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Coordinated Optimal Operations for Integrated Community Energy System and Multiple Prosumers with Peer-to-Peer Behaviors

Xiaoyu Wang[1,2], Xiaolong Jin[1,2*], Hongjie Jia[1,2], Yunfei Mu[1,2], Wei Wei[1,2], Xiaodan Yu[1,2], Shuo Liang[1,2]

1 Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 30072, China

2 Key Laboratory of Smart Energy & Information Technology of Tianjin Municipality, Tianjin University, Tianjin 30072, China
(*Corresponding Author: xljin@tju.edu.cn)

ABSTRACT

Peer-to-Peer (P2P) multi-energy trading is crucial to improve the utilities and the local energy resource utilization of end-side prosumers. However, the benefits balance between the network operator (e.g., the integrated community energy system (ICES) operator) and the prosumers are not well addressed. In this context, this paper proposes a novel coordinated optimal operation method and an optimal network charge pricing strategy for the ICES operator to multiple prosumers with P2P behaviors. The interaction between the ICES operator and prosumers is modeled as a bi-level optimization problem. At the upper level, the ICES operator optimizes the electricity/heating network charge prices to maximize its network charge revenue, while considering the network constraints. At the lower level, prosumers optimize the P2P multi-energy trading schedules to minimize the operational cost. Moreover, to protect the information privacy of the ICES operator and prosumers, a distributed optimization method based on alternating direction method of multipliers (ADMM) is applied to solve this bi-level optimization problem. Finally, case studies demonstrate that the proposed method can effectively benefit both the ICES operator and prosumers in P2P multi-energy trading.

Keywords: Integrated community energy system (ICES) operator, Prosumers, Alternating direction method of multipliers (ADMM), P2P multi-energy trading

NONMENCLATURE

Indices and Sets	
i, j	Index for prosumers
t	Index for time slots
m	Index for electrical nodes
h	Index for heating nodes
Parameters	
c_t^{Elec}	Electricity price for ICES operator at *t*
c_t^{Heat}	Heating price for ICES operator at *t*
$\gamma_t^{\max}$	Maximum network charge price at *t*
$\gamma_t^{\min}$	Minimum network charge price at *t*
c_p	Specific heat capacity of water flow
T_s , T_r	Temperature of supply and return water in heating distribution network
ρ	Step size in ADMM procedure
Variables	
$P_{i,t}^{\mathrm{Grid}}$, $H_{i,t}^{\mathrm{Grid}}$	The electricity and heating exchanged with ICES operator for prosumers at *t*
$P_{i(j),t}^{\mathrm{P2P}}$, $H_{i(j),t}^{\mathrm{P2P}}$	The P2P electricity and heating power for prosumers at *t*
γ_t	Network charge price at *t*
m_t	Water flow rate for ICES operator or prosumers at *t*
$\lambda_{i(j)}$	Lagrangian multiplier

1. INTRODUCTION

With the continuous and widespread application of distributed energy resources (DERs), the operation and optimization of power system are changing [1]. The integration of multiple DERs has increased the demand for efficient energy management. As a feasible solution method, Peer-to-Peer (P2P) energy trading between end-side prosumers with various DERs has gained attention [2]. It allows prosumers to trade the redundant energy to others, which can improve the benefits of individual prosumers and the local energy utilization of the whole system.

Works on P2P energy trading between prosumers mainly focus on studying the market mechanism and

