Optimal Electric and Heat Energy Management of Multi-Microgrids with Sequentially-Coordinated Operations

Authors:

Nah-Oak Song, Ji-Hye Lee, Hak-Man Kim

Date Submitted: 2018-11-28

Keywords: optimal operation, energy trading, sequential operation, energy management system (EMS), cooperative multi-microgrids, heat energy

Abstract:

We propose an optimal electric and heat energy management for a cooperative multi-microgrid community. The sequentiallycoordinated operation for heat energy is proposed in order to distribute the computational burden as an extension of "Optimal Energy Management of Multi-Microgrids with Sequentially Coordinated Operations" and is following the sequentially-coordinated operations for electric energy in it. This sequentially-coordinated operation for heat energy is mathematically modeled and how to obtain the global heat energy optimization solution in the cooperative multi-microgrid community is presented. The global heat energy optimization is achieved for the cooperative community by adjusting the combined electric and heat energy production amounts of combined heat and power (CHP) generators and the heat energy production amount of heat only boilers (HOBs) which satisfy all heat loads, as well as optimize the external electric energy trading in order to minimize the unnecessary cost from the external electric trading, and/or maximize the profit from the external electric trading. To validate the proposed mathematical energy management models, a simulation study is also conducted.

Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version):	LAPSE:2018.1171
Citation (this specific file, latest version):	LAPSE:2018.1171-1
Citation (this specific file, this version):	LAPSE:2018.1171-1v1

DOI of Published Version: https://doi.org/10.3390/en9060473

License: Creative Commons Attribution 4.0 International (CC BY 4.0)





Article Optimal Electric and Heat Energy Management of Multi-Microgrids with Sequentially-Coordinated Operations

Nah-Oak Song¹, Ji-Hye Lee² and Hak-Man Kim^{2,*}

- ¹ Center for Collaborative Internet Ecosystems Research Center, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Korea; nsong@kaist.ac.kr
- ² Department of Electrical Engineering, Incheon National University, 12-1 Songdo-dong, Yeonsu-gu, Incheon 406-840, Korea; jihyelee@inu.ac.kr
- * Correspondence: hmkim@inu.ac.kr; Tel.: +82-32-835-8769; Fax: +82-32-835-0773

Academic Editor: Josep M. Guerrero Received: 19 February 2016; Accepted: 1 June 2016; Published: 21 June 2016

Abstract: We propose an optimal electric and heat energy management for a cooperative multi-microgrid community. The sequentially-coordinated operation for heat energy is proposed in order to distribute the computational burden as an extension of "Optimal Energy Management of Multi-Microgrids with Sequentially Coordinated Operations" and is following the sequentially-coordinated operations for electric energy in it. This sequentially-coordinated operation for heat energy optimization solution in the cooperative multi-microgrid community is presented. The global heat energy optimization is achieved for the cooperative community by adjusting the combined electric and heat energy production amounts of combined heat and power (CHP) generators and the heat energy production amounts of the minimize the unnecessary cost from the external electric trading, and/or maximize the profit from the external electric trading. To validate the proposed mathematical energy management models, a simulation study is also conducted.

Keywords: heat energy; cooperative multi-microgrids; energy management system (EMS); sequential operation; energy trading; optimal operation

1. Introduction

The concept of microgrids was proposed to make the electricity grid less centralized and provide local consumers a more reliable and cheaper electrical power supply [1]. Nowadays, heat energy becomes as important as electric energy for energy management of microgrids as combined heat and power (CHP) are commonly included in microgrids for heating and hot water services [2]. The microgrid concept can be applied to various electric grid customers, such as a university campus, a research park, a business building, an apartment complex, and/or an island. Energy management of microgrid has received tremendous interest by many researchers. One of the practical solutions for electric energy management of microgrid is multi-agent system-based operation, which has been applied in islanded mode [3,4] and in grid-connected mode [5–7]. This paper, however, concerns the optimal operation of energy management in multi-microgrids as defined in [8]. In this paper, we consider heat energy as well as electric energy for an optimal energy management of multi-microgrids; this paper presents sequentially-coordinated operations to manage electric and heat energy optimally for minimizing operational costs of both electric and heat energy in cooperative multi-microgrids. This paper is a heat energy extension of [9], which optimizes the electric energy management in cooperative multi-microgrids.

The optimal energy management system (EMS) has been studied for a microgrid which operates in islanded mode [10,11] or in grid-connected mode [11–17]. In islanded mode, when the microgrid is isolated from the power grid, an energy optimization for military forward operating base camp was solved by a dynamic programing algorithm to minimize the total daily operation cost in [10] and a resiliency-oriented microgrid optimal scheduling model is proposed to minimize the microgrid load curtailment by scheduling available resources in [11]. While the operation cost minimization problem for energy management of a microgrid has been mostly investigated, the profit maximization problem was also studied in [13]. On the other hand, an online cost minimization scheduling model for co-generation has been developed in [14]. In addition to renewable sources commonly included in a microgrid, controllable energy sources, such as CHP generators, were also considered and managed optimally by controlling their energy production amounts in [11,15,17].

Heat energy has been also considered along with electric energy in many studies of a microgrid in [18–20]. While the authors [19–21] minimized the operating cost, Bagheria and Tafreshi [18] maximized the profit from trading of electric energy by considering the operation cost. Furthermore, heat energy storage is also considered as a component of the microgrid in [19–21].

The energy management problem for cooperative multi-microgrids is investigated in [9,22,23], which targeted minimizing the operation cost of electric energy. For the energy management of cooperative multi-microgrids, electric energy trading was allowed not only internally between microgrids, but also externally with the power grid. Rahbar *et al.* [22] 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 [23] employed the scenario-based two-stage stochastic optimization approach to deal with the uncertainties of renewable energy resources and load demand in the energy scheduling problem in addition to controllable electric energy sources such as CHPs and diesel generators. Furthermore, Song *et al.* [9] proposed an optimal electric energy management of a cooperative multi-microgrid community with sequentially-coordinated operations in order to distribute the computational burden.

In this paper, an optimal electric and heat energy management for a cooperative multi-microgrid community is proposed. The proposed sequentially-coordinated operation for heat energy is a heat extension of [9], which is following the sequentially-coordinated operations for electric energy in [9]. The global heat energy optimization is achieved for the cooperative community by adjusting the combined electric and heat energy production amounts of CHP generators and the heat energy production amount of heat only boilers (HOBs) which satisfy all heat loads in the multi-microgrids, as well as optimize the external electric energy trading. Such adjusting of energy production amounts is performed in order to minimize the unnecessary cost from the external electric trading and/or maximize the profit from the external electric trading. A simulation study is also conducted to validate the proposed mathematical energy for heat loads. Since electric heaters can satisfy heat loads using electric energy which can be traded externally, they can enable external heat trading by means of external electric trading. Currently, we consider electric heaters in the cooperative multi-microgrid community and are investigating an optimal energy management of the cooperative multi-microgrid community. Its results 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 mathematical model of the cooperative multi-microgrid operation process for electric energy in [9] is summarized in Section 3. Then, the sequentially-coordinated operation of heat energy optimization is mathematically modeled and how to obtain the optimal heat energy solution is presented in Section 4. Additionally, a simulation study for a cooperative multi-microgrid community with three microgrids is demonstrated in Section 5. Finally, our conclusions and future works are discussed in Section 6. Additionally, Appendices A and B explain how to find the optimization solution from the adjusted cost function in Section 4 and offers an illustrated interpretation of the optimization process for heat energy, respectively.

2. Proposed Optimal Electric and Heat Energy Management of Cooperative Multi-Microgrids

2.1. Cooperative Multi-Microgrid Community

A cooperative multi-microgrid community is composed of a group of multiple microgrids as in Figure 1 and is a cooperative operation model of electric and heat 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 of electric and heat energy for such a cooperative community are dealt with in this paper:

- microgrids are equipped with photovoltaic (PV) systems, CHP generators, HOBs, and solar heat systems, but the production costs of CHP generators are different;
- microgrids can trade electric energy not only internally with other microgrids in the cooperative community but also externally with the power grid;
- microgrids allow only internal trading for heat energy with other microgrids in the cooperative community; this means that all heat loads should be self-supplemented by heat energy sources in the cooperative multi-microgrid community;
- a microgrid energy management system (µEMS) manages electric energy of its microgrid; and
- a central energy management system (central EMS) has a global optimization function to manage energy generators in multi-microgrids and to satisfy both electric and heat energy loads demanded by all multi-microgrids in the cooperative community.



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

2.2. Operation Process of Cooperative Multi-Microgrids

Our multi-microgrid community has two kinds of EMSs, central EMS and μ EMS. A central EMS manages the electric energy globally in the microgrid, while a μ EMS in a microgrid manages the electric energy locally. A central EMS and μ EMSs operate cooperatively, coordinated with economic viewpoints as described in the Figure 2, and this cooperative operation process of the central EMS and μ EMSs consists the following three steps:

- Step E-1: Local optimization of electric energy in each microgrid by the μEMS;
- Step E-2: Global electric energy trading optimization by the central EMS;
- Step H: Global heat energy optimization by the central EMS.



Figure 2. Operation process of the cooperative multi-microgrid community.

3. Mathematical Modeling of Cooperative Multi-Microgrid Operation for Electric Energy [9]

In this section, the mathematical model of the cooperative multi-microgrid operation process for electric energy in [9] is summarized. Mathematical notations are first listed in Section 3.1, and the mathematical models of the operation process for electric energy are presented sequentially.

3.1. Nomenclature

Mathematical notations for electric energy are listed 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 microgrid

j = the identifier of HOB

J = the number of HOBs

e = the identifier of electric energy

 $C_{CHP_{l}}^{e}$ = the electric energy production cost of the CHP in the l^{th} microgrid (won/kWh)

 $C_{\text{BUY}_{l}}^{e}(t)$ = the buying price from the power grid in the *l*th microgrid at *t* (won /kWh)

 $C_{\text{SELL}_{l}}^{e}(t)$ = the selling price to the power grid in the *l*th microgrid at *t* (won /kWh)

 $C_{\text{CHP}_l}^h$ = the heat energy production cost of the CHP in the l^{th} microgrid (won /kWh)

 $C_{\text{HOB}_{l}}^{h}$ = the cost of the *j*th HOB in the *l*th microgrid (won /kWh)

 $M_{\text{LOAD}_{l}}^{e}(t)$ = electric energy demand in the l^{th} microgrid at t (kWh)

 $M_l^{e+}(t)$ = the amount of surplus electric energy in the *l*th microgrid at *t* (kWh)

 $M_l^{e-}(t)$ = the amount of short electric energy in the *l*th microgrid at *t* (kWh)

 $M_{PV_{t}}^{e}(t)$ = the output produced from the PV system in the l^{th} microgrid at t (kWh)

 $M_{\text{CHP}_{l}}^{e}(t)$ = the electric energy production amount of the CHP in the l^{th} microgrid at t (kWh)

 $M_{\text{CHP}_{l}}^{e+}(t)$ = the increased electric energy production amount of the CHP in the *l*th microgrid at *t* (kWh) for the ancillary internal trading

 $M_{CHP_l}^{e-}(t)$ = the decreased electric energy production amount of the CHP in the *l*th microgrid at *t* (kWh) for the ancillary internal trading

 $M_{\text{BUY}_{l}}^{e}(t)$ = the amount of the buying electric energy in the *l*th microgrid determined by central EMS at *t* (kWh)

