Cooperative energy management of multi-energy hub systems considering demand response programs and ice storage

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Abstract

Energy hub systems integrate various energy sources and interconnect different energy carriers in order to enhance the flexibility of the system. In this paper, a cooperative framework is proposed in which a network of energy hubs collaborate together and share their resources in order to reduce their costs. Each hub has several sources including CHP, boiler, renewable sources, electrical chiller, and absorption chiller. Moreover, energy storages are considered for electrical, heating, and cooling systems in order to increase the flexibility of energy hubs. Unlike the methods based on Nash-equilibrium points, which find the equilibrium point and have no guarantee for optimality of the solution, the employed cooperative method finds the optimal solution for the problem. We utilize the Shapley value to allocate the overall gain of the hub's coalition based on the contribution and efficiency of the energy hubs. The proposed method is modeled as a mixed integer linear programming problem, and the cost of network energy hubs are decreased in the cooperative operation, which shows the efficiency of this model. The results show 18.89, 10.23, and 8.72% improvement for hub1, hub2, and hub3, respectively, by using the fair revenue mechanism.

Keywords: Integrated energy hubs, Demand response, Cooperative methods, Multi-carrier systems, Shapley value.

NOMENCLATURE

Indices		$P_g^{i,max}$	Imported power from upstream network limit
i	Index of energy hub	P_h^{max}	Heat pipe transmission limit
t	Index of time	OM_{CHP}	Maintenance cost coefficient of CHP units
Abbreviations		OM_B	Maintenance cost coefficient of Boilers
CHP	Combined heat and power	MR_{up}^e/MR_{down}^e	Maximum coefficient for up/down of electrical load
Boiler	Heat only boiler	λ_t^G	Natural gas price
AC	Absorption chiller	LHV	Low calorific value of natural gas
EC	Electrical Chiller	$\eta_{CHP}^e/\eta_{CHP}^h$	CHP gas to electricity/heat coefficients
CS	Ice storage	η_B	Boiler gas to coefficient
ES	Electrical storage	$COP_{ec}, COP_{ice}, COP_{ac}$	Performance coefficients of EC, CS, and AC
HS	Heat storage	CO_{curt}	Coefficient of maximum curtailed load
DR	Demand response	PEN_{curt}	Penalty of load curtailment
Parameters		**Variables**	
π_g	Price of purchasing power from the main grid	$P_g^{i,t}$	Purchased power from the upstream network
λ_t^G	Price of purchasing gas from the gas network	$G_{CHP}^{i,t}$	Consumed gas in CHP unit
$E_{es}^{max,i}/E_{es}^{min,i}$	Minimum/maximum capacities of ES	$PE_{CHP}^{i,t}/PH_{CHP}^{i,t}$	Output power/heat from CHP units
$P_{es,c}^{max,i}/P_{es,d}^{max,i}$	Maximum charging/discharging rate of ES	$G_B^{i,t}$	Consumed gas in boiler
$\eta_{es,c}^i/\ \eta_{es,d}^i$	Charging/discharging efficiency of ES	$PH_B^{i,t}$	Output heat from boiler
$E_{hs}^{max,i}/E_{hs}^{min,i}$	Minimum/maximum capacities of HS	$P_{curt}^{e,i,t}$	Curtailed load
$P_{hs,c}^{max,i}/P_{hs,d}^{max,i}$	Maximum charging/discharging rate of HS	$P_{up}^{e,i,t}/P_{down}^{e,i,t}$	Shift up/down of electrical load by DR
$\eta_{hs,c}^i/\eta_{hs,d}^i$	Charging/discharging efficiency of HS	$P_{up}^{h,i,t}/P_{down}^{h,i,t}$	Shift up/down of heat load by DR
$E_{cs}^{max,i}/E_{cs}^{min,i}$	Minimum/maximum capacities of CS	$I_{up}^{e,i,t}/I_{down}^{e,i,t}$	Binary variable for shift up/down of electrical load by DR
$P_{cs,c}^{max,i}/P_{cs,d}^{max,i}$	Maximum charging/discharging rate of CS	$I_{up}^{h,i,t}/I_{down}^{h,i,t}$	Binary variable for shift up/down of heat load by DR
$\eta_{cs,c}^i/\eta_{cs,d}^i$	Charging/discharging efficiency of CS	$E_{es}^{i,t}, E_{hs}^{i,t}, E_{cs}^{i,t}$	Stored power in ES,HS,CS
δ_{cs}^i	Energy loss constant of CS	$P_{es,c}^{i,t}/P_{es,d}^{i,t}$	Power charging/discharging rate of ES
$G_{CHP}^{max,i}$	Maximum purchasable natural gas of CHP units	$P_{hs,c}^{i,t}/P_{hs,d}^{i,t}$	Heat charging/discharging rate of HS
$G_B^{max,i}$	Maximum purchasable natural gas of Boiler	$P_{cs,c}^{i,t}/P_{cs,d}^{i,t}$	Cooling charging/discharging rate of CS
$PH_{ac}^{max,i}$	Maximum heat input of AC	$k_c^{e,i,t}/k_d^{e,i,t}$	Binary variable for ES charging/discharging constraint
$P_{icc}^{max,i}/P_{ec}^{max,i}$	Maximum electricity input of CS/ES	$k_c^{h,i,t}/k_d^{h,i,t}$	Binary variable for HS charging/discharging constraint
$P^{el,i,t}$	Electrical load	$k_c^{cs,i,t}/k_d^{cs,i,t}$	Binary variable for CS charging/discharging constraint
$P^{hl,i,t}$	Heat load	$P_{ice}^{i}{}^{i,t}/P_{ec}^{i,t}$	Input power of CS/EC
$CL^{i,t}$	Cooling load	$PH_{ac}^{i,t}$	Input heat of AC
$P_{pv}^{i,t}$	Generated power from Photovoltaic	$C_{ec}^{i,t}, C_{ac}^{i,t}, P_{cs,d}^{i,t}$	Cooling output from EC, AC, and CS
$p_{wt}^{i,t}$	Generated power from wind turbines		

I. INTRODUCTION

Today, energy consumption is increasing rapidly around the world, which encourages researchers to find novel ways to solve this issue. There are various energy sources to supply energy for the consumption sector such as electricity, gas, and renewable energy sources (RES). In recent years, electricity and gas are employed simultaneously in scheduling and operating energy systems which are investigated as multi-carrier energy systems. Using gas and electricity for energy optimization enhances the reliability and efficiency of the system, since they can increase the flexibility of the system in both the normal and critical conditions. One of the frameworks that are used to integrated energy management in multi-carrier energy systems is the energy hub. Energy hub consists of different energy sources and demands such as electrical, heating, and cooling, which are interconnected by several units. Energy hubs have various units, namely power generation, RES, and storage units, which cooperate to serve the demands and achieve the optimal operation scheduling [1]. Nowadays, energy hubs are investigated vastly and are modeled for distinct systems such as residential, commercial, and industrial sector.

By interconnecting energy hubs, the concept of networked energy hubs (NEH) is formed, from which the system gains many benefits. In this context, NEH includes several energy hubs that increase the flexibility of the system significantly by having access to different units and sources [2]. Moreover, NEH can use the strength of each hub to overcome the weakness of other hubs, resulting in more appropriate energy management in the system. Also, NEH employs local energy sources more effectively, enhancing the reliability of the system and reducing the required power from the main grid. Therefore, NEH not only provides the whole system considerable benefits but also improves the performance of each energy hub individually.

In order to increase flexibility, energy storage systems play a crucial role in the system. These facilities store the energy so that the overall performance of the system enhances. For instance, the electrical storage saves energy at low price intervals and discharge it in peak hours [3]. A stochastic day-ahead bidding strategy for energy hub is proposed in [4], considering the presence of various energy storages including battery energy storage, heating storage, and ice storage while neglecting the cooperation of various hubs and demand response programs. A networked energy hub system is proposed in [5], which aims to maximize the profit of the system by using the alternating direction method of multipliers (ADMM) method. However, the demand response programs and cooling system modeling are not considered. In [6], a cooperative framework is proposed in the multi-energy systems that integrate the renewable energy resources and energy storage systems in the energy hubs. However, the impacts of ice storage systems and the electrical and thermal demand response programs were not studied. The operation scheduling of energy hub is considered in [7] and uncertainty of the inputs and various storage systems such as electrical, heat, and ice storage are taken into account. However, the cooperation of different energy hubs and heat demand response are not investigated.

The authors in [8] presented a stochastic model for a multi-carrier energy hub in which the demand response program, electricity market, and thermal energy market are taken into account. In contrast, the network of energy hubs and cooling system are not considered. In [9], optimal day-ahead scheduling of an active distribution system including multiple energy hubs is investigated wherein the transacted energy between the participants is calculated using their bids and offers. However, the fair cost allocation for participants and maintenance cost are ignored. Economic optimization of a multi-carrier system using the coupling matrix and virtual nodes insertion is proposed in [10]. Although this study considers several energy sources for energy carriers and the effect of demand response programs is taken into account, the cooling system and the cooperation of different energy hubs in a fair condition are not studied. In [11], multi-carrier networked microgrids are investigated which can exchange energy with each other, but the fair cost allocation and demand response programs are not discussed.

From the cooperation perspective, networked systems are separated into cooperative and non-cooperative systems. In the cooperative methods, the objective is to find the Pareto optimal solution of the problem, but finding the equilibrium point is the objective in the non-cooperative models. The authors in [12] proposed a cooperative model including power to gas (P2G) devices for integrated power and gas networks and considered the demand smoothness and cost reduction in the network. Nevertheless, the effect of cooling system, demand response program, and fair allocation of costs are not investigated. A multi-objective model is proposed in [13] to optimize cost savings and carbon emissions in NEH using ε - constraint technique and max-min fuzzy decision making. This paper considers the cooperation of energy hubs while neglecting the fair cost allocation and cooling system. In [14], a congestion game is modeled, guaranteeing the existence of the Nash equilibrium. However, demand response and cooling system are not modeled in this paper. An optimal planning framework is presented in [15], which explores the effect of allocation and sizing of the hubs in optimal design of networked energy hubs.

