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Article

Optimal Energy Management of Multi-Microgrids with Sequentially Coordinated Operations

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Abstract: We propose an optimal electric energy management of a cooperative multi-microgrid community with sequentially coordinated operations. The sequentially coordinated operations are suggested to distribute computational burden and yet to make the optimal 24 energy management of multi-microgrids possible. The sequential operations are mathematically modeled to find the optimal operation conditions and illustrated with physical interpretation of how to achieve optimal energy management in the cooperative multi-microgrid community. This global electric energy optimization of the cooperative community is realized by the ancillary internal trading between the microgrids in the cooperative community which reduces the extra cost from unnecessary external trading by adjusting the electric energy production amounts of combined heat and power (CHP) generators and amounts of both internal and external electric energy trading of the cooperative community. A simulation study is also conducted to validate the proposed mathematical energy management models.

Keywords: multi-microgrids; cooperative microgrids; energy management system; sequential operation; energy trading

1. Introduction

To make the electricity grid less centralized, the concept of microgrids was proposed [1]. Within the microgrid of a local community, a variety of small-scale power generators called distributed generation systems (DGs) are installed locally to provide electricity to the consumers within the community boundary. Therefore, the losses due to electricity delivery and distribution can be reduced and local consumers are provided with a more reliable and cheaper electrical power supply [2]. Since a variety of DGs in a microgrid make the corresponding local community more independent from the macrogrid, the microgrid could be much more secure in an emergency situation such as a sudden blackout in the macrogrid by simply isolating itself from the macrogrid [1]. Thus, the electricity provision in a microgrid becomes not only economical, but also much secure and reliable than ever before.

This microgrid concept can be applied to various electric grids customers such as a university campus, a research park, an apartment complex, or a village. Energy management of microgrid(s) has received tremendous interest. Multi-agent system-based operation is one of practical solutions for electric energy management of microgrid(s); this has been applied in islanded mode [3] and [4] and grid-connected mode [5–8]. However, our interest in this paper is concentrated on the optimal operation of energy management in multi-microgrids as defined in [9].

First, the optimal operation of energy management system has been applied to a microgrid either in islanded mode [10] or in grid-connected mode [11–16], similar to the conventional operation of electric grids. The cost minimization problem of electric energy was investigated mostly, but the profit maximization problem was studied in [12]. Renewable sources were commonly included while controllable electric energy sources such as combined heat and power (CHP) generators were considered to minimize the cost by controlling their energy production amounts in [14–16]. Khodaei [16] also proposed a resiliency-oriented microgrid optimal scheduling model aimed at minimizing the microgrid load curtailment by scheduling of available resources when the microgrid is isolated from the power grid. Heat energy has been also considered along with electric energy in many studies of a microgrid in [17–19]. While the authors [18–20] minimized the operating cost, Bagheria and Tafreshi [17] maximized the profit from trading of electric energy by considering of the operation cost. Furthermore, the authors [18–20] also included heat energy storage as a component of the microgrid.

The energy management problem was then extended into multi-microgrids in [21,22], which targeted minimizing the cost of electric energy. For the energy management, electric energy trading was allowed not only internally between microgrids, but also externally with the power grid. Rahbar *et al.* [21] considered only uncontrollable electric energy sources where the amount of production cannot be controlled for energy management purposes. On the other hand, Nguyen and Le in [22] also considered controllable electric energy sources such as CHPs and diesel generators where the amounts of production can be controlled by the energy management system.

Energy trading, another important subject in microgrids, has been also investigated. In [14] and [17], only external trading between a microgrid and the main power grid were considered. Nguyen and Le [22] considered both external trading and internal trading between microgrids within a cooperative multi-microgrid community to minimize the total cost.

In this paper, we propose an optimal energy management of a cooperative multi-microgrid community with sequentially coordinated operations. While external trading is allowed between a microgrid and the power grid just like [13] and [16], the internal trading between microgrids is allowed within this cooperative multi-microgrid community just like in [22]. Unlike the centralized approach in [22], sequentially coordinated operations are suggested to distribute the computational burden and yet make the optimal energy management of multi-microgrids possible. The ancillary internal trading in addition to the main internal trading enables such sequentially coordinated operations to achieve the optimal energy management of multi-microgrids possible, which reduces the extra cost from unnecessary external trading by adjusting the production amounts of CHP generators. The sequential operation processes for the energy management in the multi-microgrid community are mathematically modeled to find the optimal operation conditions which minimize the global operation cost; the optimal operation conditions include the electric energy production amounts of CHP generators and the amounts of both internal and external electric energy trading.

Furthermore, the global electric energy optimization processes are also illustrated with physical interpretation of sequentially coordinated operations how to achieve optimal energy management in the cooperative multi-microgrid community. A simulation study is also conducted to show the validation of the proposed sequential operations of the optimal energy management. In this paper, we limit our study to electric energy, but a study including heat energy along with electric energy as an extension of this paper will be published in the near future.

The paper is organized as follows: first, we present a cooperative multi-microgrid community and conceptually describe the sequentially coordinated operations of energy management for a cooperative multi-microgrid community in Section 2. Next, the sequentially coordinated operations are mathematically modeled and the physical interpretation of how to achieve the optimal energy management is illustrated in Section 3. Then, a simulation study for a cooperative multi-microgrid community with three microgrids is presented in Section 4. Finally, our conclusions and future works are discussed in Section 5.

2. Proposed Optimal Energy Management of Cooperative Multi-Microgrids

2.1. Cooperative Multi-Microgrid Community

A cooperative multi-microgrid community composed of a group of multiple microgrids is a cooperative operation model of electric energy for a group of microgrids from an economic standpoint. Although various types of microgrids can exist according to specific configurations, a cooperative multi-microgrid community having the following configurations and features is assumed and the sequentially coordinated operations for such a cooperative community are dealt with in this paper:

- Microgrids are equipped with photovoltaic (PV) systems and CHP generators as electric energy sources but the production costs of CHP generators are different;

- Microgrids can trade electric energy internally with other microgrids in the cooperative community as well as externally with the power grid;
- A μEMS in a microgrid is a centralized energy management system of its own microgrid;
- A central energy management system (central EMS) has a global optimization function to manage any electric energy surplus/shortage of involved microgrids in the cooperative community.

In this paper, our optimal energy management deals with electric energy cooperatively with economic viewpoints in the cooperative multi-microgrid community. Electric energy can be traded internally and externally; electric energy trades can happen internally between microgrids in the cooperative community and externally with the power grid as illustrated by red dotted and solid arrow lines, respectively, in Figure 1. Sequentially coordinated operations of μEMSs and a central EMS in the cooperative community are described in the following subsection.

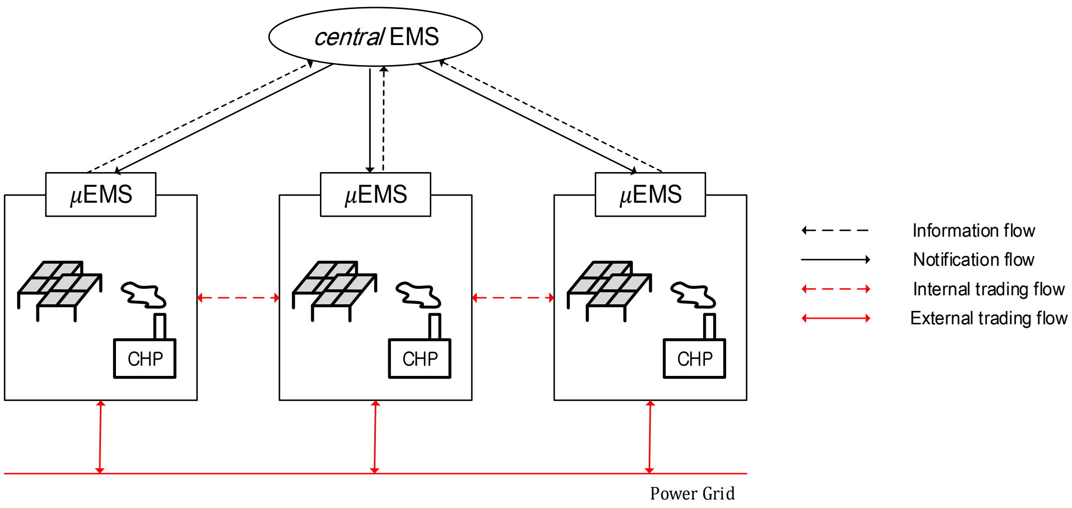

Figure 1. Information and energy flows in cooperative multi-microgrid community. EMS: energy management system; and CHP: combined heat and power.

