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Energy flow modeling and optimal operation analysis of the micro energy grid based on energy hub

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ABSTRACT

The energy security and environmental problems impel people to explore a more efficient, environment friendly and economical energy utilization pattern. In this paper, the coordinated operation and optimal dispatch strategies for multiple energy system are studied at the whole Micro Energy Grid level. To augment the operation flexibility of energy hub, the innovation sub-energy hub structure including power hub, heating hub and cooling hub is put forward. Basing on it, a generic energy hub architecture integrating renewable energy, combined cooling heating and power, and energy storage devices is developed. Moreover, a generic modeling method for the energy flow of micro energy grid is proposed. To minimize the daily operation cost, a day-ahead dynamic optimal operation model is formulated as a mixed integer linear programming optimization problem with considering the demand response. Case studies are

1. Introduction

Energy security and environmental protection issues are attracting significant attentions worldwide with the gradual depletion of fossil fuels and deterioration of environment. At present, the common energy infrastructures such as electricity network and natural gas network are mostly planned and operated independently which will lead to low energy efficiency, high operation cost and low robustness [1]. So optimizing energy structure for integrating more renewable energy, improving energy efficiency and protecting ecological environment are core issues for the development of energy system [2].

With the development of micro grid and smart grid technologies, more renewable energy are integrated which lead the power systems to be more clean, efficient and reliable. However, the energy consumers not only need electricity, but also need cooling, heating and natural gas. In conventional energy systems, these types of energy are supplied independently which lead low energy efficiency and costly operation cost. Recently, combined cooling, heating and power (CCHP) as an advanced efficient nature gas utilization technology is developing rapidly. CCHP system integrates gas turbine, heat collector, boiler and refrigeration device as a whole to implement the energy cascade utilization, reduce carbon emission and meet the cooling, heating and electricity demands simultaneously [3]. The energy efficiency of CCHP system can be up to 60–80% which will greatly improve the energy comprehensive utilization efficiency and bring better economic and environmental benefits [4]. As the coupling node between power system and natural gas system, the CCHP will promote the integration of multiple energy carriers. With the integration of electricity system, natural gas system and other energy system, the power systems are evolving into the integrated energy system. Meanwhile, some new forms of energy system are proposed which are similar to integrated energy system. Such as, the concept of multiple-energy carrier systems proposed in [5] and the concept of Smart Multi-Energy systems introduced in [6]. As the vision for the development of energy system, the Energy Internet proposed in [7] depicts an efficient power grid integrating high penetration of green energy and enables energy sharing in the distributed network just like the information sharing in the Internet today.

Abbreviations: MEG, micro energy grid; PV, photovoltaic; WT, wind turbine; ESD, energy storage device; ES, electricity storage; HS, heating storage; CS, cooling storage; DR, demand respond; TOU, time-of-use price; RTP, real time price; PL, power load; HL, heating load; CL, cooling load; GT, gas turbine; EC, electric chiller; ISC, ice storage conditioner; GB, gas boiler; AC, absorption chiller.

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However, there are many challenges to overcome to achieve the envisioned Energy Internet. Before the Energy Internet, the integrated energy systems is the development trend of power system. Integrated energy systems generally consist of at least two of the following systems: electricity, natural gas, cooling, heating or traffic systems. Thus, different types of energy will interact and couple. Therefore, integrated analysis of the whole energy system are necessary to coordinate the multiple energy carriers, improve energy efficiency and decrease operation cost [8].

In recent years, the concept of energy hub proposed in Ref. [9] is widely used in the integrated analysis of multiple energy carrier systems. An energy hub is taken as a unit where multiple energy carriers can be converted, conditioned and stored. A typical energy hub consumes electricity and natural gas at input port and provides the electricity, heating and cooling energy services at output port [10]. Extensive researches are carried out on the energy hub, including modeling, optimizing system structures and operation strategies. A framework for integrated modeling and optimization of multiple energy carriers systems is presented and a nonlinear programming model is formulated for the optimization of energy flow basing on the concept of energy hub in [11]. A residential energy hub model for a smart multi-carrier energy home is designed in [12], and the optimal operation mode of the energy hub is analyzed. According to [13], a new framework is developed to coordinate the charging process of plug-in hybrid electric vehicles with the energy hub approach and the 2-point estimation method is used to model the uncertainties of wind energy. Mathematical optimization models of residential energy hub are formulated in [14], which can be incorporated into automated decision making technologies in smart grid. In addition, they can be solved

proposed in [15], including a residential combined heat and power as a co-generation technology and a plug-in hybrid electric vehicle. However, the objects investigated in these references are mainly focused on the energy systems of residential buildings, official buildings or factories. What's more, the proposed modeling methods for energy hubs lack flexibility and versatility which can't intuitively reflect the energy flow relationship.

As demand response (DR) can guide the customers to consume electricity rationally and play a vital role in peak load shifting, more attentions are paid to it nowadays. However, the researches on DR implemented in multiple energy system are rare and the DR models or strategies are far from full investigation. Considering the possible uncertainties in the decisions of customers, the DR module is embedded into the energy hub as a unit and then a model of multi energy DR based on stochastic model is established in [16]. In [17], the integrated scheduling of renewable generations and demand response programs for a micro grid is investigated. Different types of electricity customers can participate in demand response programs to respond to the energy or reserve scheduling. According to [18], a stochastic energy procurement problem is proposed for large electricity consumers with considering the effects of demand response programs. Results show that the demand response programs can shift the loads from high price period to low price period which will decrease the expected operation cost. In order to identify and quantify the potential of distributed generations to participate in real-time DR programs, a comprehensive framework is established and the novel concept of electricity shifting potential is introduced in [19]. However, these studies are mainly concentrated on the modeling and potential analysis of DR. The coordinated operation and optimal scheduling of multi energy carriers with DR are not considered enough.

In contrast to the existing researches introduced above, this paper try to expand the well known concept of micro grid which is mainly concentrated on improving the distributed renewable resources penetration of the distribution networks [20]. The expanded concept of micro grid is entitled Micro Energy Grid (MEG). The main difference between Micro Energy Grid and micro grid is that the former is an integrated energy system including cold, heat, power, gas and other forms of energy. Besides, the coordinated operation and optimal scheduling strategies of multi energy carriers will be investigated at the whole MEG level. The innovative contributions of this paper are mainly embodied in the following three aspects. (1) A novel sub energy hub structure is developed including power hub, heating hub and cooling hub which can realize the collection and allocation of energy. According to the sub energy hub structure, a generic architecture of energy hub integrating CCHP is designed and a generic modeling method of energy flow is proposed. (2) A generic optimal dispatch model for the MEG is formulated with considering the operation cost and environmental cost. This model is a mixed integer linear programming problem essentially which aims to maximize the local consumption of renewable energy and minimize the total operation cost. (3) A real time pricing model is developed and the roles of renewable energy, electricity/cold/heat energy storage devices and demand response are discussed separately.

The remainder of the paper is organized as follows: Section 2 introduces the MEG and designs a basic architecture for the MEG basing on energy hub. Section 3 designs the structure of energy hub and formulates its energy flow as well as the optimal dispatch model. Case studies and numerical simulation results are discussed in Section 4. Finally, the conclusions are summarized in Section 5.

a new evolution trend for the traditional distribution network. MEG mainly has the following three advantages. (1) From the energy supply aspect, the MEG can promote the local consumption of renewable resources and coordinate natural gas, electricity, cooling, heat and other energy carriers. Moreover, it can implement multi energy complement, alternative utilization of energy and improve the security and reliability of the energy supply system with considering the effects of energy price and environment. (2) From the energy service perspective, the MEG can decrease the energy cost, reduce carbon emission and realize peak load shifting through optimal dispatch. (3) From the energy grid angle, the coordinated operation of electricity network, gas grid and thermal network will accelerate the development of the multi energy technology and improve the energy efficiency which will promote the sustainable development of energy system eventually.

The physical objects of MEG can be buildings, residential communities, industrial parks, towns, cities and so on. As illustrated in Fig. 1, this paper designs an architecture of a community MEG whose critical component is energy hub. To be specific, the energy hub is composed of input energy carriers (gas and electricity), energy converters (transformer, gas turbine, gas boiler, electrical chiller and absorption chiller), energy storage devices and output energy carriers (power, cooling and heating). Through the energy hub, the natural gas from natural gas network and the electricity supplied by utility grid are converted to power, cold and heat to satisfy multi energy demands.

