

Matching-based Energy and Carbon Sharing for Prosumers Considering Social Behavior and Low-carbon Preferences

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Abstract—Peer-to-peer (P2P) energy and carbon sharing among prosumers promotes the local decarbonization, yet it faces new challenges due to the dynamic roles and heterogeneous individual characteristics of prosumers. This paper considers the social behavior and low-carbon preferences of prosumers, and proposes a novel matching-based energy and carbon sharing scheme. First, a bidirectional carbon emission obligation transfer model via sensitivity coefficients is developed, enabling dynamic allocation of emission obligation based on the energy sharing strategies of prosumers. Second, the hybrid preference model of prosumers in P2P energy and carbon sharing is formulated, which integrates, besides economic-based preferences, the considerations of social behavior and low-carbon preferences. Third, a supply-demand ratio (SDR) based proposal method combined with a modified stable matching algorithm is developed, achieving faster market clearing than conventional alternating direction method of multipliers (ADMM) methods while guaranteeing weak Pareto-optimality. Implemented on an IEEE 33-bus system with 32 prosumers, the proposed matching-based energy and carbon sharing scheme can enhance the participation of prosumers, encourage prosumers to choose cleaner energy, and then reduce the total carbon emissions of cluster.

Index Terms—Peer-to-peer (P2P), prosumer, energy sharing, carbon emission, social behavior, low-carbon preference, matching theory.

NOMENCLATURE

A. Sets and Indices

Φ	Set of all prosumers
a, b	Indices of any prosumer, where a is either buyer or seller side, and b is the other side

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C_i, o_i	Child and parent nodes of node i
i, j	Indices of nodes where prosumers locate
l, L	Index and set of lines
$\mathcal{M}$	Matching policy
ME, MC	Energy and carbon matching result matrices
$\mathcal{N}_{BB,t}$ $\mathcal{N}_{SB,t}$	Sets of energy buyers/carbon buyers, and energy sellers/carbon buyers in time slot t
$\mathcal{N}_{BS,t}$ $\mathcal{N}_{SS,t}$	Sets of energy buyers/carbon sellers, and energy sellers/carbon sellers in time slot t
$\mathcal{N}_{S,t}, \mathcal{N}_{B,t}$	Sets of energy sellers and buyers in time slot t
$\mathcal{N}_{S,t}, \mathcal{N}_{B,t}$	Sets of carbon sellers and buyers in time slot t
$ne_{s,i}, ne_{b,j}$	Indices of the i^{th} energy seller and j^{th} energy buyer
$nc_{s,i}, nc_{b,j}$	Indices of the i^{th} carbon seller and j^{th} carbon buyer
Pl	Preference list of prosumers
t	Index of time slot
TE, TC	Peer-to-peer (P2P) energy and carbon sharing result matrices

B. Parameters

α_i^{CPP}	Carbon intensity of captive power plant (CPP) of node i
$\bar{\alpha}_i^{ex}$	Carbon intensity of energy from external grid in time slot t
ε_{ij}	Power loss sensitivity parameter between nodes i and j
θ_i	Parameter of prosumer of node i to quantity satisfaction when consuming energy
φ	Weighting parameter indicating impact of friend-of-friend (FOF) parameter and credit scores in social layer
$\sigma_{a,b}, \sigma_{b,a}$	Credit scores between prosumers a and b in social layer
τ_1, τ_2, τ_3	Weighting parameters of hybrid preferences
$\mathcal{T}_a, \mathcal{T}_b, \mathcal{T}_{a,b}$	Friend sets of prosumers a and b , and common friend set of prosumers a and b

$\pi_{i,t}^e, \pi_{i,t}^c$	Reservation prices of prosumer of node i in energy and carbon sharing in time slot t	$e_{ij,t}$	P2P energy sharing quantity between nodes i and j in time slot t
$\pi_{a,k}$	Reservation price of prosumer a at current sharing iteration k	$f(x)$	Function describing whether x is larger than 0
$\pi_{a,b,m}$	Sharing price between prosumers a and b for the m^{th} energy or carbon sharing	$g_{ij,t}$	P2P carbon sharing quantity between nodes i and j in time slot t
$\lambda_{ex,s}^e, \lambda_{ex,b}^e$	Energy selling and buying prices with external market	I	Square of current magnitudes of line
$\lambda_{ex,s}^c, \lambda_{ex,b}^c$	Carbon selling and buying prices with external market	$lp_{a,b}$	Low-carbon preference of prosumer a to b
$\omega_{a,b}^{sum}$	Hybrid preference value of prosumer a to b	P_{i,o_i}, Q_{i,o_i}	Active and reactive power flows of line (i, o_i)
c^{CPP}	Cost coefficient of CPP output	$P_{l,t}$	Power flow through line l in time slot t
$\mathcal{D}, \mathcal{R}$	Remaining energy demand and surplus energy of prosumer	$PTDF_{ij,l}$	Power transfer distribution factor between nodes i and j through line l
$ICQ_{i,t}$	Initial free carbon quota of node i in time slot t	$P_{CPP,i,t}, P_{i,t}^{grid}$	CPP power output and transactive energy with external grid of node i in time slot t
$I^{\max}, I^{\min}$	Upper and lower limits of square of current magnitudes for branch	$P_{load,i,t}$	Optimized load of prosumer of node i in time slot t
k, K	Current calculation iteration and total iterations of credit score calculation	$pf_{i,t}$	Fee of trading of node i with external grid in time slot t
m	Index of historical energy or carbon sharing	$Q_{i,t}^e, Q_{i,t}^c$	Tradable energy and carbon quota volume of each prosumer of node i in time slot t
$P_{PV,i,t}, P_{load,i,t}^0$	Photovoltaic (PV) generation and initial load demand of node i in time slot t	$Q_{i,t}^{e, reactive}$	Injected reactive power of node i in time slot t
$P_{CPP,i}^{\max}$	Upper limit of CPP power output of node i	$R_{i,t}^{ex}$	Unbalanced carbon trading of node i with external market in time slot t
$r_{i,j}, x_{i,j}$	Resistance and reactance of branch between nodes i and j	$SF_{i,l}$	Shift factor between node i and line l
$v^{\max}, v^{\min}$	Upper and lower limits of node voltage	$U_{i,t}, U_{ECSP,t}$	Utility functions of prosumer of node i and energy and carbon sharing provider (ECSP) in time slot t
		v_i	Square of voltage magnitudes of node i

C. Variables and Functions

$\alpha_{i,t}, \alpha_{ij,t}^P$	Node weighted carbon intensity of node i , and carbon intensity of sharing energy between nodes i and j in time slot t
$\alpha_{i,t}, \alpha_{ij,t}^P$	Node weighted carbon intensity of node i , and carbon intensity of sharing energy between nodes i and j in time slot t
$\alpha_{i,t}^{grid}$	Carbon intensity of sharing energy between node i and external grid in time slot t
$\alpha_{l,t}^{line}$	Carbon intensity of line l in time slot t
$\psi_{a \rightarrow b}^e, \psi_{a \rightarrow b}^c$	Economic-based preferences of prosumer a to b in energy and carbon sharing
$\beta_{a,b}$	Preference degree of social behavior of prosumer a to b
ρ_{ij}^e, ρ_{ij}^c	P2P energy and carbon sharing prices between nodes i and j
$CP_{CPP,i,t}$	Carbon emission of CPP units of node i in time slot t
$CP_{trading,ij,t}$	Carbon emission of energy sharing between nodes i and j in time slot t
$CP_{loss,ij,t}$	Carbon emission of power losses between nodes i and j in time slot t
$c_{f,i,t}^e$	Fees of trading with external carbon market in time slot t

I. INTRODUCTION

UNDER the policy of total carbon emission control, both carbon quotas and energy are treated as scarce, tradeable commodities. Peer-to-peer (P2P) energy and carbon sharing among prosumers is regarded as an effective solution to promote local prosumer-centric decarbonization [1], [2]. Fueled by rapid advances in information and communication technologies, P2P energy and carbon sharing network already function as cyber-physical system (CPS) in energy [3]. Actually, P2P energy and carbon sharing foregrounds the active participation of individual prosumers, yet the multi-agent nature of these prosumers is driven by social attributes of heterogeneous and value-laden preferences. Incorporating the individual behaviors and interactions of all the participants in CPS, P2P energy and carbon sharing network can be further considered as the cyber-physical-social system (CPSS) in energy [4], [5].