The authors in [16] and [17] proposed a non-cooperative game in which gas and electricity demand response are employed in order to maximize the profit of the utility companies. However, the fair cost-sharing and the cooling system are ignored in this study. An exact potential game is proposed in [18] to design an online distribution algorithm and explore the existence of the Nash equilibrium while ignoring the demand response programs and heat energy storage. A non-cooperative framework is presented in [19] for networked energy hubs in which the interaction among energy hubs is studied. However, the fair cost allocation and cooling system are not taken into account. Li et al. [20] proposed a decentralized optimization framework for the energy scheduling of multiple energy hubs. The proposed model integrates the electric distribution and natural gas systems to improve the performance of multi-carrier systems. Although the role of electrical and gas storage systems had been studied, the impact of the ice storage system was ignored. However, the impact of the electrical and thermal DR programs on the operation scheduling of the energy hubs was not investigated. Authors in [21, 22] suggest the bi-level game theory to model the energy scheduling of the energy hubs. The impact of energy storage systems on the market mechanism was investigated in [21]. Although the uncertainty of demand loads had been applied to the model, the role of the DR programs and ice storage on the control of uncertainty was not studied. In [22], the interaction among distribution company and energy hubs had been formulated as the leader multi-follower optimization. At the upper-level, the distribution company tries to minimize its total cost, while the cost of the energy hubs had been considered at the lower-levels. Although the impacts of the renewable resources on the operation of energy hubs had been investigated, the role of storage systems and demand response programs were not studied. Also, the cooperation among the energy hubs at the lower-level was not investigated.

In the non-cooperative games, the Nash equilibrium points (NEPs) are the solution to the problem. The NEPs provide stable solutions, while there is no guarantee of optimality. In other words, in the NEPs, no player has anything to gain by changing only his own strategy. If the optimization problem has a better unstable solution, it cannot be chosen by the non-cooperative games. The bi-level approaches are non-cooperative games (Stackelberg games) that find the NEPs by iteration. Therefore, they cannot ensure the best plan from an economic point of view. Also, in the non-cooperative games, each actor only considers its objectives. Unlike non-cooperative games, the total cost/profit of the system had been optimized in the cooperative games. The cooperative games focus on the predicting that forming coalitions will form, the joint actions that players take and the resulting collective payoffs. When energy hubs cooperate, they can share their electrical, thermal, and cooling resources. Compared to the non-cooperative games, cooperation enhances the flexibility of the system because the energy hubs can use the surplus capacity of the other resources. Therefore, the cooperative games ensure the optimal solution for the system. Also, the emission of greenhouse gasses and power losses in the cooperative model is less than the non-cooperative model.

According to the above, we propose a cooperative framework for the energy scheduling of multiple energy hubs, which considers fair energy sharing between energy hubs by using Shapley value. Furthermore, energy hubs contain electrical, heating, and cooling load, and they can employ both the electrical and heating demand response programs. In this regard, a Mixed Integer Linear Programming (MILP) model is used in order to achieve the global optimum solution for the problem. Various energy sources and generation units such as PV, WT, CHP, heat only boiler, electrical chiller, and absorption chiller are also employed. In the proposed model, the energy hubs form a coalition and share their resources to optimize the cost of the system. The overall gain of the coalition should be divided among the hubs trough a fair mechanism. We utilize the Shapley value and consider the contribution of each energy hub for cost minimization to allocate the benefit of coalition among each hub. A summary of the recently published paper on the energy hubs is provided in Table 1.

Table 1. *Summary of literature in energy hub systems*

Ref.	Proposed model	Pros	Cons
[7]	• Stochastic optimization	• The role of ice storage has been studied • The impact of the electrical demand response program was investigated • A comprehensive structure of energy hub consists of heating, and cooling system is introduced	• The connection among energy hubs was not investigated • The role of thermal DR programs has not studied
[13]	• Cooperative approach	• The energy scheduling of the multi-energy hubs had been studied • The role of electrical and thermal DR programs was deliberated	• The fair cost allocation was not investigated • The cooling system was not considered • The impact of ice storage was not studied
[15]	• Cooperative approach	• The role of electrical and heat storage systems was studied • The absorption chiller was considered in the hub structure • The optimal planning of the multi-energy hubs had been studied	• The impact of ice storage was not studied • The effect of renewable resources was not investigated • The electrical and thermal DR programs were not considered • The fair cost allocation for the cooperator energy hubs was not investigated
[18]	• Non-cooperative approach	• The energy scheduling of multiple energy systems had been modeled • The uncertain nature of market prices and demand loads had been applied to the model	• The electric chiller and absorption chiller were not considered • The impacts of renewable resources were ignored • The efficiency of the thermal and ice storage systems had not been studied
[20]	• Non-cooperative approach	• Considering the electrical and natural gas networks for the optimal energy scheduling of integrated energy hub • The role of electrical and heat storage was investigated	• The role of ice storage was not deliberated • The cooling systems were not applied to the proposed structure • The cooperation among energy hubs was not studied
[21]	• Non-cooperative approach	• The impact of the energy storage systems had been investigated • The natural gas network had been modeled • The interaction among the distribution company and energy hubs had been modeled as the bi-level optimization framework	• The role of electrical and thermal DR programs was not studied • The cooling systems were not integrated into the hub structure • The performance of ice storage was not deliberated • The cooperation and fair cost-allocation among energy hubs had not studied
[22]	• Non-cooperative approach	• The role of static VAR compensator had been studied • The renewable resources had been considered	• The energy storage systems were not considered • The impacts of electrical and thermal DR programs were not investigated • The cooperation among energy hubs at the lower-level of optimization had not been studied
[23]	• Deterministic optimization	• The renewable energy resources had been integrated to the energy management of the energy hub • The role of the electrical, thermal, and cooling storage systems was considered	• The connection among energy hubs was not studied • The effects of thermal DR programs were ignored • The uncertainty of demand loads, market prices, and renewable resources had been ignored
[24]	• Probabilistic optimization	• The efficiency of the cooling storage had been investigated • The electrical DR program was considered	• The energy scheduling of a single energy hub is investigated • The role of thermal DR had been ignored

		• The absorption chiller and electric chiller had been applied to the model	• The natural gas network was not considered
This paper	• Cooperative approach	• Presenting a comprehensive structure of the energy hub considering cooling systems such as absorption and electric chiller, and ice storage • Modeling of the interconnected energy hubs by the cooperative approach • The impacts of electrical and thermal DR programs had been investigated • The overall gain of the coalition has been divided as a fair solution	• The natural gas network will be studied in future work

The main advantage of the proposed model is that it guarantees the optimal solution for the system and can be easily used for multi-owner systems.

The main contributions of this paper are summarized as follows:

- We model the interaction among multi-carrier microgrids as a comprehensive energy hub that considers various electrical, heating, and cooling resources. Unlike [11], [15], [18], [19] and [25], we integrate the ice storage into the energy hub to improve the performance of the energy hubs.
- Presenting a cooperative model to ensure the best plan for the operation of multi-energy hubs. Unlike [7], [18], [19], [25], and [26] in the proposed model, the energy hubs are able to share their resources to use the surplus capacity of other hubs as the back-up. Therefore, the amount of shortage of power will be decreased which enhances the social welfare of the customers.
- The overall gain of the coalition is divided among cooperator energy hubs based on their contribution, efficiency, and bargaining power. Unlike, [7], [11], [13], [18], [19], and [25-29], the proposed model proposes a rational and fair solution to allocate the profit of the coalition among the energy hubs. Therefore, this comprehensive structure can be applied for multi-owner systems, where each operator tries to increase their efficiency.
- The proposed scheme enhances the flexibility of the studied system because the energy hubs can utilize the dispatchable resources of other hubs with different ramp-rates.

The rest of this paper is organized as follows: The mathematical formulation of the model is presented in section II. Section III describes the cooperative strategy and cost allocation of the proposed model. Simulation and results are presented in section IV. Finally, the conclusion is provided in section V.

II. MATHEMATICAL FORMULATION OF THE MODEL

Several energy sources including WT, PV, CHP, boiler, electrical chiller, absorption chiller in addition to DR programs and energy storage systems are employed in this paper. Each energy hub can import natural gas and electricity from the main grid. The energy hub model is illustrated in Fig.1.

The objective function and constraints of the problem are as follow:

1. Objective Function

The objective function of the presented model is the cost minimization of energy hubs as follows:

$$min\left\{\sum_{t}\left(\sum_{i} P_g^{i,t}\pi_g^t + G_{CHP}^{i,t}\lambda_t^G + (PE_{CHP}^{i,t} + PH_{CHP}^{i,t})OM_{CHP} + G_B^{i,t}\lambda_t^G + PH_B^{i,t}OM_B + P_{curt}^{e,i,t}PEN_{curt}\right)\right\} \quad (1)$$

In the objective function, the cost of imported electricity from the power grid, consumed natural gas for CHP units, operation and maintenance of the CHP units, consumed natural gas for boilers, operation as well as maintenance cost of the boilers, and the penalty for the curtailed load are included, respectively.