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trading strategy with the objective of reducing the scheduling costs [3]-[4]. These studies have verified that P2P energy trading can enhance the economics in the virtual layer. However, considering the physical constraints of networks is instrumental to implement the trading schedules in practice. Moreover, prosumers with P2P trading schedules treat the network as the energy backup that can provide the free physical network for transmitting P2P energy. Thus, it is challenging to make the network operator willing to support energy trading without benefits. To this end, imposing network charges to prosumers has been developed to improve the network benefit [5]-[6]. Note that the network charge price in current studies is applied on the electrical distribution network, and this has not been extended in the integrated community energy system (ICES). In this paper, multiple energy trading problem in ICES has considered the costs of prosumers and the ICES operator's benefit by charging network fees, which can yield a coordinated bi-level optimization problem. To further meet the privacy demand of prosumers in energy trading, the concept of centralized control method is inapplicable. Distributed optimization algorithms have been developed that do not require the operator to collect all the information, including analytical target cascading (ATC) method, auxiliary problem principle (APP) method and alternating direction method of multipliers (ADMM) [7]. The ADMM method involves the design optimization of a hierarchically decomposed bi-level model and has been extended for the P2P multi-energy trading in this paper.

A coordinated optimal operation method for the ICES operator and prosumers with P2P trading is proposed. The main contributions are presented：

1) A coordinated bi-level optimization model between the ICES operator and prosumers is established to benefit both of them simultaneously. At the upper level, the ICES operator generates the electrical and heating network charge prices to prosumers aiming at maximizing its benefit. And it guides the trading schedules of prosumers at the lower level, while the trading schedules in turn affect the network charge prices.
2) To achieve the information privacy of the ICES operator and prosumers, the ADMM-based scheduling method is incorporated in the bi-level optimal scheme without revealing all information to the ICES operator and prosumers. Moreover, an optimal network charge pricing strategy for the ICES operator with prosumers is proposed which is determined by the electrical and heating distance.

2. COORDINATED BI-LEVEL OPTIMIZATION

For a P2P multi-energy trading market, several prosumers are integrated with the ICES operator, as shown in Fig. 1. Different prosumers with various energy resources are coupled through the electrical and heating distribution networks that are managed by the ICES operator. They are equipped with photovoltaic (PV) and heat pump, and they can trade the surplus energy such as electricity and heat with others according to the scheduling results. Meanwhile, the ICES operator can charge the network fee to prosumers with P2P trading, while providing the energy balance service. This interaction between the ICES operator and prosumers calls a bi-level optimization problem. ICES operator at the upper level develops the optimal network charge pricing strategy for prosumers, and prosumers optimize the energy resources including P2P trading schedules based on the network charge prices from ICES operator. The network charge prices and the P2P trading schedules influence each other. In this text, to improve the computational efficiency and protect information privacy, the extension of ADMM method to bi-level optimization problem is developed, which enables the ICES operator and prosumers to operate separately to solve their own subproblems with limited sharing information.

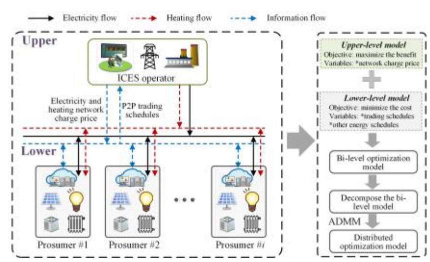

Fig. 1. Framework of ICES operator with prosumers

3. BI-LEVEL OPTIMIZATION MODELLING

3.1 Upper-level model of ICES operator

1) Objective

The ICES operator maximizes its profit by optimizing the electrical and heating network charge prices. The objective function is as follows:

$$\begin{aligned} \max \text{Profit} = & \sum_{t=1}^{T}[\sum_{i\in I}\sum_{j\in I}\gamma_t^{\text{Elec}} d_{i(j)}^{\text{Elec}} P_{i(j),t}^{\text{P2P}} \\ & + \sum_{i\in I}\sum_{j\in I}\gamma_t^{\text{Heat}} d_{i(j)}^{\text{Heat}} H_{i(j),t}^{\text{P2P}} + \sum_{i\in I}(c_t^{\text{Elec}} P_{i,t}^{\text{Grid}} + c_t^{\text{Heat}} H_{i,t}^{\text{Grid}})] \end{aligned} \tag{1}$$