Recently, the mechanism of P2P energy and carbon sharing has attracted much research attention. Like energy sharing, a number of existing studies model the P2P energy and carbon sharing problem from a game theory perspective, aiming to model the competitive or cooperative interactions among autonomous prosumers. In [6] and [7], the multi-leader-multi-follower Stackelberg game is utilized to model the integrated P2P electricity-carbon market, and the Stackelberg game-based model is utilized in [8] and [9]. Reference [10]

applies a cooperative game with externalities to model the energy and carbon allowance transactive market behavior for microgrids. Reference [11] proposes an auction-based market mechanism. Among these algorithms, the alternating direction method of multipliers (ADMM) algorithm is the main solution to obtaining market-clearing results [6], [8], [9].

Despite the efforts dedicated to this problem, to better promote energy and carbon sharing for prosumers, two challenges remain to be discussed. ① How to track and quantify the carbon footprint associated with P2P energy sharing among prosumers? To promote low-carbon consumption, when the traded energy is carbon-intensive, the carbon emission obligation should be transferred from the seller to the buyer since the user side is the underlying driver. ② From the CPSS perspective, how to consider the social attributes and low-carbon interactions of prosumers during P2P energy and carbon sharing, and promote their engagement? The engagement of heterogeneous entities is a key factor that directly affects the autonomy and efficiency of prosumer clusters [5], [12].

For the first challenge, considering that user-side energy consumption behaviors are the fundamental drivers of carbon emissions in power system, it is essential to clarify the indirect carbon emissions attributed to terminal users, a process also known as the distribution of carbon emission obligation [13]. The concept of carbon emission flow (CEF) has been proposed, defined as a type of virtual carbon flow that accompanies energy flow [14]. By utilizing the CEF model, the dynamic carbon emission of prosumer aggregator is calculated instead of carbon sharing among prosumers [8]. References [9] and [15] derive a carbon-aware distribution locational marginal price to guide the P2P electricity and carbon transactions among prosumers. However, the stand-alone distributed energy resources (DERs) are strictly set as electricity sellers, and other load nodes serve as buyers [15]. The one-way carbon flow is directly from carbon-containing DERs to consumers. Actually, prosumers can behave as different roles in the P2P energy and carbon sharing process, but the existing studies do not address the carbon emission obligation assignment for the bi-directional energy sharing behaviors of prosumers. Therefore, this area remains underexplored [16], [17].

For the second challenge, most existing studies regard energy and carbon quotas as homogeneous products, differentiating them solely based on their sharing prices [18], [19]. Specifically, the characteristics of energy such as its generation technology, carbon intensity, geographical origin, and even the reputation of the trading entity, contribute to its heterogeneity. However, this simplification overlooks the diverse social behaviors of prosumers in P2P energy and carbon sharing, which are critical for enhancing their engagement and cooperation [4]. In our previous work [20], it is demonstrated that incorporating both physical energy dynamics and social reciprocity of prosumers into energy sharing not only enhances the overall utility but also stimulates effective cooperation. Prosumers show preferences for various attributes of traded electricity beyond price such as renewable energy, subsidized energy, and other specific types [21]-[23]. Additionally, prosumers express preferences not only for

product attributes but also for their sharing partners [24], [25]. For example, a decentralized market mechanism proposed in [24] highlights the preferences of prosumers for trading green energy, partner reputation, and network location. Social relationships also play a significant role, as prosumers are more willing to engage in P2P energy and carbon sharing when they share positive relationships with others in the cluster [26]. And for local prosumer-centric decarbonization initiatives, prosumers demonstrate heightened attention to the energy generation methods, particularly its low-carbon attributes [27] - [29]. Therefore, further investigation is required to systematically integrate diverse prosumer preferences into energy and carbon sharing schemes, ensuring both economic efficiency and social acceptance.

In summary, this paper will focus on the following key issues. ① How to assign the carbon emission obligation of prosumers with changeable roles and bidirectional energy sharing? ② How to consider and formulate the hybrid preference model considering social behavior and low-carbon preferences of prosumers in P2P energy and carbon sharing? ③ How to model the P2P energy and carbon sharing problem with preferences and propose an effective solution to the problem? Driven by the above background and inspired by [20], this paper further investigates the carbon emission obligations related to P2P energy and carbon sharing, and studies market clearing when integrating hybrid preferences of prosumers. To model this duality of competition and cooperation among prosumers with hybrid preferences, matching theory presents a viable modeling solution, which is widely applied in device-to-device (D2D) spectrum resource allocation in communication networks [30], [31]. It can minimize the solution complexity and mitigate the complex information interactions of traditional game theory schemes.

This paper proposes a matching-based energy and carbon sharing scheme for prosumers considering social behavior and low-carbon preferences of prosumers. The main contributions are summarized in three aspects as follows.

1) Instead of modelling the unidirectional carbon flow which is directly from carbon-containing producers to consumers [9], [15], a bidirectional carbon emission obligation transfer model via sensitivity coefficients is proposed, which tracks the bidirectional flows of energy sharing and is applicable to the dynamic change of roles of prosumers. Besides, this calculation process incorporates carbon emissions of power loss, and can explicitly link each energy transaction to its carbon footprint.

2) The hybrid preference model of prosumers in P2P energy and carbon sharing is formulated, which integrates, besides economic-based preferences, their considerations of social behavior and low-carbon preferences. A weighted index is utilized to quantify these hybrid preferences. It is demonstrated that the formulated hybrid preference model can enhance the participation of prosumers and encourage low-carbon sharing of prosumers when considering social behavior and low-carbon preferences.

3) A supply-demand ratio (SDR) based proposal method combined with a modified stable matching algorithm is developed to realize efficient energy and carbon transactive market clearing, which preserves weak Pareto optimality

while reducing the computational complexity compared with conventional ADMM algorithms.

The remainder of this paper is organized as follows. Section II presents the P2P energy and carbon sharing framework, and Section III describes the bidirectional carbon emission obligation transfer model. Then in Section IV, the hybrid preference model of prosumers is defined, followed by Section V where the proposed matching-based energy and carbon sharing scheme is illustrated. Section VI presents case study and analyzes the simulation result. Finally, Section VII concludes this paper.

II. P2P ENERGY AND CARBON SHARING FRAMEWORK

The P2P energy and carbon sharing framework is illustrated in Fig. 1, where the P2P energy and carbon sharing network consists of an energy and carbon sharing provider (ECSP) and N prosumers with the user energy management system (UEMS). Each prosumer has photovoltaic (PV) panels and flexible electric loads, and some prosumers are equipped with a captive power plant (CPP). The role of ECSP is to coordinate the whole energy and carbon market, and provide differentiated services for prosumers to meet their heterogeneous preferences in P2P energy and carbon sharing. Under the P2P energy and carbon sharing framework, prosumers have different roles, which will be introduced in Section III-B. And prosumers can implement P2P energy and carbon sharing with local prosumers freely, as they are independent entities with their interests. Through P2P energy and carbon sharing, their goals are to: ① balance their energy and carbon quotas; and ② maximize their profits considering their preferences.

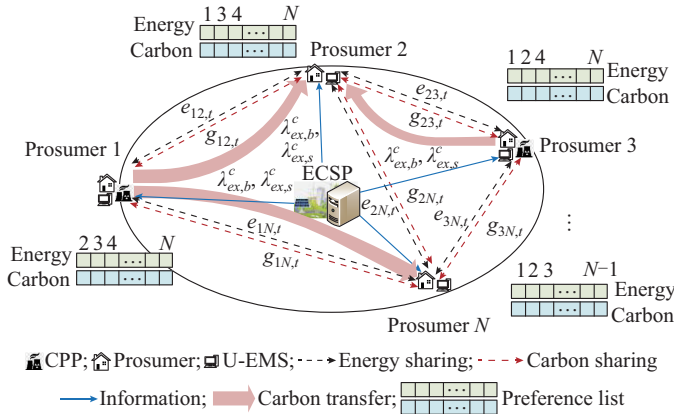


Fig. 1. P2P energy and carbon sharing framework.

