Energy hub model for energy management in energy internet

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Abstract: In this study, a novel model of energy hub is proposed, which can promote the utilisation of clean energy and energy efficiency, and achieve the purpose of the local energy consumption. Secondly, based on the framework of interconnected energy hubs, call action is applied in energy internet. Then, a distributed energy management strategy is designed for energy hubs by consistency theory. Case studies show that the price adjustment mechanism is stable with more than 500 energy hubs and the price adjustment tends to a constant value after 15 times. Compared with traditional energy management, the management strategy proposed in this study is more beneficial for both surplus-hubs and short-hubs.

1 Introduction
The pressures of the energy crisis and environmental pollution have prompted people to reflect on the existing energy consumption patterns and begin to study the comprehensive utilisation of various forms of energy such as electricity, gas, and heat [1]. In recent years, with the development of cogeneration technology and the deepening of the concept of energy interconnection [2–4], the coupling relationship between multi-energy systems has gradually attracted attention [1, 5–7]. The coupling between multiple energy sources is reflected in all aspects of production and life [8]. On the energy production side, such as cogeneration plants, natural gas wells are consumed to provide electricity and heat. On the energy consumption side, users can choose different energy supply forms to meet demand, such as the complementary heating of air conditioning and heating.

Energy hub is a typical multi-input multi-output, multi-level energy flow and information flow integration interconnect node, which is shown as Fig. 1. As the interface between energy producers and energy consumers, energy hub describes the transmission, conversion, and storage of multiple energy and energy forms. Based on the energy hub model, a series of studies have been carried out [9–15]. Aiming at the problem of energy complementary potential mining, maximising renewable energy utilisation and minimising operating costs, a coordinated operation model of multi-integrated energy systems based on linear coupling relationship was established in [9]. In order to establish an accurate interconnected energy hub model, the linear weighted sum algorithm and the grasshopper optimisation algorithm were combined to propose a comprehensive strategy to solve energy management problems, improved energy comprehensive efficiency, and achieved regional coordination optimisation. An intelligent energy hub optimisation operation framework based on scenario/interval/information gap hybrid decision theory was proposed in [10]. The effects of economic priority, distribution network technology constraints and uncertainty on the optimal operation of smart energy hubs were studied. Considering that smart hubs have smart facilities, demand side management plans include price response and load response services to motivate power consumers to modify their consumption patterns to meet the economic priorities of energy hubs. A two-layer stochastic programming model for energy hubs was proposed in [11], where the profit maximisation of the hub managers and the minimisation of customer costs were the goals of the upper and lower layers, respectively. A new framework for energy management of renewable energy residential energy hubs based on probability optimisation was proposed in [12]. The Energy Center considers different energy converters and storage, including cogeneration, plug-in hybrids, thermal storage units, solar panels, and general household appliances. Sheikhi et al. [13] modelled the smart energy hub and proposes a modern energy management technology for electric power natural gas network based on integrated demand side management, in which the interaction among hubs was a non-cooperative game. Zhang et al. [14] proposed long-term optimisation and expansion planning for energy hubs of various energy carriers such as electricity, natural gas, and thermal energy. In addition, the energy efficiency, emissions, and reliability matrices were considered the evaluation criteria for optimal planning to minimise the cost planning of the constrained energy infrastructure that meets the hub load within the scope of the plan. Sun et al. [15] proposed an energy hub dual control scheme that takes into account both safe operation and economic benefits. The scheme consisted of energy hub output and internal equipment control. The control method of the energy hub output can proportionally distribute the electrical output and heat output of the energy hub.