Dispatch center is responsible for the energy management of the MEG. The information including the device status, energy consumption historical data, weather reports, appliance parameters, electricity price and gas tariff will be collected by advanced meters and sent to the dispatch center. After analyzing and processing these data, the dispatch center will forecast the energy demands, the outputs of renewable resource and send optimal dispatch sig-

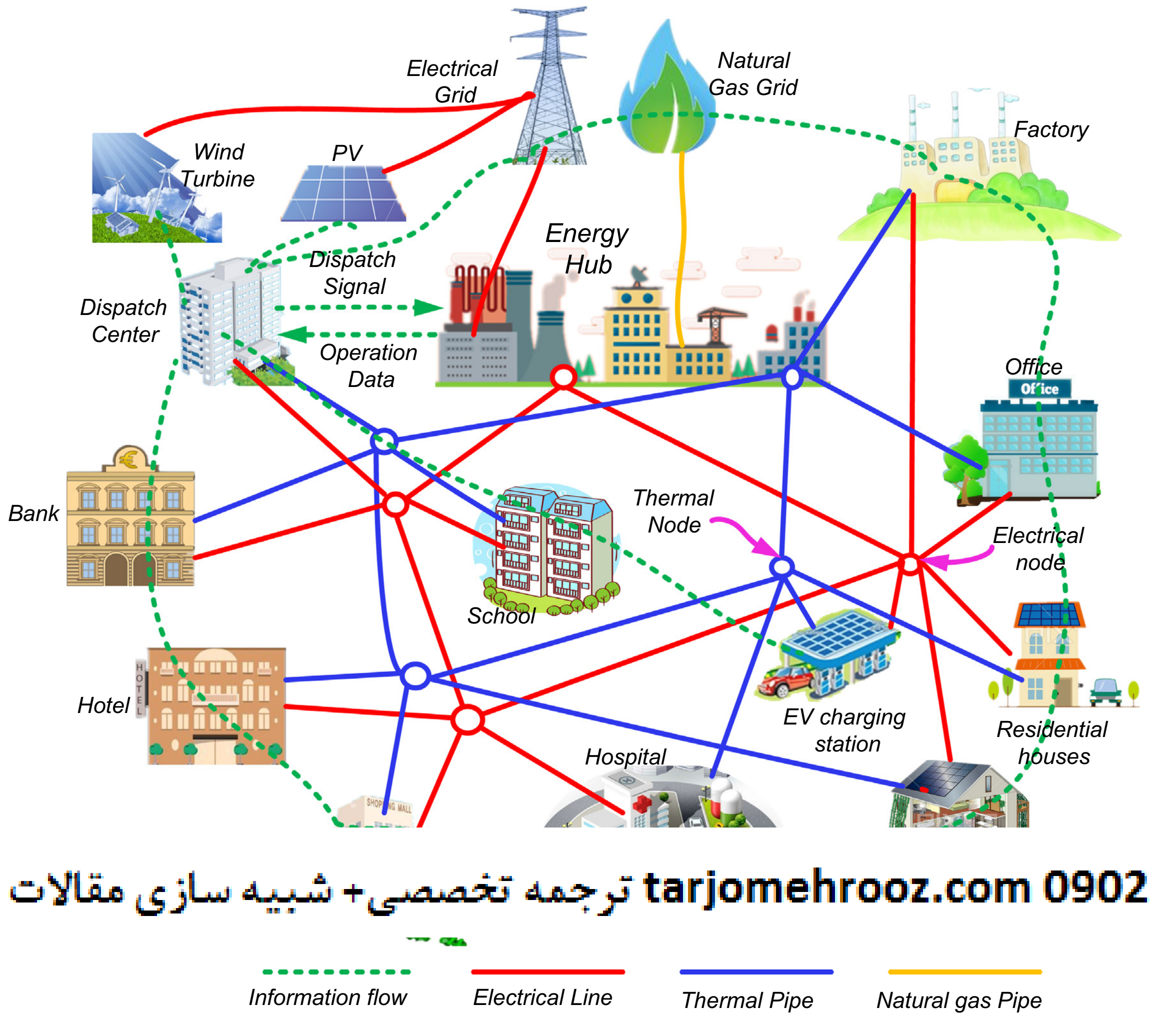


Fig. 1. Overview of micro energy grid architecture.

nals to the energy hub. The output energy carriers (such as electricity, cooling, heating) will be distributed to the users through electrical lines and thermal pipes to meet their energy demands.

3. Energy hub

As illustrated in Fig. 2, the classic combined cooling, heating and power (CCHP) mainly consists of gas turbine, gas boiler, absorption chiller, electric chiller and transformer. The comprehensive utilization efficiency of energy can be up to 60–80% which will accelerate the development of MEG and improve the environmental and economic benefits. However, neither renewable energy resources nor energy storage devices are contained in a typical CCHP. To enhance the flexibility and reliability, a novel energy hub including renewable energy, energy storage devices and CCHP will be designed. Besides, in order to intuitively display the architecture of energy hub integrated CCHP, the novel sub-energy hub structure is proposed including power hub, heating hub and cooling hub which can realize the collections and allocations of power, heat and cold respectively and keep the energy flow balance simultaneously.

3.1. The architecture of energy hub integrated CCHP and sub-energy hub

As demonstrated in Fig. 3, the architecture of the energy hub designed basing on the sub-energy hub and CCHP mainly contains five parts. (1) Energy sources, such as natural gas, photovoltaic (PV), wind turbine (WT) and electricity supplied by utility grid. (2) Energy conversion, including gas turbine, gas boiler, electric chiller, absorption chiller, heat exchanger and ice storage conditioner. (3) Energy collection and distribution, the power, cold and heat are collected and distributed respectively by the power hub, cooling hub and heating hub while the energy flow at each sub-energy hub will keep balance at every time interval. (4) Energy storage, including electricity storage, heat storage and cooling energy storage. (5) Energy delivery, containing the power distribution network, gas grid and thermal network. According to the architecture of the proposed energy hub, the connections between the devices can be indicated intuitively and the energy flow processes can be displayed distinctly.

3.2. Energy hub modeling

Energy hub involves the multi energy conversion and multi energy storage. The equivalent model of energy conversion will be established from the energy flow equivalent conversion perspective while the generic electricity/heat/cold energy storage model is formulated from the aspect of energy flow transfer in time series.

3.2.1. The equivalent model of energy conversion

The equivalent models of energy conversion mainly include the following three sub models.

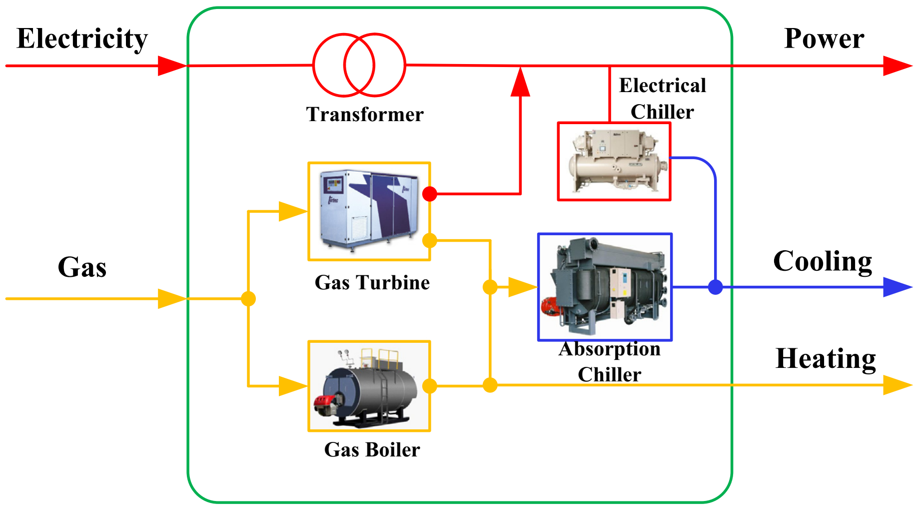


Fig. 2. Architecture of CCHP.

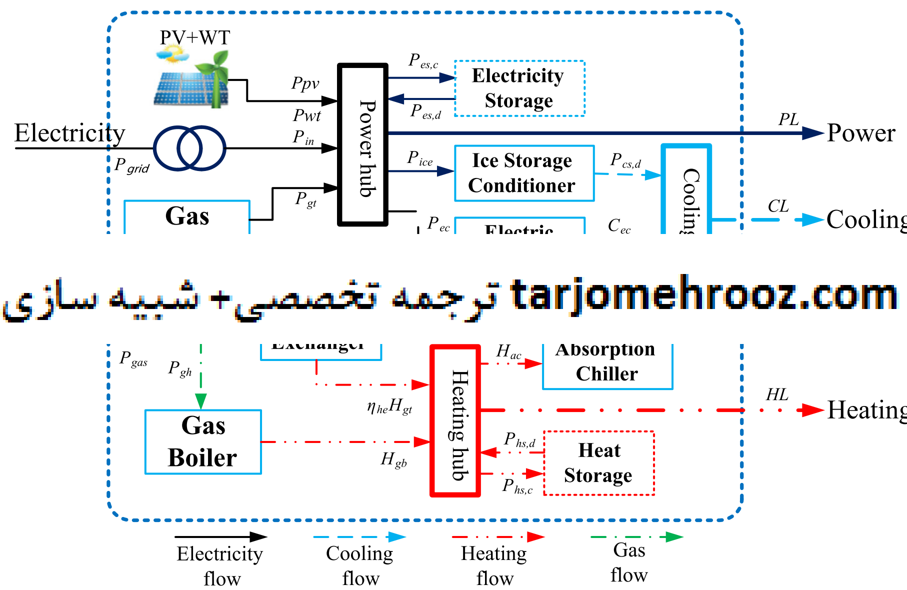


Fig. 3. Overview of Energy Hub architecture integrated CCHP and Sub-Energy hub.

