A Three-Stage Multi-Energy Trading Strategy Based on P2P Trading Mode

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***Abstract*—This paper proposes a three-stage multi-energy sharing strategy for a gas-electricity integrated energy system (IES). It aims to solve the multi-energy imbalance problem among energy hubs (EHs) based on the peer-to-peer (P2P) trading mode. First, considering the characteristics of multi-energy coupling and conversion, the quantity of shareable energy is determined for EHs that participate in the P2P trading. Furthermore, EHs conduct multi-bilateral negotiations based on the Raiffa-Kalai-Smorodinsky bargaining solution (RBS) to determine the optimal energy trading price. Finally, the buyer agent and the seller agent will design the optimal energy sharing trading strategy for all EHs. Moreover, the results show that the pricing mechanism improves the fairness of satisfaction obtained by the EHs from the utility distribution, and the social welfare of the system is improved, which proves that the three-stage multi-energy sharing trading strategy is effective.**

***Index Terms*—Integrated energy system (IES), energy hub (EH), energy sharing, peer-to-peer (P2P), Raiffa-Kalai-Smorodinsky bargaining solution (RBS).**

I. Introduction

With the increase of distributed renewable energy and multi-energy loads in IES, the energy imbalance problem becomes increasingly significant [1], and the information in the energy market is becoming more and more complex and decentralized. Prosumers play a more active role in the decentralized energy market [2]. Compared with the traditional monopoly energy market, the decentralized market allows prosumers to adopt the feed-in tariff strategy and trade energy with neighboring prosumers according to personal preferences [3]. Therefore, it is important to design an appropriate energy management scheme to guarantee the stability of IES [4]. Generally, the system is installed with energy storage devices to alleviate energy imbalance, but the operation and maintenance cost is still high [5]. The energy sharing has drawn attention which solves the energy imbalance problem by encouraging energy trading among the interconnected systems [6].

A common energy sharing trading mode in the decentralized market is P2P trading [7]. For the centralized trading market, each participant has a fixed role which provides energy as a seller or consumes energy as a buyer according to bidding profile [8]. However, participants in P2P trading are usually called prosumers due to the buyer or seller role is not fixed. Moreover, trades are conducted bilaterally, and maximum financial independence, privacy, freedom of choice should be guaranteed in P2P trading markets [9]. Prosumers should make their own decisions of selling or buying energy based on energy generations, load schedules and energy prices to achieve a high energy efficiency and low energy costs [10]. Hence, the P2P trading mode can release the flexibility of prosumers by encouraging them to participate in energy management [11]. Furthermore, the P2P trading mode can incentivize prosumers to coordinate with each other, because there is no individual agent with market power [12]. The ultimate objective of P2P trading is to reduce the cost of energy purchase [13] balance local supply and demand [14] and improve social engagement of prosumers [15], [16] by incentive interaction among prosumers [17].

In the existing literature on P2P trading, many researches develop pricing mechanism to increase the benefits of participants in virtual layer. For example, a three-stage Stackelberg game for energy pricing and sharing was proposed in [18] to achieve a win-win situation for all inner participants. Similarly, dynamic price frameworks were proposed in P2P based on cooperative Stackelberg game [19], evolutionary game [20], they can help the system to reduce the cost of energy production and supply to the prosumers. A hybrid incentive method which combines feed-in tariff and flexibility grid access type was studied in [21] to increase economic viability and benefits of P2P energy markets. An optimal bidding strategy based on a double-auction mechanism was proposed in [22] to deal with the uncertainties of load demand and renewable generation in P2P. An energy trading system based on Stackelberg game was proposed in [23] for demand-side management of a neighborhood area network. A two-stage credit-based sharing model between the coordinator who manages the shared energy storage system and the prosumers who borrow the capacity and energy from the coordinator was presented in [24]. A P2P energy sharing scheme was proposed in [25] to encourage users to participate in energy management and reduce the dependence on dispatchable

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resources. However, in the above literature, the energy trading price was set by the system operator rather than determined by the prosumers, which cannot guarantee that each prosumer gains profit through P2P energy sharing.

In addition, for the participants of P2P energy sharing, they not only need to gain profits compared to the case without energy sharing, but also consider the fairness of utility distribution. A reasonable pricing method can improve the fairness of utility distribution and encourage them to participate in energy sharing. Some energy trading problem were modeled as bargaining cooperative games [26], [27]. However, they established the pricing model through Nash bargaining solution (NBS) method, each participant gains the same profits which can only ensure the absolute fairness of profit distribution, but they ignore the impact of satisfaction on fairness. If the profits of different market power are equal in the energy trading market, the trading process may be dominated by the participants with larger market power, thus reducing the satisfaction of other participants, which is detrimental to the operation of the energy trading market. RBS method focuses on the fairness of utility distribution when negotiating the trading price, and one participant considers not only its own utility relative to the minimum utility, but also the other participant's expense relative to the maximum utility. Hence, the satisfaction obtained by both participants from the negotiated price is the same, which improves the fairness of satisfaction obtained by the EHs from the utility distribution.

Furthermore, there are some research on the physical layer of P2P energy trading in the existing literature. For example, the author proposed a method based on sensitivity analysis to assess the impact of P2P transactions on the network and to guarantee that an exchange of energy does not violate network constraints [28]. Several methods were proposed in [29], [30] to reduce costs of common infrastructure and services in P2P trading. Some authors designed transparent loss allocation framework to guarantee economic efficiency and fairness [31], [32]. However, for the P2P trading among EHs, the impact of multi-energy coupling and conversion on the energy trading cannot be ignored. The multi-energy coupling and conversion are coupled with the energy trading in energy hubs. Hence, for single energy trading, some optimization methods take into account the coupling relationship, and the solution complexity is very high. This paper proposed a three-stage optimization method to deal with the coupling problem. Furthermore, the multi-energy collaborative optimization make prosumers know their multi-energy scheduling plan on the energy supply side, and they can flexibly choose to become sellers or buyers according to their multi-energy scheduling planning. Moreover, prosumers can manage their energy sharing profits and payments based on their own energy scheduling plan in P2P energy sharing [33].

