# Calculation Model and Allocation Strategy of Network Usage Charge for Peer-to-peer and Community-based Energy Transaction Market

Dong Han, Lei Wu, Xijun Ren, and Shiwei Xia

*Abstract*—**The emergence of prosumers in distribution systems has enabled competitive electricity markets to transition from traditional hierarchical structures to more decentralized models such as peer-to-peer (P2P) and community-based (CB) energy transaction markets. However, the network usage charge (NUC) that prosumers pay to the electric power utility for network services is not adjusted to suit these energy transactions, which causes a reduction in revenue streams of the utility. In this study, we propose an NUC calculation method for P2P and CB transactions to address holistically economic and technical issues in transactive energy markets and distribution system operations, respectively. Based on the Nash bargaining (NB) theory, we formulate an NB problem for P2P and CB transactions to solve the conflicts of interest among prosumers, where the problem is further decomposed into two convex subproblems of social welfare maximization and payment bargaining. We then build the NUC calculation model by coupling the NB model and AC optimal power flow model. We also employ the Shapley value to allocate the NUC to consumers fairly for the NUC model of CB transactions. Finally, numerical studies on IEEE 15-bus and 123-bus distribution systems demonstrate the effectiveness of the proposed NUC calculation method for P2P and CB transactions.**

*Index Terms*—**Electricity market, network usage charge, distribution locational marginal prices, Shapley value, Nash bargaining, transactive energy, peer-to-peer transaction, community-based transaction.**

## I. Introduction

In recent years, with the gradual maturity of renewable energy generation technologies and continual reduction in installation costs, prosumers with small-scale distributed generation in distribution energy networks play an increasingly critical role in transactive energy markets [1]. Emerging prosumers change the generation structure of power grids, imposing technical challenges on the operation mechanism and market transaction model of distribution systems. In addition, the self-interest transaction behaviors of prosumers increase the operation and maintenance burdens of the distribution network, forcing the electric power utility to increase network investment and expand network line capacity. These challenges can be overcome by using the network usage charge (NUC) through efficient price signals that maintain the stable operation of the distribution system and assist in recovering the costs of network operation and maintenance [2]. Therefore, the design of an appropriate NUC for prosumers and electric power utilities is a critical topic given the diversity of energy trading markets.

Currently, the common methods used to determine the NUC include: ① the postage stamp method [3], which is based on the quantity of transmitted energy; ② the contract path method [4], which subjectively limits the power flow direction; and ③ the MW-km method [5], which is based on the power flow distribution of the power grid. However, when the NUC is calculated using these methods, effectively reflecting the utilization of grid assets by users becomes difficult. To address this problem, an active power-flow tracking method that can accurately analyze the power-flow distribution of users is proposed [6]. However, these NUC calculation methods are generally only applicable to transmission networks with unidirectional power flow and a single-market operation model. Thus, limitations remain in terms of calculating the NUC for active distribution networks with bidirectional power flows. Currently, NUC designs for active distribution networks can be divided into: ① a unique cost allocation method; ② an electrical distance method; ③ dynamic energy prices; and ④ distribution locational marginal prices (DLMPs).

The NUC design based on a unique cost allocation method requires prosumers to share the incurred costs equally or proportionally. In [7], the NUC indicates the implementation of energy policies for each prosumer in the peer-to-peer (P2P) market, which is used to build an optimization problem. This problem does not change the decision as a constant term in the objective function. In addition, two network charge mechanisms, namely, volumetric network and peak-

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D. Han (corresponding author) and L. Wu are with the Electrical Engineering Department, University of Shanghai for Science and Technology, Shanghai 200093, China (e-mail: han_dong@usst.edu.cn; wuleiyjs@163.com).

X. Ren is with the State Grid Anhui Electric Power Economic Research Institute, Hefei 230022, China (e-mail: rxjkira@163.com).

S. Xia is with the Electrical Engineering Department, North China Electric Power University, Beijing 102206, China (e-mail: s.w.xia@ncepu.edu.cn).

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coincident capacity network charges, are proposed [8] that can integrate distributed photovoltaic and battery systems more efficiently in the wholesale market. To compensate for the operational costs of the distribution system operator (DSO) during P2P transactions, the NUC is introduced into the model and considered as a variable [9], [10]. Reference [11] proposes that the NUC should be allocated to consumers while considering the difference between transmission and distribution prices, and the NUC is free when the transactions are matched under the same voltage. Further analysis of the NUC is provided in [12] and [13], where the NUC for the P2P transaction is calculated by multiplying the electrical distances between producers and consumers based on the NUC (p. u.) electrical distance; and the latter is determined subjectively by the network owner while considering network construction and maintenance costs, taxes, policies, etc. However, these NUC designs based on the unique cost allocation method and electrical distance method are mainly in the form of static uniform pricing. This means that achieving a balance of interests among multiple parties such as distributed generation, electric power utility, and customers is difficult.

As a solution, dynamic energy pricing and DLMP methods with dynamic characteristics have been introduced to calculate the NUC to balance and maximize the interests of multiple parties. Time-of-use (ToU) tariffs with dynamic change characteristics are considered in the NUC as an efficient pricing mechanism to improve social welfare and facilitate energy utilization. In [14] and [15], the energy transfer cost associated with shifted demand based on ToU is proposed, which benefits the performance of the entire system by formulating consumer behaviors. Similarly, in [16] and [17], the NUC also includes a fee based on the peak demand on the customer side, and consumers indirectly reduce the payment of the NUC by changing their demand schedules under the incentive of a dynamic pricing mechanism. Due to the large temporal granularity and lack of spatial characteristics, the NUC based on dynamic energy prices, e. g., ToU rates, cannot completely capture the operational characteristics of distribution systems. To increase the spatiotemporal granularity of tariffs, [18] introduces DLMPs that capture the characteristics of the distribution network and dynamically change the demand schedules using an effective price signal. In [19], the NUC design based on the DLMP approach is used to encourage P2P transactions that improve the performance of the distribution system and generate additional revenue to offset the reduction in revenue stream for electric power utilities caused by large rollouts of distributed energy resources. Reference [20] further proposes that the NUC for P2P trading is composed of costs associated with network congestion, loss, and modernization of network infrastructures, which are calculated by DLMPs and the Thevenin impedance.

The aforementioned NUC calculation methods mostly focus on the design of the pricing mechanism, which is not only related to pricing but also to the quantity of transactive energy transmitted over the network. The energy management problem for P2P transactions is viewed as a Nash bargaining (NB) game in which the agents mutually negotiate to achieve fair profit allocation [21], [22]. In [23], an incentive mechanism based on NB is designed to encourage proactive energy trading among interconnected microgrids, which realizes benefit-sharing without considering system network loss. Instead, in [24], a distributed P2P transaction between load aggregators and microgrid operators is formulated as an NB problem that considers network loss to achieve the optimal trading volume of electricity and payment. However, ensuring that P2P transactions comply with the operational constraints of the distribution network is critical, which is not considered in the aforementioned research. In [25], a security-constrained decentralized P2P transactive energy trading framework is proposed, where the P2P energy transaction model is established based on the NB theory to acquire the optimal quantity and price of energy.

To these ends, this paper proposes a calculation method for the distribution of NUCs for P2P and community-based (CB) market structures, which allocates the NUC efficiently to consumers while considering the operational characteristics of the distribution network in the context of the prosumer era. The design of the NUC considers the effects of both the energy pricing mechanism based on the DLMP method and the transaction behavior of users based on NB theory in the transactive energy market. First, based on NB theory, we formulate the NB problem for P2P and CB transactions and then decompose the problem into two convex subproblems: the social welfare maximization problem (P1 and S1) and the payment bargaining problem (P2 and S2), which can determine the optimal transaction quantity and price. Second, the NUC calculation model is constructed by coupling the NB model and AC optimal power flow (OPF) model, in which the DLMPs are composed of the dual multipliers in the AC OPF model. In addition, the Shapley value is employed to allocate the NUC to consumers fairly for the NUC model of CB transactions. In the simulation, the NUC, welfare, and network operational characteristics of P2P and CB transactions are compared. The main contributions of this study are as follows.