(1) The equivalent model of nature gas conversion

A portion of the purchased natural gas will flow into the gas turbine to generate electricity and co-product heat while the other portion is fired by gas boiler to produce heat. So the dispatch of nature gas can be described as follows.

$$P_{gas} = P_{ge} + P_{gh} \tag{1}$$

where P_{ge} and P_{gh} are respectively the nature gas fired by gas turbine and gas boiler.

- The equivalent model for nature gas to electricity conversion

The nature gas P_{ge} is fired by gas turbine to generate electricity as illustrated in Fig. 3.

$$\eta_{ge} P_{ge} = P_{gt} \tag{2}$$

where η_{ge} is the efficiency of gas turbine and P_{gt} is the electricity generated by gas turbine.

- The equivalent model for nature gas to heat conversion

The nature gas P_{gh} is consumed by gas boiler to generate heat while the nature gas P_{ge} fired by gas turbine will also generate co-product heat.

$$\eta_{gh,gb} P_{gh} = H_{gb} \tag{3}$$

$$\eta_{gh,gt} P_{ge} = H_{gt} \tag{4}$$

where $\eta_{gh,gb}$ and $\eta_{gh,gt}$ are respectively the efficiency for heat generation of gas boiler and the efficiency for co-product heat of gas turbine. H_{gb} and H_{gt} are respectively the heat generated by gas boiler and gas turbine.

(2) The equivalent model of electricity conversion

- The electricity exchange between energy hub and utility grid

The energy hub exchanges electricity with the utility grid through transformer. When the electricity is insufficient for the MEG, the hub will purchase electricity from utility grid. While when the electricity is redundant, the hub will sell the electricity to the utility grid.

$$P_{grid}\eta_t = P_{in} \tag{5}$$

where P_{grid} is the exchange electricity between energy hub and the utility grid, η_t is the efficiency of transformer, P_{in} is the actual value for the exchange electricity. For $P_{in,}$ it is obvious that positive value indicates purchasing electricity while negative means selling electricity.

- The equivalent model for electricity to cooling energy conversion

The electric chiller consumes electricity to generate cooling energy and the conversion can be formulated as follows.

$$P_{ec} \cdot COP_{ec} = C_{ec} \tag{6}$$

where COP_{ec} and C_{ec} are coefficients for the performance of electric chiller and output of electric chiller respectively.

Except the electric chiller, the ice storage conditioner is also widely used to meet cooling demands [21]. The ice storage conditioner (ISC) has an advantage of shifting electricity consumption at peak hours to the off-peak periods which can alleviate the power supply tension during peak hours [22]. The ISC in this paper is mainly composed of single duty chiller and ice storage tank. The chiller can only work in the ice-making mode and the ice is stored in the ice storage tank which will be melt during the peak hours. It is worth mentioning that ISC can not work at ice-making mode and ice-melting mode simultaneously. The ice-making capacity of the chiller can be described as formula (7).

the chiller and $P_{is,c}$ is the ice-making capacity of ISC.

(3) The equivalent model for heat to cooling energy conversion

The co-product heat H_{gt} from gas turbine is fed into the heat exchanger while the output heat of heat exchanger $\eta_{he}H_{gt}$ along with the heat generated by boiler is collected by the heating hub. Then one part of the heat is sent into the absorption chiller to generate cooling energy.

$$H_{ac} \cdot COP_{ac} = C_{ac} \tag{8}$$

where η_{he} is the efficiency of heat exchanger, COP_{ac} is the coefficient of performance, H_{ac} is the heat fed into the absorption chiller and C_{ac} is the cooling capacity of absorption chiller.

3.2.2. The generic model for energy transfer in time series

Energy storage devices are vital components for the micro energy grid and they can realize energy transfer in time dimension. Energy storage devices store the redundant energy or cheap energy and discharge when energy is insufficient or the energy price is high [23]. The generalized energy storage not only includes the electricity storage (such as battery) but also contain heat storage (such as phase change fusion heat) and cooling storage (such as the ice storage tank of ice storage conditioner). The charging and discharging processes are similar for electricity, heating and cooling energy. They all subject to the charging/discharging energy constraints, the limits of their capacity and other technical constraints [24]. Thus the generalized dynamic model for electricity/cold/heat energy storage is proposed.

$$E_x^{t+1} = E_x^t(1-\delta_x) + \left(P_{x,c}^t\eta_{x,c} - \frac{P_{x,d}^t}{\eta_{x,d}}\right)\Delta t \tag{9}$$

$$0 \leqslant P_{x,c}^t \leqslant u_x \cdot P_{x,c}^{\max} \tag{10}$$

$$0 \leqslant P_{x,d}^t \leqslant (1-u_x) \cdot P_{x,d}^{\max} \tag{11}$$

$$E_x^{\min} \leqslant E_x^t \leqslant E_x^{\max} \tag{12}$$

$$E_x^{24} = E_x^0 \tag{13}$$

The subscript x indicates the energy type which can be electricity, heat or cold. Eq. (9) presents the energy variation in energy device during time interval Δt before and after charging/discharging. E_x^{t+1} is the stored energy after charging/discharging energy while E_x^t is the stored energy before charging/discharging energy at time t. δ_x is the energy loss ration of energy storage device, $P_{x,c}^t$ is the charging power and $P_{x,d}^t$ is the discharging power. $\eta_{x,c}$ and $\eta_{x,d}$ are charging efficiency and discharging efficiency respectively.

Eqs. (10) and (11) indicate that the charging/discharging power can not exceed their maximums. Where u_x is 0–1 variable which is introduced to constrain the charging and discharging process will not happen simultaneously. Eq. (12) is the upper and lower limitations of the stored energy of energy storage device. Eq. (13) denotes that the state of stored energy at the end of the dispatch period should be equal to the initial value. The dispatch period in this paper is 24 h and the time step is 1 h.

3.3. Demand response modeling

Demand response can increase flexibility on the demand side by reducing peak energy demand or temporarily shifting as responses

cessfully implementation of demand response. A real time pricing model is developed according to the predicted data for electricity demand and this model will be used to implement the demand response program.

$$W_d = \sum_{i=1}^{24} P_i \tag{14}$$

where W_d is the total electricity demand of MEG on a typical summer day, P_i is the electricity demand at time i. Thereby, the average electricity demand can be formulated as Eq. (15).

$$P_{av} = \frac{W_d}{24} \tag{15}$$

The float factor of real time pricing can be solved with Eq. (16).

$$\gamma = \frac{P_i}{P_{av}} \tag{16}$$

The real time pricing model can be expressed as follows.

$$RTP = \gamma \cdot P_r \tag{17}$$

$$RTP_{\min} \leqslant RTP \leqslant RTP_{\max} \tag{18}$$

where P_r is the benchmark price which is the time of use pricing in this paper. RTP_{min} and RTP_{max} are respectively the lower and upper limits of the real time pricing.

The demand response (DR) is mainly divided into two types, price-based DR and incentive-based DR [26]. In this paper, the price-based DR is chosen to analyze the effects of DR on the optimal operation of micro energy grid. With considering the DR, the load demand can be formulated as Eq. (19) and the derivations can be found in the Refs. [27,28].

$$d_t = d_0 + E \cdot d_0(P_t - p_0)/p_0 \tag{19}$$

where d_0 denotes the initial electricity demand, p_0 is the initial electricity price which will take the time of use price and P_t is the spot electricity price which can be calculated with the real time pricing model proposed above. E is the demand-price elasticity coefficient which can be determined by analyzing the customer types and historical load demand data. According to the Ref. [29], E can be assumed to take the values in the interval $[-0.5,\ 0]$.

3.4. The optimal operation model

The optimal operation model will be formulated basing on the energy hub model developed in Section 3.2, which would be a generic model for analyzing the optimal operation or dispatch problems of micro energy grid.

