loss of the ESS [%]
τ_{DISCH} = the discharging loss of the ESS [%]
$M_{ESS}^{SOC}(t)$ = the state of charge the ESS [%]
$\overline{M_{ESS}^{SOC}}$ = the maximum state of charge of the ESS [%]
$\underline{M_{ESS}^{SOC}}$ = the minimum state of charge of the ESS [%]

$C^{e}_{CHP_l}$= the electric energy production cost of the CHP in the l^{th} building [won/kWh]
$C^{h}_{CHP_l}$= the hgeat energy production cost of the CHP in the l^{th} building [won/kWh]
$C^{h}_{HOB_{l,j}}$= the cost of the j^{th} HOB in the l^{th} building [won/kWh]
$PR^{e}_{BUY_l}(t)$ = the buying price from the power grid in the l^{th} building [won/kWh]
$PR^{e}_{SELL_l}(t)$ = the selling price to the power grid in the l^{th} building [won/kWh]
$M^{e}_{PV_l}(t)$ = the output produced from the photovoltaic (PV) system in the l^{th} building [won/kWh]
$M^{e}_{CHP_l}(t)$ = the electric energy production amount of the CHP in the l^{th} building [won/kWh]
$M^{e}_{BUY}(t)$ = the amount of electric energy purchased from the power grid at t [kWh]
$M^{e}_{SELL}(t)$ = the amount of electric energy sold to the power grid at t [kWh]
$M^{e}_{DISCH}(t)$ = the discharging amount of the ESS [kWh]
$M^{e}_{CH}(t)$ = the charging amount of the ESS [kWh]
$M^{e}_{SEND_l}(t)$ = the sending electric energy amount in the l^{th} building [won/kWh]
$M^{e}_{REC_l}(t)$ = the receiving electric energy amount in the l^{th} building [won/kWh]
$M^{e}_{LOAD_l}(t)$ = electric energy demand in the l^{th} building [won/kWh]
$M^{e\to h}_{CHP_l}(t)$ = the amount of electric energy generated from the CHP in the l^{th} building that is consumed by the heater in the l^{th} building [won/kWh]
$M^{e\to h}_{BUY_l}(t)$ = the purchasing amount of electric energy consumed by the heater in the l^{th} building [won/kWh]
$M^{h}_{SH_l}(t)$ = the output produced from the solar heat system in the l^{th} building [won/kWh]
$M^{h}_{CHP_l}(t)$ = the heat energy production amount of the CHP in the l^{th} building [won/kWh]
$M^{h}_{HOB_{l,j}}(t)$ = the heat energy production amount of the j^{th} HOB in the l^{th} building [won/kWh]
$M^{h}_{SEND_l}(t)$ = the sending heat energy amount in the l^{th} building [won/kWh]
$M^{e}_{REC_l}(t)$ = the receiving heat energy amount in the l^{th} building [won/kWh]
$M^{h}_{LOAD_l}(t)$ = heat energy demand in the l^{th} building [won/kWh]
M^{CAP}_{ESS} = the capacity of the energy storage system (ESS) [kWh]
M^{INT}_{ESS} = the initial amount of the ESS [kWh]
$M^{cap}_{HOB_{l,j}}$ = the capacity of the j^{th} HOB in the l^{th} building [won/kWh]

3.2 Mathematical modeling

In this paper, the follong mathematical model for optimal operation of μENet including CHP generation based on LP is proposed. The proposed object function is established to minimize the cost of the μENet operation as shown in Eq. (1).

The objective function of optimal operation of the μENet is proposed as shown in Eq. (1). It is base on the total operation cost in the μENet when external trading of electric energy with the power grid is applied as follows:

$$\mathrm{C}^{ENet}\Big(M^{e}_{CHP_1}(t) \ldots M^{e}_{CHP_L}(t), M^{e}_{SEND_1}(t) \ldots M^{e}_{SEND_L}(t), M^{h}_{SEND_1}(t) \ldots M^{h}_{SEND_L}(t), M^{e\to h}_{CHP_1}(t) \ldots M^{e\to h}_{CHP_L}(t), M^{h}_{HOB_{1,1}}(t) \ldots M^{h}_{HOB_{L,J}}(t), M^{e}_{BUY_1}(t) \ldots M^{e}_{BUY_L}, M^{e}_{SELL_1}(t) \ldots M^{e}_{SELL_L}, M^{e\to h}_{BUY_1}(t) \ldots M^{e\to h}_{BUY_L}(t)\Big)$$