1) Compared with the existing NUC models, a holistic NUC calculation model is built for the trading optimization scheduling problems of P2P and CB for prosumers. The NUC pricing method and optimal trading scheduling are innovatively incorporated into the NUC analytic framework, which has not been previously studied.

2) The energy trading problem in the transactive energy market is formulated based on NB theory, which captures the transaction behavior of prosumers and improves their mutual benefits. The formulated non-convex bargaining problem is decomposed into the two convex subproblems of social welfare maximization and payment bargaining.

3) A cooperative NUC allocation strategy is proposed for CB trading of prosumers based on the Shapley value. Compared with the NUC of P2P trading, which is derived from the differences among DLMPs, the NUC of CB trading is fairly allocated to consumers based on the marginal contribu-

tion of the coalition, which is obtained from the Shapley value.

The remainder of this paper is organized as follows. Section II presents the energy trading model in energy transaction markets. The NUC model is discussed in Section III. The case study is presented in Section IV. Conclusions are given in Section V.

## II. Energy Trading Model in Energy Transaction Markets

### A. Overview of Prosumer Market Structures

Different prosumer markets in the prosumer era are proposed in [1], and Fig. 1 shows the structural attributes of P2P and CB markets. In addition, at the distribution level, the DSO is responsible for scheduling energy distribution and maintaining safe and reliable operation of the distribution network. The transactive energy trading framework in a distribution system is shown in Fig. 2. In the P2P market, prosumers can make decisions independently and communicate with each other to determine the prices and quantities of energy transactions [26], [27]. In the CB market, the transactions of prosuming services are coordinated by the community manager (CM) [28], where many prosumers in the community provide the feedback to the CM on their trading preferences, and the CM matches energy transactions.

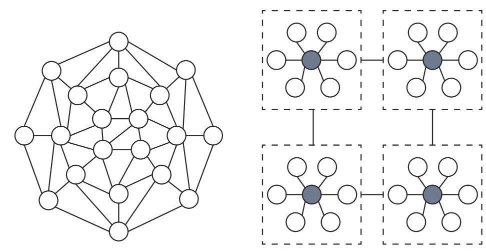


Fig. 1. Structural attributes of P2P and CB markets. (a) P2P market. (b) CB market.

The P2P market is more scalable due to the lack of a central coordinator required for the negotiation process. However, in a transactive energy market with many prosumers, the P2P transaction model generates a heavy computational burden because each prosumer must interact both directly and simultaneously. Compared with the P2P market, the CB market can form an independent community based on the preferences of prosumers, e.g., trading with other closest prosumers, which can effectively improve the operational efficiency of systems and reduce the computational burden. However, the CB market generally does not have good scalability.

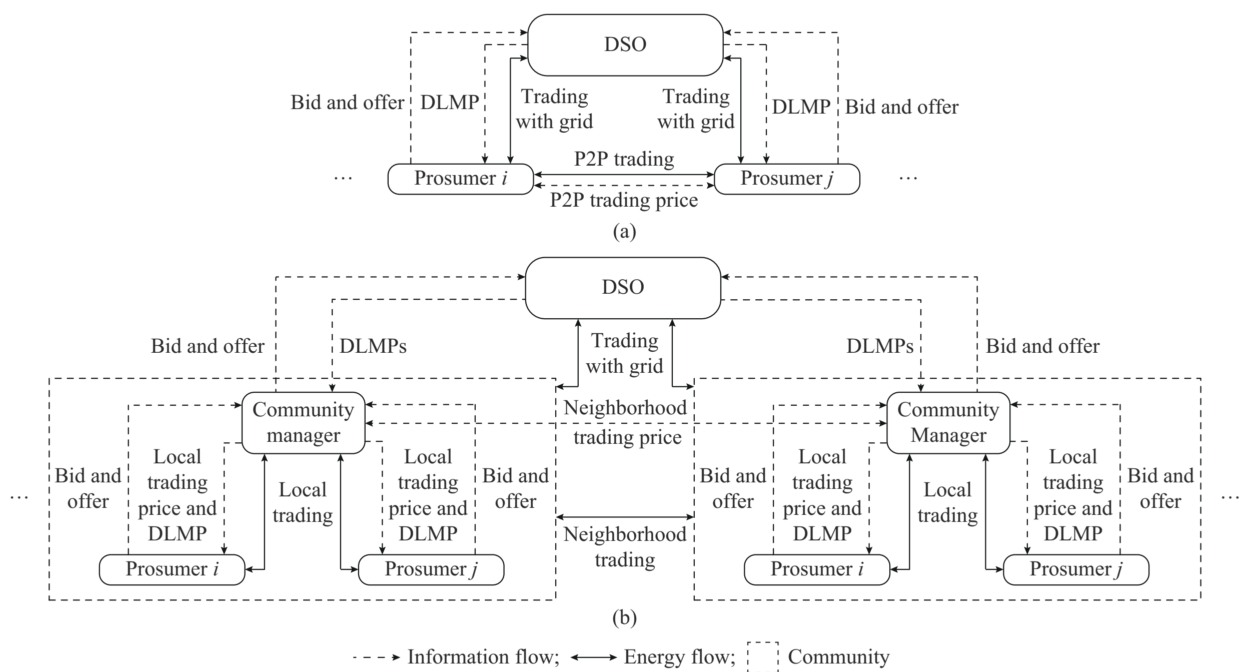


Fig. 2. Transactive energy trading framework in a distribution system. (a) P2P market. (b) CB market.

### B. Energy Trading Model Without Game Behaviors

We assume that the energy declarations of all participants for P2P and CB transactions meet the minimum entry requirements for market transactions to avoid wasting resources and all participants can benefit from the P2P and CB markets. For modeling convenience, each prosumer in the transactive energy market is defined as a producer with the index $i \in \Omega_p$ or a consumer with the index $j \in \Omega_c$, where $\Omega_p \triangleq \{1,2,...,n_p\}$, $\Omega_c \triangleq \{1,2,...,n_c\}$, and $n_p$ and $n_c$ are the numbers of producers and consumers, respectively. The set of prosumers is $\Omega = \Omega_p \cup \Omega_c$ and $\Omega_p \cap \Omega_c = \varnothing$.

Energy is traded in a P2P market consisting of $n_\text{p}$ producers and $n_\text{c}$ consumers. Bilateral transactions between producers and consumers can be described by the supply and demand matrix $\boldsymbol{D}$ given in (1). Each decision variable $p_{ij}$ of matrix $\boldsymbol{D}$ represents the energy supply of producer $i$ to consumer $j$ or the energy demand of consumer $j$ from producer $i$.

$$\boldsymbol{D}=\begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n_c} \\ p_{21} & p_{22} & \cdots & p_{2n_c} \\ \vdots & \vdots & & \vdots \\ p_{n_p1} & p_{n_p2} & \cdots & p_{n_pn_c} \end{bmatrix} \tag{1}$$

The total demand of consumer $j$ is expressed as:

$$d_j=\sum_{i\in\Omega_p} p_{ij} \tag{2}$$

Similarly, the total supply of producer $i$ is:

$$g_i=\sum_{j\in\Omega_c} p_{ij} \tag{3}$$

The energy transaction in the P2P market is modeled as:

$$\max_{\Xi^{P2P}} O^{P2P}:=\sum_{j\in\Omega_c} U_j(d_j)-\sum_{i\in\Omega_p} C_i(g_i) \tag{4}$$

$$g_i=\sum_{j\in\Omega_c} p_{ij} \quad \forall i\in\Omega_p \tag{5}$$

$$d_j=\sum_{i\in\Omega_p} p_{ij} \quad \forall j\in\Omega_c \tag{6}$$

$$\underline{G}_i\le g_i\le\bar{G}_i \quad \forall i\in\Omega_p \tag{7}$$

$$\underline{D}_j\le d_j\le\bar{D}_j \quad \forall j\in\Omega_c \tag{8}$$

$$p_{ij}\ge 0 \quad \forall (i,j)\in(\Omega_p,\Omega_c) \tag{9}$$

where $U_j$ and $C_i$ are the utility function of consumer $j$ and cost function of producer $i$, respectively; $\Xi^{P2P}=\{g_i,d_j,p_{ij}\ge0\}$ is the set of decision variables; $\underline{G}_i$ and $\bar{G}_i$ are the lower and upper limits of energy supply for producer $i$, respectively; and $\underline{D}_j$ and $\bar{D}_j$ are the lower and upper limits of energy demand for consumer $j$, respectively. The model objective function in (4) is the social welfare maximization for all prosumers. If the energy demand of the consumer is inelastic, the objective function is equivalent to minimizing the cost of the producer. In this study, the cost function is set as a general linear function. Constraints (5) and (6) indicate the total energy sold by producer $i$ and purchased by consumer $j$ in the P2P market, respectively. Constraints (7) and (8) represent the limits of the energy that can be sold by producer $i$ and purchased from consumer $j$, respectively. Constraint (9) sets the energy offered by producer $i$ to consumer $j$ as a non-negative value.