3.4.1. The objective function

The objective of the optimal operation for MEG is to minimize the daily operation cost. The daily operation cost is composed of three parts, net electricity purchasing cost M_{pe}, gas purchasing cost M_{pg} and carbon emission cost M_{ce}.

$$M = \min(M_{pe} + M_{pg} + M_{ce}) \tag{20}$$

(1) net electricity purchasing cost M_{pe}

$$M_{pe} = \sum_{t=1}^{24} (p_e^t \cdot P_{in}^t \cdot \Delta t) \tag{21}$$

where p_e^t is the electricity price at time t. In this paper, the elec-

(2) Gas purchasing cost M_{pg}

As described in Eq. (1), the gas purchased from gas grid is divided into two parts, P_{ge} and P_{gh} which are respectively fired by gas turbine and gas boiler. Assuming that the gas price is fixed price P_g, the gas purchasing cost can be formulated as:

$$M_{pg} = p_g \cdot \sum_{t=1}^{24} (P_{ge}^t + P_{gh}^t) = p_g \cdot \sum_{t=1}^{24} \left(\frac{P_{gt}^t}{\eta_{ge}} + \frac{H_{gb}^t}{\eta_{gh,gb}} \right) \Delta t \tag{22}$$

(3) Carbon emission cost M_{ce}

Carbon emission cost is composed of the equivalent emission costs for electricity purchased from the utility grid and gas purchased from gas grid. If β_e and β_g are respectively the equivalent emission coefficients for electricity and natural gas, ε is the CO_2 processing cost per kg, then the carbon emission cost can be expressed as:

$$M_{ce} = \varepsilon \cdot \sum_{t=1}^{24} \left[\beta_e \cdot P_{in}^t + \beta_g \cdot \left(\frac{P_{gt}^t}{\eta_{ge}} + \frac{H_{gb}^t}{\eta_{gh,gb}} \right) \right] \cdot \Delta t \tag{23}$$

where P_{in}^t is only denotes the electricity purchased from utility grid at time t and it is positive value.

3.4.2. Constraints

Constraints for the objective function include: energy balance at each sub energy hub, technical constraints for electricity/cold/heat energy storage, the performance constraints for all devices contained in the energy hub and constraints of tie-lines between energy hub and electric grid or gas grid.

(1) Energy balance at sub-energy hub

- Electrical power balance at power hub

$$P_{in} + P_{pv} + P_{wt} + P_{gt} + P_{es,d} = P_{ec} + P_{es,c} + P_{ice} + PL \tag{24}$$

- Heat balance at heating hub

$$\eta_{he} H_{gt} + H_{gb} + P_{hs,d} = H_{ac} + P_{hs,c} + HL \tag{25}$$

- Cooling energy balance at cooling hub

$$C_{ec} + C_{ac} + P_{cs,d} = CL \tag{26}$$

The left hand side of Eq. (24) represents the electricity collected by power hub while the right hand side is the allocations of the power. The left side of Eq. (25) denotes the heat injected into the heating hub while the distributions of heat are described on the right side. Likewise, Eq. (26) shows the cooling energy balance at cooling hub.

(2) Constrains for energy storage devices

As the Vehicles to Grid are playing a dual role, namely loads or sources, which are similar to the batteries [23], so in this paper the electric vehicles are considered as batteries. According to the generic model proposed in Section 3.2.2, the electricity storage device (battery), heat storage device and cooling energy device (ice storage tank) are respectively subjected to Eq. (27)–(29). It is worth mentioning that the charging cooling energy is just the ice making

$$\begin{cases} E_{es}^{t+1} = E_{es}^t(1-\delta_{es}) + \left(P_{es,c}^t \eta_{es,c} - \frac{P_{es,d}^t}{\eta_{es,d}} \right) \Delta t \\ 0 \leqslant P_{es,c}^t \leqslant u_{es} \cdot P_{es,c}^{\max} \\ 0 \leqslant P_{es,d}^t \leqslant (1-u_{es}) \cdot P_{es,d}^{\max} \\ E_{es}^{\min} \leqslant E_{es}^t \leqslant E_{es}^{\max} \\ E_{es}^{24} = E_{es}^0 \end{cases} \tag{27}$$

$$\begin{cases} E_{hs}^{t+1} = E_{hs}^t(1-\delta_{hs}) + \left(P_{hs,c}^t \eta_{hs,c} - \frac{P_{hs,d}^t}{\eta_{hs,d}} \right) \Delta t \\ 0 \leqslant P_{hs,c}^t \leqslant u_{hs} \cdot P_{hs,c}^{\max} \\ 0 \leqslant P_{hs,d}^t \leqslant (1-u_{hs}) \cdot P_{hs,d}^{\max} \\ E_{hs}^{\min} \leqslant E_{hs}^t \leqslant E_{hs}^{\max} \\ E_{hs}^{24} = E_{hs}^0 \end{cases} \tag{28}$$

$$\begin{cases} E_{cs}^{t+1} = E_{cs}^t(1-\delta_{cs}) + \left(P_{cs,c}^t \eta_{cs,c} - \frac{P_{cs,d}^t}{\eta_{cs,d}} \right) \Delta t \\ 0 \leqslant P_{cs,c}^t \leqslant u_{cs} \cdot P_{cs,c}^{\max} \\ 0 \leqslant P_{cs,d}^t \leqslant (1-u_{cs}) \cdot P_{cs,d}^{\max} \\ E_{cs}^{\min} \leqslant E_{cs}^t \leqslant E_{cs}^{\max} \\ E_{cs}^{24} = E_{cs}^0 \end{cases} \tag{29}$$

(3) Constraints on the performances of devices

All the devices should work between their lower and upper limits. Assuming that $P_{gt}^{\max}$, $H_{gb}^{\max}$, $H_{ac}^{\max}$, $P_{ec}^{\max}$, $P_{ice}^{\max}$, $P_{pv}^{\max}$, $P_{wt}^{\max}$ are respectively the maximum output power limits for gas turbine, boiler, absorption chiller, electric chiller, ice storage conditioner, PV and WT. Constrains are given in (30).

$$\begin{cases} 0 \leqslant P_{gt}^{t} \leqslant P_{gt}^{\max} \\ 0 \leqslant H_{gb}^{t} \leqslant H_{gb}^{\max} \\ 0 \leqslant H_{ac}^{t} \leqslant H_{ac}^{\max} \\ 0 \leqslant P_{ec}^{t} \leqslant P_{ec}^{\max} \\ 0 \leqslant P_{ice}^{t} \leqslant P_{ice}^{\max} \\ 0 \leqslant P_{pv}^{t} \leqslant P_{pv}^{\max} \\ 0 \leqslant P_{wt}^{t} \leqslant P_{wt}^{\max} \end{cases} \tag{30}$$

(4) Constraints for the performances of the tie-lines

The electricity exchanged with utility grid should not exceed the maximum capacity of the tie-line between MEG and utility grid. Furthermore, the nature gas purchased from gas grid can't surpass the maximum capacity of the tie-line between energy hub and gas grid.

$$\begin{cases} -P_{grid}^{\max} \leqslant P_{grid} \leqslant P_{grid}^{\max} \\ 0 \leqslant P_{gas} \leqslant P_{gas}^{\max} \end{cases} \tag{31}$$

where $P_{grid}^{\max}$ and $P_{gas}^{\max}$ are respectively the maximum capacity of the electrical tie-line and gas tie-line.

3.4.3. Descriptions for mathematical model and solution algorithm

The optimal operation mathematical model proposed above is 0–1 mixed integer linear programming problem essentially. The 0–1 variables are introduced to guarantee the charging and discharging process of energy storage device will not run simulta-

4. Case studies

In order to investigate the effects of renewable resources, energy storage devices and demand response programs on the optimal operation of MEG, four cases are studied according to Table 1. The symbol × represents that the energy hub illustrated in Fig. 3 does not include the device or DR program in this case, on the contrary, the sign √ indicates that the energy hub contains the device or DR program. To be specific, the energy hub doesn't contain PV, WT, energy storage devices or DR program in case 1 and the energy hub is a typical CCHP system this moment. For case 2, the energy hub is equipped with CCHP, PV and WT without considering any energy storage devices or DR programs. For case 3, the energy hub contains CCHP, PV, WT and energy storage devices but doesn't implement the DR program. However, the CCHP, PV, WT, energy storage devices and DR program are all considered in case 4. In addition, case 1, case 2, case 3 all implement the TOU tariff while case 4 takes the RTP tariff shown in Fig. 5.

4.1. Parameters for the energy hub

The parameters for Electricity/cold/heat energy storage devices are given in Table 2. The parameters for CCHP devices, gas tariff, carbon emission coefficient, carbon emission management coefficient and other parameters are given in Table 3. The predicted outputs of PV and WT are shown in Fig. 4. The detailed time of use pricing and real time pricing calculated with the model proposed above are illustrated in Fig. 5. Furthermore, the power loads, cooling loads and heating loads for the MEG on a typical summer day are shown in Fig. 6. Two assumptions are made, the first one is assumed that the load demands, the output powers for each device and the electricity tariff remain constant at each time step. Another one is deemed that the outputs of PV/WT and the day-ahead forecast data for the power, cooling and heating demands are precise.