$$= \sum_{l=1}^{L}\Big\{(C_{CHP_l}^{e}\cdot M_{CHP_l}^{e}(t)) + (C_{CHP_l}^{h}\cdot \eta_{CHP_l}\cdot M_{CHP_l}^{e}(t)) + \left(0\cdot\ M_{SEND_l}^{e}(t) +\ 0\cdot\ M_{SEND_l}^{h}(t)\right) + \left(PR_{SELL_l}^{e}(t)\cdot\ M_{CHP_l}^{e\to h}(t)\right) + \sum_{j=1}^{J}(C_{HOB_{l,j}}^{h}\cdot\ M_{HOB_{l,j}}^{h}(t))\Big\} + \left(PR_{BUY_l}^{e}(t)\cdot\ M_{BUY_l}^{e}(t)\right) - \left(PR_{SELL_l}^{e}(t)\cdot\ M_{SELL_l}^{e}(t)\right) + \left(PR_{BUY_l}^{e}(t)\cdot\ M_{BUY_l}^{e\to h}(t)\right) \quad (1)$$

for $1\ \le t \le T,\ 1 \le\ l \le L$.

Let $P_{ENet}(t) = \big(M_{CHP_1}^{e}(t) \ldots M_{CHP_L}^{e}(t), M_{SEND_1}^{e}(t) \ldots M_{SEND_L}^{e}(t), M_{SEND_1}^{h}(t) \ldots M_{SEND_L}^{h}(t), M_{CHP_1}^{e\to h}(t) \ldots M_{CHP_L}^{e\to h}(t),\ M_{HOB_{1,1}}^{h}(t) \ldots\ M_{HOB_{L,J}}^{h}(t), M_{BUY_1}^{e}(t)\ \ldots M_{BUY_L}^{e}, M_{SELL_1}^{e}(t)\ \ldots M_{SELL_L}^{e}, M_{BUY_1}^{e\to h}(t)\ \ldots\ M_{BUY_L}^{e\to h}(t)\big)$ be set of the energy generation amount and trading amount in the μENet. Since the total selling profit deducts the electric energy production cost and bying cost from the power grid, the energy optimization can be performed by minimizing the total operation cost as follows:

$$P_{ENet}^{*} = \underset{P_{ENet}(t)}{\arg\min}\left\{C^{ENet}\big(P_{ENet}(t)\big)\right\}$$

Constraints are defined as follows. CHP generators should be operated between minimum generation and maximum generation as shown in Eq. (2).

$$\min[M_{CHP_l}^{e}] \le M_{CHP_l}^{e}(t) \le \max[M_{CHP_l}^{e}] \quad (2)$$

Heat only boilers (HOBs) should be operated within there operational rages. The constraint in (3) implies that HOBs cannot produce more that there capacities.

$$M_{HOB_{l,j}}^{h}(t) \le\ M_{HOB_{l,j}}^{cap}\ ,\ 1 \le\ j \le J. \quad (3)$$

Equation (4) shows that electric energy supply in μENet should meet its electric demand considering the trading with the power grid

$$M_{LOAD_l}^{e}(t) = M_{CHP_l}^{e}(t) + M_{PV_l}^{e}(t) + M_{REC_l}^{e}(t) - M_{SEND_l}^{e}(t) + M_{DISCH}^{e}(t) - M_{CH}^{e}(t) + M_{BUY_l}^{e}(t) - M_{SELL_l}^{e}(t) \quad (4)$$

The amount of heat energy from the CHP generator is assumed to the proportional amount of electric energy from the CHP generator according to its heat and electric energy ratio[4].

$$M_{CHP_l}^{h}(t) = \eta_{CHP_l}\cdot M_{CHP_l}^{e}(t) \quad (5)$$

The constraint to the heat energy balance in (6) that heat energy supply in a μENet should be more than its heat demand.

$$\begin{aligned} M_{LOAD_l}^{h}(t) &\le M_{SH_l}^{h}(t) + M_{CHP_l}^{h}(t) +\ M_{HOB_{l,j}}^{h}(t) + M_{CHP_l}^{e\to h}(t) + M_{REC_l}^{h}(t) \\ &\quad - M_{SEND_l}^{h}(t) \\ \sum_{l=1}^{L} M_{SEND_l}^{e}(t) &= \sum_{l=1}^{L} M_{REC_l}^{e}(t) \end{aligned} \quad (6)$$