2.2. Sequentially Coordinated Operations of Cooperative Multi-Microgrids

Our multi-microgrid community has two kinds of energy management systems in each microgrid in the cooperative community: a central energy management system (central EMS) and a microgrid energy management system (μEMS). A central EMS manages the electric energy globally in the microgrid while a μEMS in a microgrid manages the electric energy locally. A central EMS and μEMSs operate cooperatively coordinated with economic viewpoints as described in Figure 2, and this sequentially coordinated operation processes of the central EMS and μEMSs consists of the following two steps as shown in Figure 2, where local optimization means the optimization conducted by each μEMS locally while global optimization means the optimization performed by the central EMS globally:

- Step 1: Local optimization of the electric energy by μEMS in each microgrid.
- Step 2: Global optimization of the electric energy cooperatively by central EMS in the cooperative community.

In Step 1, the μEMS of each microgrid in the cooperative community optimizes the electric energy of each microgrid which results the amount of electric energy production by its CHP generator and the difference between the electric energy demand and the total electric energy production amount of the microgrid in the form of either an electric energy surplus or shortage. It is assumed that the local electric load of each microgrid is considerably greater than the maximum capacity of the PV generator in the microgrid. After the local optimization, each μEMS should provide the local optimal electric energy information to the central EMS as illustrated by black dotted arrow lines in Figure 1.

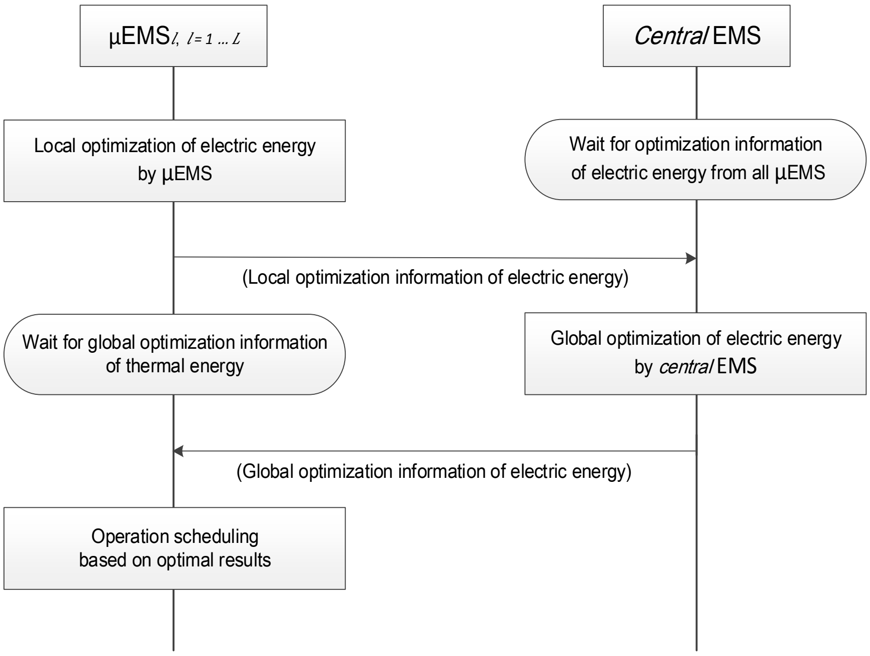

Figure 2. Sequential operations of energy management in a cooperative community.

In Step 2, the global optimization of the electric energy is first performed by the central EMS based on the local optimal electric energy information of each microgrid (μEMS) in the cooperative community from Step 1. Through the internal trading optimization of the electric energy globally, the electric energy surplus/shortage would be resolved and the global cost of the electric energy to meet all the electric energy loads can be minimized. Then, the central EMS should notify the μEMS of each microgrid about the global optimal electric energy information as illustrated by black solid arrow lines in Figure 1.

3. Mathematical Modeling of Cooperative Multi-Microgrid Operation Processes

In this section, the sequential operation processes of the cooperative multi-microgrid are mathematically modeled. Mathematical notations are first defined in Section 3.1, and the mathematical models of the sequential operation process are presented according to the two steps in the operation process. Section 3 is finalized with the total optimal operation cost of the cooperative multi-microgrid.

3.1. Nomenclature

Before presenting the mathematical models of the cooperative multi-microgrid operation process, mathematical notations necessary for the models are defined as follows:

₩	South Korea Won
t	the identifier of operation interval

T	the number of operation intervals
l	the identifier of microgrid
L	the number of microgrids
e	the identifier of electric energy
$C^{e}_{\mathrm{PV}_l}$	the electric energy production cost of the PV in the l^{th} microgrid (₩/kW h)
$C^{e}_{\mathrm{CHP}_l}$	the electric energy production cost of the CHP in the l^{th} microgrid (₩)
$C^{e}_{\mathrm{BUY}_l}(t)$	the buying price from the power grid in the l^{th} microgrid at t (₩/kW h)
$C^{e}_{\mathrm{SELL}_l}(t)$	the selling price to the power grid in the l^{th} microgrid at t (₩/kW h]
$M^{e+}_{l}(t)$	the amount of electric energy surplus in the l^{th} microgrid at t (kW h)
$M^{e-}_{l}(t)$	the amount of electric energy shortage in the l^{th} microgrid at t (kW h)
$M^{e}_{\mathrm{PV}_l}(t)$	the output produced from the PV system in the l^{th} microgrid at t (kW h)
$M^{e}_{\mathrm{CHP}_l}(t)$	the electric energy production amount of the CHP in the l^{th} microgrid at t (kW h)
$M^{e}_{\mathrm{LOAD}_l}(t)$	the electric energy demand in the l^{th} microgrid at t (kW h)
$M^{e}_{\mathrm{SELL}_l}(t)$	he amount of the selling electric energy in the l^{th} microgrid determined by central EMS at t (kW h)
$M^{e}_{\mathrm{BUY}_l}(t)$	the amount of the buying electric energy in the l^{th} microgrid determined by central EMS at t (kW h)
$M^{e}_{\mathrm{SEND}_l}(t)$	the sending electric energy amount in the l^{th} microgrid at t (kW h) for the main internal trading (kW h)
$M^{e}_{\mathrm{REC}_l}(t)$	the received electric energy amount in the l^{th} microgrid at t (kW h) for the main internal trading (kW h)
$M^{e+}_{\mathrm{CHP}_l}(t)$	the increased electric energy production amount of the CHP in the l^{th} microgrid at t (kW h) for the ancillary internal trading (kW h)
$M^{e-}_{\mathrm{CHP}_l}(t)$	the decreased electric energy production amount of the CHP in the l^{th} microgrid at t (kW h) for the ancillary internal trading (kW h)

3.2. Mathematical Modeling of Step 1: Local Optimization

Step 1 is the local electric energy optimization process of a microgrid; only electric energy is considered in this process as a preparation for the global optimization process in Step 2 where heat energy combined with electric energy is considered. As mentioned in Section 2, the electric energy from PV generators should be allocated first to the local electric load. It is assumed that the local electric load of each microgrid is considerably greater than the maximum capacity of the PV generator in the microgrid.

Electric energy from PV generators is allocated first to local loads because the producing electric energy amount of PV generators in a microgrid cannot be controlled by the μEMS unlike that of the CHP generators in the microgrid.