As illustrated in Fig. 7, the electricity load demands can be calculated with different values of demand-price elasticity coefficient E basing on the DR model proposed above. The results indicate that the DR model proposed in this paper could play a considerable role in peak load shaving and valley load filling. The bigger the absolute value of E is, the more obvious the effect of DR model on peak load shaving and valley load filling will be. To be representative, the demand-price elasticity coefficient is assumed to be −0.3 for case 4.

4.2. Optimal dispatch results analysis of energy flow at sub-energy hub in various cases

hub under different cases are respectively illustrated in Figs. 8–10. For Figs. 8–10, the upper part of the abscissa axis represents the energy injected into the sub-energy hubs while the lower part indicates the energy flowed out from the sub-energy hubs. Table 4 presents the results of various costs in four cases. It is worth mentioning that the net electricity cost in the table is equal to purchase cost minus sale revenue and \$ 1 USD is about ¥ 6.77 RMB.

From the optimal dispatch results of energy flow at sub energy hub in four scenarios (shown in Figs. 8–10), the following characteristics can be found:

(1) As shown in Figs. 8 and 9, the gas turbine does not work when the electricity tariff is quite low while the demanded electricity is mainly purchased from the utility grid. Almost all the demanded heat are supplied by the gas boiler, while the cooling demands are all supplied by the electric chillers. During the periods (such as 8:00–22:00) when electricity price is relatively high, the gas turbine starts to generate electricity and co-product heat. The power demands and

Table 1
Classifications of case studies.

Case studies	CCHP	PV + WT	ES			DR	Electricity Tariff
			ESD	HSD	CSD		
Case 1	√	×	×	×	×	×	TOU
Case 2	√	√	×	×	×	×	TOU
Case 3	√	√	√	√	√	×	TOU
Case 4	√	√	√	√	√	√	RTP

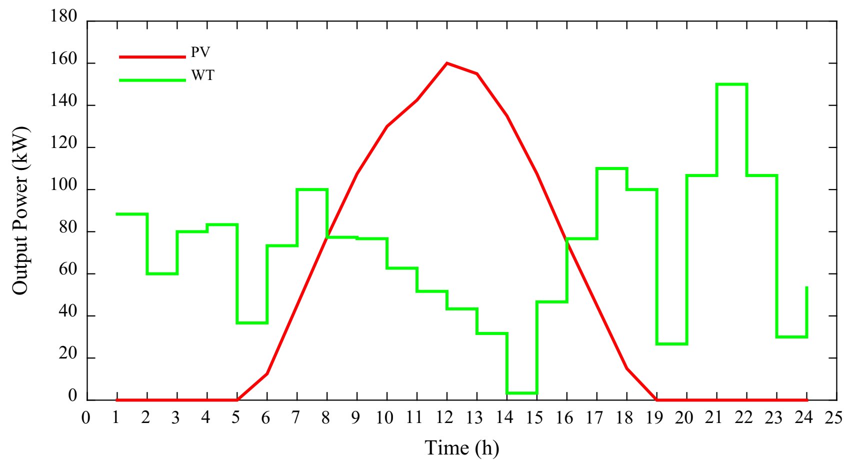


Fig. 4. Output power of PV and WT.

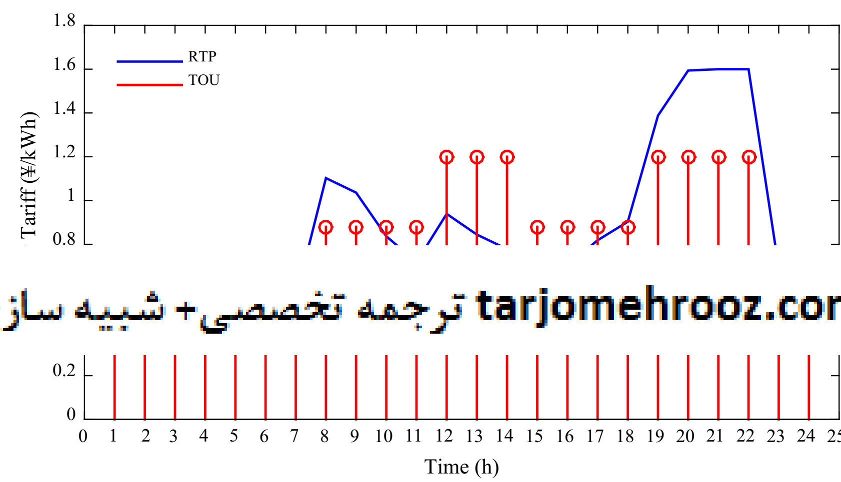


Fig. 5. The TOU and RTP.

Table 2
Parameters for energy storage devices.

$P_{es,c}^{max}$ (kW)	$P_{es,d}^{max}$ (kW)	E_{es}^{min} (kW h)	E_{es}^{max} (kW h)	$\eta_{es,c}$	$\eta_{es,d}$	δ_{es}
500	700	400	1800	0.96	0.96	0.01
$P_{hs,c}^{max}$ (kW)	$P_{hs,d}^{max}$ (kW)	E_{hs}^{min} (kW h)	E_{hs}^{max} (kW h)	$\eta_{hs,c}$	$\eta_{hs,d}$	δ_{hs}
800	800	400	1800	0.98	0.98	0.02
$P_{cs,c}^{max}$ (kW)	$P_{cs,d}^{max}$ (kW)	E_{cs}^{min} (kW h)	E_{cs}^{max} (kW h)	$\eta_{cs,c}$	$\eta_{cs,d}$	δ_{cs}
700	800	400	1800	0.97	0.95	0.02

Table 3
Parameters for CCHP, PV, WT and Carbon emission coefficients and price.

P_{gt}^{max} (kW)	H_{gb}^{max} (kW)	H_{ac}^{max} (kW)	P_{ec}^{max} (kW)	P_{ice}^{max} (kW)	P_{pv}^{max} (kW)
1000	800	1000	500	100	180
P_{wt}^{max} (kW)	η_{ge}	$\eta_{gh,gb}$	$\eta_{gh,gt}$	η_t	COP_{ec}
200	0.3	0.9	0.4	0.98	4
COP_{ac}	COP_{ice}	ε (¥/kg)	β_e (kg/kWh)	β_g (kg/kWh)	p_g (¥/kWh)
1.2	3.5	0.031	0.972	0.23	0.35
P_{grid}^{max} (kW)	P_{gax}^{max} (kW)	RTP_{min} (¥)	RTP_{max} (¥)		
1500	3400	0.3	1.6		

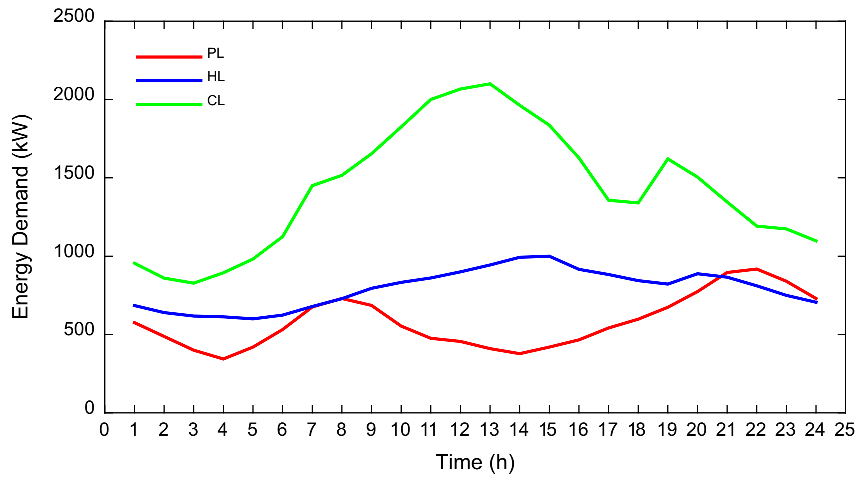


Fig. 6. The power, cooling and heating loads for micro energy grid on typical summer day.