As shown in Fig. 1, since some prosumers are equipped with CPP, the energy flow from these prosumers to others also means the virtual carbon transfer (pink arrow), the specific obligation transfer coupled with the energy sharing is introduced in Section III-A. Besides, considering that prosumers show different preferences towards other agents in P2P energy and carbon sharing, in this paper, we define hybrid preferences to represent their individual preferences in sharing, based on which each prosumer can obtain preference lists of energy sharing and carbon sharing, respectively.

Remark: for the feasibility of implementing the ECSP platform in real-world energy markets, the following remarks

are noted. Firstly, P2P market platforms such as DiDi in transportation and Airbnb in accommodation have demonstrated successful bilateral matching for participants with different preferences [32]. Secondly, advances in information and communication, measurement, and monitoring technologies provide essential technical support. Moreover, with the growing involvement of prosumers, a platform offering differentiated services can better meet personalized needs and enhance satisfaction. In China, virtual power plants (VPPs), which aggregate heterogeneous DERs, are promising candidates for such a platform [33], with supply-demand matching serving as one of its functional modules. Pricing strategies for differentiated services are beyond the scope of this paper and will be addressed in future studies.

III. BIDIRECTIONAL CARBON EMISSION OBLIGATION TRANSFER MODEL

This section firstly introduces the bidirectional carbon emission obligation transfer model via sensitivity coefficients. Based on this model, it further defines different roles of prosumers in P2P energy and carbon sharing.

A. Description of Bidirectional Carbon Emission Obligation Transfer Model

Firstly, the weighted node carbon intensity of each prosumer node is derived, which is defined as carbon emissions embedded in the production of unit active power. For prosumers, the operations of CPP inevitably result in carbon emissions since it produces electricity by burning fossil fuels, and in time slot t , the node weighted carbon intensity $\alpha_{i,t}$ is calculated as:

$$\alpha_{i,t} = \frac{CP_{CPP,i,t}}{P_{CPP,i,t} + P_{PV,i,t}} \quad (1)$$

Then, we can obtain the carbon intensity of the sharing energy $\alpha_{ij,t}^p$ between nodes i and j , and the carbon intensity of the sharing energy $\alpha_{i,t}^{grid}$ between node i and external grid, which are calculated as (2) and (3), respectively.

$$\alpha_{ij,t}^p = \begin{cases} \alpha_{i,t} & e_{ij,t} \geq 0 \\ \alpha_{j,t} & e_{ij,t} < 0 \end{cases} \quad (2)$$

$$\alpha_{i,t}^{grid} = \begin{cases} \bar{\alpha}_t^{ex} & P_{i,t}^{grid} < 0 \\ \alpha_{i,t} & P_{i,t}^{grid} \geq 0 \end{cases} \quad (3)$$

For nodes i and j , their specific carbon emissions resulted by P2P energy sharing $e_{ij,t}$ can be calculated as (4) and (5), respectively.

$$CP_{trading,ij,t} = -|e_{ij,t}| \alpha_{ij,t}^p + CP_{loss,ij,t}/2 \quad (4)$$

$$CP_{trading,ji,t} = -|e_{ji,t}| \alpha_{ji,t}^p + CP_{loss,ij,t}/2 \quad (5)$$

$CP_{loss,ij,t}$ is undertaken equally by nodes i and j , and can be calculated as:

$$CP_{loss,ij,t} = \sum_{l \in L} \alpha_{i,t}^{line} I_{l,t} r_l \frac{e_{ij,t} \cdot PTDF_{ij,l}}{P_{l,t}} \quad (6)$$

where $e_{ij,t} \cdot PTDF_{ij,l}$ is the power flow through line l due to the energy sharing between nodes i and j .

$$\alpha_{i,t}^{line} = \frac{1}{P_{i,t}} \sum_{l \in \Phi} \alpha_{i,t} Q_{l,t}^E \cdot SF_{i,l} \quad (7)$$

The total carbon emission of node i can be calculated as:

$$CP_{trading,i,t} = \sum_{j \in \mathcal{N}_{B,t}} CP_{trading,ij,t} - \alpha_{i,t}^{grid} P_{i,t}^{grid} \quad (8)$$

B. Role of Prosumers in P2P Energy and Carbon Sharing

The prosumers can behave as electricity sellers or buyers in the energy sharing process depending on their net loads.

$$Q_{i,t}^e = P_{load,i,t} - P_{PV,i,t} - P_{CPP,i,t} \quad (9)$$

$Q_{i,t}^e > 0$ or $Q_{i,t}^e < 0$ means that the prosumer is an energy buyer or seller, respectively. Similarly, for carbon sharing, each prosumer can also behave as a buyer or seller according to their net carbon obligation:

$$Q_{i,t}^c = CP_{CPP,i,t} + CP_{trading,i,t} - ICQ_{i,t} \quad (10)$$

where $CP_{CPP,i,t}$ is calculated by $CP_{CPP,i,t} = P_{CPP,i,t} \alpha_i^{CPP}$. Similarly, $Q_{i,t}^c > 0$ means that the prosumer is a carbon buyer.

IV. HYBRID PREFERENCE MODEL OF PROSUMERS

This section establishes a hybrid preference model of prosumers. Multiple factors that influence their trading preferences towards different entities are taken into consideration. For the sake of simplicity, Table I defines the signs of unbalanced energy/carbon and price under different roles of prosumers.

TABLE I

SIGNS OF UNBALANCED ENERGY/CARBON AND PRICE UNDER DIFFERENT ROLES OF PROSUMERS

Role in carbon sharing	Sign under different roles			
	Energy buyer		Energy seller	
Carbon buyer	$Q_{a,t}^e > 0, \pi_a^e > 0, Q_{a,t}^c > 0, \pi_a^c > 0$		$Q_{a,t}^e < 0, \pi_a^e < 0, Q_{a,t}^c > 0, \pi_a^c > 0$	
Carbon seller	$Q_{a,t}^e > 0, \pi_a^e > 0, Q_{a,t}^c < 0, \pi_a^c < 0$		$Q_{a,t}^e < 0, \pi_a^e < 0, Q_{a,t}^c < 0, \pi_a^c < 0$	

A. Economic-based Preferences

Economic-based preferences of prosumer a to b are calculated in (11), defined from the perspective of economic utilities that prosumer can get from P2P energy or carbon sharing.

$$\psi_{a \rightarrow b}^e = \pi_b^e \left(\min(|Q_{a,t}^e|, |Q_{b,t}^e|) \right) + \left(f(Q_{a,t}^e) \lambda_{ex,s}^e + f(-Q_{a,t}^e) \lambda_{ex,b}^e \right) \cdot \max(|Q_{a,t}^e| - |Q_{b,t}^e|, 0) \quad (11)$$

where $\pi_b^e \left(\min(|Q_{a,t}^e|, |Q_{b,t}^e|) \right)$ represents the utilities of P2P energy or carbon sharing; $\min(|Q_{a,t}^e|, |Q_{b,t}^e|)$ represents the maximum tradable volume between prosumers a and b ; and $\left(f(Q_{a,t}^e) \lambda_{ex,s}^e + f(-Q_{a,t}^e) \lambda_{ex,b}^e \right) \cdot \max(|Q_{a,t}^e| - |Q_{b,t}^e|, 0)$ represents utilities of trading with utility grid. If x is larger than zero, $f(x)$ outputs 1; otherwise, $f(x)$ outputs 0.