The cost function $C^{e}_{l}\left(M^{e}_{\mathrm{CHP}_l}(t)\right)$ of a microgrid in Step 1 is the total expenses occurred by the electric energy for the microgrid when the external trading of the electric energy with the power grid is applied as follows:

$$C_l^e\left(M_{\mathrm{CHP}_l}^e(t)\right) = C_{\mathrm{PV}_l}^e + \left(C_{\mathrm{CHP}_l}^e \cdot M_{\mathrm{CHP}_l}^e(t)\right) - \left(C_{\mathrm{SELL}_l}^e(t) \cdot M_l^{e+}(t)\right) + \left(C_{\mathrm{BUY}_l}^e(t) \cdot M_l^{e-}(t)\right) \quad (1)$$

for $1 \leq t \leq T$, $1 \leq l \leq L$. Note that the electric energy production cost of the PV in the l^{th} microgrid ($C_{PV_l}^e$) is a fixed cost which is given in advance as a forecasted value along with its forecasted production amount. Then, when the microgrid produces more electric energy than its electric energy demand ($M_{CHP_l}^e(t) + M_{PV_l}^e(t) > M_{LOAD_l}^e(t)$), the microgrid can sell the electric energy surplus to the power grid as follows:

$$M_l^{e+}(t) = M_{\mathrm{CHP}_l}^e(t) + M_{\mathrm{PV}_l}^e(t) - M_{\mathrm{LOAD}_l}^e(t), 1 \leq \ l \leq L$$

On the other hand, when the microgrid produces less electric energy that its electric energy demand ($M_{LOAD_l}^e(t) > M_{CHP_l}^e(t) + M_{PV_l}^e(t)$), the microgrid has to purchase the following amount of the electric energy shortage from the power grid as follows:

$$M_l^{e-}(t) = M_{\mathrm{LOAD}_l}^e(t) - M_{\mathrm{CHP}_l}^e(t) - M_{\mathrm{PV}_l}^e(t), 1 \leq \ l \leq L$$

Finally, the local electric energy optimization function when the external trading of electric energy is applied can be achieved by minimizing the total expenses as follows:

$$M_{CHP_l}^{e^*}(t) = \underset{M_{CHP_l}^e(t)}{\arg\min}\left\{ C_l^e\left(M_{CHP_l}^e(t)\right)\right\}$$

subject to:

$$\min[M_{\mathrm{CHP}_l}^e] \leq M_{\mathrm{CHP}_l}^e(t) \leq \max[M_{\mathrm{CHP}_l}^e] \quad (2)$$

for $1 \leq t \leq T$, $1 \leq l \leq L$. The constraint to the objective function of a μEMS in Equation (2) implies that a CHP generator should be operated within its operational ranges. Through the local electric energy optimization, the CHP generator in a microgrid has to produce electric energy either the minimum or the maximum capacity of the CHP generator, or the amount of the electric energy demand as shown in Figure 3, depending on the CHP production cost compared to the external trading prices.

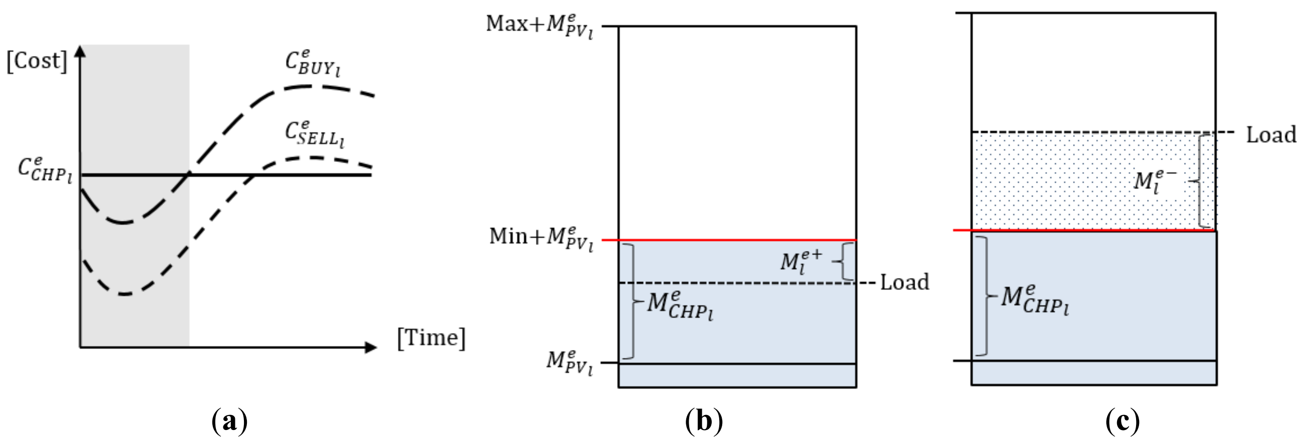

Figure 3. Cases of $C_{\mathrm{SELL}}^e(t) < C_{\mathrm{BUY}}^e(t) < C_{\mathrm{CHP}_l}^e(t)$ in Step 1: (**a**) conditions; (**b**) microgrid with the electric energy surplus; and (**c**) microgrid with the electric energy shortage.

First, Figure 3 demonstrates Step 1 when the production cost of the CHP generator in a microgrid is higher than the buying price ($C^e_{SELL}(t) < C^e_{BUY}(t) < C^e_{CHP_l}(t)$). This condition is displayed as a shadowed area in Figure 3a while the other figures show that the production amount of the CHP generator in this situation becomes the minimum capacity of the CHP as follows:

$$M^e_{CHP_l}(t) = min[M^e_{CHP_l}]$$

If the electric energy demand is lower than the amount of the electric energy production, that is, ($M^e_{LOAD_l}(t) < min[M^e_{CHP_l}] + M^e_{PV_l}(t)$), then there would be the electric energy surplus as follows:

$$M^{e+}_l(t) = min[M^e_{CHP_l}] + M^e_{PV_l}(t) - M^e_{LOAD_l}(t)$$

as shown in Figure 3b.

On the other hand, if the electric energy demand is higher than the amount of the electric energy production, that is, ($M^e_{LOAD_l}(t) > min[M^e_{CHP_l}] + M^e_{PV_l}(t)$), there would be the electric energy shortage as follows:

$$M^{e-}_l(t) = M^e_{LOAD_l}(t) - min[M^e_{CHP_l}] - M^e_{PV_l}(t)$$

as shown in Figure 3c.

Next, Figure 4 demonstrates Step 1 when the production cost of the CHP generator in a microgrid is higher than the selling price and lower than the buying price ($C^e_{SELL}(t) < C^e_{CHP_l}(t) < C^e_{BUY}(t)$). Its condition is displayed as a shadowed area in Figure 4a, while Figure 4b–d shows that the CHP generator produces the amount in this situation vary depending on the electric energy demand. If the minimum electric production amount of the CHP generator is higher than the electric demand, that is, ($min[M^e_{CHP_l}] + M^e_{PV_l}(t) > M^e_{LOAD_l}(t)$), the CHP generator should produce its minimum as follows:

$$M^e_{CHP_l}(t) = min[M^e_{CHP_l}]$$

results in the electric energy surplus as shown in Figure 4b.

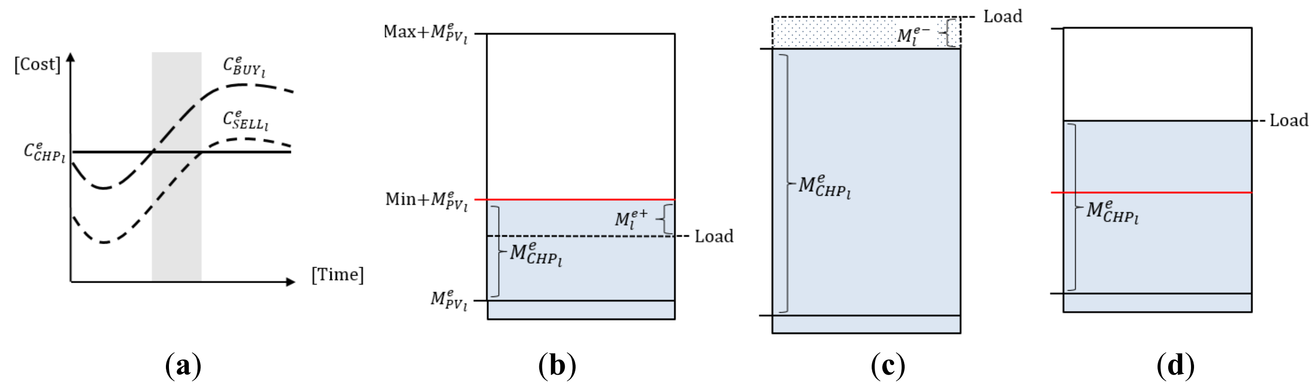

Figure 4. Cases of $C^e_{\mathrm{SELL}}(t) < C^e_{\mathrm{CHP}_l}(t) < C^e_{\mathrm{BUY}}(t)$ in Step 1: (**a**) conditions; (**b**) microgrid with the electric energy surplus; (**c**) microgrid with the electric energy shortage; and (**d**) self-sufficient microgrid $M^{e+}_l(t) = M^{e-}_l(t) = 0$.

If the maximum production amount of the CHP generator is lower than the electric demand, that is, ($max[M^e_{CHP_l}] + M^e_{PV_l}(t) < M^e_{LOAD_l}(t)$), the CHP generator should produce its maximum as follows:

$$M^e_{\mathrm{CHP}_l}(t) = \max[M^e_{\mathrm{CHP}_l}]$$

results in the electric energy shortage as shown in Figure 4c.