For the structure of P2P trading market, the research mainly focuses on refining the trading information of prosumers, introducing intelligent pricing mechanism and demand response to enable prosumers to jointly determine the price of energy sharing, which effectively saves the energy purchase cost. Compared to the existing works, this study aims to ensure that participants get extra profits through P2P energy trading, while improving the satisfaction fairness of participants' utility distribution and

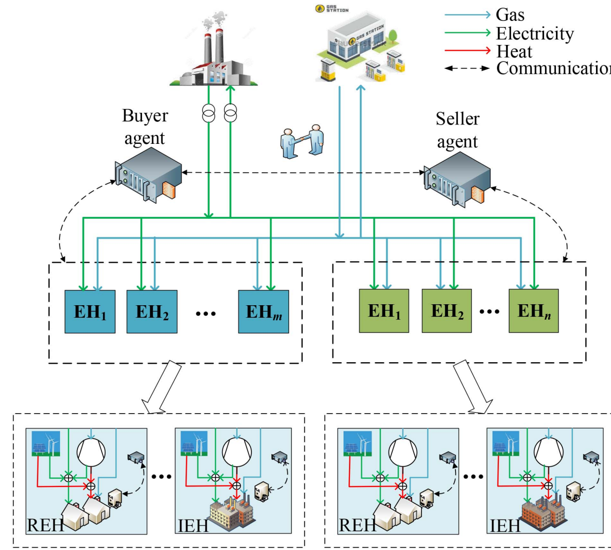

Fig. 1. System model of multi-energy trading.

social welfare of the multi-energy system. With these motivations, we designed a three-stage energy trading method for a multi-energy system based on P2P trading mode. The P2P trading mode proposed in this paper can establish an intraday market trading mechanism based on the structure of P2P trading market to improve energy efficiency and social welfare as well as the fairness of utility distribution. The major contributions of this work can be summarized as the following:

- We designed a three-stage P2P energy trading method for an IES. It combined the multi-energy sharing in physical layer and trade pricing in virtual level. The P2P energy trading method could solve the problem of local energy imbalance to some extent.
- The RBS bargaining method was used to determine the price of multi-energy trading, this method could improve the fairness of satisfaction obtained by the EHs from the utility distribution and incentive EHs to participate in the P2P multi-energy trading actively.
- Based on the pairing priority function of energy sharing, an optimal energy sharing strategy was designed for the EHs that participating in the P2P trading, so as to maximize the social welfare.

The rest of the paper are organized as follows. In Section II, the system model is established. In Section III, the P2P multi-energy trading method is proposed. In Section IV, numerical simulation and analysis are presented. Discussions are given in Section V, and conclusions are drawn in Section VI.

II. System Model

We consider the IES is composed of several regional EHs, transmission lines, natural gas pipelines, a buyer agent, a seller agent, a utility company (UC) and a natural gas company, as shown in Fig. 1. The regional EHs can connect to each other by transmission lines and natural gas pipelines, therefore it can realize energy transmission of any two EHs and ensure that

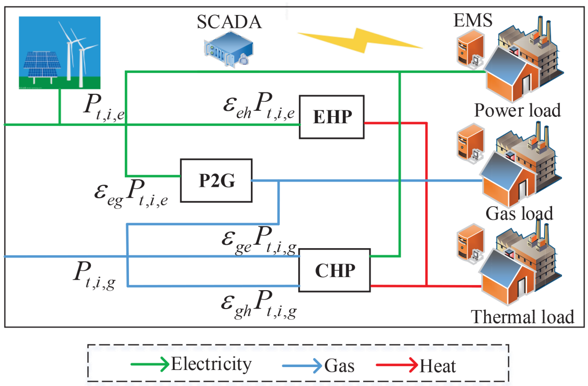

Fig. 2. Internal structure diagram of regional energy hubs.

P2P trading can be carried out in the physical level. Assuming that all regional EHs are divided into residential EHs (REHs) and industrial EHs (IEHs) according to different local load types. The living and production habits or load characteristics of residential users and industrial parks are different, which makes the EHs have the non-simultaneity of energy consumption and improves the possibility of P2P energy trading.

The regional EHs are equipped with photovoltaic generators, wind energy generators, combined heat and power (CHP) units, electric heat pumps (EHP), power-to-gas (P2G) units and an energy management systems (EMS). The internal structure diagram of regional EHs is shown in Fig. 2. The regional EHs mainly carries out data acquisition and communication through SCADA system in the supply layer and the EMS system in the demand layer. The type of communication used in supply layer is Wide Area Network (WAN) communication link, using TCP/IP communication protocol. The type of communication used in demand layer is IEEE 802.11 (WiFi) and Bluetooth protocol.

The energy input of all EHs is mainly through the external utility company and the natural gas company at wholesale prices φ_m^b or renewable energy generation. The surplus energy can also be sold to energy companies at feeder prices φ_m^s. Assuming that the load fluctuation $\triangle L$ in a period is the difference between the real-time loads and the predicted loads, the EHs that $\triangle L > 0$ constitute the buyers set {EH$_1$, EH$_2$,..., EH$_i$,..., EH$_m$}, while the EHs that $\triangle L < 0$ constitute the sellers set {EH$_1$, EH$_2$,..., EH$_j$,..., EH$_n$}. The buyer agent and the seller agent conduct multibilateral negotiation by calculating the P2P energy trading price φ_m^{ij} and energy sharing trading strategy based on the information of the buyers and the sellers. There are two ways for EH$_i$ to purchase energy: one is to purchase energy only from external energy companies at wholesale prices; the other is to conduct P2P trading with EHs in the sellers set, i.e. purchasing energy from EH$_j$ at the internal energy trading price firstly, then considering the external energy companies. There are two ways for EH$_j$ to sell surplus energy similarly.