At present, there are a lot of researches on multi-energy system coupling architecture and operation methods based on various energy carriers such as electricity, gas, and heat. Sheikhi et al. [13] propose a long-term optimal expansion planning of an energy hub with multiple energy carriers including electricity, natural gas, and heat. Additionally, energy efficiency, emission, and reliability matrices are considered as evaluation criteria for optimal planning. Fan et al. [16] model smart energy hub and propose a modern energy management technique in electricity and natural gas networks based on integrated demand side management. Fan et al. [16] developed a cooperative scheduling model for multiple energy hubs, where energy hubs not only coordinate their local operations but also conduct energy trading with each other. Utilise a distributed solution to solve the bargaining problem, which can effectively guarantee the autonomous scheduling and information privacy of energy hubs. Alipour et al. [17] propose a new framework for home energy management in the context of renewable-based residential energy hub using a probabilistic optimisation approach. Bahrami and Sheikh [18] conducted an...
optimal 24-h energy hub scheduling considering most technical constraints of energy hubs – converters and storages as well as pool market and load uncertainties. Point estimate method is implemented to handle the problem, which has superiorities over other uncertainty modelling approaches. A comprehensive linearised model for optimal design and operation of energy hubs considering reliability constraints is proposed in [19]. Zhang et al. [20] present a reliability-based optimal planning model for interconnection of energy hubs with multiple energy infrastructures.

As a typical multi-energy interface device, the current research on energy hub mainly focuses on energy management and scheduling. Bahrami et al. [21] characterised a precise potential function of the energy centre interaction game and proved that the unique Nash equilibrium corresponds to the global maximum of the potential function. Nash equilibrium is an important step for the energy hub to achieve optimal operation because, in the non-cooperative game, the existence and uniqueness of the neural network under the simple strategy are not guaranteed. Utilising the flexibility of energy resources in smart cities, Huo et al. [22] solved the optimal energy flow of adjacent energy hubs under the condition of uncertain renewable power generation, so as to minimise energy costs. Opportunistic constraints were used to model the power and natural gas flows among hubs, to allow for temporary overloads. In [23], a hybrid random/information gap decision theory method was used to evaluate the scheduling problem of the energy hub system consisting of wind turbines, CHP, auxiliary boilers and energy storage equipment. Above all, the existing results mainly focus on the hub model, hub demand response, and hub planning. However, these three aspects have not been comprehensively considered, and the overall design of the energy hub has been optimised. In this study, a novel model of energy hub is proposed, which can promote the utilisation of clean energy and thermal energy, and achieve the purpose of the local energy consumption. Secondly, based on the framework of interconnected energy hubs, call action is applied in energy internet. Then, a distributed energy management strategy is designed for energy hubs by consistency theory.

The rest of this paper is organised as follows. In Section 2, a novel model of energy hub is proposed, which can realise the bidirectional transmission of electric energy and thermal energy. In Section 4, several simulation cases are given to show the effectiveness of the proposed price adjustment and bidding strategy. The conclusion is drawn in Section 5.

## 2 Model of energy hub

As an energy interface, energy hub plays a role in integrating and converting energy. Energy hub is an important component in energy internet, which realises integrated energy management by interconnection among multiple energy hubs. Energy hub can be regarded as a black box, where energy flows from input port to output port. Input ports of energy hubs connect to each other through energy links, and output ports of energy hubs connect to a certain energy area. A conventional energy hub model contains energy transmission, energy conversion, and energy storage and energy can only flow from the input port to the output port [2]. However, in the energy internet, the energy areas connected with output ports of energy hubs not only consist of electrical loads and heat loads but also equip with distributed generation. A structure of novel energy hub with a smart house is presented in Fig. 2. The house is equipped with electric loads, gas loads, heat loads and solar cells, which can be self-sufficient through photovoltaic power generation and can also interact with other energy areas through energy hub. The novel energy hub consists of solid state transformer (SST), battery, electric boiler (EB), micro-turbine (MT), heat exchanger, heat storage (HS), which can realise the generation of electric energy and heat energy, the conversion of electric energy to heat energy, storage of electric energy and heat energy.

Different from previous researches on energy hub, the novel energy hub proposed in this study can realise the bidirectional transmission of electric energy and thermal energy. When a house has excess electric energy, it can output electric energy to an input port in reverse through SST or convert electric energy to heat energy by an electric boiler. Here, we assume that if the inlet temperature of the heating pipe network is higher than the outlet, the heat energy flows from the input port to the output port, and if the inlet temperature of the heating pipe network is lower than the outlet, the heat energy flows from the output port to the input port.