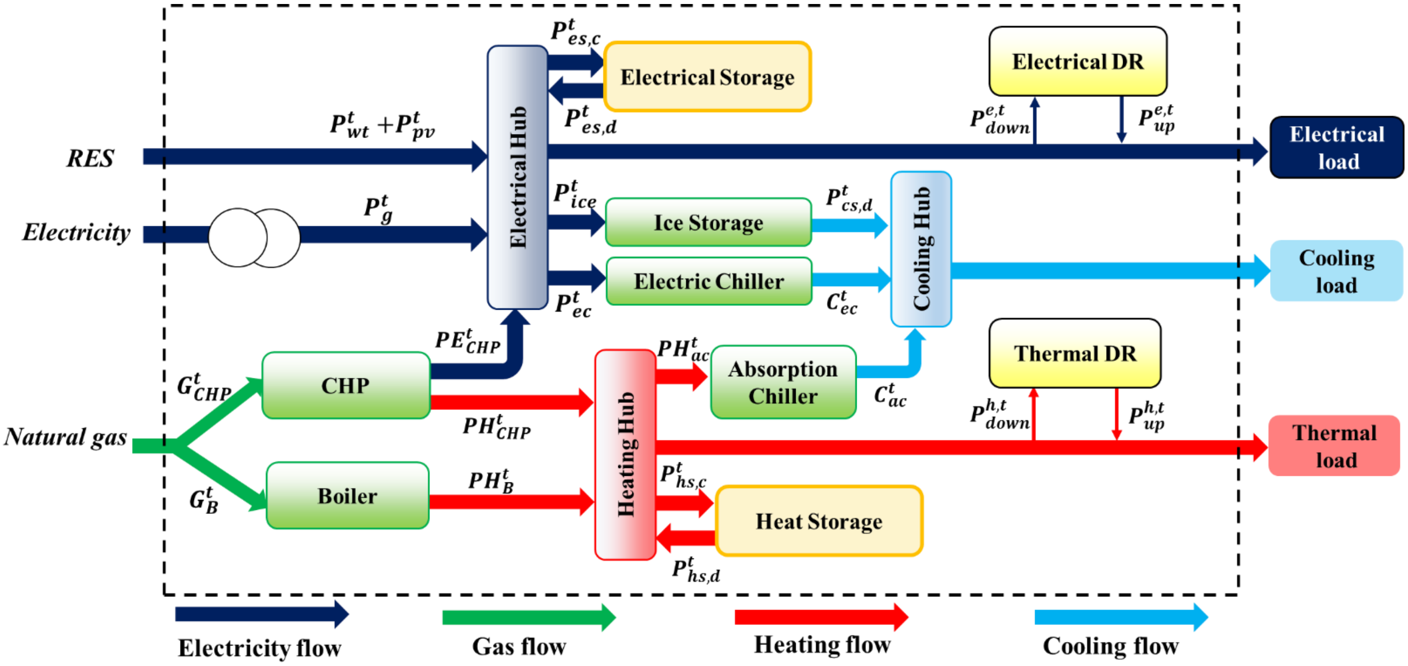

Fig. 1. *The architecture of energy hubs*

2. Constraints of the DR programs

In the DR programs, the loads are shifted or curtailed to decrease the costs. In the price-based DR programs, consumers shift their loads from peak hours so as to decrease their dependency on the power grid to buy energy. Also, consumers can use incentive-based demand response programs which curtails the loads in peak hours.

In this paper, price-based and incentive-based demand response programs are employed for electrical and thermal loads. The formulation of electrical DR is presented as follows:

$$\sum_t P_{up}^{e,i,t} = \sum_t P_{down}^{e,i,t} \qquad \forall\, i \tag{2}$$

$$0 \le P_{up}^{e,i,t} \le MR_{up}^{e} P^{el,i,t} I_{up}^{e,i,t} \qquad \forall\, i,t \tag{3}$$

$$0 \le P_{down}^{e,i,t} \le MR_{down}^{e} P^{el,i,t} I_{down}^{e,i,t} \qquad \forall\, i,t \tag{4}$$

$$0 \le I_{up}^{e,i,t} + I_{down}^{e,i,t} \le 1 \qquad \forall\, i,t \tag{5}$$

Eqs. (2)-(5) represent the price-based DR program, in which the total decreases in loads in the operation interval is equal to the total increased load. Eqs. (3) and (4) demonstrate the maximum allowed load shifting, and Eq. (5) prevents a simultaneous change in load. Similarly, Eq. (6) is used for modeling the load curtailment, which imposes a penalty to the energy hub.

$$0 \le P_{curt}^{i,t} \le P^{el,i,t} CO_{curt} \quad \forall\, i,t \tag{6}$$

In addition to electrical DR, heat DR is also used in this paper as follows:

$$\sum_t P_{up}^{h,i,t} = \sum_t P_{down}^{h,i,t} \qquad \forall\, i \tag{7}$$

$$0 \le P_{up}^{h,i,t} \le MR_{up}^{h} P^{hl,i,t} I_{up}^{h,i,t} \qquad \forall\, i,t \tag{8}$$

$$0 \le P_{down}^{h,i,t} \le MR_{down}^{h} P^{hl,i,t} I_{down}^{h,i,t} \qquad \forall\, i,t \tag{9}$$

$$0 \le I_{up}^{h,i,t} + I_{down}^{h,i,t} \le 1 \qquad \forall\, i,t \tag{10}$$

Eq. (7) represents the equality of decrement and growth in the price-based DR program for heat load. Eqs. (8)-(9) show the highest quantities for heat load shifting, and the Eq. (10) is employed for simultaneous load shifting prevention.

3. Energy storage systems

Energy storages effectively enhance the performance of the system by storing the energy in the low load hours and discharging it when required. In this paper, the storage is used for electrical, heat, and cooling systems, which will be discussed more precisely. The following relations illustrate the operation of the electrical energy storage system:

$$E_{es}^{i,t+1} = E_{es}^{i,t} + P_{es,c}^{i,t}\eta_{es,c} - \frac{P_{es,d}^{i,t}}{\eta_{es,d}} \qquad \forall\, i,t \tag{11}$$

$$E_{es}^{min,i} \le E_{es}^{i,t} \le E_{es}^{max,i} \qquad \forall\, i,t \tag{12}$$

$$0 \le P_{es,c}^{i,t} \le P_{es,c}^{max} k_c^{e,i,t} \quad \forall\, i,t \tag{13}$$

$$0 \le P_{es,d}^{i,t} \le P_{es,d}^{max} k_d^{e,i,t} \quad \forall\, i,t \tag{14}$$

$$0 \le k_c^{e,i,t} + k_d^{e,i,t} \le 1 \quad \forall\, i,t \tag{15}$$

$$E_{es}^{i,0} = E_{es}^{i,24} \quad \forall\, i \tag{16}$$

The electrical energy balance for the energy storage system is described in the Eq. (11). Eqs. (12) - (14) restrict the value of $E_{es}^{i,t}$, $P_{es,c}^{i,t}$, and $P_{es,d}^{i,t}$ because of technical issues. Eq. (15) guarantees that the storage will not be charged and discharged at the same time. As given in the Eq. (16), the stored energy in the first and final hours of operation should be equal. The model for the heat storage system is described as follows:

$$E_{hs}^{i,t+1} = E_{hs}^{i,t} + P_{hs,c}^{i,t}\eta_{hs,c} - \frac{P_{hs,d}^{i,t}}{\eta_{hs,d}} \qquad \forall\, i,t \tag{17}$$

$$E_{hs}^{min,i} \le E_{hs}^{i,t} \le E_{hs}^{max,i} \qquad \forall\, i,t \tag{18}$$

$$0 \le P_{hs,c}^{i,t} \le P_{hs,c}^{max,i} k_c^{h,i,t} \quad \forall\, i,t \tag{19}$$

$$0 \le P_{hs,d}^{i,t} \le P_{hs,d}^{max} k_d^{h,i,t} \quad \forall\, i,t \tag{20}$$

$$0 \le k_c^{h,i,t} + k_d^{h,i,t} \le 1 \quad \forall\, i,t \tag{21}$$

$$E_{hs}^{i,0} = E_{hs}^{i,24} \quad \forall\, i \tag{22}$$

According to Eq. (17), the stored heat depends on the charging rate, discharging rate, and efficiency parameters. The limits of stored energy, charging power, and discharging power are represented in (18) – (20). Eq. (21) is used for prohibiting simultaneous charge and discharge. Eq. (22) is employed to have equal quantity for the accessible heat in the heat storage in the first and the last hour of the operation planning.

Using ice storage systems will have significant impacts on the operation of the cooling system and the costs, since they will be charged when the electricity price is low and discharge when the cooling load in the peak. Ice storage cooling systems use electric power to make ice during the low price hours, and melt the ice when required. They consist of an ice storage tank and an ice storage conditioner. The following relations illustrate the ice storage modeling:

$$E_{cs}^{i,t+1} = E_{cs}^{i,t}(1-\delta_{cs}) + P_{cs,c}^{i,t}\eta_{cs,c} - \frac{P_{cs,d}^{i,t}}{\eta_{cs,d}} \qquad \forall\, i,t \tag{23}$$

$$E_{cs}^{min} \le E_{cs}^{i,t} \le E_{cs}^{max} \qquad \forall\, i,t \tag{24}$$

$$0 \le P_{cs,c}^{i,t} \le P_{cs,c}^{max} k_c^{cs,i,t} \quad \forall\, i,t \tag{25}$$

$$0 \le P_{cs,d}^{i,t} \le P_{cs,d}^{max} k_d^{cs,i,t} \quad \forall\, i,t \tag{26}$$

$$0 \le k_c^{cs,i,t} + k_d^{cs,i,t} \le 1 \quad \forall\, i,t \tag{27}$$

$$E_{cs}^{i,0} = E_{cs}^{i,24} \quad \forall\, i \tag{28}$$

Eq. (23) shows the energy balance for the ice storage system. Eqs. (24) – (26) demonstrate the technical constraints of ice storage. Eq. (27) is imposed to have either charging or discharging mode for the ice storage in each time. Eq. (28) is employed so as to have equal cooling energy stored in the storage in the first and last hour of the operation.