 $M_{\text{SELL}_{l}}^{e}(t)$ = the amount of the selling electric energy in the l^{th} microgrid determined by central EMS at t (kWh)

 $M_{\text{REC}_{l}}^{e}(t)$ = the received electric energy amount in the l^{th} microgrid at t (kWh)

 $M_{\text{SEND}}^{e}(t)$ = the sending electric energy amount in the *l*th microgrid at *t* (kWh)

3.2. Step E-1: Local Optimization of Electric Energy Operation Process

The cost function of a microgrid in Step E-1 is the total expense occurred by the electric energy for the microgrid when the external trading of the electric energy with the power grid is applied as follows:

$$C_{l}^{e}\left(M_{\mathrm{CHP}_{l}}^{e}\left(t\right)\right) = \left(C_{\mathrm{CHP}_{l}}^{e} \times M_{\mathrm{CHP}_{l}}^{e}\left(t\right)\right) - \left(C_{\mathrm{SELL}_{l}}^{e}\left(t\right) \times M_{l}^{e+}\left(t\right)\right) + \left(C_{\mathrm{BUY}_{l}}^{e}\left(t\right) \times M_{l}^{e-}\left(t\right)\right)$$
(1)

Step E-1 is the local optimization process of electric energy by the μ EMS in each microgrid. As mentioned in [1], the local electric energy optimization function when external trading of electric energy with the power grid is applied can be expressed as follows:

$$M_{\text{CHP}_{l}}^{e^{*}}(t) = \arg\min\left\{C_{l}^{e}\left(M_{\text{CHP}_{l}}^{e}(t)\right)\right\}$$

subjects to:

$$\min\left[M_{\operatorname{CHP}_{l}}^{e}\right] \leqslant M_{\operatorname{CHP}_{l}}^{e}\left(t\right) \leqslant \max\left[M_{\operatorname{CHP}_{l}}^{e}\right] \tag{2}$$

For $1 \le t \le T$, $1 \le l \le L$. The constraint to the objective function of a µEMS in Equation (2) implies that a CHP generator should be operated within its operational ranges.

3.3. Step E-2: Global Optimization of Electric Energy Operation Process

n

Step E-2 is the global optimization process of electric energy by the central EMS based on local optimization information of electric energy of each μ EMS in Step E-1.

The adjusted saving cost in Step E-2 can be obtained from both main and ancillary internal trading of the electric energy between microgrids in cooperative multi-microgrids as follows:

$$C_{\text{Elec}}^{\text{Adj}} \left(M_{\text{SEND}_{1}}^{e}(t), \dots, M_{\text{SEND}_{L}}^{e}(t), M_{\text{CHP}_{1}}^{e^{+}}(t), \dots, M_{\text{CHP}_{L}}^{e^{+}}(t), M_{\text{CHP}_{1}}^{e^{-}}(t), \dots, M_{\text{CHP}_{L}}^{e^{-}}(t) \right)$$

$$= \left(C_{\text{BUY}}^{e}(t) - C_{\text{SELL}}^{e}(t) \right) \times \sum_{l=1}^{L} M_{\text{SEND}_{l}}^{e}(t)$$

$$+ \sum_{l=1}^{L} \left(C_{\text{BUY}}^{e}(t) - C_{\text{CHP}_{l}}^{e} \right) \times M_{\text{CHP}_{l}}^{e^{+}}(t)$$

$$+ \sum_{l=1}^{L} \left(C_{\text{CHP}_{l}}^{e} - C_{\text{SELL}}^{e}(t) \right) \times M_{\text{CHP}_{l}}^{e^{-}}(t)$$
(3)

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:

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

subjects to:

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

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

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

$$M_{\text{REC}_{l}}^{e}(t) \leq M_{l}^{e-}(t) \text{ when } M_{l}^{e-}(t) > 0$$
 (5)

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

$$\sum_{l=1}^{L} M_{\text{SEND}_{l}}^{e}\left(t\right) = \sum_{l=1}^{L} M_{\text{REC}_{l}}^{e}\left(t\right)$$
(6)

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

 $M_{\text{CHP}_{l}}^{e+}(t) \leqslant \max\left[M_{\text{CHP}_{l}}^{e}\right] - M_{\text{CHP}_{l}}^{e^{*}}(t)$ (7)

$$\sum_{l=1}^{L} M_{\text{CHP}_{l}}^{e+}(t) \leq \sum_{l=1}^{L} M_{l}^{e-}(t) - \sum_{l=1}^{L} M_{l}^{e+}(t)$$
(8)

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

$$M_{\text{CHP}_{l}}^{e^{-}}(t) \leq M_{\text{CHP}_{l}}^{e^{*}}(t) - \min\left[M_{\text{CHP}_{l}}^{e}\right]$$
(9)

$$\sum_{l=1}^{L} M_{\text{CHP}_{l}}^{e-}(t) \leq \sum_{l=1}^{L} M_{l}^{e+}(t) - \sum_{l=1}^{L} M_{l}^{e-}(t)$$
(10)

As a result of the global electric energy trading optimization, the global optimal production amount of the CHP generators located in self-sufficient microgrids have to be changed as follows:

$$M_{\text{CHP}_{l}}^{e^{*}}(t) := M_{\text{CHP}_{l}}^{e^{*}}(t) + M_{\text{CHP}_{l}}^{e^{+}}(t) - M_{\text{CHP}_{l}}^{e^{-}}(t)$$
(11)

for *l*, such that $(C_{\text{SELL}}^{e}(t) < M_{\text{CHP}_{l}}^{e}(t) < C_{\text{BUY}}^{e}(t))$ and the buying and selling amount of electric energies to the power grid in a microgrid should be decided by trading the amount of electric energy as follows:

$$M_{\text{BUY}_{l}}^{e} = M_{l}^{e^{-}} + M_{\text{REC}_{l}}^{e}(t) \text{ when } M_{l}^{e^{-}}(t) > 0$$
(12)

$$M_{\text{SELL}_{l}}^{e} = M_{l}^{e+} - M_{\text{SEND}_{l}}^{e}(t) \text{ when } M_{l}^{e+}(t) > 0$$
(13)

Finally, the total operation cost of electric energy in the cooperative multi-microgrid community satisfies all of the electric energy demand and is optimally minimized sequentially in two steps, as follows:

$$C_{\text{TOTAL}}^{e*}(t) = \sum_{t=1}^{T} \left\{ \sum_{l=1}^{L} \left(C_l^e \left(M_{\text{CHP}_l}^{e*}(t) \right) \right) - C_{\text{Elec}}^{\text{Adj}} \left(P_{\text{Elec}}^{\text{Adj}*}(t) \right) \right\}$$
(14)

4. Mathematical Modeling of Cooperative Multi-Microgrid Operation for Heat Energy

In this section, the operation process of heat energy part in the microgrid energy networks (μ ENet) is mathematically modeled. The proposed sequentially-coordinated operation for heat energy is a heat extension of [9], which is following the sequentially-coordinated operations for electric energy in [9].

Mathematical notations are first defined in Section 4.1, and the mathematical models of the operation process are presented according to in the heat energy part operation process.

4.1. Nomenclature

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

$$\begin{split} h &= \text{the identifier of heat energy} \\ \eta_{\text{CHP}_l} &= \text{the heat to power ratio of CHP in the } l^{\text{th}} \text{ microgrid } (\%) \\ M^h_{\text{LOAD}_l}(t) &= \text{heat energy demand in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h+}_l(t) &= \text{the amount of surplus heat energy in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h-}_l(t) &= \text{the amount of short heat energy in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^h_{\text{CH}_l}(t) &= \text{the output produced from the solar heat system in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h-}_{\text{CHP}_l}(t) &= \text{the heat energy production amount of the CHP in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h-}_{\text{CHP}_l}(t) &= \text{the additional heat energy amount of the CHP in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h-}_{\text{CHP}_l}(t) &= \text{the reducing heat energy amount of the CHP in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h-}_{\text{CHP}_l}(t) &= \text{the reducing heat energy amount of the CHP in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{CHP}_l}(t) &= \text{the reducing heat energy amount of the CHP in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{CHP}_l}(t) &= \text{the reducing heat energy amount in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{CHP}_l}(t) &= \text{the received heat energy amount in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{REC}_l}(t) &= \text{the sending heat energy amount in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{HOB}_{l,j}}(t) &= \text{the heat energy production amount of the } j^{\text{th}} \text{ HOB in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{HOB}_{l,j}}(t) &= \text{the heat energy production amount of the } j^{\text{th}} \text{ HOB in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{HOB}_{l,j}}(t) &= \text{the heat energy production amount of the } j^{\text{th}} \text{ HOB in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{HOB}_{l,j}}(t) &= \text{the heat energy production amount of the } j^{\text{th}} \text{ HOB in the } l^{\text{th}} \text{ microgrid at } t \text{ (kWh)} \\ M^{h}_{\text{H$$

4.2. Step H: Mathematical Model of Global Heat Energy Optimization

After the global electric energy optimization, the amount of heat energy from the CHP generator in a microgrid can be expressed according to the heat and electric energy ratio of the CHP as follows:

$$M^{h}_{\text{CHP}_{I}}(t) = \eta_{\text{CHP}_{I}} \times M^{e^{*}}_{\text{CHP}_{I}}(t)$$
(15)

Then, the amount of surplus heat energy in a microgrid can be calculated as:

$$M_{l}^{h+}(t) := M_{\text{CHP}_{l}}^{h}(t) + M_{\text{SH}_{l}}^{h}(t) - M_{\text{LOAD}_{l}}^{h}(t), \text{ when } M_{\text{LOAD}_{l}}^{h}(t) \leq M_{\text{CHP}_{l}}^{h}(t) + M_{\text{SH}_{l}}^{h}(t)$$
(16)

while the amount of heat energy shortage in a microgrid can be expressed as:

$$M_{l}^{h-}(t) := M_{\text{LOAD}_{l}}^{h}(t) - \left(M_{\text{CHP}_{l}}^{h}(t) + M_{\text{SH}_{l}}^{h}(t)\right), \text{ when } M_{\text{LOAD}_{l}}^{h}(t) > M_{\text{CHP}_{l}}^{h}(t) + M_{\text{SH}_{l}}^{h}(t)$$
(17)

Let us define the set of the heat energy parameters as the internal trading amounts of heat energy between microgrids, the adjusted heat energy generation amounts of CHPs, and the heat energy generation amounts of HOBs to meet all heat demand in the cooperative multi-microgrid community;

$$P_{\text{Heat}}^{\text{Adj}}(t) = (M_{\text{SEND}_{1}}^{h}(t) \dots M_{\text{SEND}_{L}}^{h}(t), M_{\text{REC}_{1}}^{h}(t) \dots M_{\text{REC}_{L}}^{h}(t), M_{\text{CHP}_{1}^{+}}^{h}(t) \dots M_{\text{CHP}_{L}^{+}}^{h}(t), M_{\text{CHP}_{1}^{-}}^{h}(t) \dots M_{\text{CHP}_{L}^{-}}^{h}(t), M_{\text{HOB}_{1,1}}^{h}(t) \dots M_{\text{HOB}_{L,J}}^{h}(t))$$