2) Constraints of electrical and heating network charge

The electrical and heating network charge prices are determined by the electrical and heating distances. The electrical distance is calculated based on the connected branch impedance $Z_{l^{\text{Elec}},i(j)}$, as shown in (2). Similar to the electrical distance, the heating distance is obtained according to the physical distance $D_{l^{\text{Heat}},i(j)}$ between two nodes connected to the prosumers, as shown in (3).

$$d_{i(j)}^{\text{Elec}} = \sum_{l^{\text{Elec}} \in L^{\text{Elec}}} \left| Z_{l^{\text{Elec}},i(j)} \right| \tag{2}$$

$$d_{i(j)}^{\text{Heat}} = \sum_{l^{\text{Heat}} \in L^{\text{Heat}}} \left| D_{l^{\text{Heat}},i(j)} \right| \tag{3}$$

Moreover, electricity and heating network charge prices are required to be limited within a certain range as follows:

$$\gamma^{\text{Elec,min}} \le \gamma_t^{\text{Elec}} \le \gamma^{\text{Elec,max}} \tag{4}$$

$$\gamma^{\text{Heat,min}} \le \gamma_t^{\text{Heat}} \le \gamma^{\text{Heat,max}} \tag{5}$$

3) Constraints of electrical distribution network

The linearized DistFlow model is used to present the constraints of power flow and voltage, as shown in (6)-(9).

$$P_{m+1} = P_m - p_{m+1}^{\text{load}} \tag{6}$$

$$Q_{m+1} = Q_m - q_{m+1}^{\text{load}} \tag{7}$$

$$V_{m+1}^2 = V_m^2 - \frac{r_f P_m + x_f Q_m}{V_0} \tag{8}$$

$$1 - \varepsilon \le V_m \le 1 + \varepsilon \tag{9}$$

4) Constraints of heating distribution network

To enable prosumers to adjust the heat supply and demand, the quantity regulation strategy is selected. Then, the heating exchange in network can be shown as (10). Meanwhile, the heating distributed network constraints are shown in (11)-(18), which includes the limits of water flow rate that can affect the heating power (11)-(12) and the linearized water pressure drop over the pipeline (13)-(18).

$$H = c_p * m_t * (T_s - T_r) \tag{10}$$

$$\mathbf{Y}^{\text{HDN}} \dot{\mathbf{m}}^{\text{pipe}} = \dot{\mathbf{m}}^{\text{node}} \tag{11}$$

$$m_{l^{\text{Heat}},t}^{\text{pipe,min}} \le m_{l^{\text{Heat}},t}^{\text{pipe}} \le m_{l^{\text{Heat}},t}^{\text{pipe,max}} \tag{12}$$

$$\begin{aligned} p_{h,t} - p_{h+1,t} = \xi_{l^{\text{Heat}}} \cdot \sum_{q=1}^{Q} [(A_{l^{\text{Heat}},t}^{\text{pipe}} - x_{l^{\text{Heat}}}^q \delta_{l^{\text{Heat}},t}^q) k_{l^{\text{Heat}}}^q \\ + y_{l^{\text{Heat}}}^q \delta_{l^{\text{Heat}},t}^q] \end{aligned} \tag{13}$$

$$\xi_{l^{\text{Heat}}} = \frac{8 \kappa_{l^{\text{Heat}}} L_{l^{\text{Heat}}}}{d_{l^{\text{Heat}}}^5 \pi^2 \rho} \tag{14}$$

$$\begin{cases} y_{l^{\text{Heat}}}^q = 0, \quad x_{l^{\text{Heat}}}^q = 0 \quad q = 1 \\ y_{l^{\text{Heat}}}^q = (x_{l^{\text{Heat}}}^q)^2, \quad x_{l^{\text{Heat}}}^q = \dfrac{\bar{m}_{l^{\text{Heat}}}^{pipe} \cdot q}{Q} \,, \\ k_{l^{\text{Heat}}}^q = \dfrac{y_{l^{\text{Heat}}}^q - y_{l^{\text{Heat}}}^{q-1}}{x_{l^{\text{Heat}}}^q - x_{l^{\text{Heat}}}^{q-1}} \quad q \ge 2 \end{cases} \tag{15}$$