If $|Q_{a,t}^e|$ and $|Q_{b,t}^e|$ are closer, prosumers are less inclined to trade with the external grid or carbon market. This can lead to higher economic utilities since the following constraint is always satisfied.

$$\lambda_{ex,b}^e \leq \pi_b^e / \pi_a^e \leq \lambda_{ex,s}^e \quad (12)$$

Therefore, prosumers will show a stronger economic-based preference when $|Q_{a,t}^e|$ and $|Q_{b,t}^e|$ are closer. This indicates greater mutual willingness to trade and thus higher clearing efficiency in the bilateral market. Similarly, for carbon quota sharing, the economic-based preference of prosumer a on

one side towards prosumer b on the other side is defined as:

$$\psi_{a \rightarrow b}^c = \pi_b^c \left(\min(|Q_{a,t}^c|, |Q_{b,t}^c|) \right) + \left(f(Q_{a,t}^c) \lambda_{ex,s}^c + f(-Q_{a,t}^c) \lambda_{ex,b}^c \right) \cdot \max(|Q_{a,t}^c| - |Q_{b,t}^c|, 0) \quad (13)$$

B. Social Behavior

Social reciprocity and homophily are both important social behaviors in P2P energy and carbon sharing. Driven by inherent social behavior tendencies, prosumers are more willing to engage in P2P energy and carbon sharing with trustworthy counterparts and those who have deeper social tightness. In this paper, $\beta_{a,b}$ is defined as a weighted combination of two social behavior-dependent components: historical trading credit scores and social-psychological factors [20]. The former reflects the trust accumulation between prosumers from past transactions, and the later shows social behavior principle of homophily. Individuals sharing more common acquaintances tend to form stronger social connections, which is often translated into more willingness of energy sharing.

Mathematically, $\beta_{a,b}$ is defined as:

$$\beta_{a,b} = \varphi \left| \frac{\mathcal{T}_{a,b}}{\mathcal{T}_a \cup \mathcal{T}_b} \right| + (1 - \varphi) \sigma_{a,b} \quad (14)$$

$$\sigma_{a,b,k} = \sigma_{a,b,k-1} + \frac{|e_{a,b,k}| (|\pi_{a,k}| + |\pi_{b,k}|) / 2}{\sum_{m=1}^K \pi_{a,b,m} |e_{a,b,m}|} \quad (15)$$

In (15), $|e_{a,b,k}| (|\pi_{a,k}| + |\pi_{b,k}|) / 2$ represents the payments of current transactions, and $\sum_{m=1}^K \pi_{a,b,m} |e_{a,b,m}|$ is the total payments corresponding to transactions between prosumers a and b of the previous iterations. Successful transaction records contribute to the increase of credit scores, and when there exists P2P energy and carbon sharing record between prosumers a and b , k will be added by 1, i.e., $k = k + 1$.

C. Low-carbon Preferences

In response to the low-carbon development strategy, prosumers also show low-carbon preferences when consuming energy [27]. They cooperate with each other to drive the total carbon emissions down, and then, with a high carbon intensity and high carbon emission costs, they are more willing to engage in transactions compared with those with a lower average carbon intensity, in order to reduce the carbon emission costs. Meanwhile, in line with the overall low-carbon goals of the prosumer cluster, prosumers with a lower average carbon intensity are more inclined to sell energy to those with higher emissions and energy demands. Therefore, for energy sharing, the low-carbon preference index $lp_{a,b}$ is defined as:

$$lp_{a,b} = lp_{b,a} = \begin{cases} \alpha_b - \frac{\alpha_a + \alpha_b}{2} & \alpha_b > \alpha_a \\ 0 & \alpha_b \leq \alpha_a \end{cases} \quad (16)$$

D. Hybrid Preferences

For energy and carbon sharing, the hybrid preference model of prosumer a to b is calculated as:

$$\omega_{a,b}^{sum} = \tau_1 (\bar{\psi}_{a,b}^e + \bar{\psi}_{a,b}^c) + \tau_2 \bar{\beta}_{a,b} + \tau_3 \bar{p}_{a,b} \quad (17)$$

where $\bar{(\cdot)}$ represents the normalized value and is calculated by utilizing the min-max scaling method; and $\tau_1, \tau_2, \tau_3 \in [0, 1]$, and $\tau_1 + \tau_2 + \tau_3 = 1$.

Specifically, the preference structure is dynamic and the values of weight coefficients vary from prosumer to prosumer, which belong to the private information of prosumers.

V. PROPOSED MATCHING-BASED ENERGY AND CARBON SHARING SCHEME

In this section, we formulate the P2P energy and carbon sharing model among prosumers with hybrid preferences as a two-step problem. In the first step, the joint energy and carbon optimization problem is formulated as a social welfare maximization problem, where the total P2P energy and carbon sharing quantities, i.e., $\sum_{j \in \Phi} e_{ij,t}$ and $\sum_{j \in \Phi} g_{ij,t}$ are viewed as a single variable. In the second step, matching theory is used to solve the energy and carbon sharing problem based on the formulated hybrid preference model, in which we can determine detailed P2P energy and carbon sharing results $e_{ij,t}$ and $g_{ij,t}$, $\forall i, \forall j$.

A. Joint Energy and Carbon Optimization

The objective function of joint energy and carbon optimization is to maximize the social welfare, including the utilities of all prosumers and ECSP, which is expressed as:

$$\max \left(\sum_{i \in \Phi} U_{i,t} + U_{ECSP,t} \right) \quad (18)$$

$$U_{i,t} = \theta_i \cdot \ln(1 + P_{load,i,t}) - c_{i,t}^{CPP} P_{CPP,i,t} + \sum_{j \in \Phi} \rho_{ij}^e \left(e_{ij} - \frac{\varepsilon_{ij} e_{ij}}{2} \right) + \sum_{j \in \Phi} \rho_{ij}^c (g_{ij}) - pf_{i,t} - cf_{i,t} \quad (19a)$$

$$pf_{i,t} = -\lambda_{ex,b}^e \cdot \min(P_{i,t}^{ex}, 0) + \lambda_{ex,s}^e \cdot \max(P_{i,t}^{ex}, 0) \quad (19b)$$

$$cf_{i,t} = -\lambda_{ex,b}^c \cdot \min(R_{i,t}^{ex}, 0) + \lambda_{ex,s}^c \cdot \max(R_{i,t}^{ex}, 0) \quad (19c)$$

$$U_{ECSP,t} = \sum_{i \in \Phi} pf_{i,t} + \sum_{i \in \Phi} cf_{i,t} \quad (20)$$

In (19a), the utility model of prosumer i composes the following four parts on the right-hand side. The first term $\theta_i \cdot \ln(1 + P_{load,i,t})$ denotes the utility of energy consumption; the second term denotes the operation cost of CPP; the third and fourth terms denote the revenues of sharing energy and carbon with other prosumers, respectively. Specially, $\varepsilon_{ij} e_{ij}$ is the power loss resulted by energy sharing e_{ij} and is shared equally by the two prosumers. And the last two terms $pf_{i,t}$ and $cf_{i,t}$ denote the fees of trading with external grid and carbon market, respectively.

And the constraints are listed as:

$$P_{load,i,t} = P_{CPP,i,t} + P_{PV,i,t} - \sum_{j \in \Phi} e_{ij,t} + P_{i,t}^{grid} \quad (21)$$

$$ICQ_{i,t} + R_{i,t}^{ex} = CP_{CPP,i,t} + CP_{trading,i,t} - \sum_{j \in \Phi} g_{ij,t} \quad (22)$$

$$0.8P_{load,i,t}^0 \leq P_{load,i,t} \leq 1.2P_{load,i,t}^0 \quad (23)$$

$$0 \leq P_{CPP,i,t} \leq P_{CPP,i}^{\max} \quad (24)$$

$$e_{ij,t} + e_{ji,t} = \varepsilon_{ij,t} e_{ij,t} \quad (25)$$

$$g_{ij,t} + g_{ji,t} = 0 \quad (26)$$

$$P_{i,o_i} = \sum_{h \in C_i} (P_{h,i} - r_{h,i} I_{h,i}) + Q_{i,t}^e \quad (27)$$

$$Q_{i,o_i} = \sum_{h \in C_i} (Q_{h,i} - x_{h,i} I_{h,i}) + Q_{i,t}^{e,reactive} \quad (28)$$

$$v_{o_i} = v_i - 2(r_{o,i} P_{i,o_i} + x_{o,i} Q_{i,o_i}) + (r_{o,i}^2 + x_{o,i}^2) I_{o,i} \quad (29)$$

$$I_{o,i} v_i = P_{i,o_i}^2 + Q_{i,o_i}^2 \quad (30)$$

$$v_i^{\min} \leq v_i \leq v_i^{\max} \quad (31)$$

$$I_{o,i}^{\min} \leq I_{o,i} \leq I_{o,i}^{\max} \quad (32)$$

$$\sum_i CP_{CPP,i,t} - \bar{\alpha}_t^{ex} P_{i,t}^{grid} = \sum_i (ICQ_{i,t} + R_{i,t}^{ex}) \quad (33)$$

where (21)-(24) are constraints of each prosumer; (25) and (26) are the constraints of energy and carbon sharing, respectively; (27)-(32) denote the DistFlow model of power flow; and (33) denotes the carbon balance of the system. This joint energy and carbon optimization problem can be solved by commercial solver such as CPLEX.