Energies 2016, 9, 473

The amounts of heat energy from the solar heat generators are not included since their heat energy production amounts cannot be adjusted. Then, the adjusted cost in Step H to meet all heat demand in the cooperative multi-microgrid community can be defined as the total heat production cost of HOBs, increased energy production of CHPs, and decreased energy production of CHPs as follows:

$$C_{\text{Heat}}^{\text{Adj}}\left(P_{\text{Heat}}^{\text{Adj}}\left(t\right)\right) = \sum_{l=1}^{L} \left\{\sum_{j=1}^{J} C_{\text{HOB}_{l,j}}^{h}\left(t\right) \times M_{\text{HOB}_{l,j}}^{h}\left(t\right)\right\} + C_{\text{CHP}^{+}}^{\text{Adj}}\left(\sum_{l=1}^{L} M_{\text{CHP}^{+}}^{h}\left(t\right)\right) - C_{\text{CHP}^{-}}^{\text{Adj}}\left(\sum_{l=1}^{L} M_{\text{CHP}^{-}}^{h}\left(t\right)\right)$$

$$(18)$$

The second term in Equation (18) is the extra cost from the increased energy production of CHPs; the extra production cost, the profit of selling surplus electric energy resulting from increased amount of CHP electric energy production, and the savings from the decreased amount of buying electric energy is as follows:

$$C_{CHP^{+}}^{Adj} \left(\sum_{l=1}^{L} M_{CHP_{l}^{+}}^{h}(t) \right)$$

$$= \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{CHP_{l}}} C_{CHP_{l}}^{e}(t) + C_{CHP_{l}}^{h}(t) \right) \times M_{CHP_{l}^{+}}^{h}(t) \right)$$

$$- C_{SELL}^{e}(t) \left(\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{+}}^{h}(t) \right)$$

$$- \min \left[\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{+}}^{h}(t), \sum_{l=1}^{L} M_{BUY_{l}}^{e}(t) \right] \right) - C_{BUY}^{e}(t)$$

$$\times \min \left[\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{+}}^{h}(t), \sum_{l=1}^{L} M_{BUY_{l}}^{e}(t) \right]$$

$$(19)$$

The third term in Equation (18) is the reduced cost from the reduced energy production of CHP, which consists of the reduced production cost, the extra cost of buying electric energy due to shortage resulting from a decreased amount of CHP electric energy production, and the reduced profit from decreased selling electric energy, as follows:

$$C_{CHP^{-}}^{Adj} \left(\sum_{l=1}^{L} M_{CHP_{l}^{-}}^{h}(t) \right)$$

$$= \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{CHP_{l}}} C_{CHP_{l}}^{e}(t) + C_{CHP_{l}}^{h}(t) \right) \times M_{CHP_{l}^{-}}^{h}(t) \right)$$

$$- C_{BUY}^{e}(t) \left(\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{-}}^{h}(t) - C_{SELL}^{e}(t) \right)$$

$$- \min \left[\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{-}}^{h}(t), \sum_{l=1}^{L} M_{SELL_{l}}^{e}(t) \right] - C_{SELL}^{e}(t)$$

$$\times \min \left[\frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}^{-}}^{h}(t), \sum_{l=1}^{L} M_{SELL_{l}}^{e}(t) \right]$$

$$(20)$$

Note that both the second term and the third term in Equation (18) cannot exist at the same time. Then, the globally-optimized adjusted production amounts of heat energy in Step H can be obtained, as follows:

$$P_{\text{Heat}}^{\text{Adj}*}(t) = \arg\min\left\{C_{\text{Heat}}^{\text{Adj}}\left(P_{\text{Heat}}^{\text{Adj}}(t)\right)\right\}$$
(21)

subject to:

$$M_{\text{LOAD}_{l}}^{h}(t) \leq M_{\text{SH}_{l}}^{h}(t) + M_{\text{CHP}_{l}}^{h}(t) + M_{\text{CHP}_{l}^{+}}^{h}(t) - M_{\text{CHP}_{l}^{-}}^{h}(t) + M_{\text{REC}_{l}}^{h}(t) - M_{\text{SEND}_{l}}^{h}(t) + M_{\text{HOB}_{l,j}}^{h}(t)$$
(22)

$$M^{h}_{\operatorname{CHP}_{l}^{+}}(t) \leqslant \max\left[M^{h}_{\operatorname{CHP}_{l}}\right] - M^{h}_{\operatorname{CHP}_{l}}(t)$$
(23)

$$M^{h}_{\operatorname{CHP}_{l}^{-}}(t) \leq M^{h}_{\operatorname{CHP}_{l}}(t) - \min[M^{h}_{\operatorname{CHP}_{l}}]$$
(24)

$$M^{h}_{\text{HOB}_{l,j}}(t) \leqslant M^{\text{cap}}_{\text{HOB}_{l,j'}} \ 1 \leqslant j \leqslant J_l$$
(25)

$$M_{\text{SEND}_{l}}^{h}(t) \leq M_{\text{CHP}_{l}}^{h+}(t) + M_{\text{CHP}_{l}}^{h}(t) - M_{\text{CHP}_{l}}^{h-}(t) + \sum_{j=1}^{J} M_{\text{HOB}_{l,j}}^{h}(t)$$
(26)

$$\sum_{l=1}^{L} M_{\text{SEND}_{l}}^{h}(t) = \sum_{l=1}^{L} M_{\text{REC}_{l}}^{h}(t)$$
(27)

for $1 \le l \le L$, $1 \le t \le T$. The first constraint to the global heat energy optimization in Equation (22) imposes that the heat demand in a microgrid has to be satisfied. Inequality in Equation (22) allows heat energy to be produced more than needed so that the total cost of both electric and heat energy can be minimized by adjusting external electric energy trading amounts while wasting heat energy. The constraints in Equations (23) and (24) are applied to the CHPs, while the constraints in Equation (25) are to HOBs. The constraints on the internal trading amounts of heat energy between microgrids are expressed in Equations (26) and (27).

Since the adjusted cost function in Step H has a min() function, it has to be linearized to find the global heat energy optimization solution as in Appendix A; first the linearized adjusted cost function has to be optimized by CPLEX for each case, and then the global heat energy optimization solution has to be selected as the optimization solution for the case which results in the minimum adjusted cost among the five cases, as in Appendix A. Please refer to Appendix B, which gives an illustrated interpretation of the heat energy optimization process for typical cases.

After the global heat energy optimization is completed, the external trading amount of electric energy with the main grid has be re-arranged again, as follows:

when $\sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) > 0$:

$$\sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) := \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) + \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t)$$
(28)

for $\frac{1}{\eta_{\text{CHP}_l}} \sum_{l=1}^{L} M^h_{\text{CHP}_l^+}(t) \ge 0$:

$$\sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) := \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) - \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t)$$
(29)

for $\frac{1}{\eta_{\text{CHP}_l}} \sum_{l=1}^{L} M_{\text{CHP}_l}^h(t) \leq M_{\text{SELL}}^e(t)$ when $\sum_{l=1}^{L} M_{\text{CHP}_l}^h(t) > 0$:

$$\sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e}(t) := \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t) - \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t), \text{ and } \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) := 0$$
(30)

for $\frac{1}{\eta_{\text{CHP}_l}} \sum_{l=1}^{L} M_{\text{CHP}_l}^h(t) > \sum_{l=1}^{L} M_{\text{SELL}_l}^e(t)$ when $\sum_{l=1}^{L} M_{\text{CHP}_l}^h(t) > 0$ and when $\sum_{l=1}^{L} M_{\text{BUY}_l}^e(t) > 0$:

$$\sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e}(t) := \sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e}(t) + \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t)$$
(31)

for $\sum_{l=1}^{L} M_{\text{CHP}_{l}^{-}}^{h}(t) > 0$:

$$\sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e}(t) := \sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e}(t) - \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t)$$
(32)

for
$$\frac{1}{\eta_{CHP_l}} \sum_{l=1}^{L} M_{CHP_l}^h(t) \leq \sum_{l=1}^{L} M_{BUY_l}^e(t)$$
 when $\sum_{l=1}^{L} M_{CHP_l}^h(t) > 0$:

$$\sum_{l=1}^{L} M_{SELL_l}^e(t) := \frac{1}{\eta_{CHP_l}} \sum_{l=1}^{L} M_{CHP_l}^h(t) - \sum_{l=1}^{L} M_{BUY_l}^e(t) \text{ and } \sum_{l=1}^{L} M_{BUY_l}^e(t) = 0 \quad (33)$$

for $\frac{1}{\eta_{\text{CHP}_l}} \sum_{l=1}^{L} M_{\text{CHP}_l^+}^h(t) > \sum_{l=1}^{L} M_{\text{BUY}_l}^e(t)$ when $\sum_{l=1}^{L} M_{\text{CHP}_l^+}^h(t) > 0$.

Furthermore, the total heat energy produced by the CHP generator in a microgrid can be re-arranged, as follows:

$$M_{\text{CHP}_{l}}^{h^{*}}(t) := M_{\text{CHP}_{l}}^{h}(t) + M_{\text{CHP}_{l}}^{h^{*}}(t) \text{ when } M_{\text{CHP}_{l}}^{h^{*}}(t) > 0$$
(34)

$$M_{\text{CHP}_{l}}^{h^{*}}(t) := M_{\text{CHP}_{l}}^{h}(t) - M_{\text{CHP}_{l}^{-}}^{h^{*}}(t) \text{ when } M_{\text{CHP}_{l}^{-}}^{h^{*}}(t) > 0$$
(35)

4.3. Total Operation Costs

Finally, the total optimum operation cost can be expressed with the objective functions defined earlier, as follows:

$$C_{\text{TOTAL}}^{*}(t) = \sum_{l=1}^{L} \left(C_{l}^{e} \left(M_{\text{CHP}_{l}}^{e^{*}}(t) \right) + C_{\text{CHP}_{l}}^{h}(t) \times M_{\text{CHP}_{l}}^{h^{*}}(t) \right) - C_{\text{Elec}}^{\text{Adj}} \left(P_{\text{Elec}}^{\text{Adj}^{*}}(t) \right) + C_{\text{Heat}}^{\text{Adj}} \left(P_{\text{Heat}}^{\text{Adj}^{*}}(t) \right)$$
(36)

The total operation cost of the cooperative multi-microgrid for electric energy and heat energy can be reduced significantly by performing all of the energy optimization processes sequentially in the three steps as shown in Sections 3 and 4.

5. Simulation Study

A simulation study has been conducted for a cooperative multi-microgrid community to show the optimal electric and heat energy management with sequential operation processes and its results, especially for the global heat energy optimization, are presented in this section.

In our simulation study, a cooperative multi-microgrid community is composed of three microgrids having different CHPs and HOBs. Note that when a CHP produces 1 kWh electric energy, η_{CHP_l} kWh heat energy is produced; the unit production cost of combined electric and heat energy of a CHP can be defined as the combined production cost of 1 kWh electric energy and η_{CHP_l} kWh heat energy; that is, $(C_{CHP_l}^e(t) + \eta_{CHP_l}C_{CHP_l}^h(t))$ as shown in Table 1. For simplicity, we assume that $C_{CHP_l}^e(t) = C_{CHP_l}^h(t)$. The production costs $(C_{HOB_l}^h(t))$ of HOB A, B, and C are 240, 230, and 240, respectively.

Table 1. Combined electric and heat (*E* and *H*) energy production cost of CHPs.

Characteristics	CHP A	CHP B	CHP C
Combined electric and heat (<i>E</i> and <i>H</i>) energy	90	120	165
1 kWh Electric energy $(C_{CHP_{l}}^{e}(t))$	42.86	53.33	66
η_{CHP_l} kWh Heat energy ($C_{\text{CHP}_l}^{h}(t)$)	47.14	66.67	99
Heat and power ratio (η_{CHP_l})	1.1	1.25	1.5

The external trading prices of electric energy are designed as time of use (TOU) plan having off-peak, non-peak, and peak hours for 24 h of a day as in Table 2; the buying price is always set higher than the selling price. The combined *E* and *H* production costs of CHPs are compared to external trading prices by the TOU plan in Figure 3.