Inspired by the method of decomposition and coordination, producers and consumers in the CB market can choose to participate in energy transactions within or outside the community according to their preferences, and thus the scope of communities is divided. By matching energy transactions based on the transaction preferences of producers and consumers, the CM submits the matching information to the DSO, which completes the energy dispatch and clears the CB market. The CM can be considered a nonprofit local data-sharing center or a small-scale aggregator [29]. The energy transaction in the CB market is modeled as follows and the community is indexed by $m\in M$ and the set of $M\triangleq\{1,2,...,n_m\}$.

$$\max_{\Xi^{CB}} O^{CB}:=\sum_{m\in M}\sum_{j\in\Omega_c^m} U_{m,j}(d_{m,j},e_{m,j},\beta_{m,j})-\sum_{m\in M}\sum_{i\in\Omega_p^m} C_{m,i}(g_{m,i},e_{m,i},\alpha_{m,i})-\sum_{m\in M} H_m(e_m^{imp},e_m^{exp}) \tag{10}$$

$$g_{m,i}=e_{m,i}+\alpha_{m,i} \quad \forall (m,i)\in(M,\Omega_p^m) \tag{11}$$

$$d_{m,j}=e_{m,j}+\beta_{m,j} \quad \forall (m,j)\in(M,\Omega_c^m) \tag{12}$$

$$\sum_{i\in\Omega_p^m}\alpha_{m,i}=e_m^{exp} \quad \forall m\in M \tag{13}$$

$$\sum_{j\in\Omega_c^m}\beta_{m,j}=e_m^{imp} \quad \forall m\in M \tag{14}$$

$$\sum_{i\in\Omega_p^m} e_{m,i}=\sum_{j\in\Omega_c^m} e_{m,j} \quad \forall m\in M \tag{15}$$

$$\sum_{m\in M}\sum_{j\in\Omega_c^m} d_{m,j}=\sum_{m\in M}\sum_{i\in\Omega_p^m} g_{m,i} \tag{16}$$

$$\underline{G}_{m,i}\le g_{m,i}\le\bar{G}_{m,i} \quad \forall (m,i)\in(M,\Omega_p^m) \tag{17}$$

$$\underline{D}_{m,j}\le d_{m,j}\le\bar{D}_{m,j} \quad \forall (m,j)\in(M,\Omega_c^m) \tag{18}$$

where $\Omega_p^m$ and $\Omega_c^m$ are the sets of producers and consumers in community $m$, respectively; $\Xi^{CB}=\{g_{m,i},d_{m,j},e_{m,i},e_{m,j},\alpha_{m,i},\beta_{m,j}\ge0\}$ is the set of decision variables; $U_{m,j}$ and $C_{m,i}$ are the utility function of producer $j$ and cost function of consumer $i$ in community $m$, respectively; $H_m$ is the transaction function of CM in community $m$; $e_{m,i}$ and $\alpha_{m,i}$ are the energy sold by producer $i$ of community $m$ to consumers in community $m$ and other communities, respectively; $e_{m,j}$ and $\beta_{m,j}$ are the energy purchased by consumer $j$ of community $m$ from producers in community $m$ and other communities, respectively; and $e_m^{imp}$ and $e_m^{exp}$ are the import and export energy of community $m$, respectively. The objective function of the CB market is the social welfare maximization in (10). Constraint (11) represents the energy offered by producer $i$ of community $m$. Constraint (12) represents the energy demanded by consumer $j$ of community $m$. Constraints (13) and (14) represent the energy transactions handled centrally by the CM among the communities. For each producer and consumer, we consider the energy balance in community $m$ and CB market of (15) and (16). Constraints (17) and (18) represent the limits of the energy that can be sold by producer $i$ and purchased from consumer $j$ in community $m$, respectively.

For the CB model, the utility function of consumer $j$ in community $m$ is given by:

$$U_{m,j}(d_{m,j},e_{m,j},\beta_{m,j})=\kappa_{m,j}d_{m,j}-(\gamma_{com}e_{m,j}+\gamma_{imp}\beta_{m,j}) \tag{19}$$

where the constant $\kappa_{m,j}$ is the satisfaction parameter of consumer $j$, which indicates the utilization value of the energy demand; and $\gamma_{com}$ and $\gamma_{imp}$ are the favorable transaction costs for internal energy transactions and the additional penalty factor for external energy trading, respectively, which can effectively encourage energy transactions within the community.

The cost function of producer $i$ in community $m$ with energy trading is defined as:

$$C_{m,i}(g_{m,i},e_{m,i},\alpha_{m,i})=\pi_{m,i}g_{m,i}+\gamma_{com}e_{m,i}+\gamma_{exp}\alpha_{m,i} \tag{20}$$

where $\pi_{m,i}$ is the generation cost of producer $i$ in community

$m$; and $\gamma_{exp}$ is the additional penalization for producers, which reflects the will of producer $i$ to improve community autonomy in the context of the CB market.

In the negotiation process for CM, the focus of the CB market operation is to achieve a common agreement on prosumer preferences in matching energy inside and outside the community. We address the critical role of CM and define $H_m$ as the transaction function, which represents the cost for community $m$ to conduct a common agreement with other communities. The transaction function of the CM in community $m$ is given by [30]:

$$H_m(e_m^{imp}, e_m^{exp}) = \gamma_{imp} e_m^{imp} + \gamma_{exp} e_m^{exp} \tag{21}$$

### C. NB Based on Energy Trading Model

Prosumer transactions in the transactive energy market have self-interest properties. These include the cases in which prosumers in the P2P market share energy transactions with the aim of maximizing individual benefits, and prosumers in the CB market rely on transaction preferences to divide communities based on transactions to maximize individual satisfaction and enhance transaction value. We assume that prosumers who trade in the transactive energy market are independent and rational. As independent rational individuals, each prosumer expects to achieve a consensus through negotiation and seeks a balanced strategy to maximize their benefits; otherwise, a disagreement is the result. Reference [31] analytically modeled this bargaining process and uniquely identified a bargaining solution called the NB solution (NBS) that can accommodate both individual and collective interests. The NBS is formulated by solving the following optimization problem:

$$\max \prod_{k \in K} (F_k - F_k^0) \tag{22}$$

s.t.

$$F_k \geq F_k^0 \tag{23}$$

where $K$ is the set of negotiators; and $F_k$ and $F_k^0$ are the benefits of negotiator $k$ before and after the bargaining process, respectively. Constraint (23) indicates that the benefits of negotiator $k$ in bargaining transactions are enhanced.

Previous studies have considered the application of NBS in market-clearing models of P2P and CB markets [32], [33]. In bargaining transactions, the operational benefits for each producer $i$ and consumer $j$ also must consider mutual energy exchange payments. The energy exchange payments of producers and consumers in a P2P market are given by (24) and (25), respectively.

$$G_i(p_{ij}) = \sum_{j \in \Omega_c} a_{ij} p_{ij} \tag{24}$$

$$G_j(p_{ij}) = -\sum_{i \in \Omega_p} a_{ij} p_{ij} \tag{25}$$

where $a_{ij}$ is the transaction price for producer $i$ and consumer $j$.