Otherwise, if the electric demand is between the minimum electric production amount of the CHP generator and the maximum electric production amount of the CHP generator, that is, $(min[M^e_{CHP_l}] + M^e_{PV_l}(t) \leq M^e_{LOAD_l}(t) \leq max[M^e_{CHP_l}] + M^e_{PV_l}(t))$, the CHP generator should produce the amount as follows:

$$M^e_{\mathrm{CHP}_l}(t) = M^e_{\mathrm{LOAD}_l}(t) - M^e_{\mathrm{PV}_l}(t)$$

meets the electric demand as shown in Figure 4d. We will call such a microgrid a self-sufficient microgrid which does not need any trade with the power grid since there is no surplus/short electric energy, that is, $M^{e+}_l(t) = M^{e-}_l(t) = 0$.

Lastly, Figure 5 demonstrates Step 1 when the production cost of the CHP generator in a microgrid is lower than the selling price $(C^e_{CHP_l}(t) < C^e_{SELL}(t) < C^e_{BUY}(t))$. Its condition is displayed as a shadowed area in Figure 5a while the other figures in Figure 5 show that the production amount of the CHP generator in this situation becomes the maximum capacity of the CHP as follows:

$$M^e_{\mathrm{CHP}_l}(t) = \max[M^e_{\mathrm{CHP}_l}].$$

If the electric energy demand is lower than the production amount of the electric energy $(M^e_{LOAD_l}(t) < max[M^e_{CHP_l}] + M^e_{PV_l}(t))$, then there would be the electric energy surplus as follows:

$$M^{e+}_l(t) = \max[M^e_{\mathrm{CHP}_l}] + M^e_{\mathrm{PV}_l}(t) - M^e_{\mathrm{LOAD}_l}(t)$$

as shown in Figure 5b.

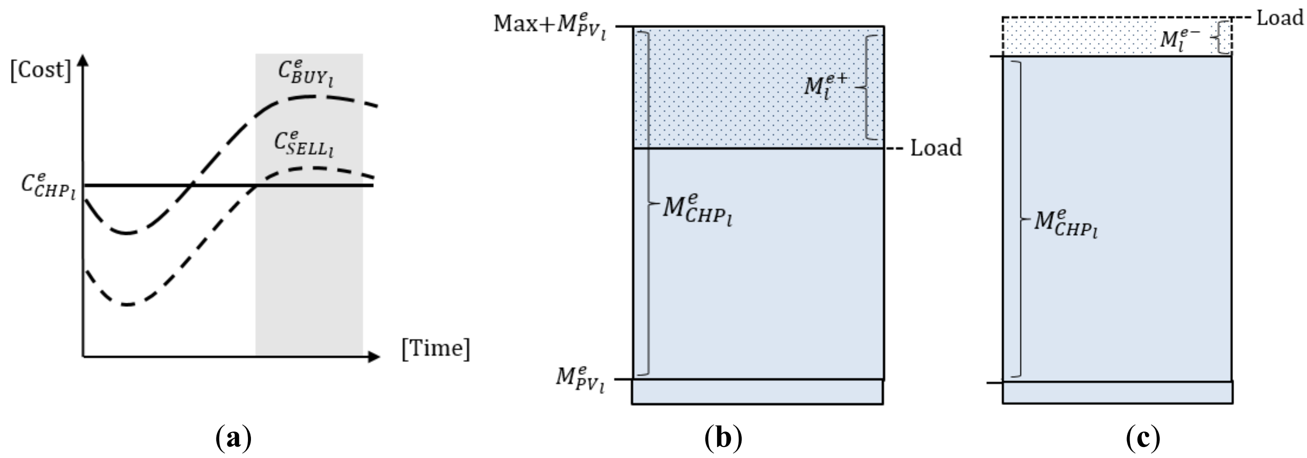

Figure 5. Cases of $C^e_{\mathrm{CHP}_l}(t) < C^e_{\mathrm{SELL}}(t) < C^e_{\mathrm{BUY}}(t)$ in Step 1: (**a**) conditions; (**b**) microgrid with the electric energy surplus; and (**c**) microgrid with the electric energy shortage.

On the other hand, if the electric energy demand is higher than the amount of the electric energy production $(M^e_{LOAD_l}(t) > \max[M^e_{CHP_l}] + M^e_{PV_l}(t))$, there would be the electric energy shortage as follows:

$$M^{e-}_l(t) = M^e_{\mathrm{LOAD}_l}(t) - \max[M^e_{CHP_l}] - M^e_{\mathrm{PV}_l}(t)$$

as shown in Figure 5c.

As a result of Step 1, the total cost becomes the sum of the local optimal production cost of all the CHPs in the microgrid and the external trading cost from the electric energy surplus/shortage:

$$C_{\text{local}}^{e^*}(t) = \sum_{l=1}^{L} C_l^e\left(M_{\text{CHP}_l}^{e^*}(t)\right)$$
$$= \sum_{l=1}^{L}\left(C_{\text{CHP}_l}^{e} \cdot M_{\text{CHP}_l}^{e^*}(t)\right) + C_{\text{BUY}}^{e}(t) \cdot \sum_{l=1}^{L} M_l^{e-}(t) - C_{\text{SELL}}^{e}(t) \cdot \sum_{l=1}^{L} M_l^{e+}(t)$$

In the next step, this electric energy cost will be optimally minimized by internal trading in Step 2 as the global electric energy optimization process.

3.3. Mathematical Modeling of Step 2: Global Optimization

Step 2 is the global optimization process of electric energy by means of internal trading based on local optimization information about the electric energy from all μEMSs in the cooperative community from Step 1 which optimized the electric energy locally. Note that this global electric energy optimization can be realized by maximizing the internal trading amount between the microgrids in the cooperative community which prevents the extra cost from unnecessary external trading.

First, the main internal trading should be performed between microgrids with the electric energy surplus and microgrids with the electric energy shortage in the cooperative community. If there are the remaining surplus/short electric energy after the main internal trading, then the ancillary internal trading with self-sufficient microgrids should be followed.

Since the internal trading decreases the cost for the electric energy by reducing the amount of external trading, the adjusted saving cost for the central EMS in Step 2 can be obtained from both the main internal trading and the ancillary trading of the electric energy in the microgrid. Therefore, the adjusted saving cost in Step 2 can be expressed as:

$$C_{\text{Elec}}^{\text{Adj}}\left(M_{\text{SEND}_1}^{e}(t), \dots, M_{\text{SEND}_L}^{e}(t), M_{\text{CHP}_1}^{e+}(t), \dots, M_{\text{CHP}_L}^{e+}(t), M_{\text{CHP}_1}^{e-}(t), \dots, M_{\text{CHP}_L}^{e-}(t)\right)$$
$$= \left(C_{\text{BUY}}^{e}(t) - C_{\text{SELL}}^{e}(t)\right) \cdot \textstyle\sum_{l=1}^{L} M_{\text{SEND}_l}^{e}(t) + \sum_{l=1}^{L}\left(C_{\text{BUY}}^{e}(t) - C_{\text{CHP}_l}^{e}\right) \cdot M_{\text{CHP}_l}^{e+}(t)$$
$$+ \sum_{l=1}^{L}\left(C_{\text{CHP}_l}^{e} - C_{\text{SELL}}^{e}(t)\right) \cdot M_{\text{CHP}_l}^{e-}(t) \quad (3)$$

The first term is from the main internal trading between microgrids with the electric energy surplus and microgrids with the electric energy shortage in the cooperative community while the second and third terms are from the ancillary internal trading with self-sufficient microgrids.