180

60

40

20

Unit Production Cost of Combined Energy [Won]



Figure 3. Unit production cost of combined *E* and *H* energy of CHPs.

Table 2. External trading prices by time of use (TOU) plan.

Price	Off-Peak	Non-Peak	Peak
Buying price	57	105	130
Selling price	47	85	110

The simulation results for the cooperative multi-microgrids are arranged in Tables 3–5 for Steps E-1, E-2, and H, respectively. First, the local and global optimal operation results of electric energy from Steps E-1 and E-2 are arranged in Tables 3 and 4. Since the heat energy optimization process is the main focus of this paper, electric energy optimization results in Tables 3 and 4 will not be discussed here (please refer [9] for a better understanding of electric energy optimization process).

Table 3. Local optimization of electric energy in Step E-1.

-		Micro	grid A				Micro	grid B		Microgrid C					
T	$M^e_{\mathrm{LOAD}_l}$	$M^{e}_{\operatorname{CHP}_{l}}$	$M^{e}_{\mathbf{PV}_{l}}$	M_l^{e-}	M_l^{e+}	$M^e_{\mathrm{LOAD}_l}$	$M^{e}_{\operatorname{CHP}_{l}}$	$M^{e}_{\mathbf{PV}_{l}}$	M_l^{e-}	M_l^{e+}	$M^e_{\mathrm{LOAD}_l}$	$M^{e}_{\operatorname{CHP}_{l}}$	$M^{e}_{\mathbf{PV}_{l}}$	M_l^{e-}	M_l^{e+}
1	369	450	0	0	81	192	360	0	0	168	550	480	0	70	0
2	345	450	0	0	105	187	360	0	0	173	525	480	0	45	0
3	382	450	0	0	68	402	402	0	0	0	575	480	0	95	0
4	351	450	0	0	99	330	360	0	0	30	472	480	0	0	8
5	381	450	0	0	69	399	399	0	0	0	485	480	0	5	0
6	372	450	0	0	78	372	372	0	0	0	495	480	0	15	0
7	350	450	0	0	100	177	600	0	0	423	530	700	0	0	170
8	336	450	6	0	120	165	600	0	0	435	492	700	7	0	215
9	371	450	9	0	88	143	600	0	0	457	497	700	10	0	213
10	387	450	10	0	73	212	600	5	0	393	467	700	12	0	245
11	393	450	13	0	70	201	600	8	0	407	497	700	16	0	219
12	428	450	18	0	40	317	600	10	0	293	793	700	25	68	0
13	417	450	23	0	56	299	600	15	0	316	723	700	28	0	5
14	414	450	25	0	61	247	600	19	0	372	664	700	24	0	60
15	400	450	24	0	74	216	600	20	0	404	604	700	20	0	116
16	351	450	21	0	120	603	600	14	0	11	807	700	13	94	0
17	357	450	18	0	111	600	600	12	0	12	769	700	4	65	0
18	356	450	8	0	102	652	600	4	48	0	601	700	0	0	99
19	347	450	0	0	103	436	600	0	0	164	558	700	0	0	142
20	467	450	0	17	0	423	600	0	0	177	719	700	0	19	0
21	432	450	0	0	18	532	600	0	0	68	533	700	0	0	167
22	416	450	0	0	34	651	600	0	51	0	729	700	0	29	0
23	357	450	0	0	93	600	600	0	0	0	769	700	0	69	0
24	400	450	0	0	50	216	600	0	0	384	604	700	0	0	96

Buying price

Selling price

	Microgrid A							Microgrid B							Microgrid C					
Т	$M^e_{\mathrm{CHP}^+_l}$	$M^e_{\mathrm{CHP}_l^-}$	M ^e _{SEND_l}	$M^e_{\operatorname{REC}_l}$	$M^e_{{ m BUY}_l}$	$M^e_{\mathrm{SELL}_l}$	$M^e_{\mathrm{CHP}^+_l}$	$M^e_{\mathrm{CHP}_l^-}$	M ^e _{SEND1}	$M^e_{\text{REC}_l}$	$M^e_{\mathrm{BUY}_l}$	$M^{e}_{\mathrm{SELL}_{l}}$	$\overline{M^e_{\mathrm{CHP}^+_l}}$	$M^e_{\mathrm{CHP}_l^-}$	M ^e _{SEND_l}	$M^e_{\text{REC}_l}$	$M^e_{\mathrm{BUY}_l}$	$M^e_{\mathrm{SELL}_l}$		
1	0	0	23	0	0	58	0	0	0	70	0	0	0	0	47	0	0	120		
2	0	0	17	0	0	88	0	0	0	45	0	0	0	0	28	0	0	144		
3	0	0	68	0	0	0	0	0	0	95	0	0	27	0	27	0	0	0		
4	0	0	0	0	0	99	0	0	0	0	0	8	0	0	0	0	0	30		
5	0	0	44	0	0	25	0	0	0	5	0	0	0	39	0	39	0	0		
6	0	0	27	0	0	51	0	0	0	15	0	0	0	12	0	12	0	0		
7	0	0	0	0	0	100	0	0	0	0	0	170	0	0	0	0	0	423		
8	0	0	0	0	0	120	0	0	0	0	0	215	0	0	0	0	0	435		
9	0	0	0	0	0	88	0	0	0	0	0	213	0	0	0	0	0	457		
10	0	0	0	0	0	73	0	0	0	0	0	245	0	0	0	0	0	393		
11	0	0	0	0	0	70	0	0	0	0	0	219	0	0	0	0	0	407		
12	0	0	8	0	0	32	0	0	0	68	0	0	0	0	60	0	0	233		
13	0	0	0	0	0	56	0	0	0	0	0	5	0	0	0	0	0	316		
14	0	0	0	0	0	61	0	0	0	0	0	60	0	0	0	0	0	372		
15	0	0	0	0	0	74	0	0	0	0	0	116	0	0	0	0	0	404		
16	0	0	86	0	0	34	0	0	0	94	0	0	0	0	8	0	0	3		
17	0	0	59	0	0	52	0	0	0	65	0	0	0	0	6	0	0	6		
18	0	0	24	0	0	78	0	0	23	0	0	75	0	0	0	48	0	0		
19	0	0	0	0	0	103	0	0	0	0	0	142	0	0	0	0	0	164		
20	0	0	0	17	0	0	0	0	0	19	0	0	0	0	36	0	0	141		
21	0	0	0	0	0	18	0	0	0	0	0	167	0	0	0	0	0	68		
22	0	0	34	0	0	0	0	0	0	12	0	0	0	0	0	21	0	0		
23	0	0	69	0	0	24	0	0	0	69	0	0	0	0	0	0	0	0		
24	0	0	0	0	0	50	0	0	0	0	0	96	0	0	0	0	0	384		

 Table 4. Global optimization of electric energy in Step E-2.

Table 5. Global optimization	n of heat energy in Step H.
------------------------------	-----------------------------