4. Energy balance of the system

The energy balance in the proposed model in the electrical and heat section is as follows:

$$P_g^{i,t} + P_{pv}^{i,t} + p_{wt}^{i,t} + PE_{CHP}^{i,t} + P_{es,d}^{i,t} + P_{down}^{e,i,t} + P_{curt}^{i,t} = P^{el,i,t} + P_{es,c}^{i,t} + P_{up}^{e,i,t} + {P_{ice}^{i}}^{i,t} + P_{ec}^{i,t} \tag{29}$$

$$PH_{CHP}^{i,t} + PH_B^{i,t} + P_{hs,d}^{i,t} + P_{down}^{h,i,t} = P^{hl,i,t} + P_{hs,c}^{i,t} + P_{up}^{h,i,t} + PH_{ac}^{i,t} \tag{30}$$

$$PH_B^{i,t} = G_B^{i,t} LHV \eta_B \tag{31}$$

$$PE_{CHP}^{i,t} = G_{CHP}^{i,t} LHV \eta_B^e \tag{32}$$

$$PH_{CHP}^{i,t} = G_{CHP}^{i,t} LHV \eta_B^h \tag{33}$$

$$0 \leq G_{CHP}^{i,t} \leq G_{CHP}^{max,i} \tag{34}$$

$$0 \leq G_B^{i,t} \leq G_B^{max,i} \tag{35}$$

$$-P_g^{i,max} \leq P_g^{i,t} \leq P_g^{i,max} \tag{36}$$

$$0 \leq PH_{CHP}^{i,t} + PH_B^{i,t} + P_{hs,d}^{i,t} - P_{hs,c}^{i,t} \leq P_h^{max} \tag{37}$$

The balance between supply and demand in the electrical as well as heat section of the hubs are demonstrated by Eq. (29) and (30), respectively. The produced heat from the boiler is described in Eq. (31). The output of electricity and heat of the CHP units are respectively shown in Eq. (32) and (33). The constraints of the purchasable natural gas for CHP units, and boilers are represented in Eq. (34) and (35), respectively. The constraints of the imported power from the main grid and the heat pipes are respectively demonstrated in Eq. (36) and (37). In order to meet the energy balance in the cooling section, the following relations are proposed:

$$C_{ec}^{i,t} + C_{ac}^{i,t} + P_{cs,d}^{i,t} = CL^{i,t} \tag{38}$$

$$P_{cs,c}^{i,t} = P_{ice}^{i,t} COP_{ice} \tag{39}$$

$$0 \leq P_{ice}^{i,t} \leq P_{ice}^{max,i} \tag{40}$$

$$C_{ac}^{i,t} = PH_{ac}^{i,t} COP_{ac} \tag{41}$$

$$0 \leq PH_{ac}^{i,t} \leq PH_{ac}^{max,i} \tag{42}$$

$$C_{ec}^{i,t} = P_{ec}^{i,t} COP_{ec} \tag{43}$$

$$0 \leq P_{ec}^{i,t} \leq P_{ec}^{max,i} \tag{44}$$

Eq. (38) shows the cooling system balance between supply and demand for each hub. According to Eq. (39), the charging energy for the ice storage depends on the COP_{ice} and the amount of input electricity which makes the ice. The power input limit for the ice storage is described in Eq. (40). Another cooling production unit in this paper is the absorption chiller, which receives heat and produces cooling energy for the system, and is illustrated in Eqs. (41) and (42). The last cooling supply unit is the electrical chiller in which the input electricity provides cooling energy for the system, which is demonstrated in Eqs. (43) and (44).

III. Cooperative strategy and fairly cost allocation

In this paper, we propose cooperative energy management for integrated energy hubs. Unlike non-cooperative games, cooperative strategies guarantee the optimal solution for the system. A coalition is formed when a group cooperates together. The overall gain of the coalition should be divided fairly among participants. Shapley value is a classic cooperative solution concept that allocates a unique distribution to the participants. The Shapley value allocates the overall gain of the coalition between participants based on their contribution, efficacy, and bargaining power of participants [30], and [31]. The amount that hub i gets given in a coalitional game is achieved as (45):

$$\varphi_i(v) = \frac{1}{N!} \sum_{S \subseteq N/\{i\}} |S|!\,(N - |S| - 1)!\,(v(S \cup \{i\}) - v(S)) \tag{45}$$

Where *N* is the total number of hubs and the function *v* maps subsets of hubs to the real numbers. The *S* shows a coalition of hubs and *v(S)* called the worth of coalition *S*. The Eq. (45) can be replaced by (46) and (47):

$$\varphi_i(v) = \frac{1}{N!} \sum_{R} \left[v\left(P_i^R \cup \{i\}\right) - v\left(P_i^R\right) \right] \tag{46}$$

$$\varphi_i(v) = \frac{1}{N!} \sum_{S \subseteq N/\{i\}} \frac{(v(S \cup \{i\}) - v(S))}{\binom{N-1}{|S|}} \tag{47}$$

Where P_i^R is the set of hubs in *N*, which precede *i* in order *R*. It should be noted that for a single-owner system, we can utilize the proposed cooperative model, but we do not need the cost allocation.

IV. Simulations and results

In this section, the simulation parameters and input power data are represented. Afterward, the results are analyzed and discussed. The proposed model includes several energy hubs, which have various generation units and demands. The parameters of the electrical, heat, and ice storage systems are shown in Table 2 [25, 26]. The parameters of the ice storage system and CCHP are described in Table 3 [25, 26]. The other simulation parameters are described in Table 4 [25, 26]. The input power from the PV and WT units are taken from [25]. The hourly electricity price is illustrated in Fig.2 .The electrical, heat, and cooling loads of the hubs are depicted in Figs. 3-5, respectively [25, 26] and [7].

Table 2. *Parameters of electrical and heat storage system*

Electrical storage parameters				**Heat storage parameters**			
Parameter	Hub1	Hub2	Hub3	Parameter	Hub1	Hub2	Hub3
$E_{es}^{max,i}$ (kWh)	90	130	100	$E_{hs}^{max,i}$ $(kW\text{h})$	160	100	-
$E_{es}^{min,i}$ (kWh)	9	15	10	$E_{hs}^{min,i}$ (kWh)	30	20	-
$P_{es,c}^{max,i}$ (kW)	15	30	20	$P_{hs,c}^{max,i}$ (kW)	40	25	-
$P_{es,d}^{max,i}$ (kW)	15	30	20	$P_{hs,d}^{max,i}$ (kW)	40	25	-
$\eta_{es,c}^{i}$	0.9	0.9	0.9	$\eta_{hs,c}^{i}$	0.9	0.9	-
$\eta_{es,d}^{i}$	0.9	0.9	0.9	$\eta_{hs,d}^{i}$	0.9	0.9	-

Table 3. *Parameters of ice storage and CCHP units*

Ice storage parameters				**CCHP parameters**			
Parameter	Hub1	Hub2	Hub3	Parameter	Hub1	Hub2	Hub3
$E_{cs}^{max,i}$ (kWh)	320	-	300	$G_{CHP}^{max,i}$ (m^3/h)	60	75	50
$E_{cs}^{min,i}(kWh)$	60	-	60				
$P_{cs,c}^{max,i}(kWh)$	120	-	120	$G_{B}^{max,i}(m^3/h)$	30	35	30
$P_{cs,d}^{max,i}(kWh)$	140	-	140	$PH_{ac}^{max,i}$ (kW)	-	-	180
$\eta_{cs,c}^{i}$	0.97	-	0.97	$P_{icc}^{max,i}$(kW)	50	-	50
$\eta_{cs,d}^{i}$	0.95	-	0.95	$P_{ec}^{max,i}$(kW)	100	-	80
δ_{cs}^{i}	0.02	-	0.02				

Table 4. *Simulation Parameters*

Parameter	Value	Parameter	Value
OM_{CHP} $(cent/kWh)$	2	η_{CHP}^{e}	0.35

$OM_B\ (cent/kWh)$	2.7	η_{CHP}^{h}	0.45
MR_{up}^{e}	0.5	η_B	0.8
MR_{down}^{e}	0.2	COP_{ec}	4
MR_{up}^{h}	0.5	COP_{ice}	3.5
MR_{down}^{h}	0.2	COP_{ac}	1.2
$\lambda_t^G\ (cent/m^3)$	22	CO_{curt}	0.25
$LHV\ (kWh/m^3)$	9.7	$PEN_{curt}(cent/kWh)$	20