### 2.1 Energy transmission

Energy is inevitably lost due to the effect of resistance during transmission. The output port energy quality is assumed as a fixed value, which the voltage of the output port is $u_{0}^{\text{out}}$, the fluid velocity of the output port is $u_{0}^{\text{out}}$, and the gas pressure of the output port is $P_{0}^{\text{out}}$. According to the system structure shown in Fig. 1, the active power loss $\Delta P_{\text{e,1}}$ in the energy hub can be expressed as

$$\Delta P_{\text{e,1}} = \frac{r_{1}}{r_{1} + j \chi_{1}} (u_{0}^{\text{in}} - u_{0}^{\text{out}})^{2},$$

where $r_{1} + j \chi_{1}$ is the line impedance between the input port and output port and $u_{0}^{\text{in}}$ is the voltage of the input port.

In the heating pipe network, the heat energy quality of the fluid mainly includes temperature and flow rate. According to the calculation formula of heat, the heat power is used to characterise the heat transfer speed of the pipeline, which can be expressed as

$$P_{h} = c_{\text{liq}} m_{\text{liq}} \Delta T_{\text{liq}},$$

where $P_{h}$ is the heat power, $c_{\text{liq}}$ is the specific heat capacity of liquid, $m_{\text{liq}}$ is the mass flow rate, $\Delta T_{\text{liq}} = T_{\text{liq}}^{\text{in}} - T_{\text{liq}}^{\text{out}}$ is the temperature difference of liquid between inlet and outlet.

Thus, the heat power loss $\Delta P_{\text{h,1}}$ in the energy hub can be expressed as
\[ \Delta P_{\text{h,1}} = \eta_{\text{h,1}} \rho_{\text{h,1}} \Delta v_{\text{pipe}} \left( T_{\text{h,1}}^{\text{in}} - T_{\text{h,1}}^{\text{out}} \right) \]  

where \( \rho_{\text{h,1}} \) is the liquid density, \( S_{\text{pipe}} \) is the cross-sectional area of the pipe.

In the gas pipeline network, gas quality mainly includes gas density, gas velocity, and gas pressure. According to the state equation of ideal gas, the relationship between gas density and gas velocity can be expressed as

\[ p_{\text{gas}} M_{\text{gas}} = \rho_{\text{gas}} R T_{\text{gas}}, \]  

where \( p_{\text{gas}} \) is the gas pressure, \( M_{\text{gas}} \) is the molar mass, \( \rho_{\text{gas}} \) is the gas density, \( R \) is the gas constant, and \( T_{\text{gas}} \) is the gas temperature.

According to (4), the gas density at each point in the pipeline can be expressed as

\[ \Delta \rho_{\text{gas}} = \frac{M_{\text{gas}}}{RT_{\text{gas}}} (p_{\text{gas}}^{\text{in}} - p_{\text{gas}}^{\text{out}}). \]  

Thus, the loss of gas mass flow rate \( \Delta m_{\text{h,1}} \) in the energy hub can be expressed as

\[ \Delta m_{\text{h,1}} = \Delta \rho_{\text{gas}} V_{\text{gas}} S_{\text{pipe}}. \]