Let $P_{Elec}^{Adj}(t) = (M_{SEND_1}^{e}(t), \dots, M_{SEND_L}^{e}(t), M_{CHP_1}^{e+}(t), \dots, M_{CHP_L}^{e+}(t), M_{CHP_1}^{e-}(t), \dots, M_{CHP_L}^{e-}(t))$ be the set of the internal trading amounts of the electric energy of all the microgrids in the cooperative community. Sending amount of electric energy $M_{SEND_l}^{e}(t)$ represents main internal trading amount while increased/decreased amount of a CHP generator $M_{CHP_l}^{e+}(t)/M_{CHP_l}^{e-}(t)$ represents ancillary trading amount of electric energy. Then, the adjusted cost function in Step 2 can be optimized by maximizing the profit resulted by the internal trading of the electric energy as follows:

$$P_{Elec}^{Adj^*}(t) = \underset{P_{Elec}^{Adj}(t)}{\arg\max}\left\{C_{Elec}^{Adj}\left(P_{Elec}^{Adj}(t)\right)\right\}$$

subject to:

for l such that $M_l^{e+}(t) > 0$:

$$M_{\mathrm{SEND}_l}^{e}(t) \leq M_l^{e+}(t) \text{ when } M_l^{e+}(t) > 0 \tag{4}$$

for l such that $M_l^{e-}(t) > 0$:

$$M_{\mathrm{REC}_l}^{e}(t) \leq M_l^{e-}(t) \text{ when } M_l^{e-}(t) > 0 \tag{5}$$

for l such that $M_l^{e+}(t) > 0$ or $M_l^{e-}(t) > 0$:

$$\sum_{l=1}^{L} M_{\mathrm{SEND}_l}^{e}(t) = \sum_{l=1}^{L} M_{\mathrm{REC}_l}^{e}(t) \tag{6}$$

for l such that $M_l^{e+}(t) = M_l^{e-}(t) = 0$ and $\sum_{l=1}^{L} M_l^{e+}(t) < \sum_{l=1}^{L} M_l^{e-}(t)$:

$$M_{\mathrm{CHP}_l}^{e+}(t) \leq \max[M_{\mathrm{CHP}_l}^{e}] - M_{\mathrm{CHP}_l}^{e^*}(t) \tag{7}$$

$$\sum_{l=1}^{L} M_{\mathrm{CHP}_l}^{e+}(t) \leq \sum_{l=1}^{L} M_l^{e-}(t) - \sum_{l=1}^{L} M_l^{e+}(t) \tag{8}$$

for l such that $M_l^{e+}(t) = M_l^{e-}(t) = 0$ and $\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t)$:

$$M_{\mathrm{CHP}_l}^{e-}(t) \leq M_{\mathrm{CHP}_l}^{e^*}(t) - \min[M_{\mathrm{CHP}_l}^{e}] \tag{9}$$

$$\sum_{l=1}^{L} M_{\mathrm{CHP}_l}^{e-}(t) \leq \sum_{l=1}^{L} M_l^{e+}(t) - \sum_{l=1}^{L} M_l^{e-}(t) \tag{10}$$

for $1 \leq t \leq T$. The constraints in Equations (4)–(6) are for the main internal trading between microgrids with the electric energy surplus/shortage in the multi-microgrid; the constraints in Equations (4) and (5) imply that the internal trading amount between microgrids with the electric energy surplus/shortage should be bounded by the amount of the electric energy surplus/shortage, and the constraint in Equation (6) implies that the total sending amount of the electric energy should be equal to the total receiving amount of the electric energy.

When the total electric energy surplus from microgrids in the cooperative community is smaller than the total electric shortage from other microgrids in the cooperative community, that is, $(\sum_{l=1}^{L} M_l^{e+}(t) < \sum_{l=1}^{L} M_l^{e-}(t))$, all the electric energy surplus should be sent to the microgrids with the electric energy shortage. Thus, the total amount of the main internal trading becomes:

$$\sum_{l=1}^{L} M_l^{e+}(t) = \sum_{l=1}^{L} M_{\mathrm{SEND}_l}^{e}(t)$$

On the other hand, when the total electric energy surplus from microgrids in the cooperative community is larger than the total electric shortage from other microgrids in the cooperative community, that is, $(\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t))$, all the electric energy shortage in the microgrid can be supplemented by the electric energy surplus in the microgrid. Thus, the total amount of the main internal trading becomes:

$$\sum_{l=1}^{L} M_l^{e-}(t) = \sum_{l=1}^{L} M_{\mathrm{REC}_l}^{e}(t) = \sum_{l=1}^{L} M_{\mathrm{SEND}_l}^{e}(t)$$

since $(\sum_{l=1}^{L} M_{\mathrm{SEND}_l}^{e}(t) = \sum_{l=1}^{L} M_{\mathrm{REC}_l}^{e}(t))$. Since this ancillary internal trading will reduce the amount of the electric energy purchase from the power grid, the total cost is saved as much as follows:

$$\left(C_{\mathrm{BUY}}^{e}(t)-C_{\mathrm{SELL}}^{e}(t)\right)\cdot\sum_{l=1}^{L}M_{\mathrm{SEND}_l}^{e}(t)$$

as in the first term of the adjusted saving cost function in Equation (3). Note that those microgrids with electric energy short/surplus should not increase or decrease their CHP production amount for the ancillary internal trading ($M_{\mathrm{CHP}_l}^{e+}(t)=M_{\mathrm{CHP}_l}^{e-}(t)=0$).

Next, the constraints in Equations (7)–(10) provide the upper bound for the increasing/decreasing production amount of the electric energy of CHPs in self-sufficient microgrids, ($M_l^{e+}(t)=M_l^{e-}(t)=0$) as shown in Figures 4c. When all the electric energy shortage cannot be supplemented by all the electric energy surplus, that is, ($\sum_{l=1}^{L}M_l^{e+}(t)<\sum_{l=1}^{L}M_l^{e-}(t)$), the CHP generators in self-sufficient microgrids can increase the amount of the electricity energy production to supplement the remaining electric energy shortage with the ancillary internal trading as shown in Figure 6b. Since the CHP generator in a self-sufficient microgrid can produce up to its maximum production capacity of the CHP, the amount of the increased electric energy of a self-sufficient microgrid should be upper bounded as in Equation (7) as follows:

$$M_{\mathrm{CHP}_l}^{e+}(t)\leq\left\{\max[M_{\mathrm{CHP}_l}^{e}]-M_{\mathrm{CHP}_l}^{e^*}(t)\right\}$$

for a self-sufficient microgrid *l* such that ($M_l^{e+}(t)=M_l^{e-}(t)=0$) and ($\sum_{l=1}^{L}M_l^{e+}(t)<\sum_{l=1}^{L}M_l^{e-}(t)$). In addition to this constraint, the total amount of the increased electric energy of all the self-sufficient microgrid ($\sum_{l=1}^{L}M_{CHP_l}^{e+}(t)$) has to be bounded by the remaining electric energy shortage ($\sum_{l=1}^{L}M_l^{e-}(t)-\sum_{l=1}^{L}M_l^{e+}(t)$) for the ancillary trading as in Equation (8).

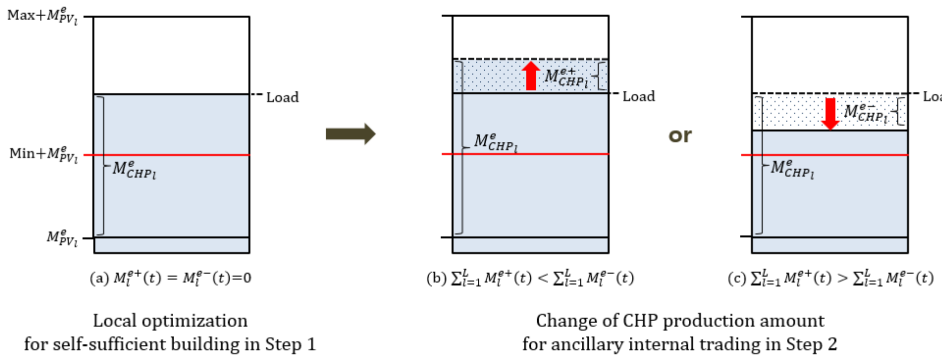

Figure 6. Self-sufficient microgrid.

To help understanding this ancillary trading, Figure 7 illustrates a simple example of the ancillary trading with a self-sufficient microgrid which increases the electric energy production of its CHP generator to supplement the remaining electric energy shortage after being supplemented by all the electric energy surplus in the multi-microgrid ($\sum_{l=1}^{L}M_l^{e+}(t)<\sum_{l=1}^{L}M_l^{e-}(t)$). Therefore, the amount of the increased (surplus) electric energy has to be also bounded by the remaining electric energy shortage. Since this ancillary internal trading will reduce the amount of the electric energy purchase from the power grid, the total cost is saved as much as follows:

$$\sum_{l=1}^{L}\left(C_{\mathrm{BUY}}^{e}(t)-C_{\mathrm{CHP}_l}^{e}\right)\cdot M_{\mathrm{CHP}_l}^{e+}(t)$$

as in the second term of the adjusted saving cost function (3). Note that the CHP generator with the lowest production cost should increase its production first in order to reduce production cost optimally.