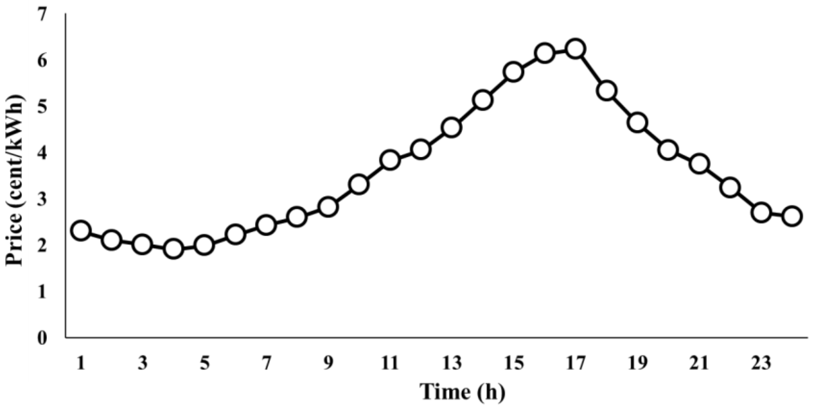

Fig. 2. *Wholesale electricity market prices*

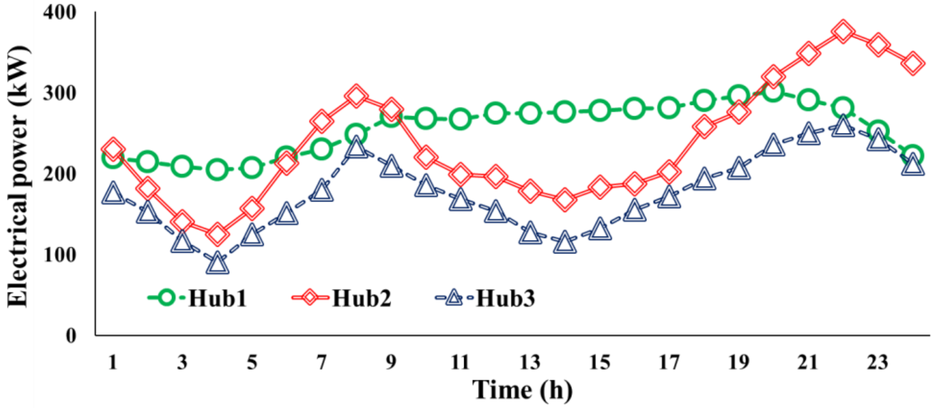

Fig. 3. *The electrical demand of energy hubs*

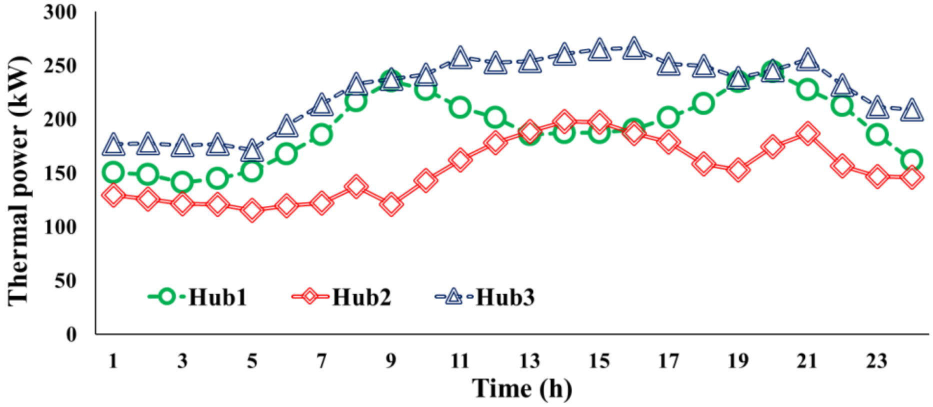

Fig. 4. *The thermal demand of energy hubs*

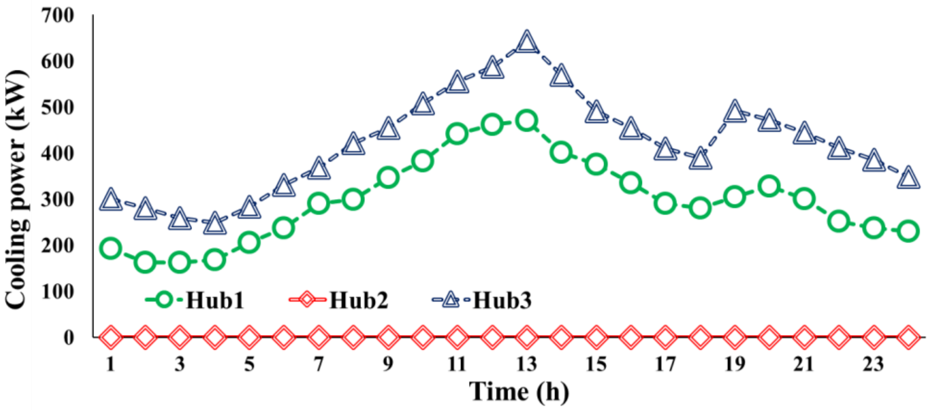

Fig. 5. *The cooling demand of energy hubs*

In order to show the efficiency of the proposed cooperative approach, two following case studies have been studied:

- Case I: In this case study, the energy hubs perform an autonomous operation scheduling to minimize their operation costs. Similar to this case study had been presented in [7], [23], [24], [25], and [26]. This case study is a base case and the energy hubs cannot cooperate to share their resources.
- Case II: The proposed cooperative approach has been investigated in this case study. The energy hubs cooperate together to form a coalition. In this case, the energy hubs can share their local resources to provide a back-up for other energy hubs. The overall profit of the coalition is divided among the energy hubs based on their efficiency, bargaining power, and contribution. The Simulation results of case studies are presented in Table 5.

Table 5. *The optimal results of case studies*

Case study	**Cost (cents)**			**Energy not supply**	**Interrupt**
	Hub1	**Hub2**	**Hub3**	**(kWh)**	**(times)**
Case I	73103.24	33574.75	50323.25	1205.37	24
Case II	59290.7	30140.68	45934.82	0	0
Improvement (%)	+18.89	+10.23	+8.72	+100	+100

The results of Table 5 show that the operating costs of the energy hubs have been improved by the proposed cooperative model. Compared to the case I, the operation cost of energy hub1 has been improved from 73103.24 cents to 59290.7 cents. Also, the operation costs of the energy hubs2 and 3 reach from 33574.75 cents and 50323.25 cents to 30140.68 cents and 45934.82 cents, respectively. Actually, the proposed model improves the operation costs of the energy hubs 1, 2, and 3 by 18.89%, 10.23%, and 8.72%, respectively. When energy hubs cooperate and share their resources, the total cost of the energy hubs had been reduced by 21635.04 cents. Based on the contribution and the efficiency of each energy hub, the profit of the coalition is divided among them that most of the overall gain goes to hub 1. In the proposed model, the energy hubs are able to use the local resources of the other energy hubs as the back-up. Therefore, the amount of curtailed load and the number of interrupts significantly have been improved by the proposed cooperative model. In the autonomous operation scheduling, the amount of the curtailed load is 1205.37 kWh, while in the proposed model all of the required loads have been supplied by the local resources. The analysis of each case study is presented as follows:

1. *The electrical, heating, and cooling results of case I*

In this section, the results of case I are analyzed in details.

i) The electrical results of energy hubs in case I

In Fig. 6-8, the amount of each electric production and demand including power resources, energy storages, DR programs, and electricity consumers such as ice storage and electrical chiller is demonstrated. As illustrated, hub1 faces a serious electrical energy shortage, since it has restrictions to import energy from the main grid. Thus, hub1 employs its own resources as much as possible to provide the required power for the demands, and it uses CHP unit to produce most of the required power in most of the operation time. Furthermore, this hub uses DR programs to shift and curtail the loads, resulting in enhancing its ability to serve the demands. Hub1 also possesses electrical chiller and ice storage, which consume a large part of the accessible electricity.

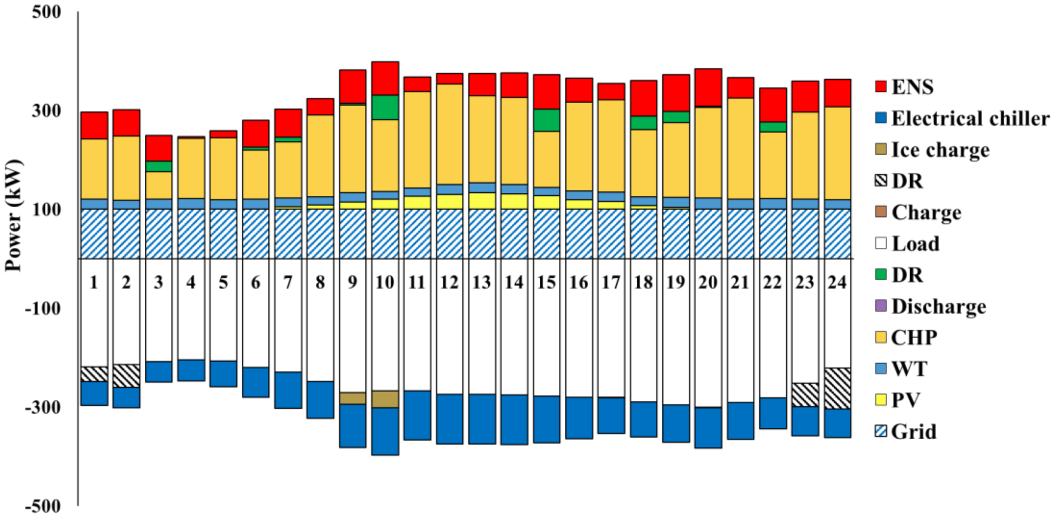

Fig. 6. *The electrical balance of energy hub 1*

As shown in Fig. 7, hub2 can import more power from the main grid, and it has not cooling loads to serve. With this in mind, it imports power in the low price hours and sells the extra power in the high price moments, which reduces its dependency on the CHP unit, and use CHP unit mostly to make profit during the high price hours and sell the power to the grid. Moreover, hub2 has shifted its loads from the peak load hours to low load hours using demand response programs to reduce the required energy in peak hours.

Hub3 contains various production units and demands, which has increased its flexibility in serving the demands. As depicted in Fig. 8, hub3 has shifted the loads from peak hours to low load periods, which results in a reduction in its operation cost. Also, it has injected power to the main grid during hours 11-18, since it has a large amount of renewable energy, enabling hub 3 to produce a large amount of energy.