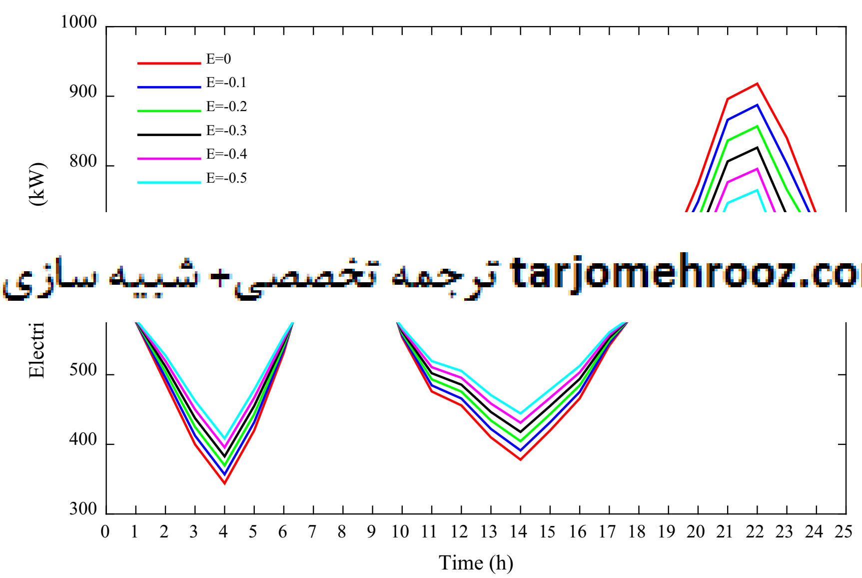


Fig. 7. The electricity demands with different values of *E*.

heat demands are mainly supplied by the gas turbine. Limited by the heat capacity of gas turbine, the cold supply are shared by electrical chiller, absorption chiller and the ice storage conditioner.

(2) The PV only work from 6:00 am to 18:00 pm during the daytime while the WT will work day and night if the wind speed is high enough. The PV and WT will meet a portion of electricity load to reduce the electricity cost or bring some revenues through selling electricity to the utility grid when their output power is redundant. With considering the contribution of PV and WT, as shown in Table 4, the total cost for case 2 is ¥20068.3 which is obviously smaller than ¥22714.6 for case 1. Besides, as demonstrated in Fig. 7, the demand response programs play a vital role in peak load shifting and valley filling which will not only bring significant economic benefits (as shown in Table 4) but also lead to more efficient operation of micro energy grid.

(3) From the case 3 and case 4 in Figs. 8–10, it can be seen that the electricity energy storage devices will charge when the electricity is redundant or the electricity tariff is high, otherwise, the batteries will discharge. Likewise, the heat energy storage devices will store heat when the heat is redundant, while release heat when heat supply is insufficient to meet heat demand. During off-peak hours, the ice storage conditioner will work in the ice-making mode to store ice, while the ice will be melt to meet the cooling load when electricity tariff is high or the cold supply is insufficient. So it can be seen that the electricity/heat/cold energy storage devices play a vital role in load balance and load shifting. Besides, comparing the operation cost of case 2 and case 3 in Table 4 can be found that energy storage devices can reduce operation cost considerably. The detailed states (charging/discharging processes) of energy storage devices in case 3 and case 4 are respectively illustrated in Appendix A Figs. A1 and A2.

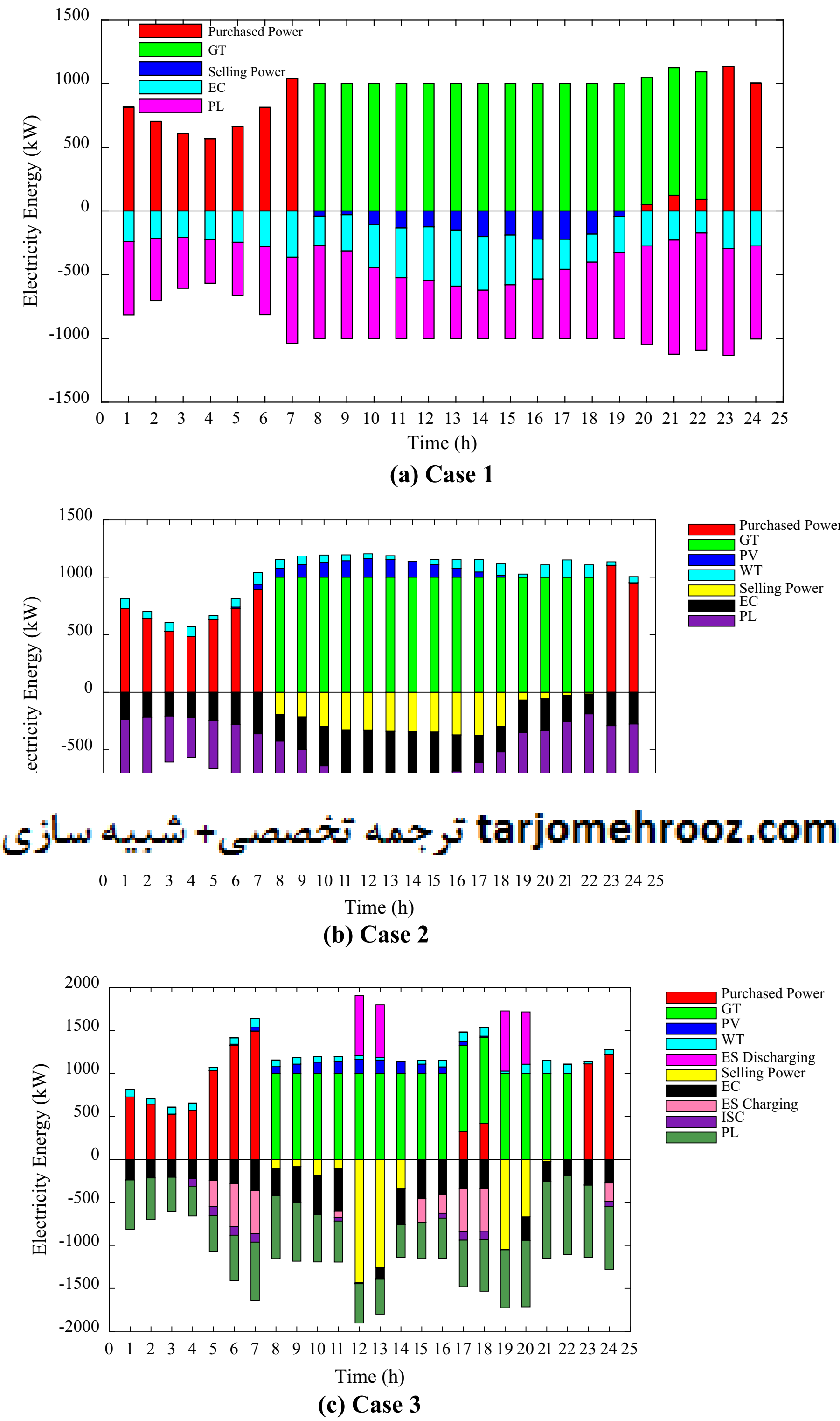
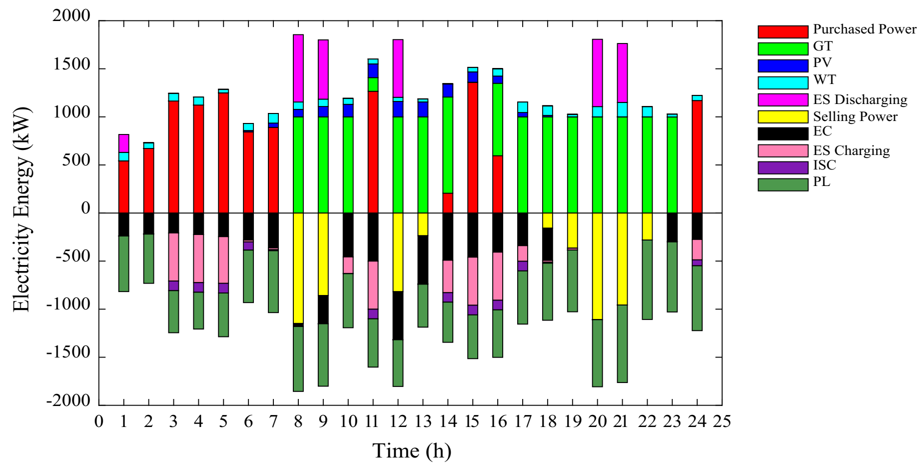


Fig. 8. Optimal dispatch results of power flow at power hub in different cases.

As discussed above, the optimal dispatch results demonstrate that the great advantages of micro energy grid are mainly reflected in the following aspects. (1) The MEG can realize the cascade utilization of energy, the complement and coordinated operation of multi energy carriers, which will not only decrease the operation cost but also improve the energy efficiency considerably and robustness. (2) The MEG can promote the penetration of renewable energy resource, which will alleviate the power supply tension during peak hours and reduce the carbon emission. (3) With applying the electricity/heat/cold energy storage devices and implementing demand response programs, the MEG can balance the fluctuations of renewable resources and load demand. Furthermore, the tension between energy supply and demand can also be alleviated.