III. P2P Multi-Energy Trading Method

The P2P multi-energy trading method is realized through a three-stage optimization to maximize the social welfare of the system. The relationship among three stages is shown in Fig. 3. In the first stage, according to the known energy imbalance and the multi-energy coupling relationship of buyer EHs, the quantity of electricity or gas to be purchased is optimized with the goal of minimizing the energy purchase cost without energy sharing. Furthermore, the quantity of electricity and gas in the first stage will be used as the upper bound of energy trading quantity in the next two stages. In the second stage, in order to improve the fairness of utility distribution, the RBS method is adopted to make all buyer EHs and seller EHs conduct bilateral negotiation simultaneously, the objective function of RBS method is constructed according to the quantity of shareable energy in the first stage, so as to determine the one-to-one trading price. In the third stage, the buyer agent and the seller agent collect the information of the EHs such as the upper bound of energy trading quantity in the first stage and the trading price in the second stage. Independent System Operator (ISO) will act as the third party to formulate the optimal energy sharing strategy for all EHs to maximize the social welfare of the system.

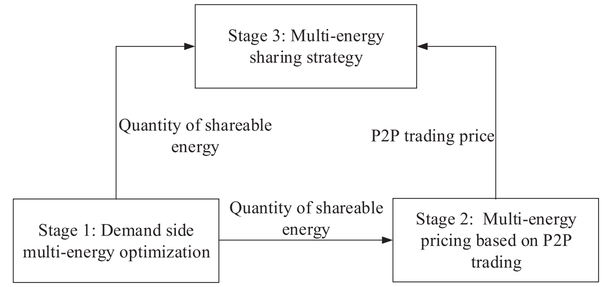

Fig. 3. The relationship among three stages.

A. Demand Side Multi-Energy Optimization

The objective function of the demand side multi-energy optimization is to minimize the energy purchase cost of buyer EH without energy sharing, which is presented as

$$\min \quad C_{t,i}^{non} = \varphi_{t,i,e}^b P_{t,i,e} + \varphi_{t,i,g}^b P_{t,i,g} + (\rho_{eg}\varepsilon_{eg} + \rho_{eh}\varepsilon_{eh})P_{t,i,e} + \rho_g(\varepsilon_{ge} + \varepsilon_{gh})P_{t,i,g}, \quad (1)$$

where the first term denotes the purchase cost of electricity, the second term denotes the purchase cost of gas, the last two terms denote the conversion cost of units, ρ_{eg}, ρ_{eh}, ρ_g are cost factors of multi-energy conversion, respectively.

The constraints of energy coupling and unit output are as follows:

$$(1 - \varepsilon_{eg} - \varepsilon_{eh})P_{t,i,e} + \varepsilon_{ge}P_{t,i,g}\eta_{CHP}^{g-e} = \Delta L_{t,i,e}, \quad (2)$$

$$\varepsilon_{eh}P_{t,i,e}\eta_{EHP} + \varepsilon_{gh}P_{t,i,g}\eta_{CHP}^{g-h} = \Delta L_{t,i,h}, \quad (3)$$

$$\varepsilon_{eg}P_{t,i,e}\eta_{P2G} + (1 - \varepsilon_{ge} - \varepsilon_{gh})P_{t,i,g} = \Delta L_{t,i,g}, \quad (4)$$

$$0 < \varepsilon_{eg} < 1, 0 < \varepsilon_{eh} < 1, 0 < \varepsilon_{ge} < 1, 0 < \varepsilon_{gh} < 1, \quad (5)$$

$$0 \le P_{t,i,e} \le P_{t,i,e}^{\max}, 0 \le P_{t,i,g} \le P_{t,i,g}^{\max}, \quad (6)$$

$$P_{EHP}^{\min} \le \varepsilon_{eh}P_{t,i,e}\eta_{EHP} \le P_{EHP}^{\max}, \quad (7)$$

$$P_{P2G}^{\min} \leq \varepsilon_{eg} P_{t,i,e} \eta_{P2G} \leq P_{P2G}^{\max}, \tag{8}$$

$$P_{CHP,e}^{\min} \leq \varepsilon_{ge} P_{t,i,g} \eta_{CHP}^{g-e} \leq P_{CHP,e}^{\max}, \tag{9}$$

$$P_{CHP,h}^{\min} \leq \varepsilon_{gh} P_{t,i,g} \eta_{CHP}^{g-e} \leq P_{CHP,h}^{\max}, \tag{10}$$

where ε denotes energy conversion coefficient of units, η denotes energy conversion efficiency, $P_{t,i}$ is energy input, $\Delta L_{t,i}$ are demand caused by load fluctuation, $P^{\max}$ and $P^{\min}$ denote upper and lower limits of energy, respectively.

B. Multi-Energy Pricing Based on P2P Trading

We constructed the profit functions of buyer and seller EH that participate in the P2P trading, respectively. It is proved that determining the optimal unit price of energy trading is a RBS bargaining problem and it is one-to-one bargaining.

The profit of EH_i buying energy m and the profit of EH_j selling energy m during period t are $U_{t,i,m}$ and $U_{t,j,m}$, respectively.

$$\begin{aligned} U_{t,i,m} = & -\alpha_{t,m} P_{t,i,m} \varphi_{t,ij,m} - (1-\alpha_{t,m}) P_{t,i,m} \varphi_{t,i,m}^{b} \\ & - \gamma_i^m \alpha_{t,m} P_{t,i,m}, \end{aligned} \tag{11}$$

where $P_{t,i,m}$ represents the energy demand of energy m in EH_i, $\varphi_{t,ij,m}$ is P2P energy trading price of energy m between EH_i and EH_j, $\alpha_{t,m}$ represents the ratio of the energy trading amount between EH_i and EH_j to the total demand of EH_i; γ_i^m is the unit transmission cost of energy m in EH_i.

$$\begin{aligned} U_{t,j,m} = & \beta_{t,m} P_{t,j,m} \varphi_{t,ij,m} + (1-\beta_{t,m}) P_{t,j,m} \varphi_{t,j,m}^{s} \\ & - \gamma_j^m \beta_{t,m} P_{t,j,m}, \end{aligned} \tag{12}$$

where $P_{t,j,m}$ represents the energy surplus of energy m in EH_j, $\beta_{t,m}$ represents the ratio of the energy trading amount between EH_i and EH_j to the total surplus of EH_j; γ_j^m is the unit transmission cost of energy m in EH_j.