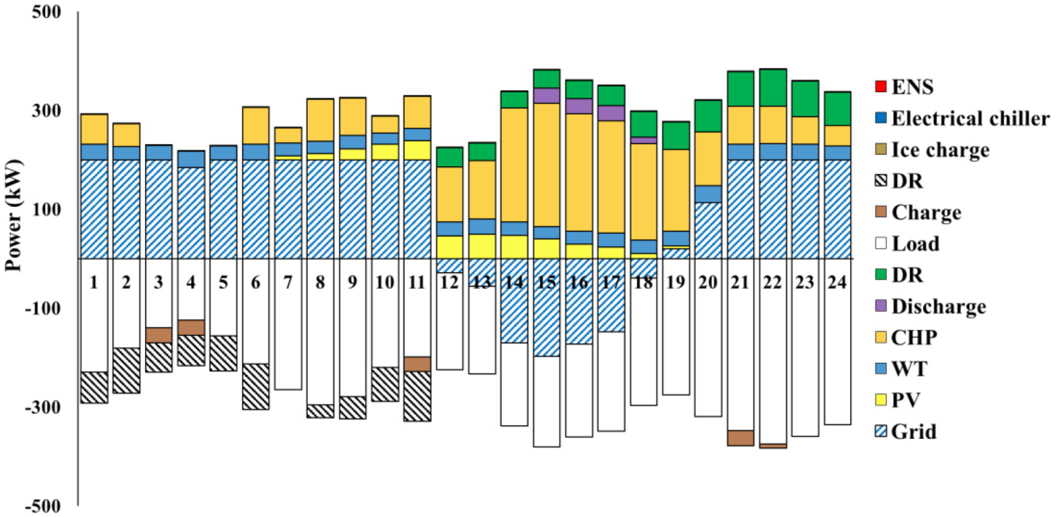

Fig. 7. *The electrical balance of energy hub 2*

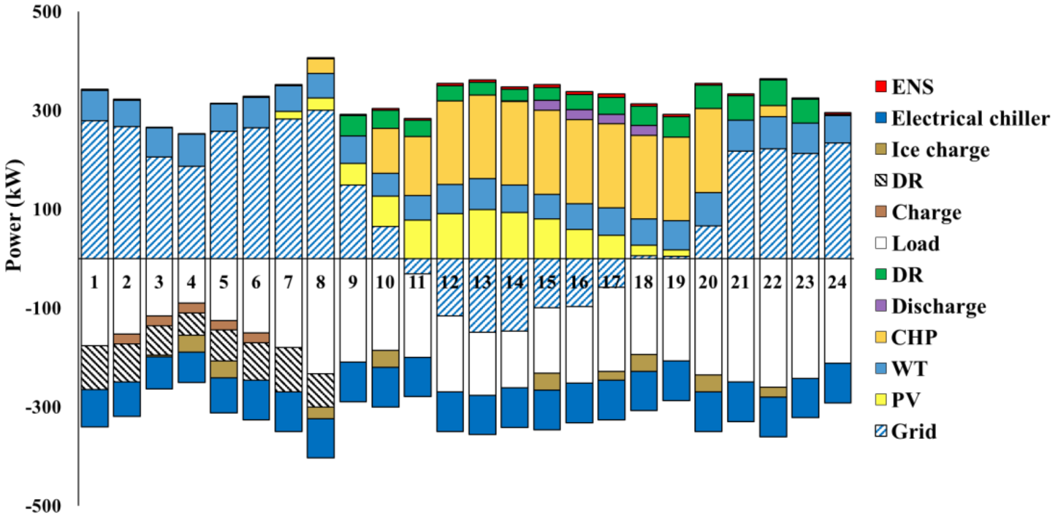

Fig. 8. *The electrical balance of energy hub 3*

ii) The heating results of energy hubs in case I

Figs. 9-11, shows an overview of the heat energy in hubs, in which the production and demands of each are described. Since hub1 should utilize its CHP to provide the required electrical power, its CHP is employed all over the operation period, and the boiler unit is not used in case I. Moreover, using the heat storage and DR programs, hub1 provides the required heat for the demands and shifts the heat load in order to decrease the operation costs. Furthermore, because of the limited flexibility in this case, hub1 is unable to use its absorption chiller and boiler.

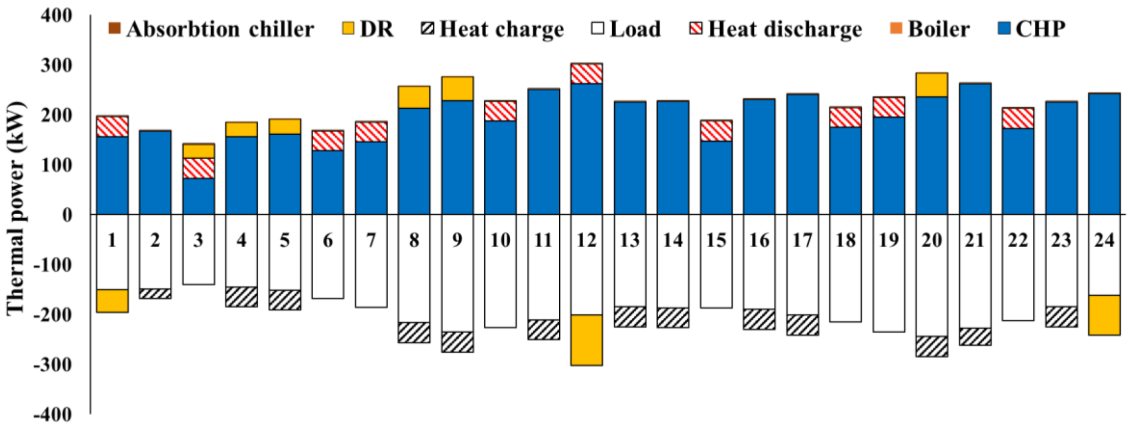

Fig. *9. The heating balance of energy hub 1*

According to Fig. 10, regarding the smaller quantity of the required electric power in hub2, less heat is produced by CHP, and boiler as well as DR program have provided the required heat for the hub. As mentioned earlier, hub2 uses its CHP to produce electrical power in the high price hours and sell the power to the main grid. Therefore, the only heat provider in the high price hours is the CHP unit. Also, the CHP unit supplies the required heat for charging the heat storage and the shifted heat loads from other intervals.

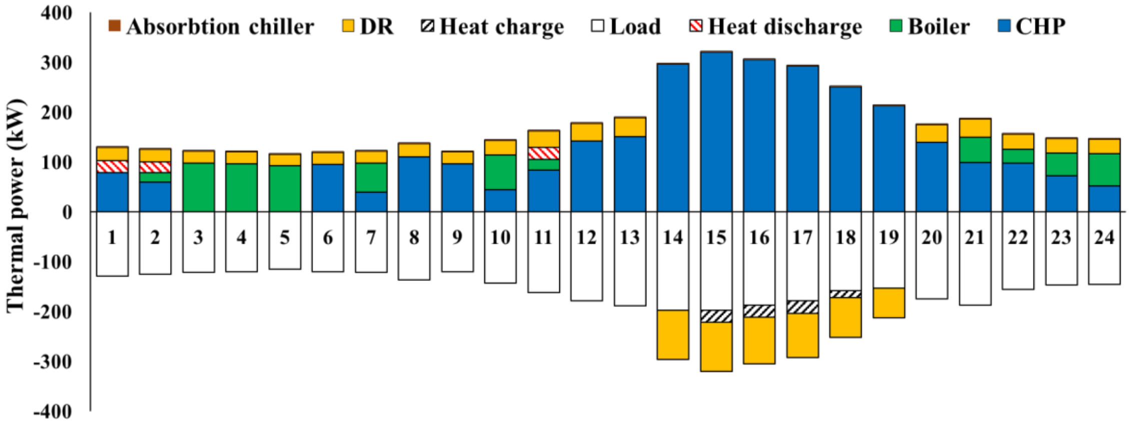

Fig. 10. *The heating balance of energy hub 2*

The main heat source of hub3 is the boiler, since it has less amount of electrical load and it can import more power from the main grid; thus it needs less electricity from the CHP units and most of the required heat is generated using boiler (see Fig. 11). Boiler and CHP provide heat together between hours 8-20, because the absorption chiller is employed during this period. During hours 9-21, CHP unit provides heat for hub3, since the generated power in these hours will reduce the imported power in the high price hours.

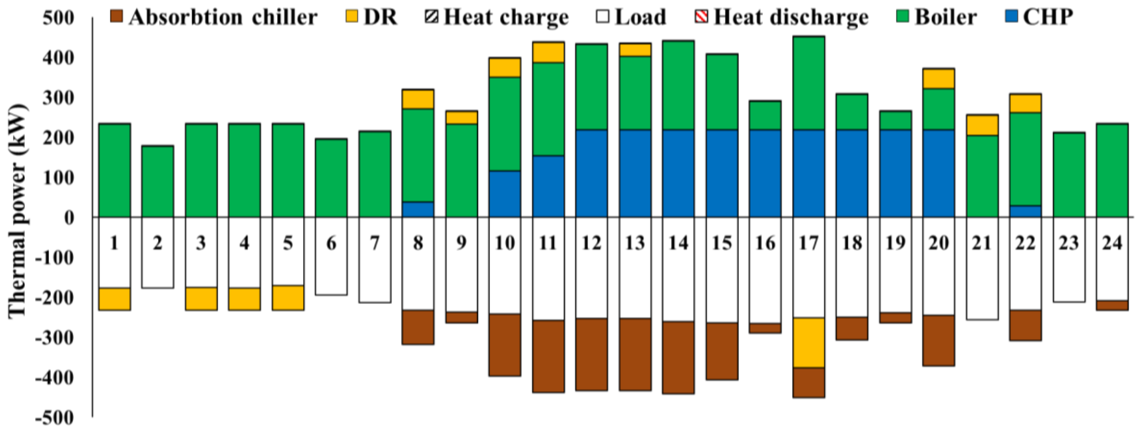

Fig. 11. *The heating balance of energy hub 3*

iii) The cooling results of energy hubs in case I

The main supplier of cooling energy in hub1 is the electrical chiller as illustrated in Fig. 12. Moreover, the ice storage system has provided more cooling energy between 11-13 when is the peak period of the cooling load.

According to Fig 13, hub3 owns absorption chiller, enabling it to have more options for cooling energy provision, although the main cooling energy provider is the electrical chiller. During the peak cooling load period, the absorption chiller and ice storage system support the electrical chiller to supply the required cooling energy for hub3. Furthermore, the ice storage supplies cooling energy in hours 19, 21, and 23 in which more cooling load is required.