### 2.2 Energy conversion

In the energy hub, the micro-turbine generates heat by burning gas, in which high-grade heat energy with higher pressure and temperature is converted into electric energy, and low-grade heat energy is supplied to the heat load through the heat exchanger. The conversion relationship of the micro-turbine can be expressed as

\[
\begin{align*}
\eta_{\text{MT}}^\text{gas} P_{\text{MT}}^\text{gas} &= M_{\text{gas}} \rho_{\text{gas}} R T_{\text{gas}}, \\
\eta_{\text{MT}}^\text{electric} P_{\text{MT}}^\text{electric} &= \eta_{\text{MT}}^\text{gas} M_{\text{gas}} \rho_{\text{gas}} R T_{\text{gas}},
\end{align*}
\]

where \( P_{\text{MT}}^\text{gas} \) and \( P_{\text{MT}}^\text{electric} \) are the electric and power heat generated by micro-turbine, \( \eta_{\text{MT}}^\text{gas} \) and \( \eta_{\text{MT}}^\text{electric} \) are the efficiency of converting gas into electrical energy and low energy, \( C_{\text{low}} \) is the low caloric value of gas, \( m_{\text{E,MT}} \) is the inlet mass flow rate of micro-turbine.

As an alternative common energy conversion device in the energy hub, the electric boiler can convert electrical power into heat power to provide heat energy to the liquid in the heating pipe network. The conversion relationship of the electric boiler can be expressed as

\[ P_{\text{EB}}^\text{electric} = \eta_{\text{EB}} P_{\text{EB}}^\text{electric}. \]

where \( P_{\text{EB}} \) is the input electric power, \( P_{\text{EB}}^\text{electric} \) is the output heat power, and \( \eta_{\text{EB}} \) is the conversion efficiency of electric boiler.

### 2.3 Energy storage

As an important part of the energy hub, energy storage devices can improve energy efficiency and reduce energy costs. In the energy hub, energy storage mainly includes electric storage and heat storage. Excess energy or cheap energy at a certain time can be stored in energy storage devices, and released at the time when energy is short or at high prices [23]. Different from other equipment, energy storage equipment needs to consider many conditions during charging and discharging, including charging and discharging state, charging and discharging energy power limit, and state of charge. The model of energy storage can be expressed as

\[
\begin{align*}
P_{\text{ES}}^\text{charge} &= \chi_{\text{ES}}^\text{charge} P_{\text{ES}}^\text{charge}, \\
P_{\text{ES}}^\text{discharge} &= \chi_{\text{ES}}^\text{discharge} P_{\text{ES}}^\text{discharge}, \\
P_{\text{HS}}^\text{charge} &= \chi_{\text{HS}}^\text{charge} P_{\text{HS}}^\text{charge}, \\
P_{\text{HS}}^\text{discharge} &= \chi_{\text{HS}}^\text{discharge} P_{\text{HS}}^\text{discharge},
\end{align*}
\]

where \( P_{\text{ES}}^\text{charge} \) and \( P_{\text{HS}}^\text{charge} \) represent the power of electric storage or heat storage, \( \chi_{\text{ES}}^\text{charge} \) and \( \chi_{\text{HS}}^\text{charge} \) represent charging and discharging power, here, \( x \) represents the type of energy storage, which can be electric storage or heat storage. According to the conditions of energy storage equipment, energy storage is subject to the following constraints:

\[
\begin{align*}
\chi_{\text{charge}}^x + \chi_{\text{discharge}}^x &\leq 1, \\
\chi_{\text{charge}}^x - \chi_{\text{discharge}}^x &= 0, \\
\chi_{\text{charge}}^x P_{\text{charge}}^x &\leq \chi_{\text{discharge}}^x P_{\text{discharge}}^x, \\
\chi_{\text{discharge}}^x P_{\text{discharge}}^x &\leq \chi_{\text{charge}}^x P_{\text{charge}}^x, \\
E_{\text{ES}}^{x+1} &= E_{\text{ES}}^x (1 - \delta_t) + (\theta_{\text{charge}}^x P_{\text{charge}}^x - \theta_{\text{discharge}}^x P_{\text{discharge}}^x) \Delta t,
\end{align*}
\]

where \( P_{\text{charge}}^x \), \( P_{\text{discharge}}^x \), \( P_{\text{charge}}^x \), and \( P_{\text{discharge}}^x \), respectively, represent the upper and lower limits of charging and discharging energy, \( \delta_t \) represents energy loss rate of energy storage, \( \theta_{\text{charge}}^x \) and \( \theta_{\text{discharge}}^x \) represent the efficiency of charging and discharging energy, \( E_x \) represents energy storage equipment capacity, which is subject to the following constraint:

\[ E_{\text{ES}}^{\text{max}} \leq E_x \leq E_{\text{ES}}^{\text{max}}. \]
where \( E_{\text{min}}^{\text{en}} \) and \( E_{\text{max}}^{\text{en}} \) represent minimum energy storage and maximum energy storage.