Theorem 1: The allocation of feasible profit between the buyer EH_i and the seller EH_j is a bargaining problem if $U_{t,i,m}$ and $U_{t,j,m}$ both are affine functions.

Proof: The set of feasible profit is defined as

$$\begin{aligned} F = \{ & U_{t,i,m}, U_{t,j,m} | \varphi_{t,ij,m}^{\min} \leq \varphi_{t,ij,m} \leq \varphi_{t,ij,m}^{\max} \\ & 0 \leq \alpha_{t,m} \leq \alpha_{t,m}^{\max}, 0 \leq \beta_{t,m} \leq \beta_{t,m}^{\max} \}, \end{aligned} \tag{13}$$

where $\varphi_{t,ij,m}^{\min}$ and $\varphi_{t,ij,m}^{\max}$ are the minimum and maximum trading price between EH_i and EH_j, $\alpha_{t,m}^{\max}$ and $\beta_{t,m}^{\max}$ denote the maximum trading energy of EH_i and EH_j, respectively.

It is easy to see that the set F is a closed subset of R^2 from the profit functions (11) and (12), respectively. We suppose any two elements $\{U_{t,i,m}^p, U_{t,j,m}^p\} \in F$ and $\{U_{t,i,m}^q, U_{t,j,m}^q\} \in F$ are as follows, respectively.

$$\begin{cases} U_{t,i,m}^p = -\alpha_{t,m}^p P_{t,i,m} \varphi_{t,ij,m}^p - (1-\alpha_{t,m}^p) P_{t,i,m} \varphi_{t,i,m}^b \\ \qquad -\gamma_i^m \alpha_{t,m}^p P_{t,i,m}, \\ U_{t,j,m}^p = \beta_{t,m}^p P_{t,j,m} \varphi_{t,ij,m}^p + (1-\beta_{t,m}^p) P_{t,j,m} \varphi_{t,j,m}^s \\ \qquad -\gamma_j^m \beta_{t,m}^p P_{t,j,m}. \end{cases} \tag{14}$$

and

$$\begin{cases} U_{t,i,m}^q = -\alpha_{t,m}^q P_{t,i,m} \varphi_{t,ij,m}^q - (1-\alpha_{t,m}^q) P_{t,i,m} \varphi_{t,i,m}^b \\ \qquad -\gamma_i^m \alpha_{t,m}^q P_{t,i,m}, \\ U_{t,j,m}^q = \beta_{t,m}^q P_{t,j,m} \varphi_{t,ij,m}^q + (1-\beta_{t,m}^q) P_{t,j,m} \varphi_{t,j,m}^s \\ \qquad -\gamma_j^m \beta_{t,m}^q P_{t,j,m}. \end{cases} \tag{15}$$

Next, we introduce a weighted coefficient $\theta \in (0,1)$ to construct the weighted summation of $U_{t,i,m}^p$ and $U_{t,i,m}^q$, the t and m are omitted in the following proof, that is,

$$\begin{aligned} \theta U_i^p + (1-\theta) U_i^q = & P_i \left(\varphi_i^b - \gamma_i \right) \left[\theta \alpha^p + (1-\theta) \alpha^q \right] \\ & - P_i \left[\theta \alpha_m^p \varphi_{ij}^p + (1-\theta) \alpha^q \varphi_{ij}^q \right] \\ & - P_i \varphi_i^b. \end{aligned} \tag{16}$$

Compared (16) with (14), (15), we define

$$\alpha^\theta = \theta \alpha^p + (1-\theta) \alpha^q. \tag{17}$$

Since $\{U_i^p, U_j^p\} \in F$ and $\{U_i^q, U_j^q\} \in F$, we have $0 \leq \alpha^p \leq \alpha^{\max}$, $0 \leq \alpha^q \leq \alpha^{\max}$, and we can obtain $0 \leq \alpha^\theta \leq \alpha^{\max}$. Compared with (16) and (17), we define

$$\varphi_{ij}^\theta = \frac{\theta \alpha^p \varphi_{ij}^p + (1-\theta) \alpha^q \varphi_{ij}^q}{\theta \alpha^p + (1-\theta) \alpha^q}. \tag{18}$$

It can be proved $\varphi_{ij}^{\min} \leq \varphi_{ij}^\theta \leq \varphi_{ij}^{\max}$ according to (13) and (17).

The proof of U_j is omitted here because it is similar to that for U_i. Therefore, we can conclude that F is closed and convex on R^2 and the multi-energy pricing between the buyer EH_i and the seller EH_j based on the P2P trading is a RBS bargaining problem. ■

We introduce the concept of normalized utility to measure bargaining participants' satisfaction with the trading price. It is the proportion of the difference between participant's profit and minimum profit to the difference between maximum and minimum profit, that is,

$$\begin{cases} \hat{U}_{t,i,m} = \frac{U_{t,i,m} - U_{t,i,m}^{\min}}{U_{t,i,m}^{\max} - U_{t,i,m}^{\min}}, \\ \hat{U}_{t,j,m} = \frac{U_{t,j,m} - U_{t,j,m}^{\min}}{U_{t,j,m}^{\max} - U_{t,j,m}^{\min}}, \end{cases} \tag{19}$$

where the maximum normalized utility is 1, the minimum normalized utility is 0.