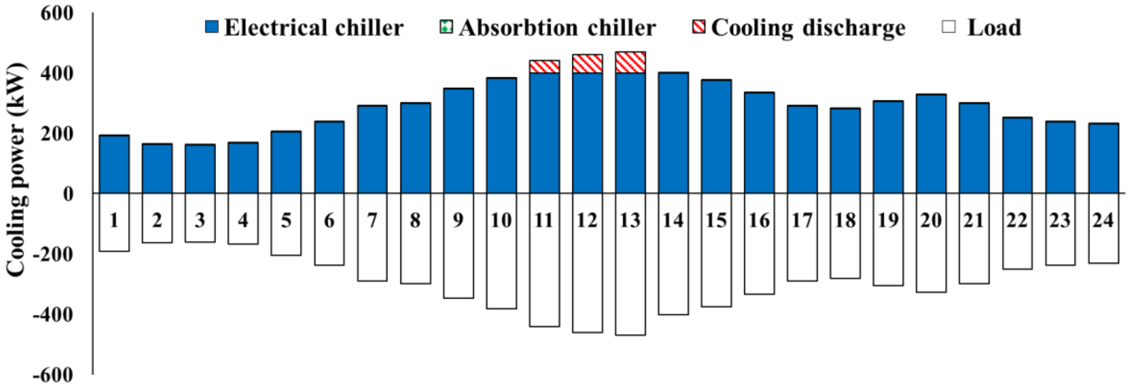

Fig. 12. *The heating balance of energy hub 1*

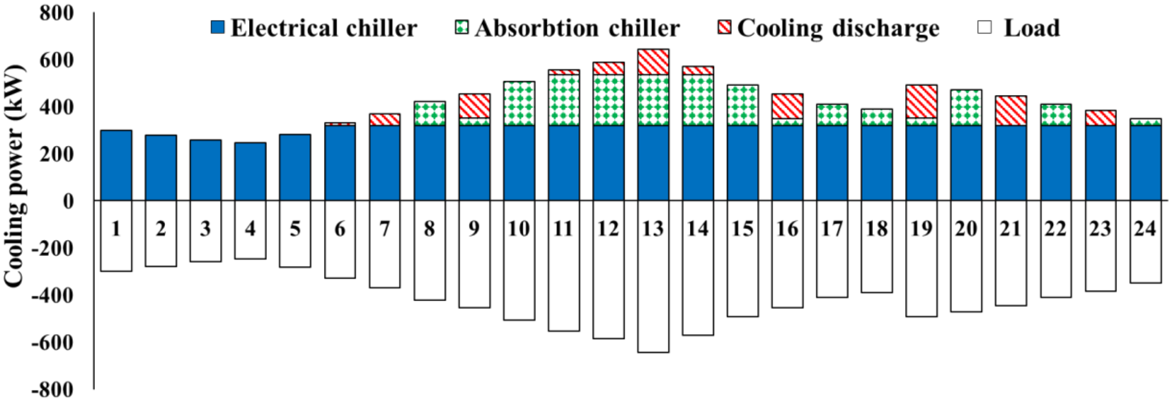

Fig. 13. *The heating balance of energy hub 3*

2. The electrical, heating, and cooling results of case II

The results of the electrical, thermal, and cooling energy of case II have been investigated in this section.

i) The electrical results of energy hubs in case II

The cooperative operation of energy hubs is investigated in case II. In the cooperative operation, the total imported power from the main grid for energy hubs is restricted to 600 kW instead of restricting purchasing power from the main grid for each of the energy hubs. According to Fig. 14, hub1 imports more amount of energy from the main grid in the cooperated operation in comparison with case I, since it has more loads to serve. Moreover, hub1 has decreased the output of CHP to increase the flexibility of the electrical and heat section. Furthermore, load curtailment is not required for hub1 in case II, because it can import sufficient power from the main grid. Unlike case I, the demand response program has been used more frequently in case II, because of the ability to import more power from the main grid.

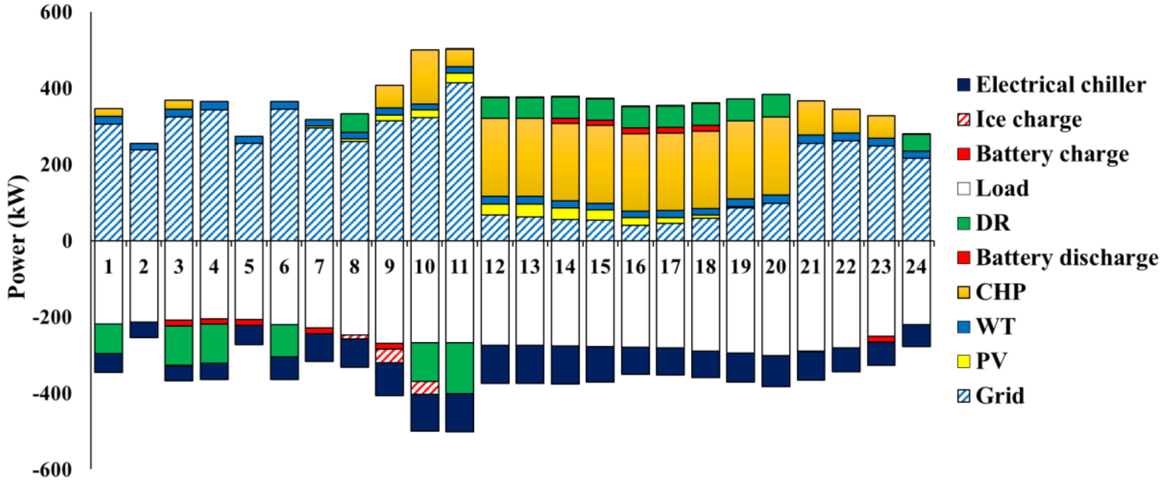

Fig.14. *The electrical balance of energy hub 1*

As we can observe from Fig. 15, hub2 is also able to import more power from the main grid in case II, resulting in decreasing the use of CHP during the operation period. However, during the high price hours, the CHP is still employed, because the obtained revenue from selling power to the grid overcomes the CHP shut down.

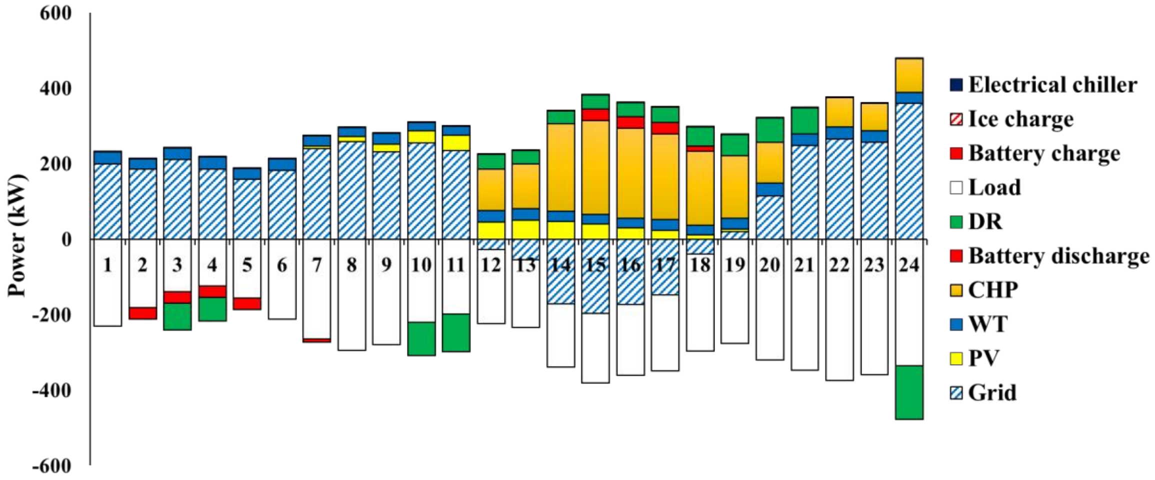

Fig.15. *The electrical balance of energy hub 2*

Hub3 has decreased the imported power from the main grid in the first hours of the operation and has used CHP units to produce the rest of required power, since energy hubs have shared the capacity of imported power from the main grid, and more capacity for importing power from the main grid is dedicated to hub1 in case II (Fig. 16).

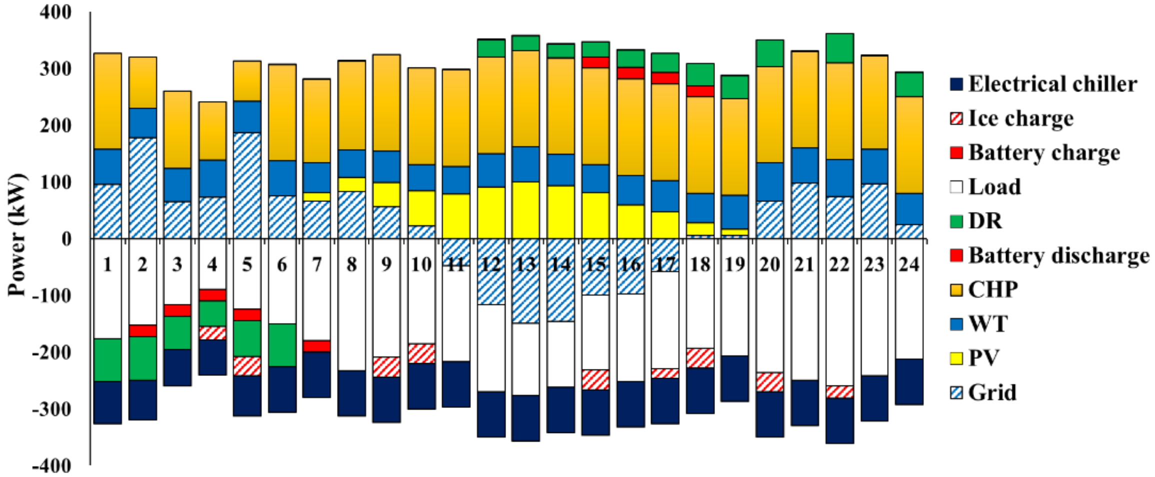

Fig. 16. *The electrical balance of energy hub 3*

ii) The heating results of energy hubs in case II

The output power of heat resources and heating load of energy hubs are presented in Figs. 17-19. The generated heat from the CHP in hub1 is decreased in case II, since hub1 needs less electricity from the CHP. Accordingly, less heat is generated from CHP, resulting in the growth in heat production from the boiler in case II. Moreover, using less amount of heat from the CHP has enabled hub1 to use more DR programs and shift the loads more appropriately. During the high price hours, CHP produces power and heat, and the boiler is not used in this interval.

Likewise, hub2 is also able to produce more heat from the boiler, because it has diminished the output of CHP during the first period of the operation. Nevertheless, the CHP heat output is the same as case I in the high price hours, as hub3 prefers to sell the generated power from the CHP to the grid. Hub3 has reduced the output of the boiler and increased the output of CHP, since it has to decline the imported power from the main grid by using its own CHP more frequently. The absorption chiller generates as same cooling energy as case I, but the heat DR program has changed in order to match with the power transmission restrictions.