(d) Case 4

Fig. 8 (*continued*)

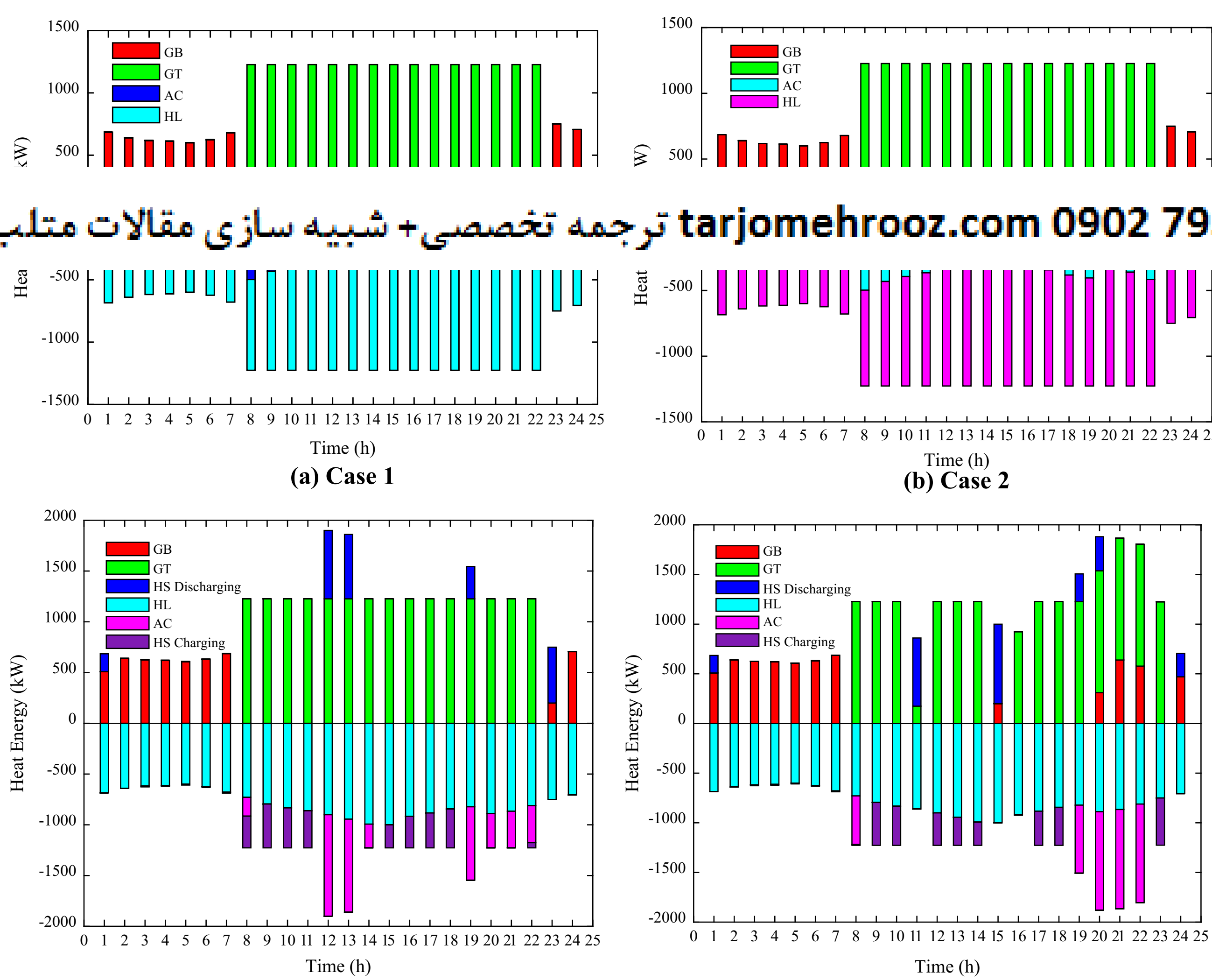


Fig. 9. Optimal dispatch results of heating flow at heating hub in different cases.

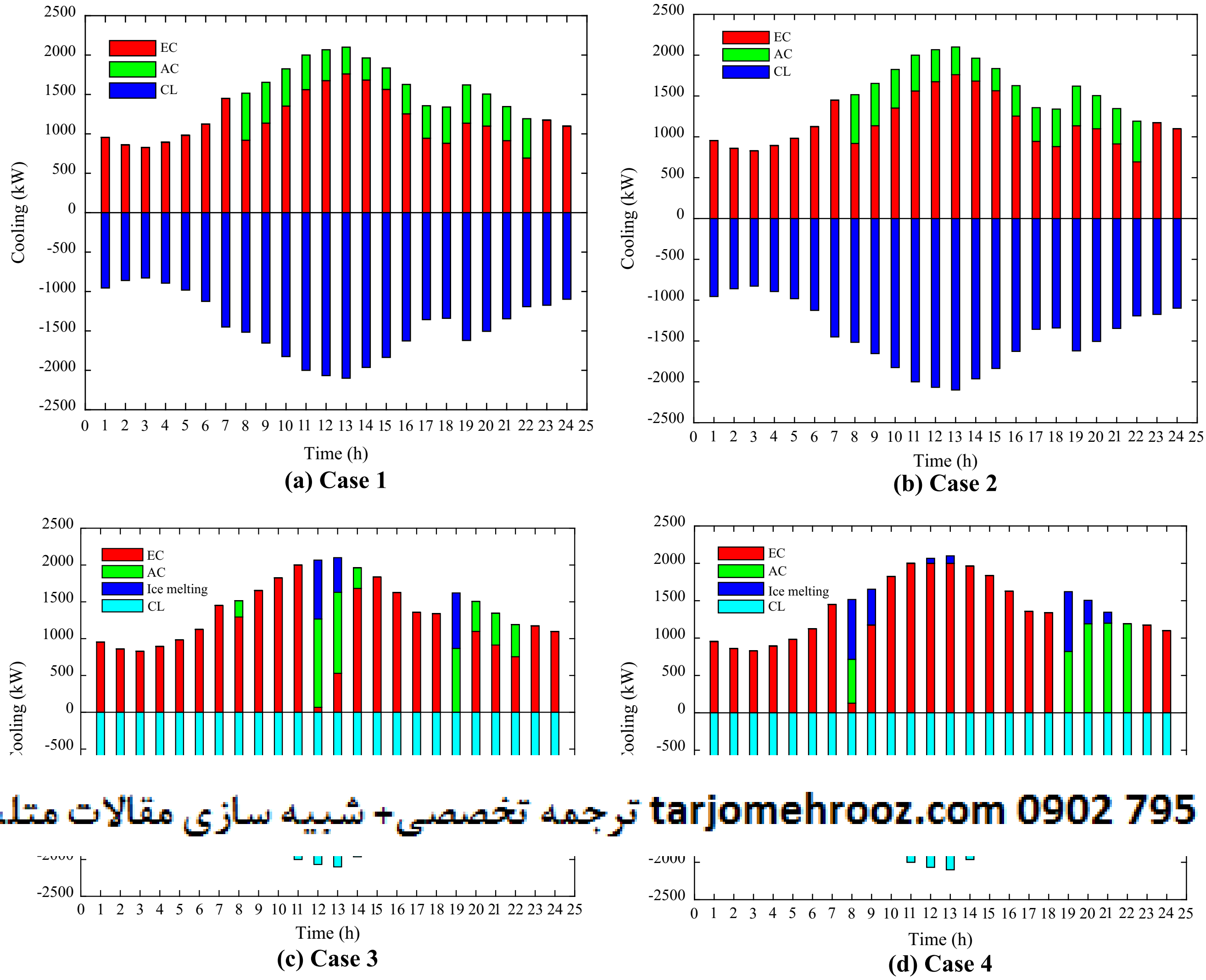


Fig. 10. Optimal dispatch results of cooling flow at cooling hub in different cases.

Table 4
The daily operation cost of micro energy grid in different cases.

Various costs	Case 1	Case 2	Case 3	Case 4
Net electricity cost (¥)	2277.2	−340.6	−1359.1	−1954.5
Gas cost (¥)	19800	19,800	19,534	18,746
Emission cost (¥)	637.4	608.9	686.98	722.66
Total cost (¥)	22714.6	20068.3	18861.88	17514.16

5. Conclusions

An architecture for the micro energy grid basing on the energy hub is proposed in this paper as well as the sub energy hub structure. Besides, energy flow models at each sub energy hub are formulated which can intuitively reflect the energy flow of MEG. Moreover, the optimal operation model for the MEG is proposed with the objective to minimize the daily operation cost. Case studies are taken in four scenarios and critical conclusions are: (1) The MEG can realize the cascade utilization of energy, the complement and coordinated operation of multi energy carriers, which will decrease the operation cost and improve the energy efficiency considerably. (2) The MEG will promote the penetration of renewable energy resource, which will alleviate the power supply tension during peak hours and reduce the carbon emission. (3) Energy storage devices and demand response programs can not only balance the fluctuations of renewable resources and load demand but also alleviate the tension between energy supply and demand.