The minimum and maximum profit of the EH_i in period t are as follows:

$$\begin{cases} U_{t,i,m}^{\min} = -P_{t,i,m} \varphi_{t,i,m}^b, \\ U_{t,i,m}^{\max} = -\alpha_{t,m}^{\max} P_{t,i,m} \varphi_{t,ij,m}^{\min} - (1-\alpha_{t,m}^{\max}) \\ \qquad P_{t,i,m} \varphi_{t,i,m}^b - \gamma_i^m \alpha_{t,m}^{\max} P_{t,i,m}, \end{cases} \tag{20}$$

The minimum and maximum profit of the EH_j in period t are as follows:

$$\begin{cases} U_{t,j,m}^{\min} = P_{t,j,m} \varphi_{t,j,m}^s, \\ U_{t,j,m}^{\max} = \beta_{t,m}^{\max} P_{t,j,m} \varphi_{t,ij,m}^{\max} + (1-\beta_{t,m}^{\max}) \\ \qquad P_{t,j,m} \varphi_{t,j,m}^s - \gamma_j^m \beta_{t,m}^{\max} P_{t,j,m}. \end{cases} \tag{21}$$

From the bargaining condition $U_{t,i,m} \geq U_{t,i,m}^{\min}$ of the EH_i, we can obtain

$$\varphi_{t,j,m}^s \leq \varphi_{t,ij,m} \leq \varphi_{t,i,m}^b - \gamma_i^m. \tag{22}$$

From the bargaining condition $U_{t,j,m} \geq U_{t,j,m}^{\min}$ of the EH_j, we can obtain

$$\varphi_{t,j,m}^{s} + \gamma_j^m \leq \varphi_{t,ij,m} \leq \varphi_{t,i,m}^{b}. \tag{23}$$

Next, the relationship between the normalized utility function and the energy trading price can be obtained by taking (11), (12), (20), (21) into (19):

$$\begin{cases} \hat{U}_{t,i,m} = \frac{\alpha_{t,m}(\varphi_{t,i,m}^{b} - \varphi_{t,ij,m} - \gamma_i^m)}{\alpha_{t,m}^{\max}(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_i^m)}, \\ \hat{U}_{t,j,m} = \frac{\beta_{t,m}(\varphi_{t,ij,m} - \varphi_{t,j,m}^{s} - \gamma_j^m)}{\beta_{t,m}^{\max}(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_j^m)}. \end{cases} \tag{24}$$

The multi-energy pricing objective function can be expressed as:

$$\max\ \hat{V}_{t,i,m}\hat{V}_{t,j,m}, \tag{25}$$

where

$$\hat{V}_{t,i,m} = \hat{U}_{t,i,m} + (1 - \hat{U}_{t,j,m}), \tag{26}$$

$$\hat{V}_{t,j,m} = \hat{U}_{t,j,m} + (1 - \hat{U}_{t,i,m}). \tag{27}$$

The optimization problem (25) is a combinatorial optimization problem. It is easy to see that $\hat{V}_{t,i,m}\hat{V}_{t,j,m}$ reaches the maximum when $\hat{V}_{t,i,m} = 1$ and $\hat{V}_{t,j,m} = 1$, because $\hat{V}_{t,i,m} + \hat{V}_{t,j,m} = 2$ and $\hat{V}_{t,i,m} \geq 0$, $\hat{V}_{t,j,m} \geq 0$ are always satisfied.

Hence, we have the following condition at the optimal solution:

$$\hat{U}_{t,i,m} = \hat{U}_{t,j,m}. \tag{28}$$

Therefore, the globally optimal solution of the RBS can be obtained as

$$\begin{cases} \alpha_{t,m} = \alpha_{t,m}^{\max}, \\ \beta_{t,m} = \beta_{t,m}^{\max}, \\ \varphi_{t,ij,m}^{RBS*} = \frac{(\varphi_{t,i,m}^{b})^2 - (\varphi_{t,j,m}^{s})^2 - \gamma_i^m \varphi_{t,i,m}^{b} - \gamma_j^m \varphi_{t,j,m}^{s}}{2(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s}) - \gamma_i^m - \gamma_j^m}. \end{cases} \tag{29}$$

Furthermore, the unit profit of the pricing strategy can be obtained as follows:

$$\begin{cases} U_{t,i,m}^{*} = \varphi_{t,i,m}^{b} - \varphi_{t,ij,m}^{RBS*} - \gamma_i^m, \\ U_{t,j,m}^{*} = \varphi_{t,ij,m}^{RBS*} - \varphi_{t,j,m}^{s} - \gamma_j^m. \end{cases} \tag{30}$$

We introduce a fair coefficient f to compare the fairness of satisfaction obtained by the EHs from the utility distribution based on RBS, and the closer f is to 1, the higher the fairness.

$$f_{RBS} = \frac{\hat{U}_{t,i,m}}{\hat{U}_{t,j,m}} = 1. \tag{31}$$

However, the market power of each EH in the NBS trading process is equal, and the pricing strategy based on NBS is as follows:

$$\hat{V}_{t,i,m} = \hat{U}_{t,i,m}. \tag{32}$$

$$\hat{V}_{t,j,m} = \hat{U}_{t,j,m}. \tag{33}$$

Combine equation (24) with (32), (33) and then bring them into equation (25), and the optimization objective of NBS can be shown as follows:

$$\max\ \frac{\alpha_{t,m}\beta_{t,m}}{\alpha_{t,m}^{\max}\beta_{t,m}^{\max}}(-A\varphi_{t,ij,m}^2 + B\varphi_{t,ij,m} + C), \tag{34}$$

where

$$A = \frac{1}{(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_i^m)(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_j^m)}, \tag{35}$$

$$B = \frac{\varphi_{t,i,m}^{b} + \varphi_{t,j,m}^{s} + \gamma_j^m - \gamma_i^m}{(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_i^m)(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_j^m)}, \tag{36}$$

$$C = \frac{-\varphi_{t,i,m}^{b}\varphi_{t,j,m}^{s} - \varphi_{t,i,m}^{b}\gamma_j^m + \varphi_{t,j,m}^{s}\gamma_i^m + \gamma_i^m\gamma_j^m}{(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_i^m)(\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_j^m)}. \tag{37}$$

The globally optimal solution of the NBS can be obtained as

$$\begin{cases} \alpha_{t,m} = \alpha_{t,m}^{\max}, \\ \beta_{t,m} = \beta_{t,m}^{\max}, \\ \varphi_{t,ij,m}^{NBS*} = \frac{\varphi_{t,i,m}^{b} + \varphi_{t,j,m}^{s} + \gamma_j^m - \gamma_i^m}{2}. \end{cases} \tag{38}$$

The fair coefficient f can be denoted as follows in the NBS pricing strategy:

$$f_{NBS} = \frac{\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_j^m}{\varphi_{t,i,m}^{b} - \varphi_{t,j,m}^{s} - \gamma_i^m}. \tag{39}$$

C. Multi-Energy Sharing Strategy

In the third stage, the buyer agent and the seller agent will formulate the optimal energy sharing strategy for all EHs to maximize the social welfare of the P2P multi-energy trading.