							Microg	grid A						
T	$M^{e}_{\mathrm{LOAD}_{l}}$	$M^h_{\mathrm{LOAD}_l}$	$M^e_{\mathbf{PV}_l}$	$M^h_{\mathbf{SH}_l}$	$M^{e}_{\operatorname{CHP}_{l}}$	$M^h_{\operatorname{CHP}_l}$	$M^e_{\mathrm{CHP}^+_l}$	$M^e_{\mathrm{CHP}^l}$	$M^h_{\mathrm{CHP}_l^+}$	$M^h_{\operatorname{CHP}_l^-}$	$M^h_{\mathrm{HOB}_l}$	$M^h_{SEND_l}$	$M^h_{\operatorname{REC}_l}$	$M^h_{WAS_l}$
1	369	778	0	0	450	495	0	0	0	0	0	0	283	0
2	345	641	0	0	450	495	0	0	0	0	0	0	146	0
3	382	590	0	0	450	495	0	0	0	0	0	0	95	0
4	351	566	0	0	450	495	0	0	0	0	0	0	71	0
5	381	455	0	0	450	495	0	0	0	0	0	40	0	0
6	372	396	0	0	359	395	0	91	0	100	0	0	1	0
/	350	641	0	0	450	495	0	0	0	0	0	0	146	0
0	271	600	0	0	450	495	0	0	0	0	0	0	101	0
9	3/1	556	9	5	450	495	0	0	0	0	0	0	43	0
10	303	474	10	7	450	495	0	0	0	0	0	28	40	0
11	393	370	13	10	450	495	0	0	0	0	0	20 63	0	72
12	420	412	22	15	450	495	0	0	0	0	0	66	0	32
14	417	412	25	15	450	495	0	0	0	0	0	20	0	0
15	400	532	23	16	450	495	0	0	0	0	0	0	21	0
16	351	512	21	14	450	495	0	0	0	Ő	Ő	Ő	3	0
17	357	532	18	9	450	495	0	0	0	0	0	0	28	0
18	356	326	8	Ó	450	495	Ő	Ő	Ő	0	0	100	0	69
19	347	301	0	0	450	495	Ő	0	0	0	0	0	0	194
20	467	240	õ	0	450	495	Ő	Ő	Ő	0	0	6	0	249
21	432	410	Ő	õ	450	495	Õ	Õ	õ	Õ	õ	Ő	õ	85
22	416	337	0	0	450	495	0	0	0	0	0	158	0	0
23	357	470	0	0	450	495	0	0	0	0	0	25	0	0
24	400	368	0	0	380	418	0	70	0	77	0	0	0	50
			-				Micro	grid B						
Т	M ^e LOAD:	M ^h LOAD:	M ^e _{PV}	M ^h _{SH} .	M ^e _{CHP}	M ^h _{CHP}	Micros	grid B M ^e _{CHP} -	$M^h_{CHP^+}$	M ^h _{CHP} -	M ^h _{HOB}	M ^h _{SEND}	$M^h_{\rm REC}$	M ^h was.
T	$M^{e}_{\text{LOAD}_{l}}$ 192	$M^h_{LOAD_l}$ 748	$M_{PV_l}^e$	$M^h_{\mathrm{SH}_l}$	$M^{e}_{\text{CHP}_{l}}$	$M^h_{\operatorname{CHP}_l}$ 750	Micros M ^e _{CHPl} + 240	grid B M ^e _{CHP1}	$M^h_{\operatorname{CHP}_l^+}$ 300	$M^{h}_{\operatorname{CHP}_{l}^{-}}$	$M^{h}_{HOB_{l}}$ 101	M ^h _{SEND_l}	$M_{\text{REC}_l}^h$	$\frac{M^{h}_{\text{WAS}_{l}}}{0}$
T 1 2	<i>M</i> ^e _{LOAD_l} 192 187	M ^h _{LOAD_l} 748 732	$\frac{M_{\mathbf{PV}_{l}}^{e}}{0}$	$M^h_{\mathbf{SH}_l}$ 0	M ^e _{CHP_l} 600 600	M ^h _{CHP_l} 750 750	Micros M ^e _{CHP_l} + 240 240	grid B <u>M^e_{CHP_l}</u> 0 0	$\frac{M^{h}_{CHP_{l}^{+}}}{300}$	$\frac{M^h_{\operatorname{CHP}_l^-}}{0}$	M ^h _{HOB_l} 101 62	M ^h _{SEND1} 103 80	$M^h_{\operatorname{REC}_l}$ 0 0	$\frac{M^h_{WAS_l}}{0}$
T 1 2 3	$M^{e}_{LOAD_{l}}$ 192 187 402	M ^h _{LOAD} 748 732 715	$\begin{array}{c} M^e_{\mathbf{PV}_l} \\ 0 \\ 0 \\ 0 \\ 0 \end{array}$	$M^h_{\mathrm{SH}_l}$ 0 0 0	<i>M</i> ^{<i>e</i>} _{CHP_{<i>l</i>}} 600 600 600	<i>M^h</i> _{CHP_l} 750 750 750	Microg M ^e _{CHPl} + 240 240 171	grid B <u>M^e_{CHP_l}</u> 0 0 0	$M^{h}_{\mathrm{CHP}_{l}^{+}}$ 300 300 213.7	$\begin{array}{c} M^h_{\operatorname{CHP}_l^-} \\ 0 \\ 0 \\ 0 \\ 0 \end{array}$	$\frac{M^h_{\mathrm{HOB}_l}}{101}$	M ^h _{SEND_l} 103 80 35	$M^h_{\operatorname{REC}_l}$ 0 0 0	$\begin{array}{c} M^h_{\mathrm{WAS}_l} \\ 0 \\ 0 \\ 0 \\ 0 \end{array}$
T 1 2 3 4	M ^e _{LOAD} 192 187 402 330	M ^h LOAD _i 748 732 715 649	<i>M</i> ^{<i>e</i>} _{PV_{<i>l</i>}} 0 0 0 0	$\frac{M^h_{\mathrm{SH}_l}}{0}\\0\\0\\0\\0$	<i>M</i> ^{<i>e</i>} _{CHP_{<i>l</i>}} 600 600 600 600	M ^h _{CHP1} 750 750 750 750	Microg M ^e _{CHPl} 240 240 171 240	grid B <u>M^e_{CHP_l}</u> 0 0 0 0 0 0	M ^h _{CHPl} + 300 300 213.7 300	$M^{h}_{\mathrm{CHP}_{l}^{-}}$ 0 0 0 0 0 0	$\begin{array}{c} M^h_{\mathrm{HOB}_l} \\ 101 \\ 62 \\ 0 \\ 0 \end{array}$	M ^h _{SEND_l} 103 80 35 101	$M^h_{\operatorname{REC}_l}$ 0 0 0 0 0	$\begin{matrix} M^h_{WAS_l} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$
T 1 2 3 4 5	M ^e _{LOAD_l} 192 187 402 330 399	M ^h LOAD _l 748 732 715 649 490	<i>M</i> ^{<i>e</i>} _{PV_{<i>l</i>}} 0 0 0 0 0 0 0	M ^h _{SH1} 0 0 0 0 0 0	M ^e _{CHP1} 600 600 600 600 380	M ^h _{CHP1} 750 750 750 750 475	Micros M ^e _{CHP} + 240 240 171 240 20	grid B M ^e _{CHP_l} 0 0 0 0 0 0 0 0	M ^h _{CHPl} 300 213.7 300 25	M ^h _{CHP_l} 0 0 0 0 0 0	$M^{h}_{\mathrm{HOB}_{l}}$ 101 62 0 0 0 0	$M^{h}_{SEND_{l}}$ 103 80 35 101 0	M ^h _{REC1} 0 0 0 15	$\begin{matrix} M^h_{WAS_l} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$
T 1 2 3 4 5 6	M ^e _{LOAD1} 192 187 402 330 399 372	M ^h _{LOAD1} 748 732 715 649 490 430	$M^{e}_{{ m PV}_{l}}$ 0 0 0 0 0 0 0 0 0 0	$M^{h}_{\mathrm{SH}_{l}}$ 0 0 0 0 0 0 0 0 0 0 0 0	M ^e _{CHP1} 600 600 600 600 380 360	<i>M^h</i> _{CHP1} 750 750 750 750 750 475 450	Micros M ^e _{CHPl} + 240 240 171 240 20 0	grid B M ^e _{CHP_l} 0 0 0 0 0 0 0 0 0 0	M ^h _{CHPl} 300 300 213.7 300 25 0	M ^h _{CHP_l} 0 0 0 0 0 0 0 0	M ^h _{HOB1} 101 62 0 0 0 0 0	M ^h _{SEND_l} 103 80 35 101 0 20	M ^h _{REC1} 0 0 0 0 15 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7	M ^e _{LOAD1} 192 187 402 330 399 372 177	M ^h _{LOAD1} 748 732 715 649 490 430 532	<i>M</i> ^{<i>e</i>} _{PV_{<i>l</i>}} 0 0 0 0 0 0 0 0 0	$M^{h}_{\mathrm{SH}_{l}}$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	$M^e_{CHP_l}$ 600 600 600 600 380 360 600	M ^h _{CHP1} 750 750 750 750 475 450 750	Micros M ^e _{CHPl} + 240 240 171 240 20 0 0 0	$ \frac{grid B}{M_{CHP_{l}}^{e}} \frac{0}{0} 0 \\ $	M ^h 300 300 213.7 300 25 0 0	M ^h _{CHP_l} 0 0 0 0 0 0 0 0 0 0 0	M ^h _{HOB1} 101 62 0 0 0 0 0 0 0 0 0 0 0	M ^h _{SEND_l} 103 80 35 101 0 20 218	$M^h_{ m REC_l}$ 0 0 0 0 15 0 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8	M ^e _{LOAD_i} 192 187 402 330 399 372 177 165	M ^h _{LOAD1} 748 732 715 649 490 430 532 722	<i>M</i> ^{<i>e</i>} _{PV_{<i>i</i>}} 0 0 0 0 0 0 0 0 0	M ^h _{SH1} 0 0 0 0 0 0 0 0 0	$M^e_{CHP_1}$ 600 600 600 600 380 360 600 600	<i>M^h</i> CHP ₁ 750 750 750 475 450 750 750 750	Micros M ^e _{CHP} + 240 240 171 240 20 0 0 0 0	$ \frac{grid B}{M_{CHP_{l}}^{e}} \begin{array}{c} 0 \\ 0 \\ 0 $	M ^h _{CHP_i+ 300 300 213.7 300 25 0 0 0}	M ^h _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0	M ^h _{HOB1} 101 62 0 0 0 0 0 0 113	M ^h _{SEND} 103 80 35 101 0 20 218 141	M ^h _{REC1} 0 0 0 0 15 0 0 0 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8 9	M ^e _{LOAD_i} 192 187 402 330 399 372 177 165 143	<i>M</i> ^h _{LOAD₁} 748 732 715 649 490 430 532 722 649	<i>M</i> ^{<i>e</i>} _{PV_{<i>i</i>}} 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{SHi} 0 0	$M^e_{CHP_I}$ 600 600 600 600 380 360 600 600 600	<i>M^h</i> CHP ₁ 750 750 750 475 450 750 750 750	Micros M ^e _{CHP} + 240 240 171 240 20 0 0 0 0 0 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHP1} 300 300 213.7 300 25 0 0 0 0 0	M ^h _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0	$\begin{array}{c} M^h_{\rm HOB_l} \\ 101 \\ 62 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 113 \\ 0 \\ \end{array}$	M ^h _{SENDi} 103 80 35 101 0 20 218 141 106	M ^h _{REC1} 0 0 0 0 15 0 0 0 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8 9 10	M ^e _{LOAD} 192 187 402 330 399 372 177 165 143 212	M ^h _{LOAD_i} 748 732 715 649 490 430 532 722 649 620	$M_{PV_l}^e$ 0 0	M ^h _{SHi} 0 0	M ^e _{CHP1} 600 600 600 380 360 600 600 600 600 600 600 600 600 600 600 600 600	M ^h _{CHP1} 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750	Micros M ^e _{CHP} 240 240 171 240 20 0 0 0 0 0 0 0 0	grid B $M^e_{CHP_l^-}$ 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHPl} 300 213.7 300 25 0 0 0 0 0 0 0 0 0	M ^h _{CHP_I} 0 0	$\begin{array}{c} M^h_{{\rm HOB}_l} \\ 101 \\ 62 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 113 \\ 0 \\ 0 \\ 0 \\ \end{array}$	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138	M ^h _{REC1} 0 0 0 0 15 0 0 0 0 0 0 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8 9 10 11	M ^e _{LOAD_i} 192 187 402 330 399 372 177 165 143 212 201	M ^h _{LOAD_i} 748 732 715 649 490 430 532 722 649 620 617	<i>M</i> ^{<i>e</i>} _{PV_{<i>l</i>}} 0 0 0 0 0 0 0 0 0 0 5 8	M ^h _{SHi} 0 12	M ^e _{CHP1} 600 600 600 380 360 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600	M ^h _{CHP1} 750 750 750 475 450 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750	Micros M ^e _{CHPl} + 240 240 240 0 0 0 0 0 0 0 0 0 0	rrid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHP1} 300 300 213.7 300 25 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHP_I} 0 0	$M^{h}_{HOB_{l}}$ 101 62 0 0 0 0 0 0 0 113 0 0 0 0	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145	M ^h _{REC1} 0 0 0 0 15 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{WASi} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12	M ^e _{LOAD_l} 192 187 402 330 399 372 177 165 143 212 201 317	M ^h _{LOAD1} 748 732 715 649 490 430 532 722 649 620 617 521	<i>M</i> ^{<i>e</i>} _{PV_{<i>i</i>}} 0 0 0 0 0 0 0 0 0 0 5 8 8 1 0	M ^h _{SHi} 0 12 15	M ^e _{CHP1} 600 600 600 380 360 600 600 500 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 555.1	M ^h _{CHP1} 750 750 750 750 475 450 750 750 750 750 750 750 693.8	Microg M ^e _{CHP1} + 240 240 240 20 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B M ^e _{CHP_i} 0 0	M ^h _{CHP1} 300 300 213.7 300 25 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHP₁} 0 0	M ^h _{HOB1} 101 62 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{SEND} 103 80 35 101 0 20 218 141 106 138 145 0	M ^h _{REC1} 0 0 0 15 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 187.8
T 1 2 3 4 5 6 7 8 9 10 11 12 13	M ^e _{LOAD} 192 187 402 330 399 372 177 165 143 212 201 317 299	M ^h _{LOAD} 732 715 649 490 430 532 722 649 620 617 521 536	$M_{PV_l}^e$ 0 10 15	$M_{SH_l}^h$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 10 5 8 12 15 18	$M^e_{CHP_1}$ 600 600 600 380 360 600	M ^h _{CHP1} 750 750 750 475 450 750 750 750 750 750 750 693.8 553.7	Microg M ^e _{CHP1} + 240 240 240 20 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B $M^e_{CHP_i^-}$ 0 157	M ^h _{CHP1} 300 213.7 300 25 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHP₁} 0 0	M ^h _{HOB1} 101 62 0	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 0	M ^h _{REC1} 0 0	M ^h _{WAS1} 0 35.8