The proposed energy hub architecture based on sub energy hub and the optimal operation model are generic methods for analyzing the energy flow and the economic dispatch problem of micro energy grid. The generic modeling method can be easily expanded to investigate more complex energy systems. However, the analysis tool proposed in this paper is only suitable for analyzing the steady state energy flow of MEG at present. In our future work, the randomness of renewable energy and the dynamic characteristics of equipment will be considered. Besides, the energy flow modeling method and the analysis tool will be expanded to be suitable for analyzing the dynamic energy flow.

Appendix A

See Figs. A1 and A2.

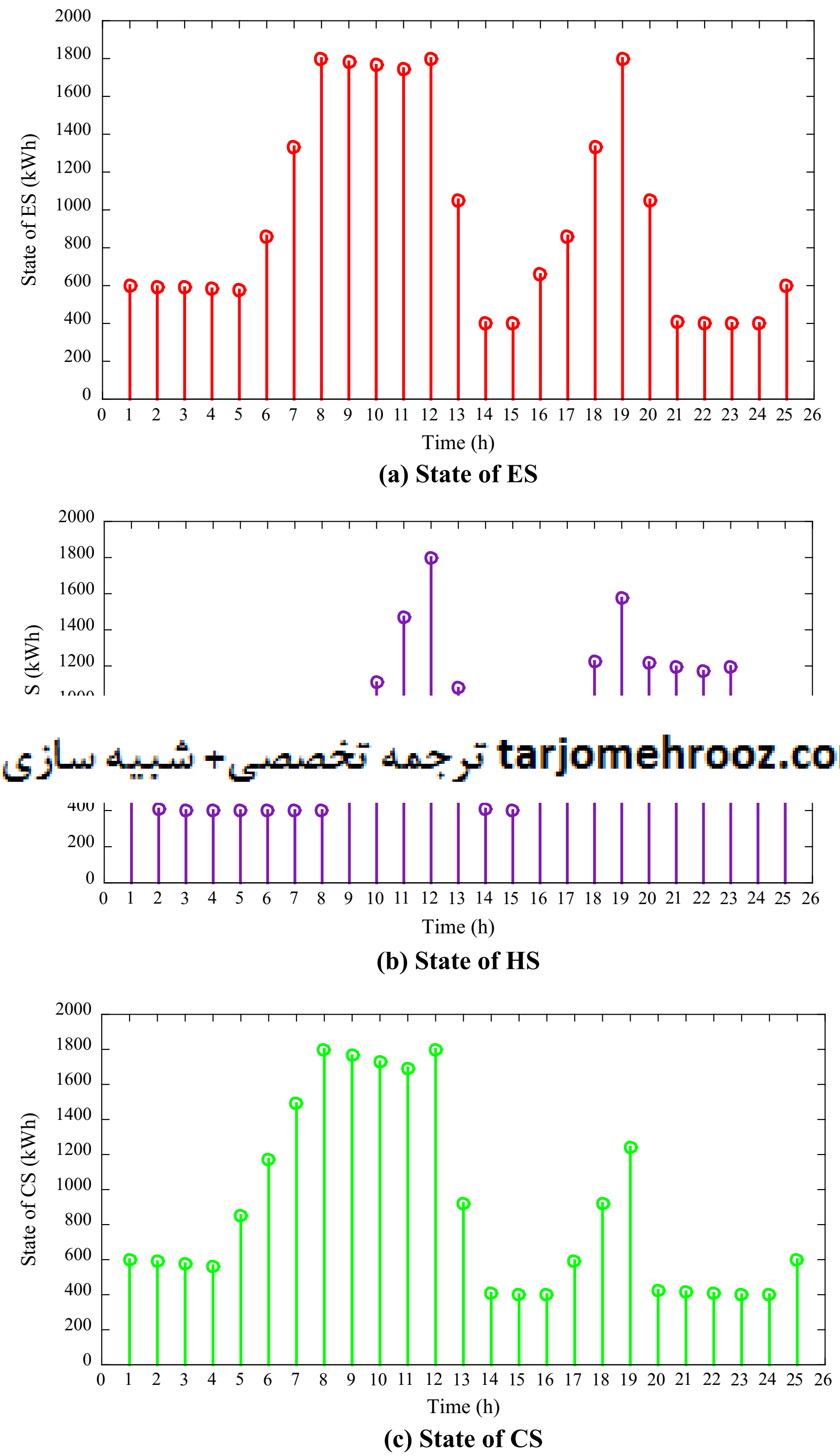
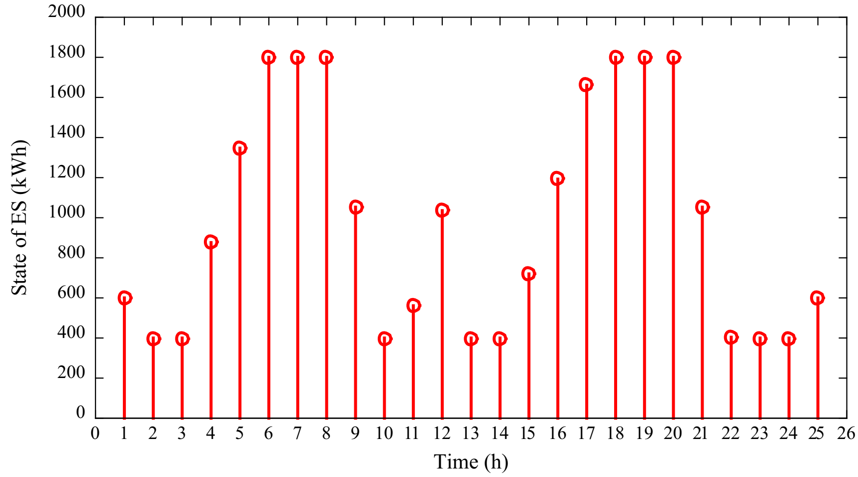
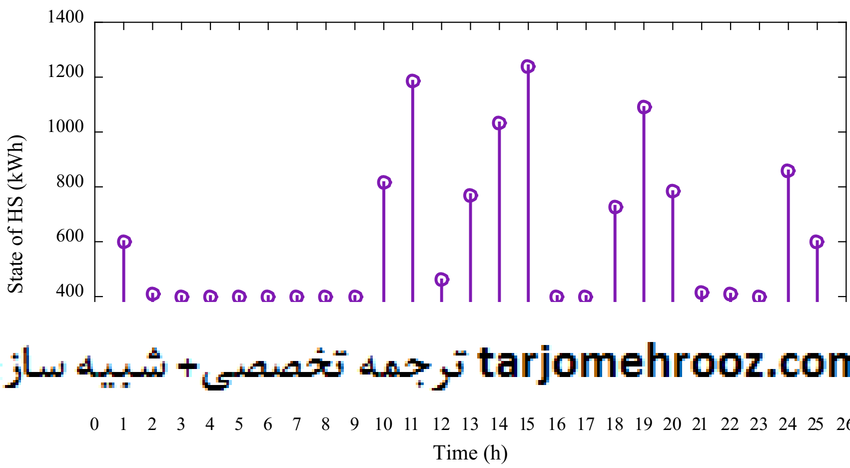


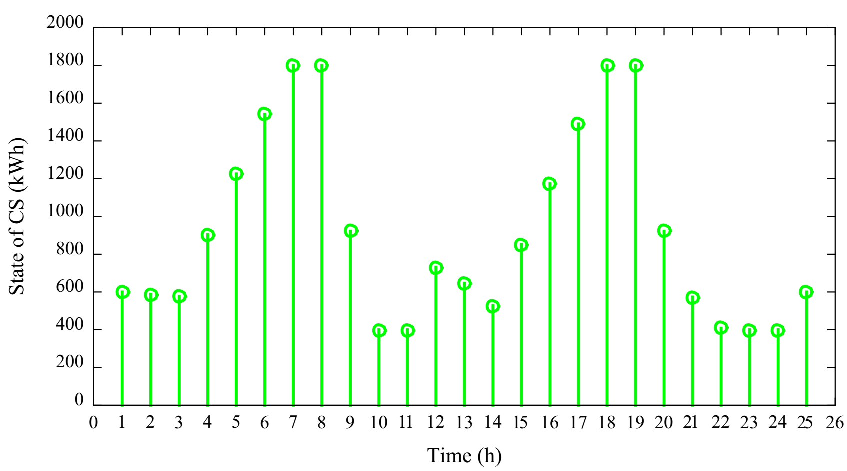
Fig. A1. State of ES, HS and CS in case 3.



(a) State of ES



(b) State of HS



(c) State of CS

Fig. A2. State of ES, HS and CS in case 4.

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