The formulation of our proposed energy trading problem based on NB in the P2P market is given as:

$$\max_{\Xi^{P2P}} \prod_{j \in \Omega_c} (U_j + G_j - \tilde{U}_j) \prod_{i \in \Omega_p} (\tilde{C}_i + G_i - C_i) \tag{26}$$

s.t.

$$\text{(5)-(9)} \tag{27}$$

$$\sum_{i \in \Omega_p} G_i + \sum_{j \in \Omega_c} G_j = 0 \tag{28}$$

$$\sum_{i \in \Omega_p} g_i - \sum_{j \in \Omega_c} d_j = 0 \tag{29}$$

$$U_j + G_j - \tilde{U}_j \geq 0 \quad \forall j \in \Omega_c \tag{30}$$

$$\tilde{C}_i + G_i - C_i \geq 0 \quad \forall i \in \Omega_p \tag{31}$$

The objective function (26) corresponds to the welfare improvement of producer $i$ and consumer $j$. Constraint (27) summarizes the local energy-scheduling constraints for each prosumer in the P2P market. Constraints (28) and (29) denote the balance of energy payments and the balance of the quantity of energy transactions, respectively. Constraints (30) and (31) correspond to (23), which indicates that prosumers increase their benefits through bargaining transactions.

The NB model in (26)-(31) for P2P transactions is a nonconvex optimization problem that is difficult to solve directly. To address this issue, the solution of model in (26)-(31) is decomposed into two convex subproblems P1 and P2 as follows. The detailed proof is presented in [33]. The first subproblem, P1, determines the optimal quantity of energy by solving a social welfare maximization problem, and the second subproblem, P2, determines the optimal price of energy for bargaining transactions by solving a payment bargaining problem.

1) P1: social welfare maximization problem

$$\max_{\Xi^{P2P}} O^{P2P} := \sum_{j \in \Omega_c} U_j - \sum_{i \in \Omega_p} C_i \tag{32}$$

s.t.

$$\text{(27) and (29)} \tag{33}$$

2) P2: payment bargaining problem

$$\max_{\{a_{ij}\}_{(i,j) \in (\Omega_p, \Omega_c)}} \prod_{j \in \Omega_c} (U_j^* + G_j - \tilde{U}_j^*) \prod_{i \in \Omega_p} (\tilde{C}_i^* + G_i - C_i^*) \tag{34}$$

s.t.

$$\text{(28), (30), and (31)} \tag{35}$$

$$p_{ij} = p_{ij}^* \quad \forall (i,j) \in (\Omega_p, \Omega_c) \tag{36}$$

where $U_j^*$, $C_i^*$, and $p_{ij}^*$ are the optimal solutions for P1; and $\tilde{U}_j^*$ and $\tilde{C}_i^*$ are the disagreement points obtained from optimization model given in (4)-(9).

Similarly, in a CB market with bargaining transactions, the energy exchange payments for producer and consumer are given by (37) and (38), respectively. Note that the bargaining transactions between producers and consumers are handled centrally by CMs, and CMs in different communities can also trade the energy with each other.

$$Z_{m,i}(e_{m,i}, \alpha_{m,i}) = \varphi_{m,i} e_{m,i} + \zeta_{m,i} \alpha_{m,i} \tag{37}$$

$$Z_{m,j}(e_{m,j}, \alpha_{m,j}) = \delta_{m,j} e_{m,j} + \chi_{m,j} \beta_{m,j} \tag{38}$$

where $\varphi_{m,i}$ and $\zeta_{m,i}$ are the transaction prices of producer $i$ inside and outside community $m$ through bargaining transactions, respectively; and $\delta_{m,j}$ and $\chi_{m,j}$ are the transaction prices of producer $j$ inside and outside community $m$ through bargaining transactions, respectively.

The mathematical model of the proposed energy-trading problem based on NB in the CB market is given as:

$$\max_{\Xi^{CB}} \prod_{m\in M, j\in\Omega_c^m}(U_{m,j}-Z_{m,j}-\gamma_{imp}\beta_{m,j}-\tilde{U}_{m,j})\cdot \prod_{m\in M, i\in\Omega_p^m}(\tilde{C}_{m,i}+Z_{m,i}-\gamma_{exp}\alpha_{m,i}-C_{m,i}) \tag{39}$$

s.t.

$$(11)\text{-}(18) \tag{40}$$

$$\sum_{m\in M}\sum_{i\in\Omega_p^m} Z_{m,i}-\sum_{m\in M}\sum_{j\in\Omega_c^m} Z_{m,j}=0 \tag{41}$$

$$U_{m,j}-Z_{m,j}-\gamma_{imp}\beta_{m,j}-\tilde{U}_{m,j}\geq 0 \quad \forall (m,j)\in(M,\Omega_c^m) \tag{42}$$

$$\tilde{C}_{m,i}+Z_{m,i}-\gamma_{exp}\alpha_{m,i}-C_{m,i}\geq 0 \quad \forall (m,i)\in(M,\Omega_p^m) \tag{43}$$

The objective function (39) corresponds to the increment in welfare for all bargaining transactions. Constraint (40) is the energy scheduling for prosumers in a CB market, and constraint (41) denotes the payment balance for bargaining transactions among prosumers. Constraints (42) and (43) indicate that the benefits to consumers and prosumers, respectively, are improved by bargaining.

We equivalently transform bargaining model (39)-(43) into two easily solvable convex subproblems, namely, social welfare maximization subproblem S1 and payment bargaining subproblem S2. The solution to the original NB model (39)-(43) can be determined by successively solving S1 and S2.

1) S1: social welfare maximization problem

$$\begin{cases}\max\limits_{\Xi^{CB}} O^{CB}:=\sum\limits_{m\in M}\sum\limits_{j\in\Omega_c^m}(U_{m,j}-\gamma_{imp}\beta_{m,j})-\sum\limits_{m\in M}\sum\limits_{i\in\Omega_p^m}(C_{m,i}+\gamma_{exp}\alpha_{m,i})\\ \text{s.t. } (40)\end{cases} \tag{44}$$

2) S2: payment bargaining problem

$$\max_{A} \prod_{m\in M, j\in\Omega_c^m}(U^*_{m,j}-Z_{m,j}-\gamma_{imp}\beta^*_{m,j}-\tilde{U}^*_{m,j})\cdot \prod_{m\in M, i\in\Omega_p^m}(\tilde{C}^*_{m,i}+Z_{m,i}-\gamma_{exp}\alpha^*_{m,i}-C^*_{m,i}) \tag{45}$$

s.t.

$$(41)\text{-}(43) \tag{46}$$

$$e_{m,i}=e^*_{m,i} \quad \forall (m,i)\in(M,\Omega_p^m) \tag{47}$$

$$e_{m,j}=e^*_{m,j} \quad \forall (m,j)\in(M,\Omega_c^m) \tag{48}$$

where $A=\{\varphi_{m,i},\zeta_{m,i},\delta_{m,j},\chi_{m,j}\}$ is the set of decision variables; $U^*_{m,j}$, $C^*_{m,i}$, and $\{\alpha^*_{m,i},\beta^*_{m,j},e^*_{m,i},e^*_{m,j}\}$ are the optimal solutions of S1; and $\tilde{U}^*_{m,j}$ and $\tilde{C}^*_{m,i}$ are the disagreement points obtained from the optimization model given in (10)-(18).

## III. NUC Model

The optimal energy transactions for the P2P and CB markets presented in Section II have no guarantee that their results will satisfy the operational constraints of distribution network, which may otherwise cause line congestion, voltage instability, and power quality degradation. To alleviate these problems, the NUC that links the energy bargaining transactions for P2P and CB markets to the secure operating conditions of the distribution network must be analyzed. The following four subsections present the modeling mechanism of NUC and the modeling process when NUC is used to coordinate transactive energy market transactions with energy dispatch in the distribution network. We formulate the DLMPs as a general function of the dual multipliers of the AC OPF to capture resource scarcity, and we use the DLMPs to derive the NUC to incentivize or penalize the transaction behaviors of the prosumer. Considering the transferability of DLMPs, the NUC is calculated by coupling the AC OPF model and the energy transaction model of transactive energy markets and is allocated using the Shapley value for CB transactions. Note that the objective of the NUC model is not to minimize the NUC, which is based on post-processing.