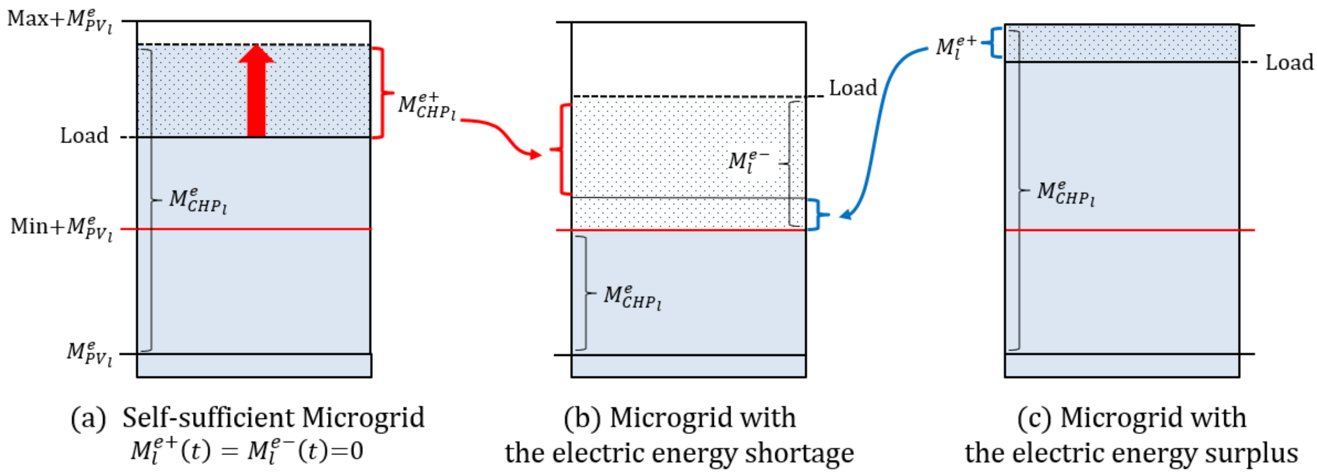

Figure 7. Example of the ancillary internal trading when $\sum_{l=1}^{L} M_l^{e+}(t) < \sum_{l=1}^{L} M_l^{e-}(t)$.

On the other hand, when there is remaining electric energy surplus after supplementing all the electric energy shortage, that is, $(\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t))$, the remaining electric energy surplus can be used for the ancillary internal trading with the self-sufficient microgrids. In this situation, the CHP generator in a self-sufficient microgrid could decrease the production amount of the electricity energy to its minimum production capacity of the CHP as shown in Figure 6c; the decreased amount of electric energy of this self-sufficient microgrid should be supplemented by the remaining electric energy surplus. Since the CHP generator in a self-sufficient microgrid should produce at least its minimum production capacity of the CHP, the amount of the decreased electric energy of this self-sufficient microgrid should be upper bounded as in Equation (9) as follows:

$$M^{e-}_{\mathrm{CHP}_l}(t) \le \{M^{e^*}_{\mathrm{CHP}_l}(t) - \min[M^e_{\mathrm{CHP}_l}]\}$$

for a self-sufficient microgrid l such that $(M_l^{e+}(t) = M_l^{e-}(t) = 0)$ and $(\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t))$. To help understanding of this ancillary trading, a simple example with three microgrids is shown in Figure 8. In addition to this constraint in Equation (9), the total amount of the decreased electric energy of all the self-sufficient microgrids$(\sum_{l=1}^{L} M^{e-}_{\mathrm{CHP}_l}(t))$ has to be bounded by the remaining electric energy surplus $(\sum_{l=1}^{L} M_l^{e+}(t) - \sum_{l=1}^{L} M_l^{e-}(t))$ for the ancillary trading as in Equation (10). Note that those self-sufficient microgrids should not participate in main internal trading $(M^e_{\mathrm{SEND}_l}(t) = M^e_{\mathrm{REC}_l}(t) = 0)$.

To help understanding this ancillary trading, Figure 8 illustrates a simple example of the ancillary trading with a self-sufficient microgrid which decreases the electric energy production of its CHP generator and receives the remaining electric energy surplus after supplementing all the electric energy shortage in the multi-microgrid $(\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t))$. Since the decreased electric energy production amount of the self-sufficient microgrid, $M^{e-}_{CHP_1}(t)$, will be supplemented by the remaining electric energy surplus, this ancillary trading can save the total cost as much as follows:

$$\sum_{l=1}^{L} (C^e_{\mathrm{CHP}_l} - C^e_{\mathrm{SELL}}(t)) \cdot M^{e-}_{\mathrm{CHP}_l}(t)$$

as in the third term of the adjusted saving cost function in Equation (3). Note that the CHP generator with the highest production cost should decrease its production first in order to save production cost optimally.

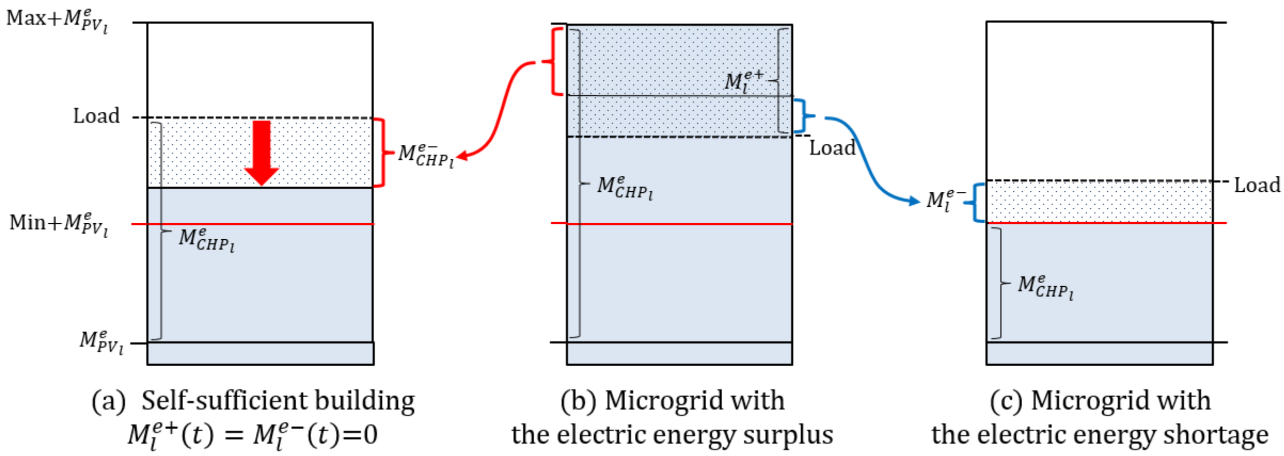

Figure 8. Example of ancillary internal trading when $\sum_{l=1}^{L} M_l^{e+}(t) > \sum_{l=1}^{L} M_l^{e-}(t)$.

Through the global electric energy optimization process, the electric energy surplus/shortage in the multi-microgrid is first internally traded between them and then additionally traded with electric energy self-sufficient microgrids, whose CHP production costs are lower than $C^e_{\text{BUY}}(t)$ and higher than $C^e_{\text{SELL}}(t)$. As a result of the ancillary internal trading, the global optimal production amount of the CHP generator for a self-sufficient microgrid is changed as follows:

$$M^{e^*}_{\text{CHP}_l}(t) = M^{e^*}_{\text{CHP}_l}(t) + M^{e+}_{\text{CHP}_l}(t) - M^{e-}_{\text{CHP}_l}(t)$$

for l such that $(C^e_{\text{SELL}}(t) < M^e_{\text{CHP}_l}(t) < C^e_{\text{BUY}}(t))$ and this change for the ancillary trading has to be informed to the corresponding self-sufficient microgrid.

3.4. Total Optimal Operation Costs

Finally, the total optimum operation cost of the cooperative multi-microgrids satisfies all the electric energy demand and is optimally minimized by performing all the electric energy optimization processes sequentially in two steps. With the objective functions defined earlier, the total optimum operation cost of the cooperative multi-microgrid can be expressed as follows:

$$C^*_{\text{TOTAL}}(t) = \sum_{t=1}^{T} \left\{ \sum_{l=1}^{L} \left(C^e_l \left(M^{e^*}_{\text{CHP}_l}(t) \right) \right) - C^{\text{Adj}}_{\text{Elec}} \left(P^{\text{Adj}^*}_{\text{Elec}}(t) \right) \right\} \tag{11}$$

4. Simulation Study

In order to validate the optimal energy management operation processes, a simulation study has been conducted for a cooperative multi-microgrid community and its results are presented in this section. In our simulation study, a cooperative multi-microgrid community is composed of three microgrids having different production costs of CHP generators as shown in Figure 9. The external trading prices of electric energy is also shown for 24 h of a day in Figure 9. These external trading prices of electric energy are designed such that the buying price is higher than the selling price. In order to increase the effect of cooperative operation of the central EMS, it is assumed that microgrids have different production conditions on production costs and minimum and maximum production capacities of CHP generators as in Figure 9.