$$x_{l^{\text{Heat}}}^q \le A_{l^{\text{Heat}},t}^{\text{pipe}} \le \delta_{l^{\text{Heat}},t}^q \; x_{l^{\text{Heat}}}^{q+1} \tag{16}$$

$$\sum_{q=1}^{Q} \delta_{l^{\text{Heat}},t}^q = 1 \tag{17}$$

$$p_h^{\min} \le p_{h,t} \le p_h^{\max} \tag{18}$$

3.2 Lower-level model of each prosumer

1)Objective

According to the electricity and heating network charge prices, the objective function of prosumer *i* is to minimize the cost, as shown in (19).

$$\begin{aligned} \min \text{Cost}_i = \sum_{t=1}^{T} [\sum_{j \in I} (\gamma_t^{\text{Elec}} d_{i(j)}^{\text{Elec}} \frac{P_{i(j),t}^{\text{P2P}}}{2} + \lambda_{i(j)}^{\text{Elec}} P_{i(j),t}^{\text{P2P}}) \\ + \sum_{j \in I} (\gamma_t^{\text{Heat}} d_{i(j)}^{\text{Heat}} \frac{H_{i(j),t}^{\text{P2P}}}{2} + \lambda_{i(j)}^{\text{Heat}} H_{i(j),t}^{\text{P2P}}) + c_t^{\text{Elec}} P_{i,t}^{\text{Grid}} + c_t^{\text{Heat}} H_{i,t}^{\text{Grid}}] \end{aligned} \tag{19}$$

2)Constraints of multi-energy trading

The consistence of P2P multi-energy trading between prosumers is considered, as shown in (20)-(21). And the trading power should be limited as (22)-(23).

$$P_{i(j),t}^{\text{P2P}} = -P_{j(i),t}^{\text{P2P}} \tag{20}$$

$$H_{i(j),t}^{\text{P2P}} = -H_{j(i),t}^{\text{P2P}} \tag{21}$$

$$-P_{i(j),t}^{\text{P2P,sell,max}} \le P_{i(j),t}^{\text{P2P}} \le P_{i(j),t}^{\text{P2P,buy,max}} \tag{22}$$

$$-H_{i(j),t}^{\text{P2P,sell,max}} \le H_{i(j),t}^{\text{P2P}} \le H_{i(j),t}^{\text{P2P,buy,max}} \tag{23}$$

3)Constraints of electricity and thermal balance

The electricity and thermal balance constraints of prosumer *i* are expressed as:

$$P_{i,t}^{\text{Grid}} + P_{i,t}^{\text{PV}} + \sum_{j \in I} P_{i(j),t}^{\text{P2P}} = P_{n,t}^{\text{unadjustload}} \tag{24}$$

$$H_{i,t}^{\text{Heat}} + H_{i,t}^{\text{HP}} + \sum_{j \in I} H_{i(j),t}^{\text{P2P}} = Q_{i,t}^{\text{unadjustload}} \tag{25}$$

4. DISTRIBUTED MATHEMATICAL SOLUTION

Based on the consensus optimization of ADMM, the bi-level optimization problem for the ICES operator and prosumers can be solved. The key is to find the couplings in this problem. The P2P trading consistence constraints in (20)-(21) can be the coupling constraints between prosumers. The P2P trading power variables $P_{i(j),t}^{\text{P2P}}$ / $H_{i(j),t}^{\text{P2P}}$ can also be introduced to be coupling variables to integrate the ICES operator with prosumers. Then, the Lagrangian relaxation approach is applied, and the augmented Lagrangian functions of ICES operator and prosumers are formulated as:

$$\begin{aligned} L^{\text{ICES}} = \text{Profit} + \sum_{t=1}^{T} \sum_{i \in I} \sum_{j \in I} [\lambda_{i(j)}^{\text{ICES,Elec}} \left(P_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Elec}} \right) \\ + \frac{\rho}{2} \left\| P_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Elec}} \right\|_2^2 + \lambda_{i(j)}^{\text{ICES,Heat}} \left(H_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Heat}} \right) \\ + \frac{\rho}{2} \left\| H_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Heat}} \right\|_2^2] \end{aligned} \tag{26}$$

$$
\begin{aligned}
L_i^{\text{Prosumer}} = \text{Cost}_i &+ \sum_{t=1}^{T}\sum_{j\in I}[\lambda_{i(j)}^{\text{Pro,Elec}}\left(P_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Elec}}\right) \\
&+ \frac{\rho}{2}\left\| P_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Elec}} \right\|_2^2 + \lambda_{i(j)}^{\text{Pro,Heat}}\left(H_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Heat}}\right) \\
&+ \frac{\rho}{2}\left\| H_{i(j),t}^{\text{P2P}} - z_{i(j),t}^{\text{Heat}} \right\|_2^2]
\end{aligned} \tag{27}
$$

Then, the iterative distributed solution procedures are shown as follows: in each iteration, the ICES operator and prosumers can solve their related subproblems for minimizing the cost. And they can share the coupling trading information in terms of the resulted coupling variables with others, then this coupling variables are obtained in (28). The Lagrangian multipliers are updated as (29).

$$\mathbf{z}_{i(j)}^{k+1} = \frac{1}{N_a}\sum_{a=1}^{N_a}(\mathbf{x}_{i(j)}^{k+1} + \frac{1}{\rho}\lambda_{i(j)}^{k}) \tag{28}$$

$$\boldsymbol{\lambda}_{i(j)}^{k+1} = \boldsymbol{\lambda}_{i(j)}^{k} + \rho(\mathbf{x}_{i(j)}^{k+1} - \mathbf{z}_{i(j)}^{k+1}) \tag{29}$$

The iterations would be stopped when the coupling variables are close enough. Thus, this distributed solution based on ADMM only requires limited sharing information between the ICES operator and prosumers, thereby avoiding information privacy issues.

5. CASE STUDIES

The ICES operator with four different prosumers are used as the text case, as shown in Fig. 2. The ICES operator is connected to the distribution network node 1. Four prosumers (i.e., prosumer #1, #2, #3 and #4) are connected to the electrical nodes 1 2, 3 and 4, and the heating nodes 4, 6, 8 and 9, respectively. Moreover, the prosumers #1 and #3 are equipped with the heat pump, and other prosumers are not. The electricity and heating prices purchased from ICES operator are referred to [8]. The solar radiation related to PV power is referred to [8].

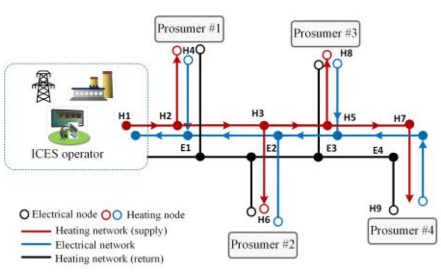

Fig. 2. Schematic of ICES operator with prosumers

As shown in Fig. 3 and Fig. 4, ICES operator optimizes the electrical and heating network charge prices based on the P2P multi-energy trading schedules of prosumers. It can be observed that when the P2P trading schedules are presented, the network charge prices are obtained to affect these schedules. Meanwhile, prosumers can adjust their P2P trading schedules to respond to the ICES operator. The peaks of the electricity network charge price at 10:00 and 15:00 lead to the valley of the electricity trading quantity of prosumers. On the contrary, the valleys of the electricity network charge prices at 11:00 and 14:00 lead to the peaks of the trading quantity. Furthermore, the adjustment trend of the heating trading quantity affected by the heating network charge price is the same to the electricity trading quantity.