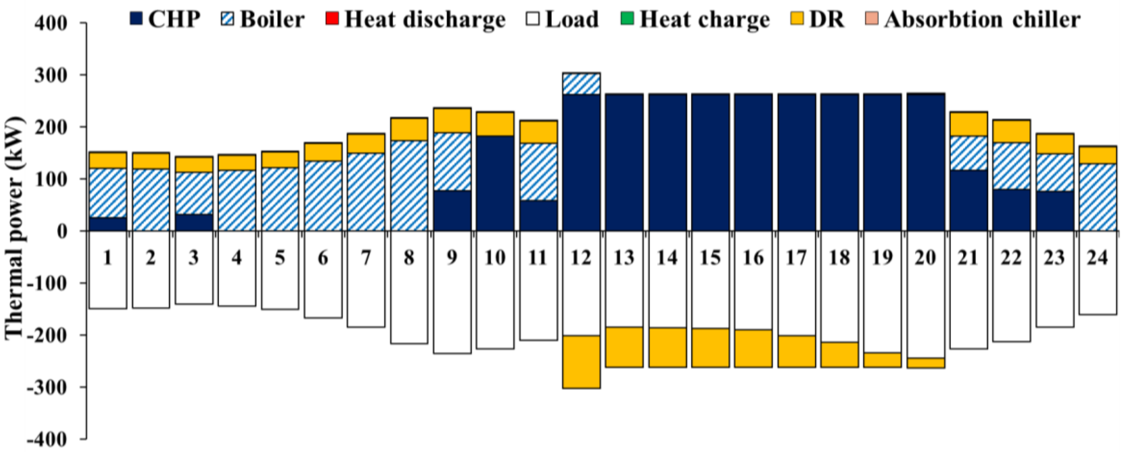

Fig. 17. *The heating balance of energy hub 1*

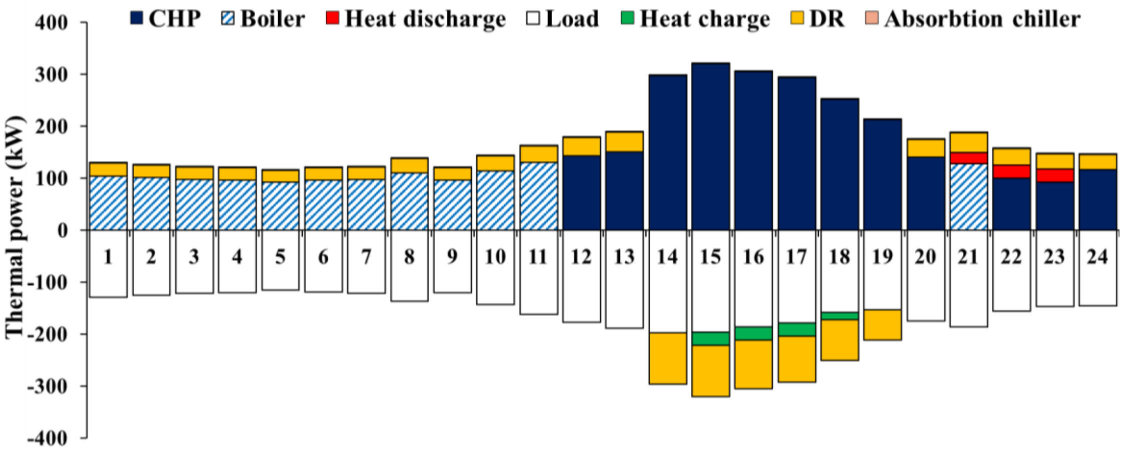

Fig. 18. *The heating balance of energy hub 2*

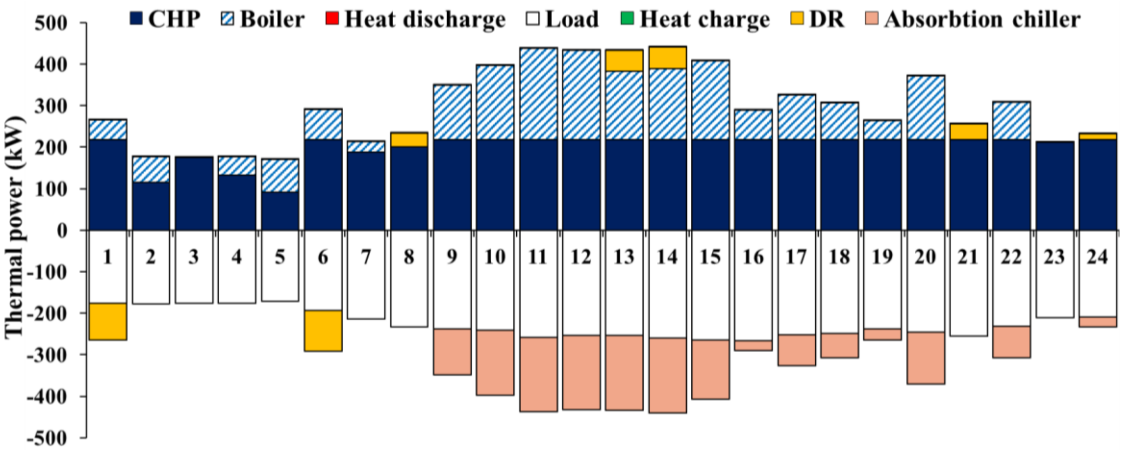

Fig. 19. *The heating balance of energy hub 3*

iii) The cooling results of energy hubs in case II

The cooling system results of case II are illustrated in Figs. 20-21 , in which the role of ice storage systems have increased in some hours, which is the result of more flexibility in the system by working in the cooperative condition. As previously mentioned, the main cooling supplier in hub1 is the electrical chiller, and ice storage collaborates in the cooling peak hours. The absorption chiller in addition to the electrical chiller is the main cooling energy supplier in hub3.

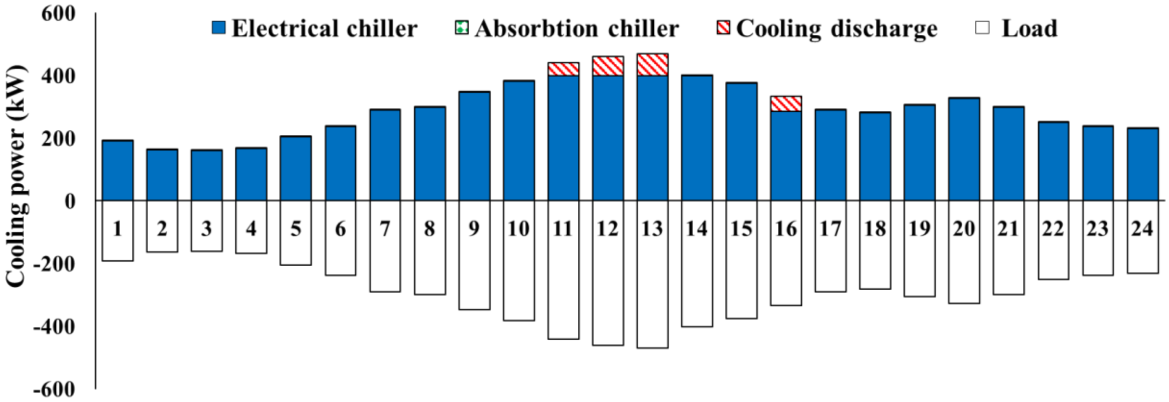

Fig. 20. The cooling balance of energy hub 1

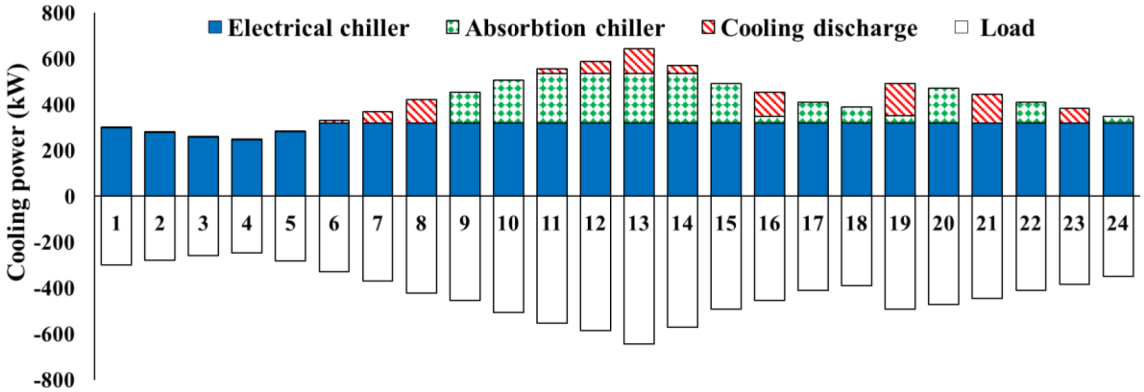

Fig. 21. The cooling balance of energy hub 3

V. Conclusion

In this paper, a cooperative model for networked energy hubs is proposed based on the fair cost allocation using the Shapley value. Several energy sources for different energy sections are used so that the optimal solution for the problem can be calculated. Energy storage systems as well as heat and electrical demand response for energy sectors are exerted in order to increase the flexibility of the system. The cooperation between energy hubs adds more flexibility to the problem, and they share their strength to reduce their weakness. The simulation results show when the energy hubs form a coalition, the total cost of the system improves by 13.78 percent. Considering the contribution of each energy hub and fairly cost allocation, the mechanism introduced in case II reduces the cost of hub1, hub2, and hub3

18.89, 10.23, and 8.72 percent, respectively. Moreover, the energy not supplied and interrupt times have improved significantly. A bi-level model considering demand response programs as well as storage systems and the ability to participate in the heat and gas market in addition to the electricity market will be investigated for networked energy hubs in our future works.

Acknowledgment:

The authors gratefully acknowledge the financial support of the Kopernikus-project "SynErgie" by the Federal Ministry of Education and Research BMBF and the project supervision by the project management organization Projektträger Jülich (PtJ) (Grant number 03SFK3G1).

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