### A. Branch Flow Model

Consider a radial distribution network ($N$, $L$), where node set $N$ consists of substation node $\{0\}$ and other nodes $N^+=L=\{1, 2, ..., |N|\}$, and each node (indexed as $n$) in $N^+$ contains a parent node $A_n$ and a set of child nodes $C_n$. The branch flow model of the radial distribution is given as [34]:

$$\max_{\Xi^{Dist}} O^{Dist}:=\sum_{n\in N^+} C_n^c p_n^c-\sum_{n\in N} C_n^g p_n^g \tag{49}$$

$$(\lambda_n): f_n^p-\sum_{k\in C_n}(f_k^p-l_k R_k)-p_n^g+p_n^c+G_n v_n=0 \quad \forall n\in N^+ \tag{50}$$

$$(\mu_n): f_n^q-\sum_{k\in C_n}(f_k^q-l_k X_k)-q_n^g+q_n^c+B_n v_n=0 \quad \forall n\in N^+ \tag{51}$$

$$(\eta_n^+): (f_n^p)^2+(f_n^q)^2\leq S_n^2 \quad \forall n\in L \tag{52}$$

$$(\eta_n^-): (f_n^p-l_n R_n)^2+(f_n^q-l_n X_n)^2\leq S_n^2 \quad \forall n\in L \tag{53}$$

$$v_n-2(R_n f_n^p+X_n f_n^q)+l_n(R_n^2+X_n^2)=v_{A_n} \quad \forall n\in L \tag{54}$$

$$\frac{(f_n^p)^2+(f_n^q)^2}{l_n}\leq v_n \quad \forall n\in L \tag{55}$$

$$\underline{V}_n\leq v_n\leq \bar{V}_n \quad \forall n\in N \tag{56}$$

$$\underline{P}_n^g\leq p_n^g\leq \bar{P}_n^g \quad \forall n\in N \tag{57}$$

$$\underline{P}_n^c\leq p_n^c\leq \bar{P}_n^c \quad \forall n\in N \tag{58}$$

$$\underline{Q}_n^g\leq q_n^g\leq \bar{Q}_n^g \quad \forall n\in N \tag{59}$$

$$\underline{Q}_n^c\leq q_n^c\leq \bar{Q}_n^c \quad \forall n\in N \tag{60}$$

where $\Xi^{Dist}=\{f_n^p,f_n^q,p_n^g,p_n^c,l_n,v_n\}$ represents the set of decision variables; the constants $C_n^c$ and $C_n^g$ indicate the marginal cost of generators and the marginal benefit of consumers, respectively; $p_n^g$ and $p_n^c$ are the active power generation and consumption, respectively; $l_n$ and $v_n$ are the current and voltage magnitudes squared, respectively; $f_n^p$ and $f_n^q$ are the active and reactive power, respectively; $G_n$ and $B_n$ are the conductance and susceptance, respectively; $S_n$ is the complex power flow limit; and $R_n$ and $X_n$ are the resistance and reactance, respectively. The objective of the model in (49) is to maximize social welfare. Constraints (50) and (51) denote the active and reactive power balances of each node, respectively. Constraints (52) and (53) correspond to the complex power flow constraints of each line. Constraint (54) corresponds to a relaxation of the power flow equations and is derived in [35]. Constraint (55) is a second-order cone constraint. Constraints (56)-(60) impose a limit on the corresponding decision variables.

The dual multipliers $\lambda_{A_n}$, $\mu_n$, $\eta_n^+$, and $\eta_n^-$ on the left of the corresponding constraints constitute the DLMPs, which are derived using the Karush-Kuhn-Tucker (KKT) condition through the AC OPF model given in (61) [34].

$$\rho_n = A_1\lambda_{A_n} + A_2\mu_n + A_3\mu_{A_n} + A_4\eta_n^+ + A_5\eta_n^- \tag{61}$$

where $A_i\,(i=1,2,...,5)$ is the nonlinear function given in [34].

### B. NUC for a P2P Market

DLMPs that offer incentive price signals are used to derive NUCs with bargaining transactions in different markets. In a P2P market, to reflect the effects of bargaining transactions on DLMPs, constraint (50) must be modified to realize an interconnection between the bargaining model with P2P transactions (26)-(31) and the branch flow model (49)-(60). The modified constraint is formulated as:

$$(\lambda_n): f_n^p - \sum_{k\in C_n}(f_k^p - l_k R_k) - p_n^g - g_{i=n} + d_{i=n} + G_n v_n = 0 \quad \forall n \in N^+ \tag{62}$$

The NUC model for the P2P market is given as:

$$\max(O^{P2P} + O^{Dist}) \tag{63}$$

s.t.

$$(33),\ (51)\text{-}(60),\ \text{and}\ (62) \tag{64}$$

The optimal solutions and DLMPs are obtained by solving the NUC optimization model in (63) and (64). The NUC is paid by consumers according to the principle of "who benefits and who bears", and the NUC of consumer $j$ with bargaining transactions in the P2P market can be calculated by:

$$NUC_j = \sum_{i\in \Omega_p}(\rho_j - \rho_i)p_{ij} \tag{65}$$

where $\rho_i$ and $\rho_j$ are the DLMPs for producer $i$ and consumer $j$, respectively.

### C. NUCs for CB Market

Unlike the P2P market, the CB market not only simplifies the complexity of the energy transaction process but also reduces the computational burden of the NUC by introducing the role of the CM and fully considering the self-organization of the community. Correspondingly, constraint (50) must be adjusted so that the bargaining transaction model given in (39)-(43) for the CB market and the branch flow model (49)-(60) are coupled. The adjusted constraint is formulated as:

$$(\lambda_n): f_n^p - \sum_{k\in C_n}(f_k^p - l_k R_k) - p_n^g - g_{m,i=n} + d_{m,i=n} + G_n v_n = 0 \quad \forall (n,m)\in(N^+, M) \tag{66}$$

The NUC model for the CB market is given by:

$$\max(O^{CB} + O^{Dist}) \tag{67}$$

s.t.

$$(45),\ (51)\text{-}(60),\ \text{and}\ (66) \tag{68}$$

The community is a self-organized structure with weakly centralized transactions, and all energy transactions are matched by the CM, which simplifies the calculation process of the NUC and reflects the advantage of the decomposition and coordination approach. The NUC of community $m$ is determined based on the average energy selling and purchasing prices, which are given by:

$$NUC_m = \left(\frac{\sum_{j\in\Omega_c}\rho_{m,j}}{N_{m,b}} - \frac{\sum_{i\in\Omega_p}\rho_{m,i}}{N_{m,s}}\right)\sum_{j\in\Omega_c} e_{m,j} + \sum_{f\in M/\{m\}}\left(\frac{\sum_{j\in\Omega_c}\rho_{m,j}}{N_{m,b}} - \frac{\sum_{i\in\Omega_p}\rho_{f,i}}{N_{f,s}}\right)e_{mf} \tag{69}$$

where $\rho_{m,i}$ and $\rho_{m,j}$ are the DLMPs for producer $i$ and consumer $j$ within community $m$, respectively; $N_{m,b}$ and $N_{m,s}$ are the numbers of consumers and producers within community $m$, respectively; and $e_{mf}$ is the energy purchased by community $m$ from community $f$. The first and second items of (69) represent the NUC generated by trading within community $m$ and with other communities, respectively. Note that, in contrast to the NUC modeling mechanism of P2P transactions, the CB market considers the participation of third-party agents, i.e., CMs, in energy bargaining transactions, making it difficult to allocate the NUC directly to consumers. Therefore, a feasible allocation scheme must be designed for each consumer to ensure the NUC of community $m$ obtained from DLMPs.

### D. Shapley Value for NUC Allocation

Because prosumers build communities based on transaction preferences and the NUC is allocated accordingly, the relationship between prosumers in the CB market is typically both cooperative and competitive. In coalitional games with self-interested characteristics, the worth of the coalition must be distributed among the players of the coalitional group using a fairness rule. The rational allocation of the NUC among community prosumers is a critical problem for CB market energy transactions. For a coalition composed of multiple participants, the Shapley value is used to design an allocation scheme that allocates coalition benefits based on the average marginal contribution of each participant. The Shapley value has been studied and widely applied in the fields of transmission network construction cost allocation [36], network loss cost allocation [37], unit start-stop cost allocation [38], and peak shaving cost allocation [39]. In this study, the NUC obtained by a coalition containing community prosumers is divided among its players using the Shapley value.