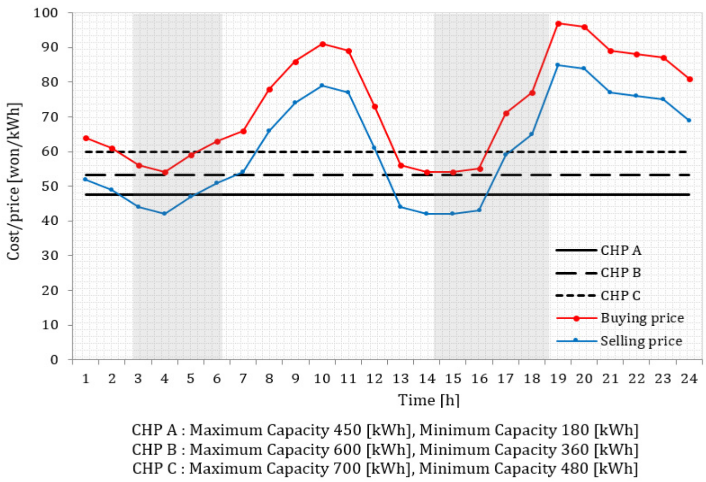

Figure 9. External trading prices compared with production costs of CHP generators.

The optimum operation results for this cooperative multi-microgrids are arranged in Tables 1 and 2 for Steps 1 and 2, respectively, and are highlighted in different color to make clear presentation of each case.

Table 1. Optimal local operation results from Step 1.

Time	Microgrid A					Microgrid B					Microgrid C				
	$M^e_{\text{LOAD}_l}$	$M^e_{\text{CHP}_l}$	$M^e_{\text{PV}_l}$	M^{e+}_l	M^{e-}_l	$M^e_{\text{LOAD}_l}$	$M^e_{\text{CHP}_l}$	$M^e_{\text{PV}_l}$	M^{e+}_l	M^{e-}_l	$M^e_{\text{LOAD}_l}$	$M^e_{\text{CHP}_l}$	$M^e_{\text{PV}_l}$	M^{e+}_l	M^{e-}_l
1	369	450	0	81	0	192	360	0	168	0	550	550	0	0	0
2	345	450	0	105	0	187	360	0	173	0	525	525	0	0	0
3	329	329	0	0	0	189	360	0	171	0	475	480	0	5	0
4	351	351	0	0	0	188	360	0	172	0	472	480	0	8	0
5	381	381	0	0	0	200	360	0	160	0	485	480	0	0	5
6	372	450	0	78	0	224	360	0	136	0	495	495	0	0	0
7	470	450	0	0	20	247	600	0	353	0	511	511	0	0	0
8	454	450	6	2	0	305	600	0	295	0	568	700	7	139	0
9	363	450	9	96	0	535	600	0	65	0	620	700	10	90	0
10	371	450	10	89	0	673	600	5	0	68	651	700	12	61	0
11	373	450	13	90	0	670	600	8	0	62	682	700	16	34	0
12	416	450	18	52	0	651	600	10	0	41	729	700	25	0	4
13	361	338	23	0	0	320	360	15	55	0	743	480	28	0	235
14	362	337	25	0	0	343	360	19	36	0	762	480	24	0	258
15	357	333	24	0	0	585	565	20	0	0	803	480	20	0	303
16	351	330	21	0	0	603	589	14	0	0	807	480	13	0	314
17	357	450	18	111	0	600	600	12	12	0	769	700	4	0	65
18	391	450	8	67	0	557	600	4	47	0	775	700	0	0	75
19	464	450	0	0	14	424	600	0	176	0	824	700	0	0	124
20	467	450	0	0	17	356	600	0	244	0	804	700	0	0	104
21	428	450	0	22	0	317	600	0	283	0	793	700	0	0	93
22	417	450	0	33	0	299	600	0	301	0	723	700	0	0	23
23	414	450	0	36	0	247	600	0	353	0	664	700	0	36	0
24	400	450	0	50	0	216	600	0	384	0	604	700	0	96	0

Table 2. Optimal global operation results from Step 2.

Time	Microgrid A						Microgrid B						Microgrid C					
	$M^{e}_{SEND,i}$	$M^{e}_{REC,i}$	$M^{e+}_{CHP,i}$	$M^{e-}_{CHP,i}$	$M^{e}_{BUY,i}$	$M^{e}_{SELL,i}$	$M^{e}_{SEND,i}$	$M^{e}_{REC,i}$	$M^{e+}_{CHP,i}$	$M^{e-}_{CHP,i}$	$M^{e}_{BUY,i}$	$M^{e}_{SELL,i}$	$M^{e}_{SEND,i}$	$M^{e}_{REC,i}$	$M^{e+}_{CHP,i}$	$M^{e-}_{CHP,i}$	$M^{e}_{BUY,i}$	$M^{e}_{SELL,i}$
1	0	0	0	0	0	58.2289	0	0	0	0	0	120.771	0	0	0	75	0	0
2	0	0	0	0	0	88.0036	0	0	0	0	0	144.996	0	0	0	45	0	0
3	0	0	0	149	0	0	0	0	0	0	0	26.233	0	0	0	0	0	0.76705
4	0	0	0	171	0	0	0	0	0	0	0	8.6	0	0	0	0	0	0.4
5	0	0	0	155	0	0	5	0	0	0	0	0	0	5	0	0	0	0
6	0	0	0	0	0	72.5327	0	0	0	0	0	126.467	0	0	0	15	0	0
7	0	20	0	0	0	0	20	0	0	0	0	302	0	0	0	31	0	0
8	0	0	0	0	0	2	0	0	0	0	0	295	0	0	0	0	0	139
9	0	0	0	0	0	96	0	0	0	0	0	65	0	0	0	0	0	90
10	40.3467	0	0	0	0	48.6533	0	68	0	0	0	0	27.6533	0	0	0	0	33.3467
11	45	0	0	0	0	45	0	62	0	0	0	0	17	0	0	0	0	17
12	45	0	0	0	0	7	0	41	0	0	0	0	0	4	0	0	0	0
13	0	0	112	0	0	0	55	0	0	0	0	0	0	55	0	0	68	0
14	0	0	113	0	0	0	36	0	0	0	0	0	0	36	0	0	109	0
15	0	0	117	0	0	0	0	0	35	0	0	0	0	0	0	0	151	0
16	0	0	120	0	0	0	0	0	11	0	0	0	0	0	0	0	183	0
17	58.6585	0	0	0	0	52.3415	6.34146	0	0	0	0	5.65854	0	65	0	0	0	0
18	44.0789	0	0	0	0	22.9211	30.9211	0	0	0	0	16.0789	0	75	0	0	0	0
19	0	14	0	0	0	0	138	0	0	0	0	38	0	124	0	0	0	0
20	0	17	0	0	0	0	121	0	0	0	0	123	0	104	0	0	0	0
21	6.7082	0	0	0	0	15.2918	86.2918	0	0	0	0	196.708	0	93	0	0	0	0
22	2.27246	0	0	0	0	30.7275	20.7275	0	0	0	0	280.273	0	23	0	0	0	0
23	0	0	0	0	0	36	0	0	0	0	0	353	0	0	0	0	0	36
24	0	0	0	0	0	50	0	0	0	0	0	384	0	0	0	0	0	96

First, the optimal local operation results from the operation of Step 1 are arranged in Table 1. The production cost of CHP C is higher than both external trading prices for *Time* = 3,4,13–16 as in Figure 9 ($C^{e}_{SELL}(t) < C^{e}_{BUY}(t) < C^{e}_{CHP_C}(t)$). Thus, CHP C produced its minimum production amount 480 kW h for these time intervals as shown in Table 1 and as also shown in Figure 3; there is an electric energy surplus ($M^{e+}_{\mathrm{C}}(t) > 0$) for *Time* = 3,4 since the electric energy demand is lower than the total amount of electric energy production, as shown in Figure 3b. On the other hand, there is an electric energy shortage ($M^{e-}_{\mathrm{C}}(t) > 0$) for *Time* = 13–16 since the electric energy demand is higher than the total amount of electric energy production as shown in Figure 3c.