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14	M ^e _{LOAD1} 192 187 402 330 399 372 177 165 143 212 201 317 299 247	M ^h _{LOAD} 742 732 715 649 490 430 532 722 649 620 617 521 536 550	$M_{PV_i}^e$ 0 0	M ^h _{SH_I} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 10 5 8 12 15 18 20	$M^e_{CHP_1}$ 600 604	M ^h _{CHP} , 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583	Microg $M^e_{CHP_1^+}$ 240 240 240 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B M ^e _{CHP_i} 0 157 133.6	M ^h _{CHP} 300 300 213.7 300 25 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{CHPi} 0 0	M ^h _{HOB_i} 01 62 0 0 0 1113 0	M ^h _{SENDi} 103 80 35 101 0 20 218 141 106 138 145 0 0 53	M ^h _{REC1} 0 0	M ^h _{WASi} 0 187.8 35.8 0
T 1 2 3 4 5 6 7 8 9 10 11 11 12 13 14 15	M ^e _{LOAD1} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216	M ^h LOAD ₁ 732 715 649 430 532 722 649 430 532 722 649 620 617 521 536 550 567	$M_{PV_i}^e$ 0 15 19 20	$M_{SH_i}^h$ 0 15 18 20 16	M ^e _{CHP1} 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 505.1 443 466.4 568.8	M ^h _{CHP} 750 750 750 750 750 750 750 750 750 750 750 750 750 750 553.7 583 711	Microg $M_{CHP_1^+}^e$ 240 171 240 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B M ^e _{CHP_i} 0 157 133.6 31.2	M ^h _{CHP_i+ 300 300 213.7 300 25 0}	M ^h _{CHP_i} 0 167 39	$M^h_{HOB_i}$ 101 62 0	M ^h _{SEND1} 103 80 35 101 0 201 218 141 106 138 145 0 0 53 160	M ^h _{RECi} 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 187.8 35.8 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16	M ^e _{LOAD1} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 602	M ^h _{LOAD1} 748 732 715 649 430 532 722 649 620 617 521 536 550 567 767	<i>M</i> ^{<i>e</i>} _{PV1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	$M_{SH_i}^h$ 0 15 18 20 16 13	$M^e_{CHP_i}$ 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 555.1 446.4 568.8 600 600	M ^h _{CHP} , 750 750 750 750 475 450 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 583 711 750	Microg $M_{CHP_1^+}^e$ 240 171 240 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 133.6 31.2 0	M ^h _{CHP1} 300 213.7 300 25 0	M ^h _{CHP} 0 167 39 0	M ^h _{HOB} 101 62 0	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 53 160 0 141	M ^h _{RECi} 0 0	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 187.8 35.8 0 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17	M ^e _{LOAD_l} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 600 652	M ^h _{LOAD1} 748 732 715 649 430 532 722 649 430 532 722 649 620 621 536 550 567 767 719	<i>M</i> ^{<i>e</i>} _{PV1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 5 8 8 10 15 19 20 14 12	$M_{SH_{l}}^{h}$ 0 0 0 0 0 0 0 0 0 0 0 0 0	$M^e_{CHP_1}$ 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 555.1 443 466.4 568.8 600 600 600 600 600	M ^h _{CHP,} 750 750 750 750 475 450 751 750 750 750 750 751 750 750 750 750 750 750 750 750 <td>Microg $M_{CHP_1^+}^e$ 240 240 171 240 0</td> <td>grid B M^e_{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 133.6 31.2 0 0 0 0</td> <td>M^h_{CHP1} 300 213.7 300 25 0</td> <td>M^h_{CHP₁} 0</td> <td>$\begin{array}{c} M^h_{\rm HOB_l} \\ M^h_{\rm HOB_l} \\ 101 \\ 62 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 113 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\$</td> <td>M^h_{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 0 145 0 0 146 138 145 0</td> <td>M^h_{REC1} 0</td> <td>$M^h_{WAS_i}$ 0</td>	Microg $M_{CHP_1^+}^e$ 240 240 171 240 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 133.6 31.2 0 0 0 0	M ^h _{CHP1} 300 213.7 300 25 0	M ^h _{CHP₁} 0 0	$\begin{array}{c} M^h_{\rm HOB_l} \\ M^h_{\rm HOB_l} \\ 101 \\ 62 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 113 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ $	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 0 145 0 0 146 138 145 0	M ^h _{REC1} 0 0	$M^h_{WAS_i}$ 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18	M ^e _{LOAD} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 600 652	M ^h _{LOAD1} 748 732 715 649 490 532 722 649 620 617 536 550 557 767 719 620	<i>M</i> ^{<i>e</i>} _{PV} , 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	$M^h_{SH_I}$ 0 15 18 20 16 13 10 8 20	$M^e_{CHP_1}$ 600 600 600 600 600 600 600 600 600 600 600 600 600 600 555.1 443 466.4 568.8 600 600 360 600 360	M ^h _{CHP,1} 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583 711 750	Microq M ^e _{CHP1} + 240 240 240 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B $M^e_{CHP_i^-}$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 157 133.6 31.2 0 0 0 240	M ^h _{CHPi} 300 213.7 300 25 0	M ^h _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 196.2 167 39 0 0 0 0 0 0	$M^h_{HOB_i}$ $M^h_{HOB_i}$ 62 0 0 0 0 0 0 0 0	M ^h _{SENDr} 103 80 35 101 0 20 218 141 106 138 145 0 0 53 160 0 41 0 0	M ^h _{REC1} 0 10	M ^h _{WAS1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 187.8 35.8 0 0 0 0 0 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 20 20 20 20 20 20 20 20 20	M ^e _{LOAD} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 600 652 436 402	M ^h _{LOAD} , 742 732 715 649 490 430 532 722 649 620 617 536 550 557 767 719 671 450	<i>M</i> ^{<i>e</i>} _{PV_i} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	$\mathcal{M}^h_{SH_I}$ 0 15 18 20 16 13 10 8 0	M ^e _{CHP} , 600 360 360	M ^h _{CHP,} 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583 711 750 450 450	Microg M ^e _{CHP1} + 240 240 171 240 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 157 133.6 31.2 0 240 240	M ^h _{CHP1} 300 300 213.7 300 25 0	M ^h 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 167 39 0 300 300	M ^h _{HOB} 0 62 0	M ^h _{SEND} 103 80 35 101 0 20 218 141 106 138 145 0 0 0 0 41 0 0	M ^h _{REC1} 0 213 0	M ^h _{WAS1} 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	M ^e _{LOAD_l} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 600 652 436 423	M ^h LOAD ₁ 748 732 715 649 430 532 722 649 430 532 722 649 620 617 521 536 550 567 767 711 430 430 604	$M_{PV_i}^e$ 0 0 0 0 0 0 0 0 0 0 0 0 0	$M^h_{SH_l}$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15 18 20 16 13 10 8 0 0 0	M ^e _{CHP} 600 600 600 600 380 360 600 600 600 600 600 600 600 600 600 600 555.1 443 466.4 568.8 600 360 360 360 360	M ^h _{CHP} 750 750 750 750 750 750 750 750 750 750 750 750 553.7 583 711 750 450 450 450	Microg M ^e _{CHP1} + 240 240 171 240 0 0 0 0 0 0 0 0 0 0 0 0 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 157 133.6 31.2 0 240 240 240	M ^h _{CCHP1} 300 300 237 300 25 0	M ^h 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 167 39 0 300 300 300	M ^h _{HOB} 101 62 0	M ^h _{SEND1} 103 80 35 101 0 2218 141 106 138 145 0 0 533 160 0 411 0 0	M ^h _{REC1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 213 0 6 154	M ^h _{WAS1} 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21	M ^e _{LOAD_l} 192 187 402 330 399 372 177 165 143 212 201 317 299 247 216 603 600 652 436 423 532	μ Λ 748 732 715 649 430 532 722 649 620 617 521 536 550 567 767 719 430 456 604	$M_{PV_i}^e$ 0 0 0 0 0 0 0 0 0 0 0 0 0	$M^h_{SH_I}$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15 18 20 16 13 10 8 0 0 0 0 0	$M^e_{CHP_i}$ 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 555.1 446.4 568.8 600 360 360 360 360 360 360	M ^h _{CHP,} 750 750 750 750 475 450 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583.7 583.7 750 450 450 450 450 450 450	Microg $M_{CHP_1^+}^e$ 240 240 171 240 0	grid B M ^e _{CHP₁} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 133.6 31.2 0 24	M ^h _{CHP1} 300 213.7 300 25 0	M ^h _{CHP} 0 0 0 0 0<	M ^h _{HOB} 101 62 0	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 0 53 160 0 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{REC1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 4 0 6 154 114	M ^h _{WAS1} 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22	M ^e _{LOAD_I} 192 187 402 330 399 372 177 165 143 212 201 317 209 247 216 603 600 652 436 423 532 651 600	M ^h _{LOAD1} 748 732 715 649 430 532 722 649 620 621 536 550 557 767 719 671 430 456 604 692 619	$M_{PV_i}^e$ 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^h _{SH_i} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15 18 20 16 13 10 8 0 0 0 0 0	M ^e _{CHP} , 600 360 360 360 360 360 360 360 360 360 360 360 360 360 360 360 360 360 360 360	M ^h _{CHP,} 750 750 750 750 475 450 750 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583 7111 750 450 450 450 450 450 450 450 450 450 450	Microg $M_{CHP_1^+}^e$ 240 240 240 0	grid B $M^e_{CHP_1^-}$ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 133.6 31.2 0 240 240 240 240 240 64	M ^h _{CHP1} 300 213.7 300 25 0	M ^h _{CHP} 0 300 300 300 300 300 300 300 300 300 300 300	M ^h _{HOB_i} 101 62 0	M ^h _{SEND1} 103 80 35 101 0 20 218 141 106 138 145 0 0 145 0 0 141 106 138 145 0	M ^h _{REC1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 6 154 114 0	M ^h _{WAS1} 0 0
T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 9 20 21 22 23 24	M ^e _{LOAD_I} 192 187 402 330 399 372 177 165 143 201 317 299 247 216 603 600 652 436 423 532 651 600 216	M ^h _{LOAD} , 748 732 715 649 490 430 532 722 649 620 617 521 536 550 567 767 719 671 430 456 604 692 619 420	$M_{PV_i}^e$ 0 0 0 0 0 0 0 0 0 0 0 0 0	$M_{SH_{i}}^{\hbar}$ 0 0 0 0 0 0 0 0 0 0 0 0 0	M ^e _{CHP} , 600 360 360 360 360 360 360	M ^h _{CHP} , 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 750 693.8 553.7 583 711 750 450 450 450 450 450	Microg $M_{CHP_1^+}^e$ 240 240 240 0	grid B $M^e_{CHP_1^-}$ 0 240 240 240 240 240 240 240 240	M ^h _{CHP1} 300 213.7 300 25 0	M ^h _{CHP} 0 300 300 300 300	$\begin{array}{c} M^h_{\rm HOB_i} \\ 101 \\ 62 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 113 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ $	M ^h _{SEND_l} 103 80 35 101 0 20 218 141 106 138 145 0 0 138 145 0	M ^h _{REC1} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 114 0 0	M ^h _{WAS_i} 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 187.8 35.8 0