B. Formulation of Proposed Matching-based Energy and Carbon Sharing Scheme

The objective of this subsection is to obtain detailed P2P energy and carbon sharing results $e_{ij,t}$, $g_{ij,t}$, $\forall i, \forall j$. This essentially involves a matching process between buyer set and seller set while guaranteeing the preference maximization. Matching theory is an effective approach to solving the problem of individuals in two sets with bilateral preferences to achieve efficient and stable bilateral matching. In this subsection, a matching policy $\mathcal{M}(\mathbf{ME}, \mathbf{MC}, \mathbf{TE}, \mathbf{TC})$ is used to describe the assignment results of the set $\mathcal{N}\mathcal{C}_{BB,t} \cup \mathcal{N}\mathcal{C}_{SB,t} \cup \mathcal{N}\mathcal{C}_{BS,t} \cup \mathcal{N}\mathcal{C}_{SS,t}$ which contains the P2P energy and carbon sharing results.

The objective function of matching is to maximize the weighted preference utilities of all prosumers in P2P energy and carbon sharing, expressed as:

$$\max_{e_{ij}, g_{ij}, P_{i,t}^{grid}, R_{i,t}^{ex}} \sum_{i \in \Phi} \sum_{j \in \Phi} \omega_{i,j}^{sum} \quad (34a)$$

s.t.

$$\begin{cases} \psi_{i,j}^e \geq 0 \\ \psi_{i,j}^c \geq 0 \end{cases} \quad \forall i, j \quad (34b)$$

$$\begin{cases} e_{ij} \leq \min(|Q_i^e|, |Q_j^e|) \\ g_{ij} \leq \min(|Q_i^c|, |Q_j^c|) \end{cases} \quad (34c)$$

$$\begin{cases} \sum_{i=1}^{\Phi} e_{ij} \leq |Q_j^e| \\ \sum_{j=1}^{\Phi} e_{ij} \leq |Q_i^e| \end{cases} \quad \forall i, j \quad (34d)$$

$$\begin{cases} \sum_{i=1}^{\phi} g_{ij} \leq |Q_j^c| \\ \sum_{j=1}^{\phi} g_{ij} \leq |Q_i^c| \end{cases} \quad \forall i, j \quad (34e)$$

where (34b) is the constraint, which shows that the prosumers are incentive-rational, i.e., the economic preference utility should be positive; and (34c)-(34e) are the sharing volume constraints.

The efficient P2P energy and carbon sharing between prosumers is formulated as a many-to-many matching game, which means that a seller can sell its energy/carbon to multiple buyers, and vice versa. The energy/carbon demands of a buyer can be satisfied by multiple sellers. The definition of energy and carbon matching is given as below.

Definition 1: a matching policy $\mathcal{M} = (\mathbf{ME}, \mathbf{MC}, \mathbf{TE}, \mathbf{TC})$ is used to illustrate the many-to-many matching results of P2P energy and carbon sharing.

$\mathcal{M}$ is essentially an assignment from the set $\mathcal{N}\mathcal{C}_{BB,t} \cup \mathcal{N}\mathcal{C}_{SB,t} \cup \mathcal{N}\mathcal{C}_{BS,t} \cup \mathcal{N}\mathcal{C}_{SS,t}$ such that:

$$\begin{cases} \mathbf{ME}(j) \subset \mathcal{N}\mathcal{E}_{S,t} \\ \mathbf{ME}(i) \subset \mathcal{N}\mathcal{E}_{B,t} \end{cases} \quad \forall i \in \mathcal{N}\mathcal{E}_{S,t}, \forall j \in \mathcal{N}\mathcal{E}_{B,t} \quad (35a)$$

$$\begin{cases} \mathbf{MC}(j) \subset \mathcal{N}\mathcal{C}_{S,t} \\ \mathbf{MC}(i) \subset \mathcal{N}\mathcal{C}_{B,t} \end{cases} \quad \forall i \in \mathcal{N}\mathcal{C}_{S,t}, \forall j \in \mathcal{N}\mathcal{C}_{B,t} \quad (35b)$$

$$\begin{cases} \mathbf{TE}_{ij} \leq \min(|Q_i^e|, |Q_j^e|) \\ \mathbf{TC}_{ij} \leq \min(|Q_i^c|, |Q_j^c|) \end{cases} \quad (35c)$$

$$\begin{cases} \sum_i \mathbf{TE}_{ij} \leq |Q_j^e| \\ \sum_i \mathbf{TE}_{ij} \leq |Q_i^e| \end{cases} \quad (35d)$$

$$\begin{cases} \sum_i \mathbf{TC}_{ij} \leq |Q_j^c| \\ \sum_i \mathbf{TC}_{ij} \leq |Q_i^c| \end{cases} \quad (35e)$$

$$\begin{aligned} Q_{i,t}^c = & CP_{CPP,i,t} - ICQ_{i,t} - \alpha_{i,t}^{grid} \left(Q_{i,t}^e - \sum_{j \in \mathbf{ME}(i,:)} \mathbf{TE}_{ij,t} \right) + \\ & \sum_{j \in \mathbf{ME}(i,:)} \left[-|TE_{ij,t}| \alpha_{ij,t}^p + \frac{1}{2} \left(\sum_{l \in L} \alpha_{l,t}^{line} I_{l,t} r_l \frac{|TE_{ij,t}| \cdot PTDF_{ij,l}}{P_{l,t}} \right) \right] \end{aligned} \quad (35f)$$

where (35a) and (35b) show that each seller can be assigned to multiple buyers; (35c)-(35e) correspond to (34c)-(34e); and (35f) is the coupling relationship between energy and carbon, which is related by energy sharing results $\mathbf{ME}$ and $Q_{i,t}^E$. In (35f), $Q_{i,t}^e - \sum_{j \in \mathbf{ME}(i,:)} \mathbf{TE}_{ij,t}$ represents the energy trading

with utility grid; $|TE_{ij,t}| \alpha_{ij,t}^p$ represents the carbon transferred from node i to node j ; and $\frac{1}{2} \left(\sum_{l \in L} \alpha_{l,t}^{line} I_{l,t} r_l \frac{|TE_{ij,t}| \cdot PTDF_{ij,l}}{P_{l,t}} \right)$ represents the carbon related to power losses.

Definition 2 (preference list): for each prosumer, the preference utilities towards other prosumer entities can be obtained according to (11)-(17), and then it constructs the preference list $Pl_{i,t} = \{pro_j \succ_{pro_i} pro_{j'} \mid \forall pro_j, pro_{j'} \in \Phi\}$ with a descending order, where $\succ_{pro_i}$ is the preference relation of any prosumer, which is expressed in (36).

$$pro_j \succ_{pro_i} pro_{j'} \Leftrightarrow \omega_{pro_i, pro_j}^{sum} > \omega_{pro_i, pro_{j'}}^{sum} \quad (36)$$

In (36), $pro_j \succ_{pro_i} pro_{j'}$ shows that pro_i prefers pro_j to $pro_{j'}$. Through the defined preference relations, each prosumer can rank all the entities in a descending order, and then obtain the preference list of P2P energy and carbon sharing.