When the production cost of CHP A is between the buying price and selling price for *Time* = 3–5 and 13–16 ($C^{e}_{SELL}(t) < C^{e}_{CHP_A}(t) < C^{e}_{BUY}(t)$), the shadowed time intervals in Figure 9, Microgrid A becomes a self-sufficient microgrid ($M^{e+}_{\mathrm{A}}(t) = M^{e-}_{\mathrm{A}}(t) = 0$) since the total amount of electric energy production just met the electric energy demand as shown in Figure 4d and also highlighted in red in Table 1. Similarly Microgrids B and C become self-sufficient microgrids as highlighted in red in Table 1 for *Time* = 15,16 and *Time* = 1,2,5–7, respectively.

Even though the production cost of CHP B is between the buying price and selling price for *Time* = 1–6,13,14 ($C^e_{\mathrm{SELL}}(t) < C^e_{\mathrm{CHP_B}}(t) < C^e_{\mathrm{BUY}}(t)$) as in Figure 9, CHP B produced its minimum production amount 360 kW h for these time intervals as shown in Figure 3; there is the electric energy surplus ($M^{e+}_{\mathrm{C}}(t) > 0$) for *Time* = 3,4 since the electric energy demand is lower than the total amount of electric energy production as shown in Figure 4b. On the other hand, the production cost of CHP C is between the buying price and selling price for *Time* = 17 ($C^e_{SELL}(t) < C^e_{CHP_C}(t) < C^e_{BUY}(t)$) as in Figure 9, and CHP C produced its maximum production amount 700 kWh for this time interval resulting in the electric energy shortage ($M^{e-}_{\mathrm{C}}(t) > 0$) since the electric energy demand is higher than the total amount of electric energy production as shown in Figure 4c.

When the production cost of CHP A is lower than both external trading prices for the non-shadowed time intervals in Figure 9 ($C^e_{CHP_A}(t) < C^e_{SELL}(t) < C^e_{BUY}(t)$), CHP A produced its maximum production amount 450 kW h for these time intervals as shown in Figure 5 and also in Table 1; there is an electric energy surplus ($M^{e+}_{\mathrm{A}}(t) > 0$) for these time intervals except *Time* = 7,19,20 since the electric energy demand is lower than the total amount of electric energy production as shown in Figure 5b. On the other hand, there is an electric energy shortage ($M^{e-}_{A}(t) > 0$) for *Time* = 7,19,20 since the electric energy demand is higher than the total amount of electric energy production as shown in Figure 5c. Similar behaviors happen in CHPs B and C for some of non-highlighted time intervals of Table 1.

Now, we present the optimal global operation results from the operation of Step 2 as arranged in Table 2. As explained earlier in Section 3, Step 2 saves the total cost for electric energy demand by internal trading: (i) main internal trading and (ii) ancillary internal trading. Table 2 shows the saving amounts resulted from internal trading in this simulation study: (i) main internal trading, (ii) ancillary internal trading, and (iii) total internal trading. There are only main internal trading happened for *Time* = 10–12,17–22 while there are only ancillary internal trading happened for *Time* = 1–4,6,15,16 as shown in both Tables 2 and 3. However, there are both main and ancillary internal trading happened for *Time* = 5,7,13,14 while there is no internal trading happened for *Time* = 8,9,23,24 as shown in both Tables 2 and 3.

Regarding the ancillary internal trading as shown in Figure 7 where a self-sufficient microgrid increases the production amount for the ancillary trading, the same instances were happened for *Time* = 13,14; CHP A increased its production amount to supplement the remaining electric energy surplus 112 kW h and 113 kW h, respectively. Diverse instances happened for *Time* = 15,16 when there is only ancillary trading with two self-sufficient microgrids. Since the production cost of CHP A is lower than that of CHP B, CHP A increased the production amount up to its maximum production (450 kW h) and then CHP B increased its production as shown in Table 2.

On the other hand, regarding the ancillary internal trading as shown in Figure 8 where a self-sufficient microgrid decreases the production amount for the ancillary trading, such an instance happened for *Time* = 5; CHP A decreased its production amount to utilize the remaining electric energy surplus 155 kW h. Similar instance was happened for *Time* = 7; the remaining amount of CHP C 31 kW h and mostly sold to the power grid. Different instances happened for *Time* = 1–4,6 with only ancillary trading.

The abovementioned instances of ancillary internal trading can be easily checked in Figure 10 where the production amounts of CHP generators are adjusted by ancillary trading in Step 2. In addition, the amounts of internal trading in Step 2 are shown in Table 3 which summarizes the overall behaviors of main and ancillary internal trading; there is no internal trading for *Time* = 8,9,23,24. Note that ancillary internal trading is as important as main internal trading as shown in Table 3.

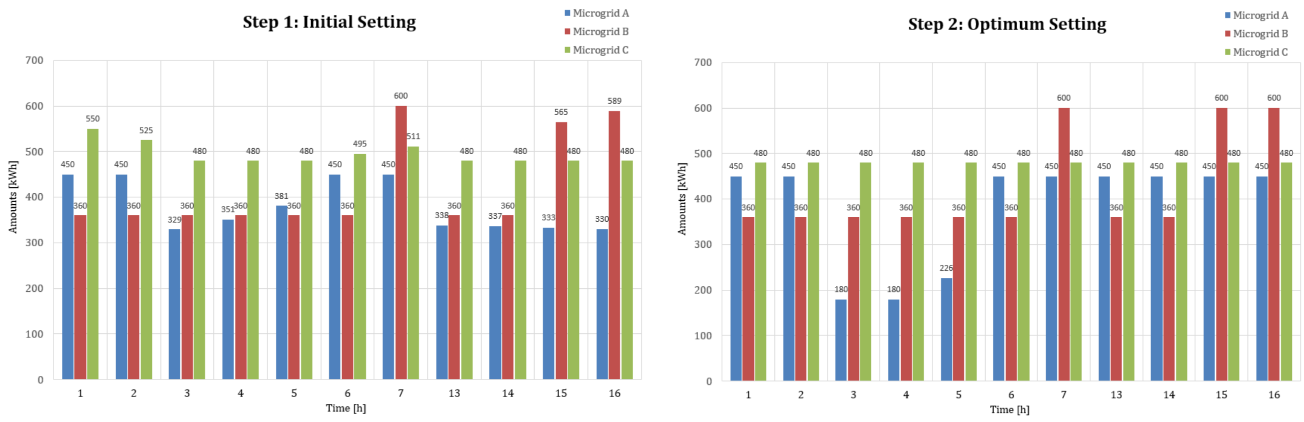

Figure 10. Production amounts of CHP generators adjusted by ancillary internal trading.

Table 3. Amounts of internal trading in Step 2.

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Main	0	0	0	0	5	0	20	0	0	68	62	45
Ancillary	70	45	149	171	155	15	31	0	0	0	0	0
Internal	70	45	149	171	160	15	51	0	0	68	62	45
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Main	55	36	0	0	65	75	138	121	93	23	0	0
Ancillary	112	113	152	131	0	0	0	0	0	0	0	0
Internal	167	149	152	131	65	75	138	121	93	23.	30	0

5. Conclusions

In this paper, we have proposed an optimal energy management method for a cooperative multi-microgrid community with sequentially coordinated operations. The sequentially coordinated operations are suggested to distribute computational burden and yet make the optimal energy management of a multi-microgrid community possible. Sequential operation processes are mathematically modeled to find the optimal operation conditions which satisfy the local electric energy demands; the optimal operation conditions include electric energy production amounts of CHP generators and amounts of both internal and external electric energy trading. A simulation study validated the proposed sequential operations of the optimal energy management.

The global electric energy optimization processes were also demonstrated with the help of illustrated interpretation of sequentially coordinated operations in addition to the simulation study. Note that this global electric energy optimization of the cooperative community is realized by the ancillary internal trading between microgrids in the cooperative community which reduces the extra cost from unnecessary external trading by adjusting the production amounts of CHP generators in the cooperative community. In this paper, we limited our study to electric energy. A study including heat energy along with electric energy will be published as an immediate future extension of this paper.

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Author Contributions

The paper was a collaborative effort between the authors. The authors contributed collectively to the theoretical analysis, modeling, simulation, and manuscript preparation.

Conflicts of Interest

The authors declare no conflict of interest.

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