2.4 Integrated model of energy hub

According to the traditional hub model, the coupling matrix in this study can be expressed as

\[
\begin{bmatrix}
P_e^{\text{in}} \\
\dot{m}_e^{\text{in}}
\end{bmatrix} = 
\begin{bmatrix}
\lambda_{e1} & \lambda_{e2} & \ldots & \lambda_{eN_e} \\
\lambda_{s1} & \lambda_{s2} & \ldots & \lambda_{sN_s}
\end{bmatrix}
\begin{bmatrix}
P_e^{\text{out}} \\
\dot{m}_e^{\text{out}}
\end{bmatrix} - 
\begin{bmatrix}
\Delta P_e^{\text{in}} \\
\Delta m_e^{\text{in}}
\end{bmatrix},
\]

where \( \lambda \) represents the energy conversion efficiency.

3 Problem formulation

In the energy internet, multiple energy hubs are interconnected to form a regional energy autonomous system, as shown in Fig. 3. Under the normal operation of the energy internet, the energy hubs are connected to each other, and the energy internet coordination control layer communicates with each energy hub. According to the optimisation result of coordinated control, energy internet will exchange energy information in real time and send it to each energy hub. Each energy hub is optimised by its supply and demand balance and its own benefits.

3.1 Consistency theory

The essence of the consistency algorithm is to update the state parameters of the local node through the information interaction between the local node and the neighbouring node [22] so that the state parameters of each node in the topology network converge to a stable common value.

For energy hub \( i \), let \( \theta_i(k) \) represent the consistency information of hub \( i \), such as system voltage, frequency, current, liquid flow rate, gas pressure etc., where \( i \in \tau, \tau = 1, 2, \ldots, n \) is the number of hubs, \( k \) is the number of iterations. In an interconnected system among multiple energy hubs, the consistency variables of each energy hub are adjusted according to the consistency variables of their neighbours. As \( k \) increases gradually, the consistency variables of any adjacent energy hubs, \( \theta_i(k) \) and \( \theta_j(k) \), tend to be consistent, which satisfy

\[
\theta_i(k) - \theta_j(k) \rightarrow 0. \quad (15)
\]

The system converges when the state variables of all energy hubs reach agreement within the convergence condition [19]. The first-order consistency algorithm is described as

\[
\theta_i(k + 1) = \sum_{j=1}^{N} d_{ij} \theta_j(k), \quad (16)
\]

The matrix form can be expressed as

\[
\theta_i(k + 1) = D(k) \theta_i(k), \quad (17)
\]

where \( d_{ij} \) is the coefficient of the state transition matrix, which is determined by the communication network topology, \( D(k) \) is the state transition matrix.

3.2 Graph theory

Energy hubs in the energy internet exchange information through the communication network to form a distributed communication network topology. In an interconnected distributed system, \( \Lambda = \{\lambda_{ij} \mid j \in \tau\} \) represents the nodes in the network structure of the system, where \( \tau = \{1, 2, \ldots, n\} \). The weighted directed graph of \( n \) nodes corresponding to the network topology is \( G = (V, E) \), which can represent the weight relationship between the distributed network topology model and the corresponding node, where

\[
V = \{v_1, v_2, \ldots, v_n\} \text{ is the point set of distributed topology, } E = \{e_1, e_2, \ldots, e_n\} \text{ is the edge set formed by adjacent nodes. In this study, the topology of the interconnected system among multiple energy hubs is assumed as a strongly connected graph, which denotes that any two nodes } A_i \text{ and } A_j \text{ in the system can realise mutual information transmission.}
\]