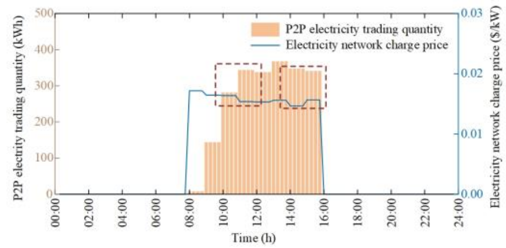

Fig. 3. P2P electricity trading results with electricity network charge prices

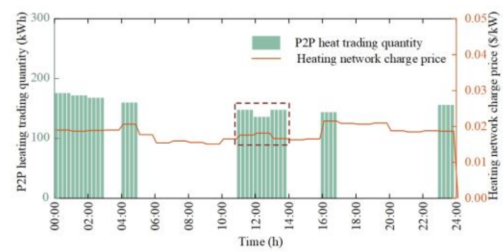

Fig. 4. P2P heat trading results with heating network charge prices

To further verify the effectiveness of this bi-level optimization, two scenarios are compared. Scenario I: Bi-level optimization as proposed in this paper. Scenario II: the ICES operator can set the fixed electricity and heating network charge prices within the range of [$\gamma^{\text{Elec,min}}$, $\gamma^{\text{Elec,max}}$] and [$\gamma^{\text{Heat,min}}$, $\gamma^{\text{Heat,max}}$] with the step size of 0.1.

Table.1 COMPARISONS OF TWO SCENARIOS

Scenario	Electricity and heating network charge price	Prosumers participate in network charge pricing
I	Optimized	√
II	[$\gamma^{\text{Elec,min}}$, $\gamma^{\text{Elec,max}}$], [$\gamma^{\text{Heat,min}}$, $\gamma^{\text{Heat,max}}$]	×

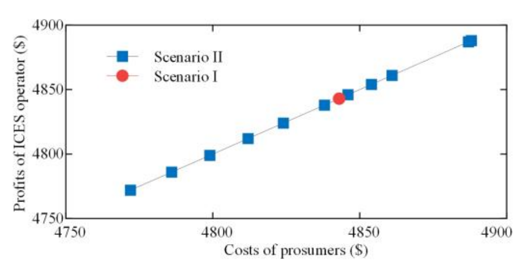

Fig. 5. ICES operator's profit and costs of prosumers in scenario I and II

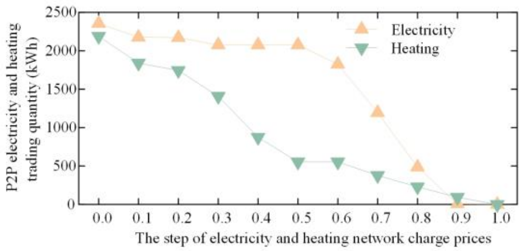

Fig. 6. P2P electricity and heating trading quantities in scenario II

As shown in Fig. 5, the higher cost of prosumers, the greater the profit of the ICES operator. Meanwhile, higher electricity and heating network charge prices are much more beneficial to the ICES operator, but lower prices are much more beneficial to prosumers. Specifically, the ICES operator with the highest electricity and heating network charge prices can impede prosumers from making the P2P trading as shown in Fig. 6. It can be seen that higher network charge prices can lead to the lower P2P electricity and heating trading quantity. Then, it can result in that the cost of prosumers and the ICES operator's profit are increased compared to scenario I. And in the situation with the lowest network charge prices of 0, the result is exactly the opposite compared to the above situation. Thus, in scenario I, the balanced scheduling scheme for the ICES operator and prosumers can be obtained.

6. CONCLUSION

This paper developed a coordinated bi-level optimization method for the ICES operator and prosumers with P2P trading. The ICES operator can optimize the electricity and heating network charge prices for prosumers aiming at maximizing its profit. And prosumers can adjust their P2P multi-energy trading schedules to respond to the ICES operator to minimize their costs. Simulation results show that this bi-level optimization can engage both prosumers and the ICES operator in pricing and consider the optimal benefit of the ICES operator. Meanwhile, this paper provides an equilibrium solution that can balance the utilities of the ICES operator and prosumers.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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