The amount of electric energy consumed by the electric heater in a μENet is limited by the capacity of the electric heater.

$$M_{CHP_l}^{e\to h}(t) \le M_{SELL_l}^{e}(t) \tag{7}$$

When the demand is lower then the supply, the energy storage system (ESS) charges electric energy at a low price. In contrast, when the demand is higher then the supply, the ESS discharges electric energy which is stored in the ESS. In addition, the ESS can be operated by trade prices of electric energy with the power market as well as amount of load. This paper considered the lithium-ion battery energy storage system (BESS) model. In order to guarantee a best performance of the battery life, full charge or discharge should be minimized so as to prevent completion of the charging cycle. By considering the minimum and maximum state of charge (SOC), these characteristic should be reflected in the operation model of the BESS.

In t interval, electric energy which is charged to the BESS can be decided within capacity of BESS including stored electric energy in the BESS as shown in Eq. (8).

$$\begin{aligned} &M_{CH}^{e}(t) \le \begin{cases} M_{ESS}^{CAP} - M_{ESS}^{INT}, & if \quad t = 1 \\ M_{ESS}^{CAP} \cdot \left(1 - M_{ESS}^{SOC}(t-1)\right) & oterwise \end{cases} \\ &M_{CH}^{e}(t) \ge 0, 1 \le t \le T. \end{aligned} \tag{8}$$

In t interval, electric energy which is discharged from the BESS can be decided within the remaining electric energy in the BESS as shown in Eq. (9).

$$\begin{aligned} &M_{DISCH}^{e}(t) \le \begin{cases} M_{ESS}^{INT}, & if \quad t = 1 \\ M_{ESS}^{CAP} \cdot M_{ESS}^{SOC}(t) & oterwise \end{cases} \\ &M_{DISCH}^{e}(t) \ge 0, \; 1 \le t \le T. \end{aligned} \tag{9}$$

In t interval, electric energy which is discharged from the BESS can be decided within the remaining electric energy in the BESS as shown in Eq. (10)

$$M_{ESS}^{CAP} \cdot \underline{M_{ESS}^{SOC}} \le M_{ESS}^{CAP} \cdot M_{ESS}^{SOC}(t) \le M_{ESS}^{CAP} \cdot \overline{M_{ESS}^{SOC}} \tag{10}$$

The SOC of BESS has to be calculated in all intervals considering the following piecewise function which depends on t ≥1:

$$M_{ESS}^{CAP} \cdot M_{ESS}^{SOC}(t) = M_{ESS}^{CAP} \cdot M_{ESS}^{SOC}(t-1) + M_{CH}^{e}(t) \cdot (1 - \tau_{CH}) - M_{DISCH}^{e}(t) \cdot \frac{1}{1-\tau_{DISCH}}$$

If $t = 1$, the function is:

$$M_{ESS}^{CAP} \cdot M_{ESS}^{SOC}(t) = M_{ESS}^{INT} + M_{CH}^{e}(t) \cdot (1 - \tau_{CH}) - M_{DISCH}^{e}(t) \cdot \frac{1}{1-\tau_{DISCH}} \tag{11}$$

After optimization is completed, the selling amount of electric energy to the power grid in a building should be adjusted by deductiing the amount of electric energy consumed by the electric heater in the building as follows:

$$M_{SELL_l}^{e}(t) := M_{SELL_l}^{e}(t) - M_{CHP_l}^{e\to h}(t) \tag{12}$$

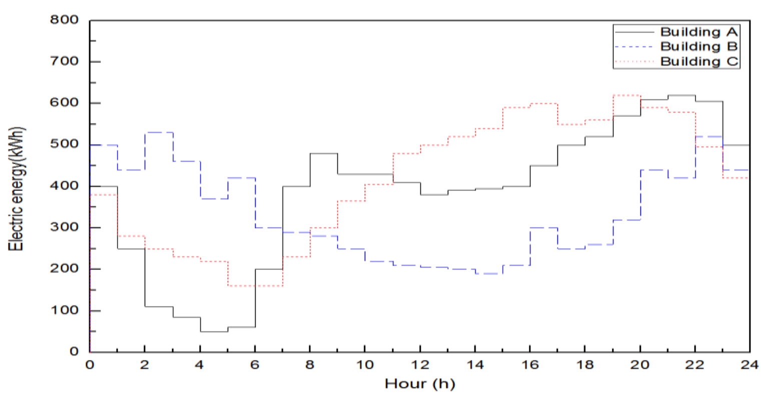
4. Simulation

4.1 Operation condition

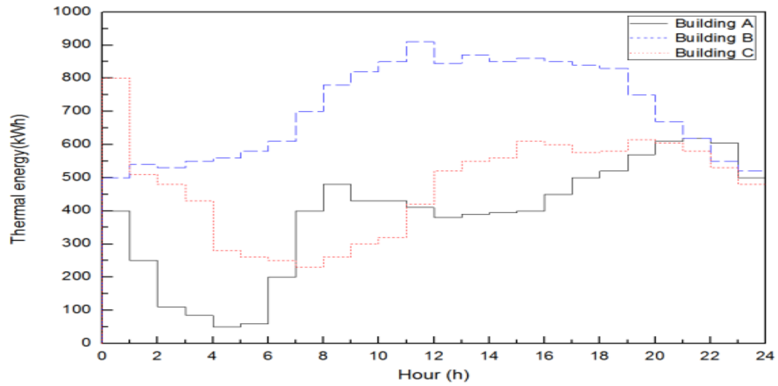
In this paper, we assume 24 intervals for optimal operation of the μENet. the data sheet of generation systems is shown in Table 1. The electric heaters (EHs) are considered in each building, and its capacity is 200kW. Loads are composed of a lumped electric load and a lumped heat load as shown in Figure 2. In order to increase the effect of cooperative operation for the μENet wich is composed of buildings having different electric and heat load patterns.

Table 1. Data of energy sources

Item	CHP A	CHP B	CHP C	HOB A	HOB B	HOB C
Electricity production cost (won/kWh)	77.78	81.71	71.11	-	-	-
Heat production cost (won/kWh)	62.22	74.28	93.88	160	170	165
Min. production capacity (kWh)	180	200	140	0	0	30
Max. production capacity (kWh)	450	500	350	200	250	200
Heat and electric power ratio	1.25	1.1	0.8	-	-	-



(a) Elecric load.



(b) Elecric load.

Figure 2. Electric and heat load

Trading price of electric energy is real-time trading prices as shown in Figure 3, where the buying price is higher than the selling price like general market prices.

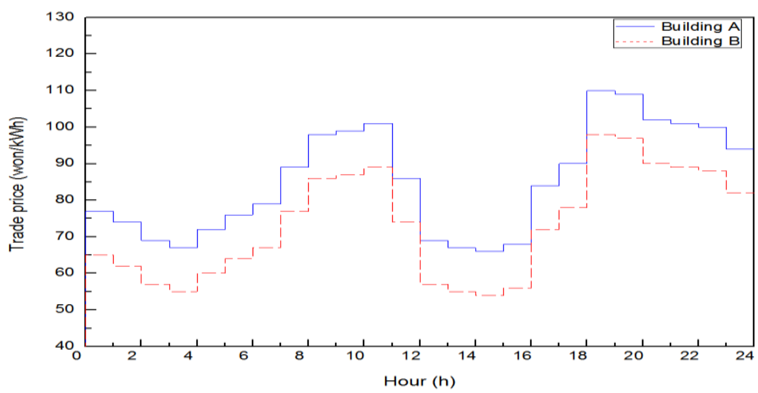


Figure 3. Trading price of electric energy with power grid

4.2 Results

Table 2 shows the optimal scheduling result of the electric energy part. The building A having the lower electric production cost is fully operated. Especially, in interval 4, 5, and 6, building A produces the more electric energy than their electric demand for using the electric heater because of high heat demand. When the trading price is higher than the electric production cost, the building B is minimally operated. Building B receives the heat energy for the short energy from other buildings in interval 5-7. In other intervals 12 and 17-22, in order to meet the electric demand of building C, building B produces the more electric energy than its electric demand.

In the case of the electric energy, it gains the profit by selling the surplus electric energy because it is conneted with the power grid (Intervals 1-5 and 13-16). However, the surplus electric energy can charge to the BESS during intervals having high electric demand and high trading price as shown in Figure 4 (Interval 14).