The adjacency matrix \( A(G) \) of graph \( G \) is an \( n \times n \)-order matrix and the adjacency matrix is a 0–1 matrix, where diagonal elements are 0 and off-diagonal elements are \( a_{ij} \). \( D_i \) is the degree of node \( v_i \) in the graph, and \( D(G) = \text{diag}(D_1, D_2, \ldots, D_n) \). Laplace matrix of graph \( G \) can be expressed as

\[
L(G) = D(G) - A(G) = [l_{ij}], \quad (18)
\]

where \( l_{ij} \) satisfies the following conditions:

\[
l_{ii} = \sum_{j \neq i} a_{ij}, \quad (19)
\]

For an undirected graph, \( L(G) \) is a symmetric semi-definite matrix, and the eigenvalues of the matrix \( L(G) \) contain a large amount of information about the topology.

3.3 Utility function of energy hub

In this study, energy hub is assumed as an independent profit organisation, and its utility function is the amount of money saved by the energy hub. For each \( i \in \tau \), we consider the following utility function:

\[
U_i = \xi_W (P_i^{\text{en}} - P_i^{\text{min}}) + \xi_h (H_i^{\text{in}} - P_i^{\text{out}}) + \xi_b (m_i^{\text{min}} - m_i^{\text{out}}), \quad (20)
\]

where \( \xi_W, \xi_h, \xi_b \) are the price of electric, heat, and gas.

In this study, call action is applied in energy hubs. When the hub supplies energy, it is defined as surplus-hub. When the hub needs energy, it is defined as short-hub. We assume that there are surplus-hubs and short-hubs on energy internet. Each of the energy hubs uploads information to information bus including the type of trading, bidding price of buying and selling, marginal price, energy amount of demand and supply, and geographic position. On energy trading platform (ETP), the prices of surplus-hubs arrange from small to big, while the prices of short-hubs arrange from big to small

\[
s_1 \leq s_2 \leq \cdots \leq s_s, \\
b_1 \geq b_2 \geq \cdots \geq b_b,
\]

where \( s \) is the price bid by surplus-hubs and \( b \) is the price bid by short-hubs.

Also, if the trading reaches a compromise, the price bid by surplus-hub should match with the price bid by short-hub. Therefore, a certain price existing in

\[
B = \{b_1, b_2, \ldots, b_s\}
\]

should be equal to or greater than an element in \( S = \{s_1, s_2, \ldots, s_s\} \) for
achieving trading. If surplus-hubs bidding prices do not match with short-hubs bidding prices, surplus-hubs need to reduce the prices, while short-hubs need to increase the prices. To facilitate the description of the action, we assume that \( b_j \geq s_i, b_{j+1} < s_i \) to begin.

It is worth noting that due to the characters of buyers and sellers, the amount of demand or supply is more, the selling price is smaller and the buying price is bigger. In order to deal rapidly and guarantee the precise price, at the beginning of adjustment, the amplitude of variation is bigger, while with the increase of game time, the amplitude of variation is smaller gradually.

The function of price adjustment \( p_i(t, P) \) is the price of surplus-hub \( i \) under surplus power \( P \) at \( t \) time. In practice, the bigger amount of energy supply is, the more urgent supplier is to sell. The price of surplus-hub \( p_i(t, P) \) is decreasing about \( t \) and the slope is increasing gradually, namely

\[
\frac{\partial p_i(t, P)}{\partial t} < 0, \quad \frac{\partial^2 p_i(t, P)}{\partial t^2} > 0, \quad (22)
\]

\[
\frac{\partial p_i(t, D)}{\partial t} > 0, \quad \frac{\partial^2 p_i(t, D)}{\partial t^2} < 0. \quad (23)
\]