In order to improve the energy efficiency and social welfare of the system, we introduced an energy sharing priority function to ensure that EHs with a large amount of shareable energy have priority to participating in P2P trading. The energy sharing pairing priority function between EH_i and EH_j is shown as follows:

$$\mu_{t,ij,m} = \frac{P_{t,i,m}}{\sum_{i=1}^{I} P_{t,i,m}} + \frac{P_{t,j,m}}{\sum_{j=1}^{J} P_{t,j,m}}, \tag{40}$$

where I and J are the number of buyers and sellers that participate in the P2P multi-energy trading, respectively.

The social welfare is the total profits of all EHs participating in P2P electricity and gas trading. Considering the impact of different market power of EHs, we introduce weight factors θ_i and θ_j to formulate the problem of social welfare maximization as follows:

$$\max\quad u_t = \sum_{m} \mu_{t,ij,m} P_{t,ij,m}^{ex} \left[\sum_{i=1}^{I} \theta_i \left(\varphi_{t,i,m}^{b} - \varphi_{t,ij,m}^{RBS*} - \gamma_i^m \right) + \sum_{j=1}^{J} \theta_j \left(\varphi_{t,ij,m}^{RBS*} - \varphi_{t,j,m}^{s} - \gamma_j^m \right) \right], \tag{41}$$

Algorithm 1: Process of The Three-Stage Multi-Energy Sharing Strategy.

Initialization: input initial data $\Delta L_{t,i,m}$, $P_{t,j,m}$, $\varphi^b_{t,i,m}$, $\varphi^s_{t,j,m}$, ε, η, ρ, γ^m.

1: **Stage 1:** Demand side multi-energy optimization
2: Call the CPLEX solver and input the objective function (1) and constraints (2)-(10).
3: Solve the quantity of energy $P_{t,i,m}$ that can be shared by buyer EHs.
4: **Stage 2:** Multi-energy pricing based on P2P trading
5: The profit functions (11), (12) and the objective function (25) of the bargaining problem are constructed according to the $P_{t,i,m}$ and $P_{t,j,m}$.
6: The optimal bargaining solution $\varphi^{RBS*}_{t,ij,m}$ of convex optimization problem (25) is derived, as shown in equation (29).
7: **Stage 3:** Multi-energy sharing strategy
8: The pairing priority function (40) of energy sharing among EHs is constructed according to the $P_{t,i,m}$ and $P_{t,j,m}$.
9: Call the CPLEX solver and input the objective function (41) and constraints (42)-(45).
10: The optimal energy sharing strategy $P^{ex}_{t,ij,m}$ among all EHs is obtained.

s.t.

$$\sum_{j=1}^{J} P^{ex}_{t,ij,m} \leq P_{t,i,m}, \tag{42}$$

$$\sum_{i=1}^{I} P^{ex}_{t,ij,m} \leq P_{t,j,m}, \tag{43}$$

$$0 \leq P^{ex}_{t,ij,m} \leq \min\{P_{t,i,m}, P_{t,j,m}\}, \tag{44}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} P^{ex}_{t,ij,m} \leq \min\left\{\sum_{i=1}^{I} P_{t,i,m}, \sum_{j=1}^{J} P_{t,j,m}\right\}, \tag{45}$$

where $P^{ex}_{t,ij,m}$ denotes the energy quantity among EHs actually participating in P2P trading in period t, which is optimized in the third stage.

The solving process of the three-stage multi-energy sharing strategy is shown in Algorithm 1.

IV. Numerical Simulation and Analysis

In the simulation, we supposed a P2P multi-energy trading model is composed of two REHs (EH_1, EH_2) and two IEHs (EH_3, EH_4) with same market power. The wholesale electricity prices of REHs and IEHs are 12.5 cents/kWh and 7 cents/kWh, the wholesale gas prices are 3.7 cents/kWh and 1.2 cents/kWh, respectively, above prices refer to the global average price. The feeder price is about one-third of the wholesale price [5]. The simulation includes four different cases to verify the proposed P2P trading mode, where the number of buyers and sellers is equal in Case A, moreover, the type of EH on buyers or sellers is different. The Case B represents the trading mode of a single buyer and multiple sellers. The Case C represents the trading mode of a single seller and multiple buyers. In Case D, the number of buyers and sellers is equal, while it is different from Case A, the type of EH on buyers or sellers is the same. The initial multi-energy imbalance of the EHs for the four cases are shown in Table I. Negative energy imbalance indicate that EHs have energy demand and can act as buyers of energy trading, while positive energy imbalance indicate that EHs have energy surplus and can act as sellers.

TABLE I
Multi-Energy Imbalance in EHs Under Four Cases

	EH	Electricity (kW)	Gas (kW)	Heat (kW)	Role
Case A	1	+100	+175	0	seller
	2	-235	-100	-180	buyer
	3	-280	-150	-196	buyer
	4	+180	+210	0	seller
Case B	1	-120	-165	-100	buyer
	2	+80	+100	0	seller
	3	+180	+50	0	seller
	4	+70	+110	0	seller
Case C	1	-60	-65	-100	buyer
	2	0	-100	-40	buyer
	3	+80	+150	0	seller
	4	-20	-45	-80	buyer
Case D	1	+90	+65	0	seller
	2	+130	+70	0	seller
	3	-200	-50	-120	buyer
	4	-40	-60	0	buyer

The simulation was conducted on a Windows 7 64-bit personal computer with Intel Core i7-5500 U 2.4 GHz CPU and 4 GB RAM using Matlab with Cplex and Yalmip. The total calculation time of the four cases in the first stage is 8.12 s, the total calculation time of the electricity trading price in the second stage and the electricity sharing strategy of the four cases in the third stage is 5.6 s, and the total calculation time of the natural gas trading price in the second stage and the natural gas sharing strategy of the four cases in the third stage is 5.48 s.