C. Algorithm Implementation

As shown in Algorithm 1, a modified stable matching algorithm is implemented to solve the P2P energy and carbon sharing problem.

Algorithm 1: modified stable matching algorithm

- 1: **Input:** PV output P_i^{PV} and original load $P_{load,i,t,0}$
 - 2: **Initialization:** initial load demand $l_{i,0}$, matching matrices $\mathbf{ME}$ and $\mathbf{MC}$, and sharing matrices $\mathbf{TE}$ and $\mathbf{TC}$
 - 3: **for** $\forall t$
 - Step 1: joint energy and carbon optimization of prosumers
 - 4: Solve the optimization problem according to (18)-(33)
 - 5: Each prosumer obtains the optimal load strategy and CPP output strategy
 - 6: Calculate the nodal carbon intensity according to (1)
 - Step 2: two-stage matching process
 - 7: Each prosumer provides its personal information $\epsilon_{i,t} = \{\pi_{i,t}^e, \pi_{i,t}^c, Q_{i,t}^e, Q_{i,t}^c, \alpha_i\}$ to ECSP
 - 8: ECSP calculates SDR of the market, and issues the information to all prosumers
 - 9: ECSP constructs the preference list for prosumers based on (11)-(17)
 - 10: ECSP executes SDR-based proposal method in energy matching process (Fig. 2), and obtain $\mathbf{ME}$ and $\mathbf{TE}$
 - 11: Calculate the quantity of unbalanced energy need to trade with ECSP
 - 12: Calculate the carbon emissions and net carbon of each prosumer according to (9) and (10)
 - 13: Execute SDR-based proposal method in carbon matching process (Fig. 2), and obtain $\mathbf{MC}$ and $\mathbf{TC}$
 - 14: Calculate the unbalanced carbon quota of all prosumers and trade with the external market via ECSP
 - 15: Calculate the utility of prosumers according to (11)
 - 16: **end for**
-

The whole matching process is implemented through an ECSP platform [34], [35], and there are several principles for the platform to implement the stable matching process:

1) Information uploading: each prosumer uploads its personal information $\epsilon_{i,t} = \{\pi_{i,t}^e, \pi_{i,t}^c, Q_{i,t}^e, Q_{i,t}^c, \alpha_i\}$ to ECSP. For buyers, $\pi_{i,t}^e$ and $\pi_{i,t}^c$ are the maximum buying prices, and for sellers, they are the minimum selling prices. Considering that many efforts have been made to this topic [36], the setting of reservation prices is not considered in this paper.

2) Matching of clearing sequence: due to the electricity-carbon coupling characteristics shown in (1)-(8), the carbon emission of branch power losses and trading energy are determined by the energy sharing results $e_{ij,t}$, $\forall i, \forall j$. Therefore, the matching process is divided into two stages: energy matching and carbon quota matching. In the first energy matching stage, the detailed energy sharing results $e_{ij,t}$ can

be determined, i.e., the results of ME and TE . Next, the EC-SP calculates the carbon emission obligation related to P2P energy sharing $CP_{trading,ij,t}$ and power losses $CP_{loss,ij,t}$, and the carbon surplus or deficit Q_i^c of each prosumer. Then, the carbon matching can be implemented to realize the carbon trajectory visualization, i.e., the results of MC and TC .

3) SDR-based proposal method in matching process: in order to guarantee the “utility-priority” principle of P2P energy and carbon sharing, we introduce the concept of buyer’s market and seller’s market [34], and the proposal direction (from buyer to seller or from seller to buyer) is based on the type of market. As shown in Fig. 2, when $SDR > 1$, i.e., the aggregated energy surplus exceeds demands, the market falls into the category of buyer’s market. The buyers aim to send demands to their most favored sellers in $Pl_{i,t}$ and the sellers will decide to provide service for their more preferred buyers based on the received demand applications. When $SDR < 1$, the market falls into the category of seller’s market.

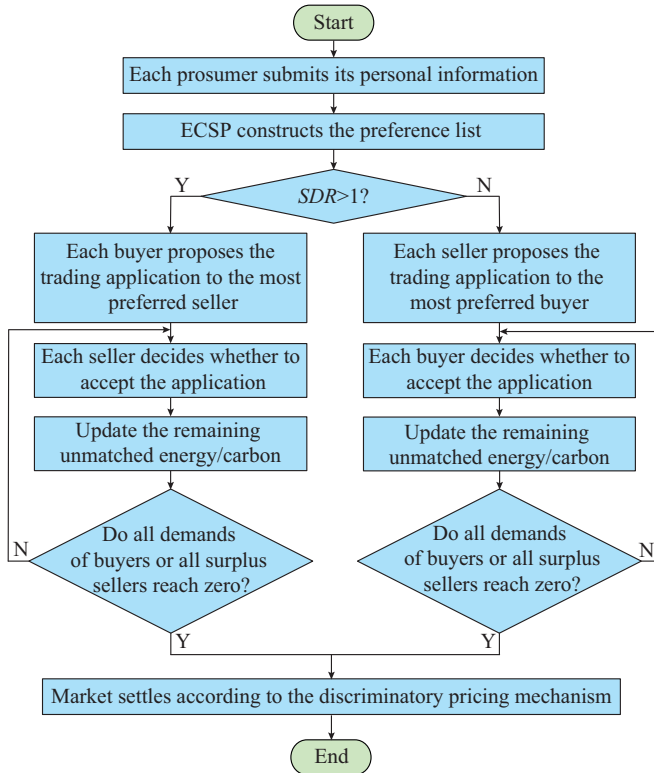


Fig. 2. SDR based proposal method in energy matching process.

Note that it is rare for the aggregated energy/carbon surplus to equal the deficit, and once this happens, one party is randomly chosen to send the application first, while the other party performs the competition.

4) Sharing price of matching: the sharing price is determined after the sealed matching process performed by the platform, and each matching pair and its sharing price are obtained simultaneously at the end of a sharing period. It is noted that in buyer’s market of energy sharing, energy buyers only send applications to energy sellers whose reservation price $\pi_{sell,t}^e$ is lower than their setting price $\pi_{buy,t}^e$, which is similar in seller’s market. Unlike uniform pricing [37], a discriminatory pricing mechanism is adopted. Once a pair of buyer and seller are matched successfully, their sharing prices

related to $|TE_{ij}|$ and $|TC_{ij}|$ are calculated by $(\pi_{buy,i,t}^e + \pi_{sell,j,t}^e)/2$ and $(\pi_{buy,i,t}^e + \pi_{sell,j,t}^e)/2$, respectively.

Theorem 1: the reached matching policy $\mathcal{M}$ converges to a stable equilibrium. $\mathcal{M}$ is a weak Pareto optimal result for buyer’s side in the buyer’s market, while it is a weak Pareto optimal result for seller’s side in the seller’s market.

Definition 3: when the matching solution has no equilibrium-blocking pairs, the matching is equilibrium.