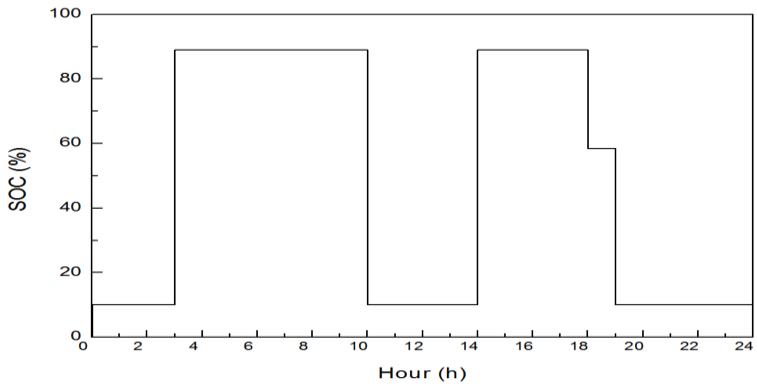


Figure 4. the state of charge (SOC) of ESS

Table 2. Optimal scheduling of electric energy part

Hour	Building A							Building B						Building C						
	$M^e_{LOAD_1}$	$M^e_{RDG_1}$	$M^e_{CHP_1}$	$M^e_{SEND_1}$	$M^e_{REC_1}$	$M^e_{BUY_1}$	$M^e_{SELL_1}$	$M^e_{LOAD_1}$	$M^e_{CHP_1}$	$M^e_{SEND_1}$	$M^e_{REC_1}$	$M^e_{BUY_1}$	$M^e_{SELL_1}$	$M^e_{LOAD_1}$	$M^e_{RDG_1}$	$M^e_{CHP_1}$	$M^e_{SEND_1}$	$M^e_{REC_1}$	$M^e_{BUY_1}$	$M^e_{SELL_1}$
1	400	0	450	0	0	85.5		500	200	0	0	330	0	380	18	140	0	0	343	0
2	250	0	450	0	0	0	0	440	200	0	0	240	0	280	16	140	0	0	229.5	0
3	110	0	206.4	0	0	103.6	0	530	200	0	0	530	0	250	17	140	0	0	233	0
4	85	0	185.778	0	0	168.158	0	460	200	0	0	460	0	230	18	140	0	0	212	0
5	50	0	385.333	234	0	0	0	370	200	0	170	0	0	220	16	140	0	64	0	0
6	60	0	414.222	222	0	0	0	420	200	0	220	0	0	160	18	140	0	2	0	0
7	200	0	450	104	0	0	0	300	200	0	100	0	0	160	16	140	0	4	0	0
8	400	6	450	56	0	0	0	290	333.571	20	0	0	0	230	14	140	0	76	0	0
9	480	9	450	0	21	0	0	280	500	21	0	0	199	300	12	350	0	0	0	62
10	430	10	450	6	0	0	24	250	500	0	0	0	250	365	9	350	0	6	0	0
11	430	13	450	0	0	0	33	220	500	0	0	0	280	405	13	350	0	0	0	33.05
12	410	18	450	58	0	0	0	210	478	268	0	0	0	480	14	140	0	326	0	0
13	380	23	450	0	0	107	0	205	200	0	0	205	0	500	8	140	0	0	492	0
14	390	25	450	0	0	115	0	200	200	0	0	200	0	520	6	140	0	0	514	0
15	395	24	448	0	0	121	0	190	200	0	0	190	0	540	4	140	0	0	619.158	0
16	400	21	450	0	0	129	0	210	200	0	0	210	0	590	9	140	0	0	581	0
17	450	18	450	18	0	0	0	300	500	200	0	0	0	600	11	234.375	0	218	136.625	0
18	500	10	450	0	40	0	0	250	500	250	0	0	0	550	13	327	0	210	0	0
19	520	0	450	0	70	0	0	260	500	240	0	0	0	560	11	350	0	170	0	0
20	570	0	450	0	120	0	0	320	500	180	0	0	0	620	13	350	0	60	150.95	0
21	610	0	450	0	60	100	0	440	500	60	0	0	0	590	18	350	0	0	222	0
22	620	0	450	0	80	90	0	420	500	80	0	0	0	580	16	350	0	0	214	0
23	605	0	450	0	0	155	0	520	500	0	0	20	0	495	17	350	0	0	128	0
24	500	0	450	0	50	0	0	440	500	60	0	0	0	420	15	350	0	10	45	0

Table 3 shows the optimal scheduling result of the heat energy part. When the heat demand is higher than the suppy, HOBs are additionally operated. Especially, all HOBs are operated in interval having the highest heat demand (Interval 19-22).