In the first stage, the optimization results of the four cases are shown in the Fig. 4. EHs with positive value of trading energy means that they have energy surplus and can be sellers, while EHs with negative value means that they have energy demand and can be buyers to participate in the P2P trading. According to the initial load data in Table I, the results show the quantity of the buyers' demand and the sellers' surplus for electricity and natural gas (i.e., the upper bound of energy trading quantity) in the four cases. Moreover, the natural gas demand in each case is significantly higher than electricity, it mainly because the wholesale price of natural gas is lower than electricity.

In the second stage, we adopted the RBS method to obtain the prices of P2P multi-energy trading, and the results are shown in

TABLE II
MULTI-ENERGY TRADING PRICE AND PROFIT BY P2P

	Buyer	Seller	$\varphi_{t,ij,e}^{min}$	$\varphi_{t,ij,e}^{max}$	$\varphi_{t,ij,e}$	$\varphi_{t,ij,g}^{min}$	$\varphi_{t,ij,g}^{max}$	$\varphi_{t,ij,g}$	Bilateral profit ($)	Total profit ($)
Case A	2	1	3.5	6	4.72	0.56	0.9	0.74	1.95	31.77
	2	4	4.25	6	5.21	1.21	0.9	–	0	
	3	1	3.6	11.5	7.44	0.56	3.4	2.00	7.23	
	3	4	4.25	11.5	7.75	1.21	3.4	2.33	22.59	
Case B	1	2	3.1	5.5	4.38	0.66	1.0	0.82	3.06	3.67
	1	3	4.75	5.5	5.17	1.41	1.0	–	0	
	1	4	4.25	5.5	5.01	1.21	1.0	–	0.61	
Case C	1	3	4.75	5.5	5.17	1.41	1.0	–	0.79	9.17
	2	3	4.75	6	5.38	1.41	0.9	–	0	
	4	3	4.75	12	8.26	1.41	3.6	2.46	8.38	
Case D	3	1	3.6	11.5	7.44	0.56	3.4	2.00	8.52	15.24
	3	2	3.1	11.5	7.3	0.66	3.4	2.03	1.39	
	4	1	3.6	12	7.58	0.56	3.6	2.06	3.33	
	4	2	3.1	12	7.43	0.66	3.6	2.08	2.00	

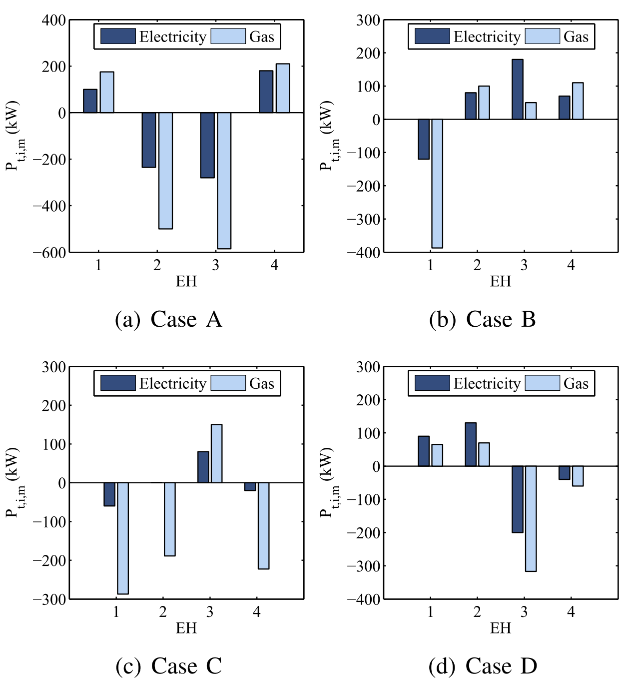

Fig. 4. Shareable multi-energy of the four cases.

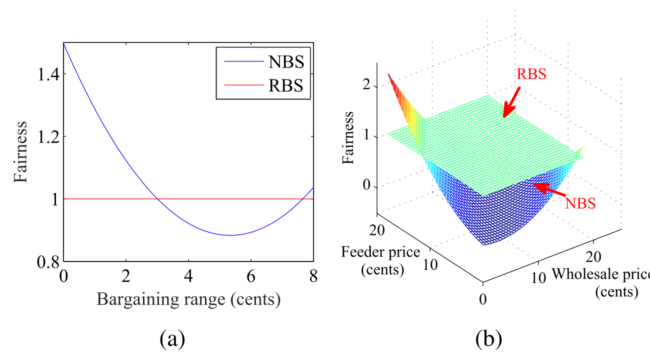

Fig. 5. The fairness comparison of satisfaction between NBS and RBS.

the Table II. We can see that the multi-energy price between the buyer and the seller is within the bargaining range in each case, which verifies the correctness of the optimal solution and the rationality of the RBS method. The fairness comparison of satisfaction between NBS and RBS is shown in the Fig. 5. The fairness of RBS is always 1, while that of NBS changes with the bargaining range, it is related to (26), (27), (32), and (33). When RBS method is used to determine the trading price of two EHs, an EH considers not only its own utility relative to the minimum utility, but also the expense of another EH relative to the maximum utility, which can ensure the same satisfaction of both EHs, therefore the RBS fairness of satisfaction is better than NBS. Furthermore, the relationship between the fairness with the wholesale price and feeder price of both P2P trading parties verifies that the fairness of RBS is better than NBS.

In the third stage, the multi-energy sharing strategies of the four cases are shown in the Fig. 6 and Fig. 7, respectively. It can be seen that electricity and gas in the four cases have different sharing strategies, it is related to their energy trading price in the second stage and the quantity of shareable energy in the first stage. The EHs with the largest amount of shareable energy will be traded firstly. Furthermore, the bilateral profits and total profits of the system in the four cases are shown in the Table II. The profit is directly proportional to the quantity of traded energy and unit profit of the buyer and the seller. Taking Case A as an example, EH_3 and EH_4 have the largest quantity of P2P trading in electricity and natural gas, hence their bilateral profits are the largest. Similarly, the quantity of P2P trading energy is the largest in Case A, hence their total profits are the largest.