In general, we denote $c(N)$ as the contribution of coalition for any of the proposed coalition benefit allocation problems, where $c(N)=NUC_{m=N}$ is derived from (69). We denote $\phi_k$ as the Shapley value, which is assigned to each game contribution represented by function $c(N)$, i.e., a vector of NUC

$\{\phi_1, \phi_2, \ldots, \phi_{|N|}\}$ for each consumer $k$ of coalition $N$ such that $\sum_{k \in N} \phi_k = c(N)$. Let $Q \subseteq N$ be any non-empty subset of consumers from the set of $N$ that may build a coalitional group, and the number of consumers in set $Q$ is $|Q|$. The marginal contribution, i. e., NUC, of a consumer $k$ with respect to the overall NUC savings obtained by a subset of $Q$ is defined by the value $c(Q \cup \{k\}) - c(Q)$. Then, the Shapley value $\phi_k$ assigned to each consumer $k$ is given by (17). This sum is calculated over all possible subsets $Q$ of $N$ without containing consumer $k$.

$$\phi_k = \sum_{Q \subseteq N/\{k\}} \frac{|Q|!\left(n - |Q| - 1\right)!}{n!} \left(c(Q \cup \{k\}) - c(Q)\right) \quad (70)$$

where $c(Q \cup \{k\})$ and $c(Q)$ are obtained by (69), i.e., $c(Q \cup \{k\}) = NUC_{m=Q \cup \{k\}}$ and $c(Q) = NUC_{m=Q}$.

## IV. Case Study

The modified IEEE 15-bus and IEEE 123-bus distribution test systems are used to validate the effectiveness of the proposed NUC calculation model. The optimization problems of P2P and CB transaction involve the use of decentralized or distributed optimization techniques, e.g., the alternating direction method of multipliers, to guarantee the privacy of prosumers. However, because the distributed optimization techniques have the problem of slow convergence or non-convergence within limited iterations, the centralized optimization method with fast convergence is applied in this study to obtain global optimal results. The program is developed in MATLAB 2017b, where the commercial solver IPOPT is used to solve the optimization problems of NUC and to acquire the DLMPs.

### A. IEEE 15-bus Distribution Test System

Figure 3 shows the IEEE 15-bus distribution test system. The system is divided into three communities containing four producers located at buses 0, 2, 3, and 7 with the installed capacities of 4.2, 0.4, 0.4, and 0.4 MW, respectively, and 11 consumers. Bus 0 is the upstream connection to the main grid. Simulation parameters for IEEE 15-bus distribution test system are listed in Table I.

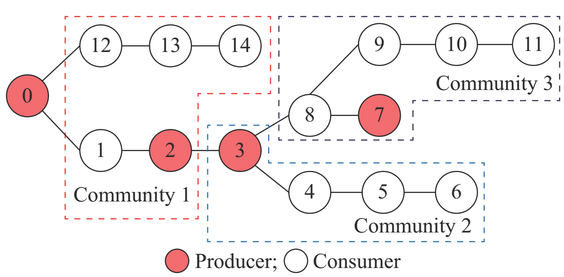


Fig. 3. IEEE 15-bus distribution test system.

Figure 4 shows energy transactions with NUCs in the IEEE 15-bus distribution test system. Figure 4(a) shows that P2P transactions are relatively decentralized, and the quantity of P2P transactions is small. In other words, each consumer purchases a varying quantity of energy from all producers, and the quantity of electric energy purchased is small. For example, consumer 1 purchases the energy of 0.6510, 0.1028, 0.0357, and 0.0041 MW from producers 0, 2, 3, and 7, respectively, and pays an NUC of \$5.7438 for P2P transactions, i.e., $0.6510 \times 0.0501 + 0.1028 \times 40.0501 + 0.0357 \times 40.0501 + 0.0041 \times 40.0501 = 5.7438$.

TABLE I
Simulation Parameters for IEEE 15-bus Distribution Test System

| Prosumer | $\pi$ (\$/MWh) | $\gamma_{com}$ (\$/MWh) | $\gamma_{imp}$ (\$/MWh) | $\gamma_{exp}$ (\$/MWh) |
|---|---|---|---|---|
| 0 | 50 | | | |
| 1 | | 0.2000 | 1.0 | |
| 2 | 10 | 0.1859 | | 0.90 |
| 3 | 10 | 0.9045 | | 0.90 |
| 4 | | 0.2000 | 1.0 | |
| 5 | | 0.2000 | 1.0 | |
| 6 | | 0.2000 | 1.0 | |
| 7 | 10 | 0.9045 | | 0.95 |
| 8 | | 0.2000 | 1.1 | |
| 9 | | 0.2000 | 1.1 | |
| 10 | | 0.2000 | 1.1 | |
| 11 | | 0.2000 | 1.1 | |
| 12 | | 0.2000 | 1.0 | |
| 13 | | 0.2000 | 1.0 | |
| 14 | | 0.2000 | 1.0 | |

Note that some consumers pay a negative NUC. For example, the NUC for consumer 4 is −\$0.2036. This is because a bidirectional power flow exists in the active distribution network, and a consumer with a negative NUC can relieve the line congestion by purchasing the power from the producer. Thus, the electric power utility subsidizes the consumer. Figure 4(b) shows the CB transactions and the NUC of the community overall. The four sets of data on the right side of the consumer index represent the NUC of the community to be paid for purchasing 1 MW of power from the upstream grid and communities 1, 2, and 3, respectively. Two numbers are on the left side of each producer and consumer. For consumers, the numbers above and below represent the amount of energy purchased from this community and the amount of energy purchased from other communities and the upstream grid through the CM, respectively. Similarly, for producers, the numbers above and below represent the amount of energy sold to this community and the amount of energy sold to other communities and the upstream grid through the CM, respectively. We can see that all prosumers complete the transaction matching within this community, except for the consumers in community 1 who purchase the power from the upstream grid. The NUC allocation results based on the Shapley value under CB market are presented in Table II. We see that consumer 1, who purchases the power from producer 2 at a lower price, causes congestion in line 2, as shown in Fig. 5(a). In addition, consumer 1 pays a relatively high NUC. By contrast, the other consumers who choose to purchase power from the upstream grid with the higher price and who rarely cause line congestion pay a nearly negligible NUC.