We can see that heat energy is also operated by the economic viewpoint based on heat production and trading prices. From the result of μENet operation, it is shown that the μENet is operated by the economic viewpoint based on the proposed operation model.

Table 3. Optimal scheduling of heat energy part

Hour	Building A						Building B							Building C					
	$M^h_{LOAD_1}$	$M^h_{CHP_1}$	$M^h_{HOB_1}$	$M^{e\to h}_{CHP_1}$	$M^h_{SEND_1}$	$M^h_{REC_1}$	$M^h_{LOAD_1}$	$M^h_{RDG_1}$	$M^h_{CHP_1}$	$M^h_{HOB_1}$	$M^{e\to h}_{CHP_1}$	$M^h_{SEND_1}$	$M^h_{REC_1}$	$M^h_{LOAD_1}$	$M^h_{CHP_1}$	$M^h_{HOB_1}$	$M^{e\to h}_{CHP_1}$	$M^h_{SEND_1}$	$M^h_{REC_1}$
1	350	250	200	135.5	548	0	500	0	220	250	30	0	0	800	112	0	140	0	548
2	150.0	250	0	200	612.5	0	540	0	220	0	0	0	320	510	112	0	105.5	0	292.5
3	120.0	250	0	200	338	0	530	0	220	0	200	0	110	480	112	0	140	0	228
4	110.0	250	0	185.78	308	0	550	0	220	0	200	0	130	430	112	0	140	0	178
5	80.0	250	0	101.33	503	0	560	5	220	0	0	0	335	280	112	0	0	0	168
6	150.0	250	0	132.22	500	0	580	8	220	0	0	0	352	260	112	0	0	0	148
7	405.0	250	200	146	503.5	0	610	12	220	12.5	0	0	365.5	250	112	0	0	0	138
8	600.0	416.9638	89.5	0	162.5	0	700	15	366.9281	250	23.571	0	44.5	230	112	0	0	0	118
9	460.0	625	157.5	0	192	0	780	18	550	0	0	0	212	260	280	0	0	20	0
10	450.0	625	164.5	0	270	0	820	20	550	0	0	0	250	300	280	0	0	0	20
11	410.0	625	200	0	317	0	850	23	550	0	0	0	277	320	280	0	0	0	40
12	340.0	597.5	200	0	422.5	0	910	25	525.8	244.7	0	0	114.5	420	112	0	0	0	308
13	310.0	250	200	200	652.5	0	845	28	220	0	200	0	384.5	520	112	0	140	0	268
14	270.0	250	200	200	692.5	0	870	24	220	0	200	0	394.5	550	112	0	140	0	298
15	290.0	250	200	114.84	672.5	0	850	20	220	0	200	0	364.5	560	112	0	140	0	308
16	280.0	250	200	200	682.5	0	860	19	220	0	200	0	324.5	610	112	0	140	0	358
17	310.0	625	200	0	452.5	0	850	10	550	250	0	0	40	600	187.5	0	0	0	412.5
18	320.0	625	200	0	442.5	0	840	8	550	152.9	0	0	129.1	575	261.6	0	0	0	313.4
19	440.0	625	200	0	322.5	0	830	0	550	250	0	0	30	580	280	7.5	0	0	292.5
20	600.0	625	200	0	162.5	0	750	0	550	250	0	50	0	615	280	122.5	0	0	212.5
21	630.0	625	200	0	132.5	0	670	0	550	250	0	130	0	605	280	62.5	0	0	262.5
22	650.0	625	200	0	112.5	0	620	0	550	250	0	180	0	580	280	7.5	0	0	292.5
23	610.0	625	200	0	152.5	0	550	0	550	97.5	0	97.5	0	530	280	0	0	0	250
24	560.0	625	167.5	0	170	0	520	0	550	0	0	30	0	480	280	0	0	0	200

5. Conclusion

In this paper, an optimal operation model for the centralized micro-energy network (μENet) managing the electric and heat energy of a group of buildins has been proposed. The mathematical model for the optimal operation has been established and has been tested suitably to show feasibility through the simulation.

As a future work, we plan to add the mathematical model for the building energy management system (BEMS) to the proposed model.

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