The multi-energy trading with energy companies by P2P and No-P2P is shown in the Fig. 8. No-P2P refers to the trading mode in which EHs only trade electricity or natural gas with the utility company or gas company. It can be seen that the quantity of energy trading with external energy companies is significantly

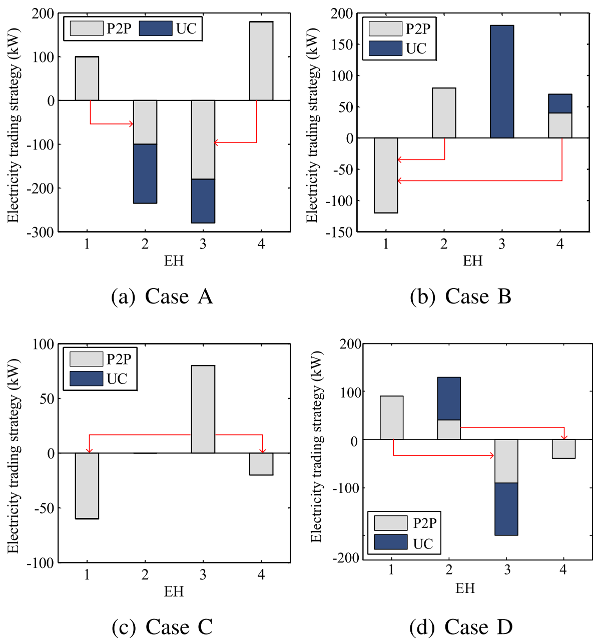

Fig. 6. Electricity trading strategy of the four cases.

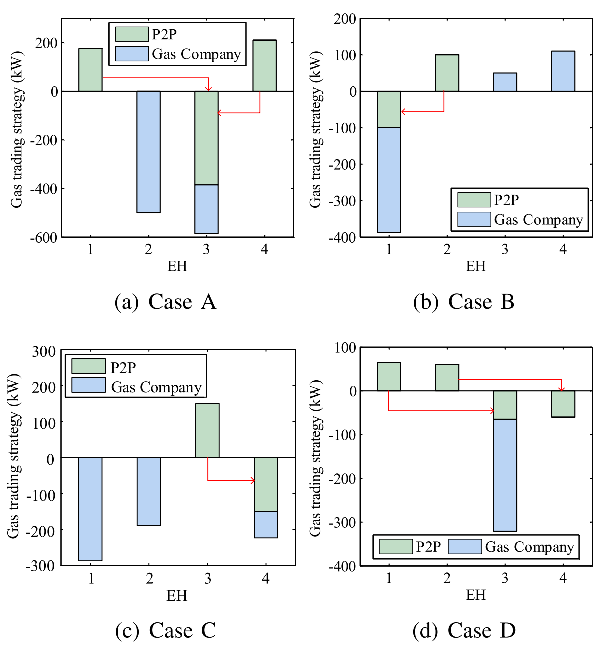

Fig. 7. Natural gas trading strategy of the four cases.

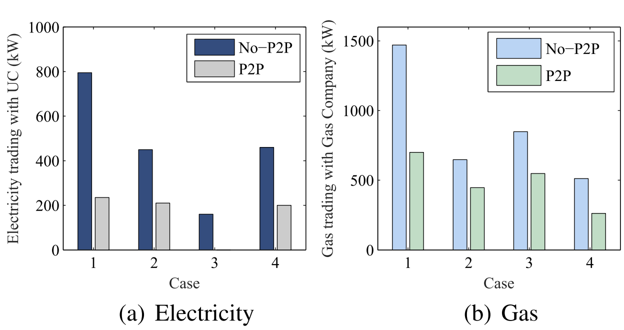

Fig. 8. Trading with energy companies by P2P and No-P2P.

reduced under the P2P trading mode. Therefore, it reduces the purchasing cost of multi-energy and improves the social welfare of the IES.

V. Discussion

First, we discuss the scalability of the proposed P2P trading mode for real systems. The first stage is the local optimization of EHs, and the scalability is not affected by the scale of the system and the number of EHs. In the second and the third stage, the scalability is mainly reflected in the computational complexity of variables and constraints. For a system with m buyer EHs and n seller EHs, the calculation complexity is $O(mn)$. However, the maximum variable or constraint scale of the Cplex solver can reach 1000, which is much larger than the calculation complexity of EHs in a real-life region. Therefore, the method proposed in this paper is scalable for real systems. However, the investment cost in the trading market may be large because all EHs need to be connected by energy transmission network in the physical level.

In addition, we use the RBS method to determine the optimal trading price. It ensures the fairness of utility distribution because an EH considers not only its own utility relative to the minimum utility, but also the expense of another EH relative to the maximum utility. However, this method is limited to one-to-one bargaining, and any two EHs in the model need to negotiate the trading price which increased the computational complexity. Hence, many-to-many bargaining is an alternate method in the future.

VI. Conclusion

This paper proposed a three-stage P2P trading method for an IES. In the virtual level of P2P, the multi-energy trading price are set for EHs based on RBS method, the RBS determines the P2P trading price according to the wholesale price and the feeder price, which can ensure that the EHs gain profits by participating in energy sharing trading. Furthermore, when the two participants of P2P trading negotiate the trading price, an EH considers not only its own utility relative to the minimum utility, but also the expense of another EH relative to the maximum utility, which can ensure the same satisfaction of both participants, and improve the fairness of satisfaction obtained by the EHs from the utility distribution. Moreover, in the physical level of P2P, the optimal energy sharing strategy is designed for EHs based on linear programming method. The simulation show that the energy trading method improves the profits of EHs and the social welfare of the system, and the profits of EHs participating in the P2P trading are positively correlated with the quantity of energy sharing.

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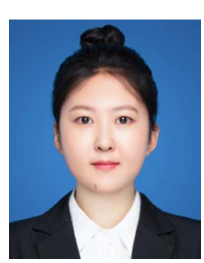

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