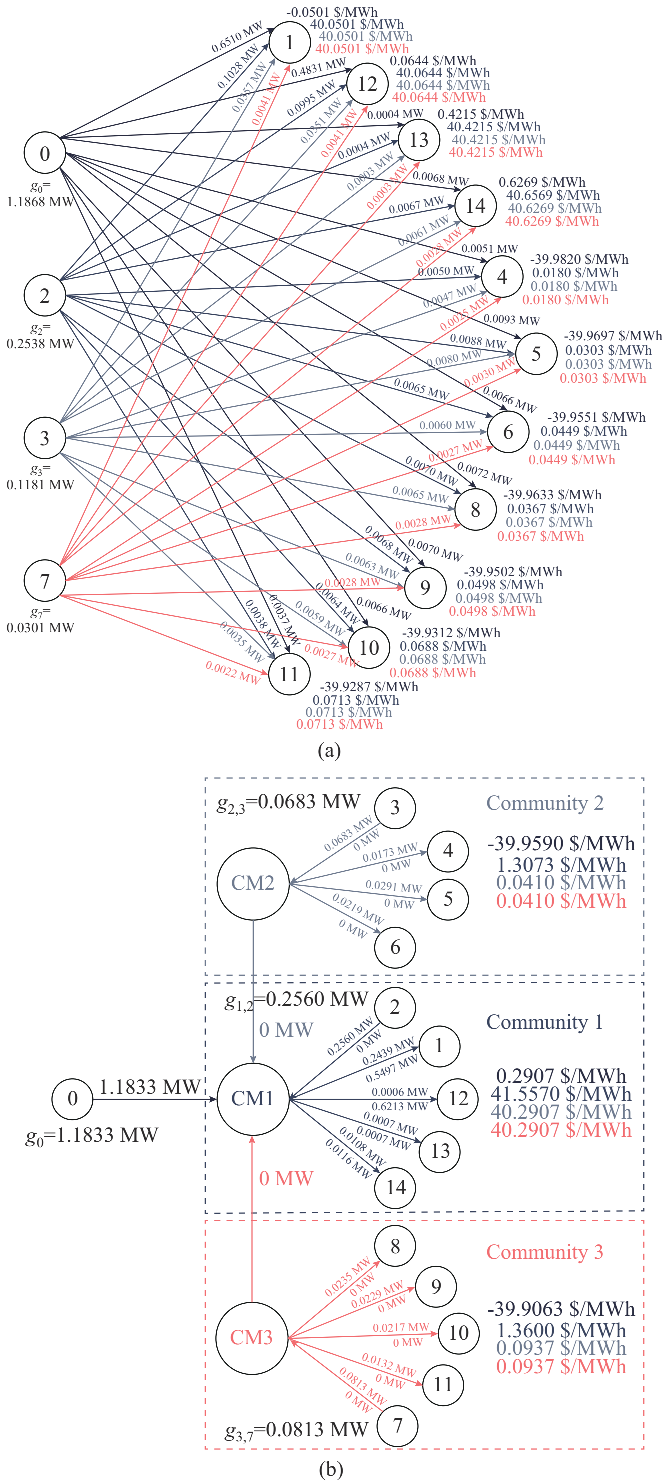

Fig. 4. Energy transactions with NUCs in IEEE 15-bus distribution test system. (a) P2P market. (b) CB market.

Figure 5 shows the comparison of line loading ratio and nodal voltage magnitude under P2P and CB markets. Here, the benchmark market represents the DSO in charge of all transactions.

In a pool-based distribution market, i. e., the proposed benchmark market, the objective is to maximize social welfare by collecting bids and offers from all market participants through the DSO and then clearing the market in a centralized manner. Simultaneously, specific operating constraints must be met to ensure the reliable operation of the power system. The centralized trading model can be modeled as model I in [34].

TABLE II
NUC ALLOCATION RESULTS BASED ON SHAPLEY VALUE UNDER CB MARKET

| Index of communities | Index of consumers | NUC ($) |
|---|---|---|
| 1 | 1 | 4.6746 |
| | 12 | 0.1029 |
| | 13 | 0.0240 |
| | 14 | 0.1766 |
| 2 | 4 | 0.0004 |
| | 5 | 0.0013 |
| | 6 | 0.0014 |
| 3 | 8 | 0.0020 |
| | 9 | 0.0023 |
| | 10 | 0.0026 |
| | 11 | 0.0015 |

Compared with the P2P and CB markets, no line congestion occurs in the benchmark market, and the voltage profile of the nodes is relatively stable because all energy transactions are scheduled uniformly by the DSO. Furthermore, the line loading ratio and nodal voltage magnitude of P2P transactions are higher than those of CB transactions. Consumers in communities 2 and 3 complete the nearby energy trading, and the energy is not transmitted through lines 3 and 8, as shown in Fig. 5(a). This reduces the energy loss in the transmission process and improves the nodal voltage profile of the entire distribution system, as shown in Fig. 5(b).

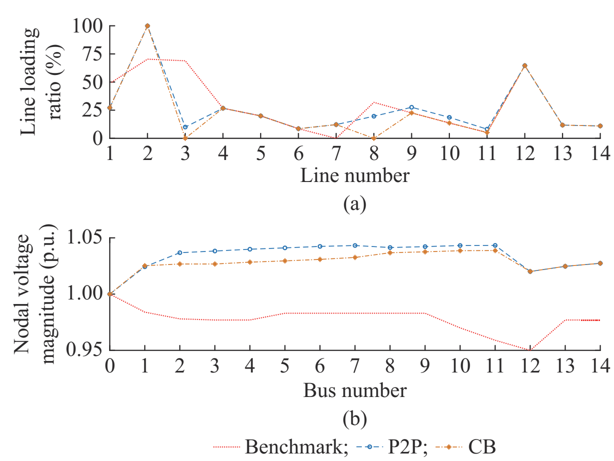

Fig. 5. Comparison of line loading ratio and nodal voltage magnitude under P2P and CB markets. (a) Line loading ratio. (b) Nodal voltage magnitude.

The prosumer payments and NUC with or without NB are presented in Table III. We can see that the welfare of the prosumer is improved through bargaining transactions, that is, the increase in revenue for producers and the reduction of payments for consumers. Moreover, the NUC of energy-bargaining transactions is reduced from \$12.2373 to \$10.1997, or by 16.7%, in the P2P market and from \$5.7732 to \$4.9896, or by 13.6%, in the CB market. The results show that the NUC of P2P bargaining transactions is higher than that of CB bargaining transactions, accurately reflecting the utilization of grid assets by prosumers.

TABLE III
PROSUMER PAYMENTS AND NUC WITH OR WITHOUT NB

| Market | Transaction behavior | Revenue of producer (\$) | Payment of consumer (\$) | NUC (\$) |
|---|---|---|---|---|
| P2P | Without NB | 72.2987 | 84.5360 | 12.2373 |
| | With NB | 73.5621 | 83.7618 | 10.1997 |
| CB | Without NB | 75.8217 | 81.5949 | 5.7732 |
| | With NB | 76.1426 | 81.1322 | 4.9896 |

### B. IEEE 123-bus Distribution Test System

Figure 6 shows the IEEE 123-bus distribution test system, which is divided into eight communities containing nine producers and 114 consumers. For the modified IEEE 123-bus distribution test system, constants $\gamma_{imp}$, $\gamma_{com}$ of consumers and $\gamma_{exp}$, $\gamma_{com}$ of producers are set to be 1, 0.2, 0.9, and 0.9045, respectively. The simulation parameters for producers with DERs are given in Table IV.

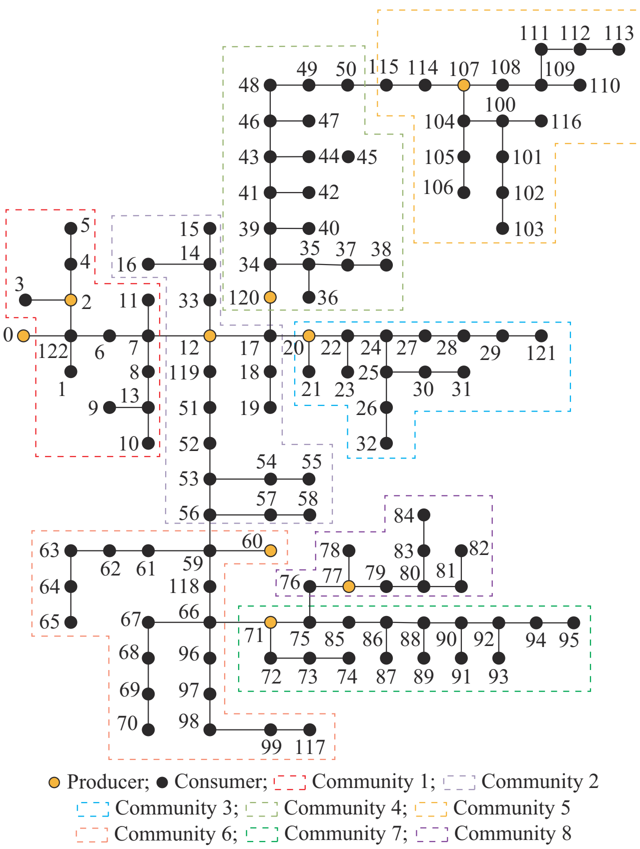


Fig. 6. IEEE 123-bus distribution test system.

Figure 7 shows the quantities of different energy transactions. We can see that the P2P transactions are decentralized so that consumers purchase varying amounts of energy from different producers, as shown in Fig. 7(a). By contrast, the CB transactions are relatively centralized so that all energy transactions are matched within the community to achieve the nearby transactions of energy, as shown in Fig. 7(b). For example, consumers with an index of 34 to 50 purchase the energy from seven producers in the P2P market. By contrast, in the CB market, they purchase the energy only from the producer with an index of 120 in community 4 and achieve a balance between the energy supply and demand.