Proof 1: if there exists a blocking pair in energy matching of $\mathcal{M}(ME, MC)$, i.e., $(ne_{s,i}, ne_{b,j})$, $ne_{s,i} \notin \mathcal{M}(ne_{b,j})$, $ne_{b,j} \notin \mathcal{M}(ne_{s,i})$, this blocking pair must hold: $\mathcal{D}(ne_{b,j}) > 0$, $ne_{b,j} \succ_{ne_{s,i}} \mathcal{M}(ne_{s,i})$, and $\mathcal{R}(ne_{s,i}) > 0$, $ne_{s,i} \succ_{ne_{b,j}} \mathcal{M}(ne_{b,j})$. Based on the SDR-based proposal method and modified stable matching algorithm, if $ne_{s,i} \succ_{ne_{b,j}} \mathcal{M}(ne_{b,j})$, $ne_{b,j}$ must have proposed to $ne_{s,i}$ when $\mathcal{R}(ne_{s,i}) > 0$ when it is the buyer’s market. Suppose that $ne_{b,j}$ has been proposed but rejected by $ne_{s,i}$ in another matching result $\mathcal{M}'(ME, MC)$, i.e., $\mathcal{M}'(ne_{s,i}) \succ_{ne_{s,i}} ne_{b,j}$. However, $ne_{s,i}$ only accepts better matching result, which means $\mathcal{M}(ne_{s,i}) \succ_{ne_{s,i}} \mathcal{M}'(ne_{s,i})$ for the obtained $\mathcal{M}(ME, MC)$. Therefore, according to the recursive-ness of $\succ_{pro}$, $\mathcal{M}'(ne_{s,i}) \succ_{ne_{s,i}} ne_{b,j}$ and $\mathcal{M}(ne_{s,i}) \succ_{ne_{s,i}} \mathcal{M}'(ne_{s,i})$ can not derive $ne_{b,j} \succ_{ne_{s,i}} \mathcal{M}(ne_{s,i})$, which is not consistent with $\mathcal{D}(ne_{b,j}) > 0$, $ne_{b,j} \succ_{ne_{s,i}} \mathcal{M}(ne_{s,i})$. Similar proof to demonstrate $\mathcal{M}(ne_{b,j}) \succ_{ne_{b,j}} ne_{s,i}$ can not be guaranteed as well. Hence, it is proven that the blocking pair $(ne_{s,i}, ne_{b,j})$ does not exist in energy sharing. The proof demonstrating the improbability of a blocking pair $(nc_{s,i}, nc_{b,j})$ in carbon sharing follows a similar process. In summary, the reached matching result $\mathcal{M}$ is proven to converge to a stable equilibrium.

Besides, in buyer’s market, buyers cannot unilaterally change their strategy to achieve higher utilities. Supposing a better matching policy $\mathcal{M}'$ exists for energy buyer $ne_{b,j}$, i.e., $\mathcal{M}'(ne_{b,j}) \succ_{ne_{b,j}} \mathcal{M}(ne_{b,j})$, $ne_{b,j}$ can match with those in $\mathcal{M}'$, which has already been rejected in $\mathcal{M}$. This means that each matching peer $\mathcal{M}'(ne_{b,j})$ of $ne_{b,j}$ under $\mathcal{M}'$ must have rejected peers under $\mathcal{M}$. However, Algorithm 1 is an adaptation of the deferred acceptance algorithm. For buyers, any seller matched with them must have never rejected their energy application demand, which contradicts our original assumption. Consequently, it is proven that $\mathcal{M}$ represents a Pareto optimal outcome for all buyers in the buyer’s market. Similar proofs are used to prove the Theorem in the seller’s market and the carbon sharing process.

VI. CASE STUDY

A. Basic Data

Several numerical results are utilized to validate the performance of the proposed matching-based energy and carbon sharing scheme with hybrid preferences. The IEEE 33-bus distribution system comprising 32 prosumers is selected as the case study, as shown in Fig. 3. All the prosumers are

equipped with PV panels and 20 prosumers are equipped with CPPs. All load data are collected from the smart residential and industrial buildings in the demonstration projects of Henan province, China.

Figure 4 shows the PV generation, load demand, and initial carbon quota data. The PV generation and load demand data are based on hour-ahead forecasting values, and the initial free carbon emission quota allocated to prosumers is calculated as 85% of the average daily values from similar historical types. The parameter settings of case study are shown in Table II.

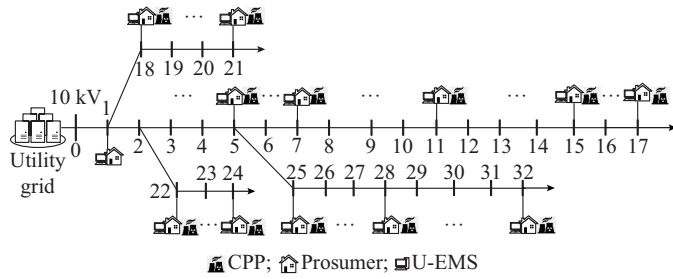


Fig. 3. IEEE 33-bus distribution system comprising 32 prosumers.

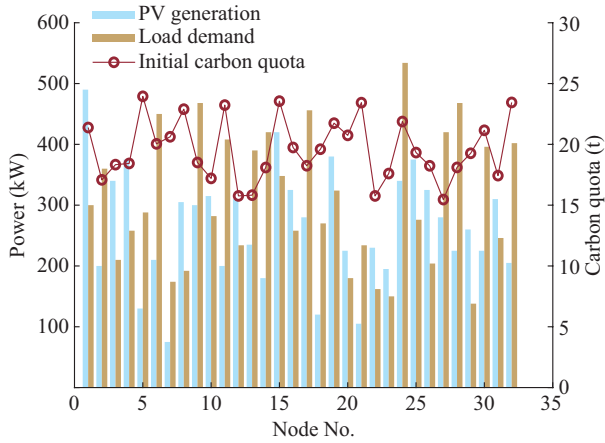


Fig. 4. PV generation, load demand, and initial carbon quota data.

TABLE II
PARAMETER SETTINGS OF CASE STUDY

Parameter	Value	Parameter	Value
Basic load demand	See Fig. 1	Upper limit of CPP output (kW)	[400, 650]
PV generation	See Fig. 1	Cost coefficient of CPP output (¥/kW)	[0.35, 0.6]
Initial free carbon quota	See Fig. 1	Carbon intensity of CPP unit (kg-CO ₂ /kWh)	[0.45, 0.55]
$\mathcal{T}_a, \mathcal{T}_b$	See Fig. 2	$v_i^{\max}, v_i^{\min}$ (p.u.)	1.07, 0.95
ϕ	[0, 1]	$\lambda_{ex,b}^e, \lambda_{ex,s}^e$ (¥/kWh)	0.7, 0.35
θ_i	[50, 200]	$\lambda_{ex,b}^c, \lambda_{ex,s}^c$ (¥/kgCO ₂)	1, 0.4
Branch resistance and reactance	Data of IEEE 33-bus distribution system	$I_{i,j}^{\max}, I_{i,j}^{\min}$	Data of IEEE 33-bus distribution system

For the social layer information related to social behavior, the social network data originate from a study of real-world relationships within a karate club. The karate club network, often used in the research on community detection within

complex networks, consists of 34 nodes and 78 edges. The 34 nodes represent the 34 members of the karate club, and the edges between nodes signify mutual acquaintance between members. In this case study, it is assumed that the set of prosumers participating in P2P energy and carbon sharing has a social network structure similar to that of the karate club members, which are randomly selected 32 nodes from the social network of karate club, and the social network of prosumers in this paper is shown in Fig. 5. The nodes in the diagram correspond to the prosumer numbers, with the size of the nodes increasing with their betweenness centrality. Besides, the initial credit $\sigma_{b,s,k}$ is set to be 0, and on the premise of only considering the economy-based bilateral matching degree, a series of 50×24 simulation tests are implemented based on the proposed matching-based energy and carbon sharing scheme to obtain the historical sharing records of P2P energy and carbon sharing among prosumers.

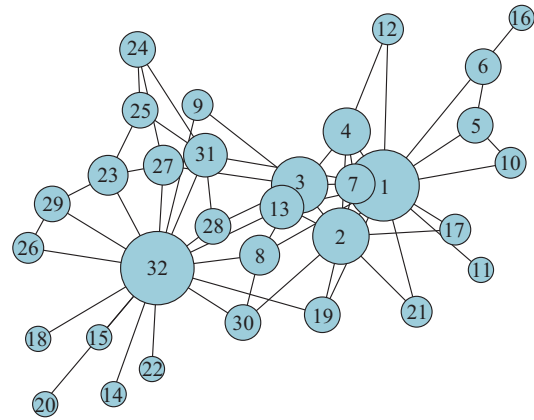


Fig. 5. Social network of prosumers.