Table 5. Cont.	Table 5. (Cont.
----------------	------------	-------

							Micro	grid C						
Т	$M^{e}_{\mathrm{LOAD}_{l}}$	$M^h_{\mathrm{LOAD}_l}$	$M^{e}_{\mathrm{PV}_{l}}$	$M^h_{\mathrm{SH}_l}$	$M^{e}_{\operatorname{CHP}_{l}}$	$M^h_{\operatorname{CHP}_l}$	$M^{e}_{\mathrm{CHP}^{+}_{l}}$	$M^{e}_{\mathrm{CHP}^{-}_{l}}$	$M^h_{\mathrm{CHP}_l^+}$	$M^h_{\mathrm{CHP}_l^-}$	$M^h_{\mathrm{HOB}_l}$	$M^h_{SEND_l}$	$M^h_{\operatorname{REC}_l}$	$M^h_{WAS_l}$
1	550	870	0	0	700	1050	220	0	330	0	0	180	0	0
2	525	984	0	0	700	1050	220	0	330	0	0	66	0	0
3	575	930	0	0	660	990	180	0	270	0	0	60	0	0
4	472	1080	0	0	700	1050	220	0	330	0	0	0	30	0
5	485	745	0	0	480	720	0	0	0	0	0	0	25	0
6	495	739	0	0	480	720	0	0	0	0	0	0	19	0
7	530	984	0	0	608	912	0	92	0	138	0	0	72	0
8	492	1030	7	0	700	1050	0	0	0	0	0	20	0	0
9	497	1080	10	0	678	1017	0	22	0	33	0	0	63	0
10	467	996	12	0	598.7	898	0	101.3	0	152	0	0	98	0
11	497	1005	16	4	552	828	0	148	0	222	0	0	173	0
12	793	789	25	6	480	720	0	220	0	330	0	0	63	0
13	723	794	28	8	480	720	0	220	0	330	0	0	66	0
14	664	803	24	10	480	720	0	220	0	330	0	0	73	0
15	604	870	20	11	480	720	0	220	0	330	0	0	139	0
16	807	780	13	13	516	774	0	184	0	276	0	7	0	0
17	769	890	4	9	578.7	868	0	121.3	0	182	0	0	13	0
18	601	612	0	5	480	720	0	220	0	330	0	213	100	0
19	558	610	0	0	480	720	0	220	0	330	0	0	0	110
20	719	702	0	0	480	720	0	220	0	330	0	0	0	18
21	533	483	0	0	480	720	0	220	0	330	0	154	0	83
22	729	764	0	0	480	720	0	220	0	330	0	0	44	0
23	769	796	0	0	480	720	0	220	0	330	0	0	76	0
24	604	700	0	0	480	720	0	220	0	330	0	0	0	20

First, Case_1 $\left(\sum_{l=1}^{L} M_{CHP_l}^{h}(t) = \sum_{l=1}^{L} M_{CHP_l}^{h}(t) = 0\right)$ occurs for *Time* = 8. Since all three CHPs already produce their maximum capacities in Step E-2 and there is still a heat energy shortage, this heat energy shortage is supplemented by the heat energy produced from HOB B in Step H. Since the production cost of HOB B is lower than other HOBs, and higher than unit production costs of combined *E* and *H* energy of all CHPs, only HOB B produces 113 kWh heat energy to fulfill the heat energy shortage in Microgrid A and, thus, achieve global heat energy optimization in Step H. The energy shortage in Microgrid A (161 kWh) is supplemented by receiving 141 kWh heat energy from Microgrid B and 20 kWh heat energy from Microgrid C.

Now, Case_2 ($\sum_{l=1}^{L} M_{CHP_l}^{h}(t) > 0$ and $\sum_{l=1}^{L} M_{CHP_l}^{h}(t) = 0$) occurs for *Time* = 1–5. CHP A for *Time* = 1–4 increases its production but the heat energy shortage in Microgrid A is supplemented by other CHPs, while CHP B for *Time* = 5 and CHP C for *Time* = 4 also works similarly to Example-1 in Figure B1. On the other hand, CHP B for *Time* = 1–5 increases its production and its surplus heat energy is sent to other microgrids while CHP C for *Time* = 1–4 also works similarly just like Example-2 in Figure B2.

Finally, Case_3 ($\sum_{l=1}^{L} M_{CHP_l}^{h}$ (t) = 0 and $\sum_{l=1}^{L} M_{CHP_l}^{h}$ (t) > 0) occurs for *Time* = 6, 7, 9–24. CHP C for *Time* = 7, 9–11, 14, 15, 17, 22–23 decreases its production and the heat energy shortage in Microgrid C is supplemented by other CHPs; CHP B for *Time* = 18, 22 also works similarly to Example-3 in Figure B3. Just like Example-4 in Figure B4, all three CHPs for *Time* = 24 reduce their production and, yet, have heat energy wasted. Similarly, CHP B for *Time* = 12, 13, 19, and CHP C for *Time* = 19–21 also waste heat energy even after reducing energy production of the CHP. For *Time* = 12 and 13, CHP A produces its maximum energy since its unit production cost of combined *E* and *H* energy is lower than the selling price of electric energy; CHP B produces the amount of energy just enough not to buy or sell any electric energy since its unit production cost of combined *E* and *H* energy is between the buying and selling prices of electric energy; and CHP C produces its minimum energy since its unit production cost of combined *E* and *H* energy is between the sum and selling prices of electric energy; and CHP C produces its minimum energy since its unit production cost of combined *E* and *H* energy is between the simulation results for *Time* = 12 and 13: the total decreased amount of electric energy in Step H is the same as the total selling amount of electric energy after global electric optimization in Step E-2.

6. Conclusions

In this paper, we considered heat energy in addition to electric energy for a cooperative multi-microgrid community and studied an optimal energy management problem with sequentially-coordinated operations to satisfy electric loads, as well as heat loads. The sequentially-coordinated operation for heat energy in this paper is following the sequentially-coordinated operations for electric energy in [9] and, thus, is a heat energy extension of [9]. First, we modeled this sequentially-coordinated operation for heat energy mathematically and presented how to obtain the global heat energy optimization solution in the cooperative multi-microgrid community. The global heat energy optimization is achieved for the cooperative community by adjusting the combined electric and heat energy production amounts of CHP generators and the heat energy production amount of HOBs; these adjusted energy production amounts satisfy all heat loads in the multi-microgrids, as well as optimize the external electric energy trading in order to minimize the unnecessary cost from the external electric trading and/or maximize the profit from the external electric trading.

As a further study, we are now considering electric heaters in this cooperative multi-microgrid community with sequentially-coordinated operations to investigate external heat trading through electric heaters, which are running by electric energy form the main grid. Its interesting result, as an extension of this paper, will be published in the near future.

Acknowledgments: This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20141020402350)

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.

Appendix A Linearization of the Adjusted Cost Function in Step H

The adjusted Equation (18) of Step H is as follows:

$$C_{\text{Heat}}^{\text{Adj}}\left(P_{\text{Heat}}^{\text{Adj}}\left(t\right)\right) = \sum_{l=1}^{L} \left\{\sum_{j=1}^{J} \left(C_{\text{HOB}_{l,j}}^{h}\left(t\right) \times M_{\text{HOB}_{l,j}}^{h}\left(t\right)\right)\right\} \\ + C_{\text{CHP}^{+}}^{\text{Adj}}\left(\sum_{l=1}^{L} M_{\text{CHP}_{l}^{+}}^{h}\left(t\right)\right) - C_{\text{CHP}^{+}}^{\text{Adj}}\left(\sum_{l=1}^{L} M_{\text{CHP}_{l}^{-}}^{h}\left(t\right)\right)$$

since the last two terms in Equation (18) have a min() function as expressed in Equations (19) and (20), CPLEX (IBM ILOG) cannot be utilized directly to find the optimization solution of the adjusted cost function for heat energy extension in Step H.

In Appendix A, the adjusted cost function in Step H will be linearized by removing min() in it depending on the conditions for $\sum_{l=1}^{L} \frac{1}{\eta_{CHP_l}} M^h_{CHP_l^+}(t)$ and $\sum_{l=1}^{L} \frac{1}{\eta_{CHP_l}} M^h_{CHP_l^-}(t)$. This linearization process of the adjusted cost function in Step H enables us to utilize CPLEX and, thus, find the global heat optimization solution.

First, let us consider when CHPs do not change their production amounts in Step H, which implies as follows:

$$\frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}^{+}}^{h}(t) = 0 \text{ and } \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} M_{\text{CHP}_{l}^{-}}^{h}(t) = 0$$

Thus, the adjusted cost function in Step H includes only the total heat production cost of HOBs as follows:

$$\operatorname{Case_1:} C_{\operatorname{Heat}}^{\operatorname{Adj}}\left(P_{\operatorname{Heat}}^{\operatorname{Adj}}\left(t\right)\right) = \sum_{l=1}^{L} \left\{\sum_{j=1}^{J} \left(C_{\operatorname{HOB}_{l,j}}^{h}\left(t\right) \times M_{\operatorname{HOB}_{l,j}}^{h}\left(t\right)\right)\right\}$$
(A1)

Secondly, let us consider when CHPs increase energy production in Step H, which implies as follows:

$$\sum_{l=1}^{L} M_{\text{CHP}_{l}^{+}}^{h}(t) > 0 \text{ and } \sum_{l=1}^{L} M_{\text{CHP}_{l}^{-}}^{h}(t) = 0$$

In this situation, the following two cases have to be considered due to the min() function in Equation (19);

$$\begin{aligned} \text{Case}_{2} - 1: \ 0 < \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} \text{M}_{\text{CHP}_{l}^{+}}^{\text{h}}(t) \leqslant \sum_{l=1}^{L} \text{M}_{\text{BUY}_{l}}^{\text{e}}(t) \\ \text{Case}_{2} - 2: \ \frac{1}{\eta_{\text{CHP}_{l}}} \sum_{l=1}^{L} \text{M}_{\text{CHP}_{l}^{+}}^{\text{h}}(t) > \sum_{l=1}^{L} \text{M}_{\text{BUY}_{l}}^{\text{e}}(t) \end{aligned}$$

Then, the adjusted cost functions in Step H for the above two cases become as follows:

$$\begin{aligned} \text{Case}_{2} - 1 : \ C_{\text{Heat}}^{\text{Adj}} \left(P_{\text{Heat}}^{\text{Adj}} \left(t \right) \right) &= \ \sum_{l=1}^{L} \left\{ \sum_{j=1}^{J} \left(C_{\text{HOB}_{l,j}}^{h} \left(t \right) \times M_{\text{HOB}_{l,j}}^{h} \left(t \right) \right) \right\} \\ &+ \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{\text{CHP}_{l}}} C_{\text{CHP}_{l}}^{e} \left(t \right) + C_{\text{CHP}_{l}}^{h} \left(t \right) \right) \times M_{\text{CHP}_{l}^{+}}^{h} \left(t \right) \right) - \ C_{\text{BUY}}^{e} \left(t \right) \times \sum_{l=1}^{L} \frac{1}{\eta_{\text{CHP}_{l}}} M_{\text{CHP}_{l}^{+}}^{h} \left(t \right) \end{aligned}$$

$$\begin{aligned} \text{Case}_{2} - 2 : \ C_{\text{Heat}}^{\text{Adj}} \left(P_{\text{Heat}}^{\text{Adj}} \left(t \right) \right) &= \ \sum_{l=1}^{L} \left\{ \sum_{j=1}^{J} \left(C_{\text{HOB}_{l,j}}^{h} \left(t \right) \times M_{\text{HOB}_{l,j}}^{h} \left(t \right) \right) \right\} \\ &+ \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{\text{CHP}_{l}}} C_{\text{CHP}_{l}}^{e} \left(t \right) + C_{\text{CHP}_{l}}^{h} \left(t \right) \right) \times M_{\text{CHP}_{l}^{+}}^{h} \left(t \right) \right) \\ &- C_{\text{SELL}}^{e} \left(t \right) \left(\sum_{l=1}^{L} \frac{1}{\eta_{\text{CHP}_{l}}} M_{\text{CHP}_{l}^{+}}^{h} \left(t \right) - \sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e} \left(t \right) \right) - \ C_{\text{BUY}}^{e} \left(t \right) \times \sum_{l=1}^{L} M_{\text{BUY}_{l}}^{e} \left(t \right) \end{aligned}$$

$$\end{aligned}$$

Finally, let us consider the situation when CHPs decrease energy production in Step H, which implies as follows:

$$\sum_{l=1}^{L} M_{\text{CHP}_{l}^{+}}^{h}(t) = 0 \text{ and } \sum_{l=1}^{L} M_{\text{CHP}_{l}^{-}}^{h}(t) > 0$$