TABLE IV
SIMULATION PARAMETERS FOR MODIFIED IEEE 123-BUS TEST SYSTEM

| Index of producers | Capacity (MW) | Incremental cost (\$/MWh) |
|---|---|---|
| 0 | 0.8 | 20 |
| 2 | 0.5 | 10 |
| 12 | 0.5 | 10 |
| 20 | 0.5 | 9 |
| 60 | 0.5 | 11 |
| 71 | 0.5 | 10 |
| 77 | 0.5 | 9 |
| 107 | 0.5 | 10 |
| 120 | 0.5 | 11 |

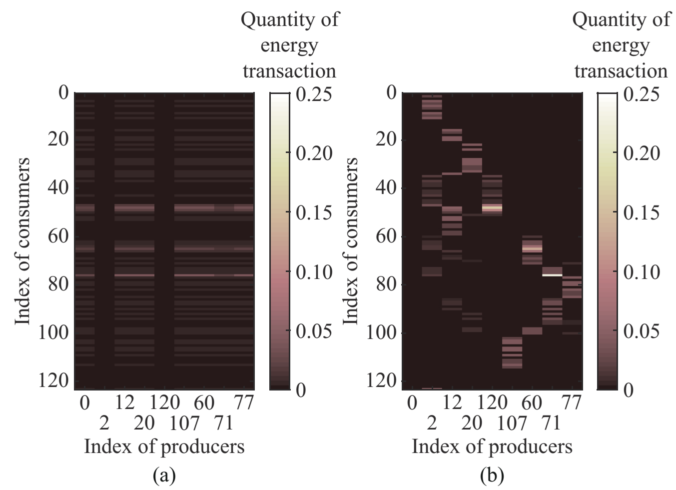


Fig. 7. Quantities of different energy transactions. (a) P2P market. (b) CB market.

Figure 8 compares the line loading ratios of different energy transactions. As Fig. 8(a) shows, the median line of the boxplot for P2P transactions is higher than that for CB transactions. In addition, the numerical distribution of the line loading ratio for CB transactions is relatively concentrated, and the upper limit and abnormal value of the line loading ratio are lower than those for P2P transactions. This indicates that CB transactions have a lower grid asset utilization than P2P transactions. Figure 8(b) shows the line loading ratio of each community for the CB transactions. When Fig. 6(b) is also considered, we see that the large energy demand of some consumers with CB transactions within communities 4, 6, and 7 generates an increase in the line loading ratio for some lines.

Figure 9 compares the numerical distributions of the nodal voltage magnitudes for different energy transactions. Similarly, Fig. 9(a) shows that the average level of nodal voltage magnitude is higher for P2P transactions than for CB transactions, indicating that the CB transactions can more easily maintain stable operation of the power grid. The energy in the CB market is traded nearby, reducing the loss of energy on the line during energy transmission and thus improving the voltage magnitude profile at each node of the entire network. Figure 9(b) shows the voltage magnitude distribution for each community. When Fig. 7(b) is also considered, we see that, relative to other communities, the higher demand for energy transactions for communities 4, 6, and 7 causes greater voltage magnitude fluctuations.

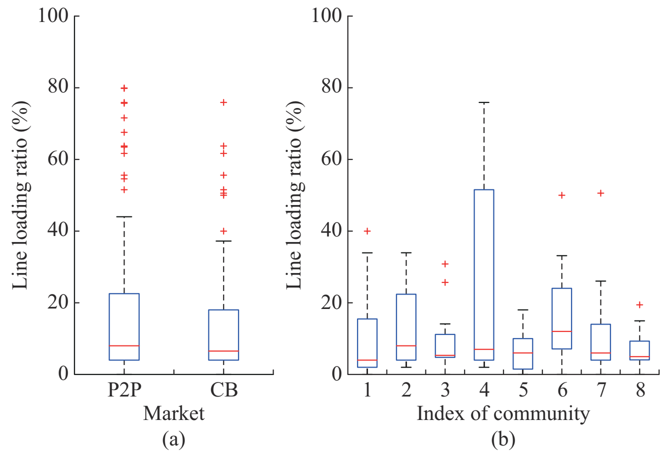


Fig. 8. Comparison of line loading ratios of different energy transactions. (a) Line loading ratio under P2P and CB markets. (b) Line loading ratio of each community under CB market.

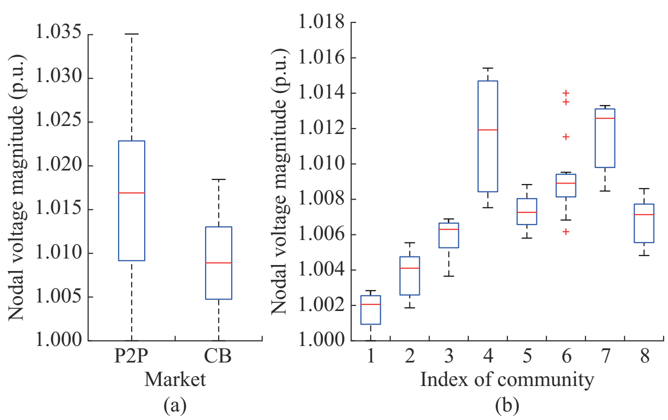


Fig. 9. Comparison of numerical distributions of nodal voltage magnitudes for different energy transactions. (a) Nodal voltage magnitude under P2P and CB markets. (b) Nodal voltage magnitude of each community under CB market.

The NUCs for P2P and CB transactions are \$81.5976 and \$34.9272, respectively, which represent the grid asset utilization of different transaction markets. The line loading ratio and the voltage magnitude profile for P2P transactions are higher than those for CB transactions. The NUCs for each community are listed in Table V. The NUCs with CB transactions of communities 4, 6, and 7 are higher than those of other communities, which is consistent with the previous analysis of the demand for energy transactions and the line loading ratio.

TABLE V
NUCs FOR EACH COMMUNITY

| Index of community | NUC (\$) | Index of community | NUC (\$) |
|---|---|---|---|
| 1 | 4.7014 | 5 | 3.4853 |
| 2 | 4.6185 | 6 | 5.0821 |
| 3 | 3.1625 | 7 | 5.6079 |
| 4 | 5.3824 | 8 | 2.8871 |

## V. CONCLUSION

In this study, we propose the methods to calculate the NUCs for P2P and CB markets with the aim of improving the revenue of network services provided by the electric power utility and effectively allocating the NUC to consumers in the prosumer era. In particular, the NB method is employed to formulate energy transaction models for the P2P and CB markets to capture the transaction behaviors of prosumers with self-interest characteristics. For both energy transaction markets, we use the DLMPs to coordinate the distribution system operation and energy trading and combine them with the Shapley value to allocate the NUC that consumers paid for the electric power utility. Case studies on modified IEEE 15-bus and 123-bus distribution test systems demonstrate the effectiveness of our proposed NUC calculation methods for P2P and CB transactions. The simulation results show that the line loading ratio and voltage magnitude fluctuation of CB transactions are lower than those of P2P transactions, indicating that the grid asset utilization and energy loss for prosumers with CB transactions are relatively low, and the NUC is less than the P2P transactions. In addition, the prosumers could improve their welfares by bargaining transactions and reduce the NUC for P2P and CB transactions.

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**Dong Han** received the Ph.D. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2015. Now, he is an Assistant Professor at University of Shanghai for Science and Technology, Shanghai, China. His research interests include evaluation of smart grid and intelligent technology application as well as electricity market.

**Lei Wu** received the B.E. degree in power system and its automation from Yancheng Institute of Technology, Yancheng, China, in 2020. He is currently pursuing the M. Sc. degree in electrical engineering in University of Shanghai for Science and Technology, Shanghai, China. His research interest includes electricity market.

**Xijun Ren** received the B. E. and M. Sc. degrees in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2012 and 2015, respectively. He is currently working at the State Grid Anhui Electric Power Economic Research Institute, Hefei, China. His research interests include electricity economy and electricity market.

**Shiwei Xia** received the Ph. D. degree in power system and its automation from The Hong Kong Polytechnic University, Hong Kong, China, in 2015, then worked as a Postdoctoral Fellow there in 2016 and 2017. He was also a Visiting Scholar in the Robert W. Galvin Center for Electricity Innovation at Illinois Institute of Technology, Chicago, USA, in 2019. Now, he is an Associate Professor at North China Electric Power University, Beijing, China. His research interests include renewable power system operation and control.