According to the call auction principle, the trading platform will deal with reported data, based on price precedence and time precedence, to find a basis price which is lower than short-hubs bidding price. Therefore, the maximum bidding pride among short-hubs will match with the minimum bidding pride among surplus-hubs firstly. If an amount of energy remained from the first trading, it will transfer to the next trading automatically. When the total amount of trading energy reaches the upper limit of surplus-hubs or short-hubs, the call action is terminated, and the market-clearing price \( \xi_c \) is decided based on the last action marginal price \( h_m \) and \( s_m \)

\[
\xi_c = \frac{h_m + s_m}{2}. \quad (24)
\]

In this study, the revenue increment of the energy hub is selected as the consistency variable. Owing to the mutual coupling between the power subsystem, the thermal subsystem and the natural gas subsystem, and the mutual conversion between the electric energy-thermal energy-natural gas, the economic benefits of the energy subsystem cannot simultaneously according to the equal micro-

4 Numerical results and discussion

4.1 Design on the function of adjustment price

According to (22) and (22), a function of adjustment price is designed as

\[
s_i^{\delta + \epsilon} = s_i^0 - \alpha_i e^{-\delta/P - \epsilon},
\]

\[
b_j^{\delta + \epsilon} = b_j^0 + \alpha_j e^{-\delta/D + \epsilon}, \quad (26)
\]

where \( \alpha \) is the coefficient of energy adjustment, \( \delta \) is the coefficient of time adjustment, \( \epsilon \) is the coefficient of solid adjustment. In the section, we assume that all of the coefficients of adjustment in surplus-hubs and short-hubs are consistent, which \( \alpha = \alpha_j = 0.01, \delta_i = \delta_j = 0.2, \) and \( \epsilon_i = \epsilon_j = 0.05. \)

The difference in the price of surplus-hubs and short-hubs are shown in Figs. 4 and 5. From Fig. 4, with the times increasing, the difference in price is decreasing, and with the amount of supply increasing, the difference in price is increasing. The price adjustment in surplus-hubs approximate 0.05 Yuan/kWh after 15 times. A similar mechanism of difference in the price of short-hubs is shown in Fig. 5. The adjustment of price with 20 kWh is \( \sim 0.21 \) Yuan/kWh for the first time.

A process of price adjustment between surplus-hubs with 0.75 Yuan/kWh and short-hubs with 0.35 Yuan/kWh is shown in Fig. 6. The amount of energy trading varies from 1 to 20 kWh. If the amount of energy trading in surplus-hubs and short-hubs are equal, the market-clearing price (MCP) appears at 0.55 Yuan/kWh when trades five times.

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4.2 Energy management among multiple energy hubs

In the energy trading, the amount of short-hubs has been forecasted in the next day which is shown as Table 1, and the amount of energy trading for each of the short-hubs is random in the interval [1 10] kW h. The bidding price of short-hubs is in the interval [0.3 0.55] Yuan/kWh and the upper bound of price in Short-hubs are different which are random in [0.6 0.8] Yuan/kWh.

For guaranteeing the stability of MCP on account of the total number of samples over 500, a solid number of surplus-hubs with 400 samples is assumed to imitate the traditional energy trading mode in Fig. 7. Owing to the supply of surplus-hubs over demand of short-hubs except for the period of 20–21, compared with the middle price 0.55 Yuan/kWh, the average MCP is 0.47 Yuan/kWh, which is more beneficial for short-hubs. Also, the surplus supply of surplus-hubs is sold to energy internet at a lower MCP.

Energy hubs trading with 600 samples are realised in Fig. 8. Compared with traditional trading mode, the average MCP is 0.53 Yuan/kWh, which is approximate to middle price. Considering the classification of energy trading among hubs, due to the amount of real-time trading in surplus-hubs more than the total demand of short-hubs during the period 2–7, therefore, the MCP is the same with trading price in the last period. Also, the surplus supply of surplus-hubs is sold to energy internet at a lower MCP.

When the demand is more than supply, the vacancy of short-hubs is supplied at a higher MCP from energy internet.

5 Conclusion

In this study, a novel model of energy hub is proposed to describe participants which differ from traditional energy trading mode.

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