In this situation, there are following two cases due to the min() function in Equation (20);

$$Case_{3} - 1: \ 0 < \frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}}^{h}(t) \le \sum_{l=1}^{L} M_{SELL_{l}}^{e}(t)$$
$$Case_{3} - 2: \ \frac{1}{\eta_{CHP_{l}}} \sum_{l=1}^{L} M_{CHP_{l}}^{h}(t) > \sum_{l=1}^{L} M_{SELL_{l}}^{e}(t)$$

Then, the adjusted cost functions in Step H for the above two cases become as follows:

$$\begin{aligned} \text{Case}_{3} - 1 : \ C_{\text{Heat}}^{\text{Adj}} \left(P_{\text{Heat}}^{\text{Adj}}(t) \right) &= \ \sum_{l=1}^{L} \left\{ \sum_{j=1}^{J} \left(C_{\text{HOB}_{l,j}}^{h}(t) \times M_{\text{HOB}_{l,j}}^{h}(t) \right) \right\} \\ &- \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{\text{CHP}_{l}}} C_{\text{CHP}_{l}}^{e}(t) + C_{\text{CHP}_{l}}^{h}(t) \right) \times M_{\text{CHP}_{l}}^{h}(t) \right) + \ C_{\text{SELL}}^{e}(t) \times \sum_{l=1}^{L} \frac{1}{\eta_{\text{CHP}_{l}}} M_{\text{CHP}_{l}}^{h}(t) \\ \text{Case}_{3} - 2 : \ C_{\text{Heat}}^{\text{Adj}} \left(P_{\text{Heat}}^{\text{Adj}}(t) \right) &= \ \sum_{l=1}^{L} \left\{ \sum_{j=1}^{J} \left(C_{\text{HOB}_{l,j}}^{h}(t) \times (t) \right) \right\} \\ &- \sum_{l=1}^{L} \left(\left(\frac{1}{\eta_{\text{CHP}_{l}}} C_{\text{CHP}_{l}}^{e}(t) + C_{\text{CHP}_{l}}^{h}(t) \right) \times M_{\text{CHP}_{l}}^{h}(t) \right) \\ &+ C_{\text{BUY}}^{e}(t) \left(\sum_{l=1}^{L} \frac{1}{\eta_{\text{CHP}_{l}}} M_{\text{CHP}_{l}}^{h}(t) - \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) \right) + \ C_{\text{SELL}}^{e}(t) \times \sum_{l=1}^{L} M_{\text{SELL}_{l}}^{e}(t) \end{aligned}$$
(A4)

Appendix B Illustrated Interpretation of Optimization Operation for Heat Energy

For Case_2-1, the increased production amount of electric energy in Step H $(\frac{1}{\eta_{CHP_l}} \sum_{l=1}^{L} M_{CHP_l^+}^h(t))$ cuts off the electric energy purchase in Step E-2 if there is electric energy purchase $(\sum_{l=1}^{L} M_{BUY_l}^e(t) > 0)$ due to an electric energy shortage. In such a case, it will be sold to the main grid $(\sum_{l=1}^{L} \frac{1}{\eta_{CHP_l}} M_{CHP_l^+}^h(t) - \sum_{l=1}^{L} M_{BUY_l}^e(t))$.

On the other hand, the heat energy shortage in a microgrid is supplemented, first, by the increased heat energy of its CHP generator, and then by the received heat energy from other microgrids with

surplus heat energy, as in Figure B1. However, even when there is a heat energy surplus in a microgrid, the microgrid can increase its CHP production and sends its surplus heat energy to other microgrids as in Figure B2.



Figure B1. Example-1 when $\sum_{l=1}^{L} M_{CHP_{l}^{+}}^{h}(t) > 0$.



Figure B2. Example-2 when $\sum_{l=1}^{L} M_{CHP_{+}}^{h}(t) > 0$.

For Case_3-1 and Case_3-2, the decreased production amount $\left(\frac{1}{\eta_{CHP_l}}\sum_{l=1}^{L}M_{CHP_l}^{h}(t)\right)$ of electric energy in Step H first cuts off the electric energy selling in Step E-2 if $\sum_{l=1}^{L}M_{SELL_l}^{e}(t) > 0$ and then can be supplemented by new electric energy purchase $\left(\sum_{l=1}^{L}\frac{1}{\eta_{CHP_l}}M_{CHP_l}^{h}(t) - \sum_{l=1}^{L}M_{SELL_l}^{e}(t)\right)$.

On the other hand, the heat energy shortage in a microgrid is supplemented by the received heat energy from other microgrids with surplus heat energy, as in Figure B3. However, the surplus heat energy can be wasted even after internal heat trading, as in Figure B4. Such heat wasting can happen when the buying price of electric energy is higher than the unit combined *E* and *H* production price of a CHP, since producing electric and heat energy by the CHP would save money instead of buying electric energy even though the produced heat is wasted. Furthermore, when the selling price of electric energy is higher than the unit combined *E* and *H* production price of a CHP, the CHP has to produce its maximum electric and heat energy since selling electric energy produced by the CHP is profitable even after the produced heat energy is wasted.



Figure B3. Example-3 when $\sum_{l=1}^{L} M_{\text{CHP}_{l}}^{h}(t) > 0$.



Figure B4. Example-4 when $\sum_{l=1}^{L} M_{CHP_{l}}^{h}(t) > 0$.

References

- 1. Marnay, C.; Bailey, O. The CERTS microgrid and the future of the macrogrid. In Proceedings of the 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 22–27 August 2004.
- 2. Wood, E. The Importance of Heat in the Energy Efficient Microgrid. Available online: http://www. microgridknowledge.com/importance-heat-energy-efficient-microgrid/ (accessed on 23 January 2016).
- 3. Kim, H.-M.; Kinoshita, T.; Shin, M.-C. A multiagent system for autonomous operation of islanded microgrids based on a power market environment. *Energies* **2010**, *3*, 1972–1990. [CrossRef]
- 4. Lim, Y.; Kim, H.-M.; Kinoshita, T. Distributed load-shedding system for agent-based autonomous microgrid operations. *Energies* **2014**, *7*, 385–401. [CrossRef]
- 5. Kim, H.-M.; Lim, Y.; Kinoshita, T. An intelligent multiagent system for autonomous microgrid operation. *Energies* **2012**, *5*, 3347–3362. [CrossRef]
- 6. Yoo, C.-H.; Chung, I.-Y.; Lee, H.-J.; Hong, S.-S. Intelligent control of battery energy storage for multi-agent based microgrid energy management. *Energies* **2013**, *6*, 4956–4979. [CrossRef]
- 7. Kuo, M.-T.; Lu, S.-D. Design and implementation of real-time intelligent control and structure based on multi-agent systems in microgrids. *Energies* **2013**, *6*, 6045–6059. [CrossRef]
- Vasiljevska, J.; Peças Lopes, J.A.; Matos, M.A. Multi-microgrid impact assessment using multi criteria decision aid methods. In Proceedings of the IEEE Bucharest 2009 PowerTech, Bucharest, Romania, 28 June–2 July 2009; pp. 1–8.
- 9. Song, N.-O.; Lee, J.-H.; Kim, H.-M.; Im, Y.-H.; Lee, J.-Y. Optimal energy management of multi-microgrids with sequentially coordinated operations. *Energies* **2015**, *8*, 8371–8390. [CrossRef]

- Nguyen, T.A.; Mariesa, L.C. Optimization in energy and power management for renewable-diesel microgrids using dynamic programming algorithm. In Proceedings of the 2012 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), Bangkok, Thailand, 27–31 May 2012; pp. 11–16.
- 11. Khodaei, A. Resiliency-oriented microgrid optimal scheduling. *IEEE Trans. Smart Grid* 2014, *5*, 1584–1591. [CrossRef]
- 12. Chakraborty, S.; Simoes, M.G. PV-microgrid operational cost minimization by neural forecasting and heuristic optimization. In Proceedings of the 2008 IEEE Industry Applications Society Annual Meeting (IAS), Edmonton, AB, Canada, 5–9 October 2008; pp. 1–8.
- 13. Chen, S.; Shroff, N.B.; Sinha, P. Energy trading in the smart grid: From end-user's perspective. In Proceedings of the 2013 Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 3–6 November 2013; pp. 327–331.
- 14. Igualada, L.; Corchero, C.; Cruz-Zambrano, M.; Heredia, F.-J. Optimal energy management for a residential microgrid including a vehicle-to-grid system. *IEEE Trans. Smart Grid* **2014**, *5*, 2163–2172. [CrossRef]
- Chen, C.; Duan, S.; Cai, T.; Liu, B.; Yin, J. Energy trading model for optimal microgrid scheduling based on genetic algorithm. In Proceedings of the IEEE International Power Electronics and Motion Control 2009, Wuhan, China, 17–20 May 2009.
- 16. Zhao, B.; Shi, Y.; Dong, X.; Laun, W.; Bornemann, J. Short-term operation scheduling in renewable-powered microgrids: A duality-based approach. *IEEE Trans. Sustain. Energy* **2014**, *5*, 209–217. [CrossRef]
- 17. Ou, X.; Shen, Y.; Zeng, Z.; Zhang, G.; Wang, L. Cost minimization online energy management for microgrids with power and thermal storages. In Proceedings of the 24th International Conference on Computer Communication and Networks (ICCCN) 2015, Las Vegas, NV, USA, 3–6 August 2015.
- 18. Bagherial, A.; Tafreshi, S.M.M. A developed energy management system for a microgrid in the competitive electricity market. In Proceedings of the IEEE PowerTech 2009, Bucharest, Romania, 28 June–2 July 2009.
- 19. Nguyen, H.T.; Le, L.B. Optimal energy management for building microgrid with constrained renewable energy utilization. In Proceedings of the IEEE International Conference on Smart Grid Communications 2014, Venice, Italy, 3–6 November 2014.
- 20. Chen, Y.-H.; Chen, Y.-H.; Hu, M.-C. Optimal energy management of microgrid systems in Taiwan. In Proceedings of the 2011 IEEE PES Innovative Smart Grid Technologies (ISGT), Hilton Anaheim, CA, USA, 17–19 January 2011; pp. 1–9.
- 21. Kriett, P.O.; Salani, M. Optimal control of a residential microgrid. Energy 2012, 42, 321-330. [CrossRef]
- 22. Rahbar, K.; Chai, C.C.; Zhang, R. Real-time energy management for cooperative microgrids with renewable energy integration. In Proceedings of the IEEE International Conference on Smart Grid Communications 2014, Venice, Italy, 3–6 November 2014.
- 23. Nguyen, D.T.; Le, L.B. Optimal energy management for cooperative microgrids with renewable energy resources. In Proceedings of the 2013 IEEE International Conference on Smart Grid Communications, Vancouver, BC, Canada, 21–24 October 2013; pp. 678–683.



© 2016 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (http://creativecommons.org/licenses/by/4.0/).