B. Simulation Results

1) Analysis of P2P Energy Sharing Results of Prosumers

Figure 6 shows the P2P energy sharing results. Figure 6(a) shows the energy balance strategies of prosumers, where each prosumer optimizes their loads and distributed generation strategies, based on which each prosumer shows their buyer or seller role at this time slot. Prosumers who hold $Q_i^e > 0$ are sellers and those who hold $Q_i^e < 0$ are buyers. And the ESCP calculates that $SDR > 1$, which means the aggregated energy surplus exceeds aggregated demands, then the market falls into the category of buyer's market. Therefore, during the energy matching process, the proposal direction is from buyer to seller, and each buyer sends its energy demands to its favorite trading entity.

2) Analysis of P2P Carbon Transfer of Energy Sharing

Figure 7(a) shows the weighted node carbon intensity and line carbon intensity, and the weighted node carbon intensity varies with the CPP and PV generations. Compared with Fig. 4, we can obtain that only the nodes with CPP generations (blue bars) have carbon emissions, and their weighted nodal carbon intensity is positive, and only 13 out of the 20 prosumers equipped with CPP are optimized for energy generation.

Based on weighted node carbon intensity, line carbon intensity, as well as the P2P energy trading volume results in Fig. 6(b), the carbon intensity $\alpha_{ij,t}^p$ of sharing energy is obtained and shown in Fig. 7(b).

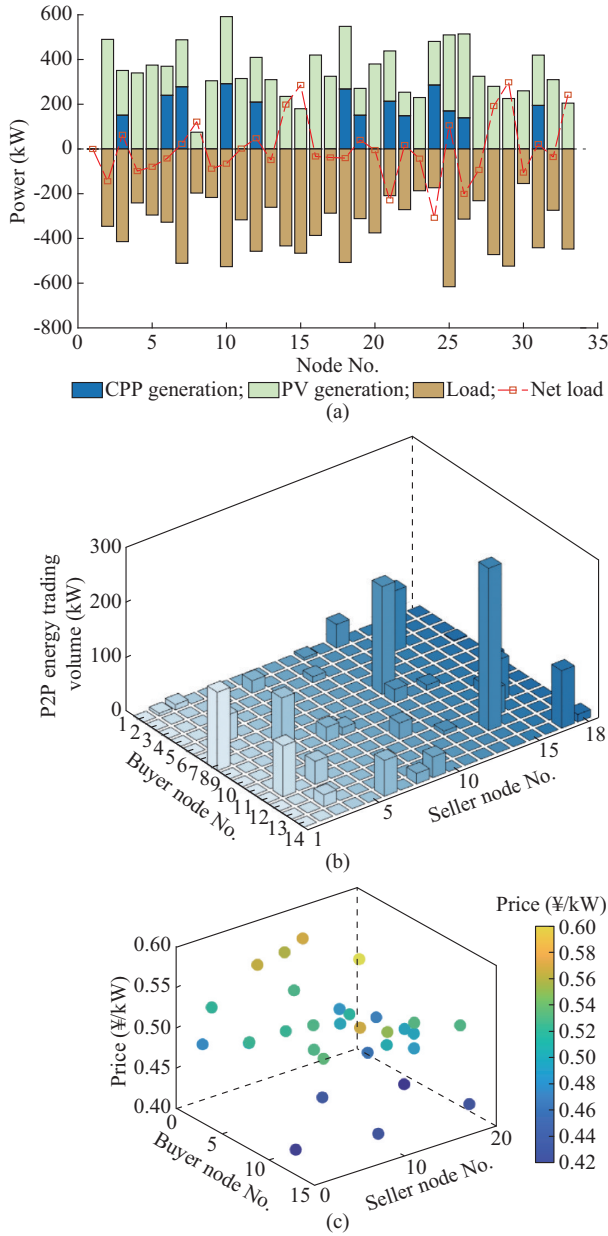


Fig. 6. P2P energy sharing results. (a) Energy balance strategies of prosumers. (b) P2P energy trading volume of prosumers. (c) P2P energy sharing price of prosumers.

Only transactions related to sellers with CPP generation have carbon transfer, and the carbon intensity of the sharing energy is equal to the weighted node carbon intensity of sellers. Figure 7(c) clearly shows the carbon transfer between prosumers. The color represents the carbon content, where the color trend from red to green corresponds to the carbon intensity from high to low.

3) Analysis of P2P Carbon Sharing Results of Prosumers

Figure 8 shows the P2P carbon sharing results. The carbon quota balance strategies of prosumers are shown in Fig. 8(a). Then, through (10), the transactive carbon volume can be obtained, which is shown as red lines. Prosumers with $Q_i^c > 0$ are buyers while those with $Q_i^c < 0$ are sellers. $SDR < 1$ means that the aggregated carbon surplus exceeds the aggregated demands. And the market falls into

the category of seller's market. Therefore, for the carbon matching process, the proposal direction is from seller to buyer.

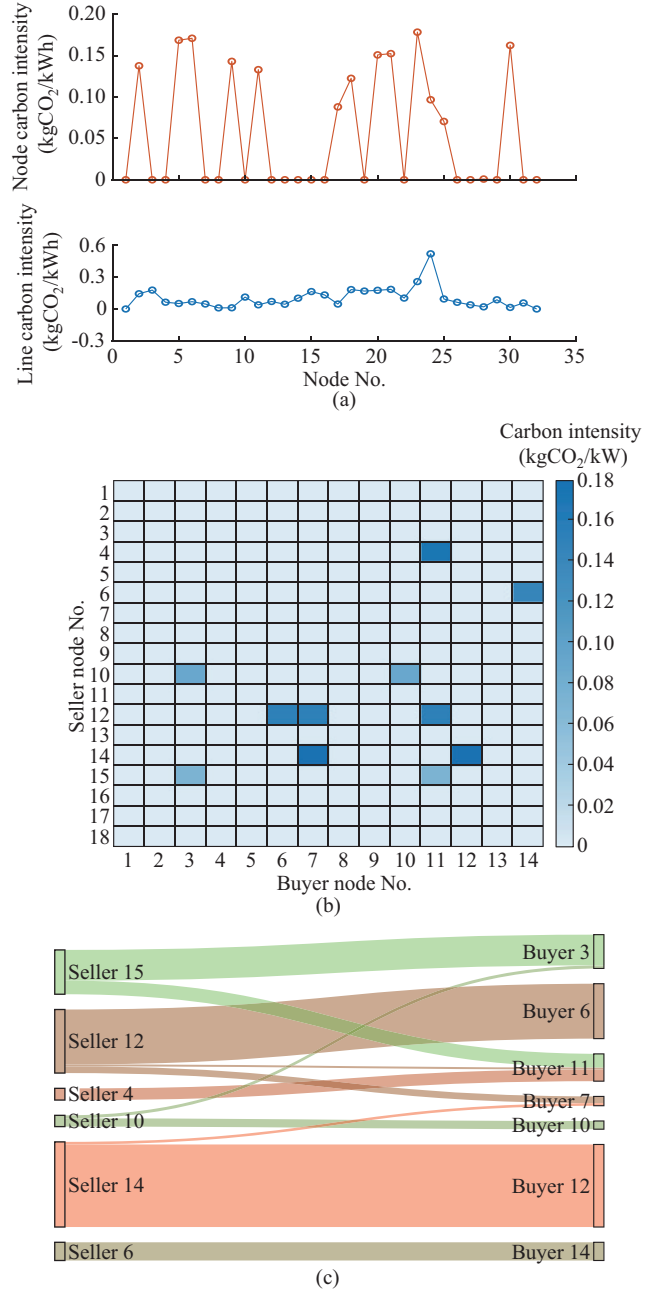


Fig. 7. Carbon transfer results. (a) Weighted node carbon intensity and line carbon intensity. (b) Carbon intensity $\alpha_{ij,t}^P$ of sharing energy. (c) Carbon transfer between prosumers.

Since the carbon emissions of power losses are very small and not obvious, they are separately shown in Fig. 9. The total carbon emissions of power losses are about 2.44 kgCO₂.

4) Performance of Hybrid Preferences

In order to verify the performance of the proposed matching-based energy and carbon sharing scheme with hybrid preferences, the following comparisons are considered. All four cases utilize Algorithm 1 to solve the problem.

Case 1: only economy-based preferences are considered, without considering social behavior or low-carbon preferences.

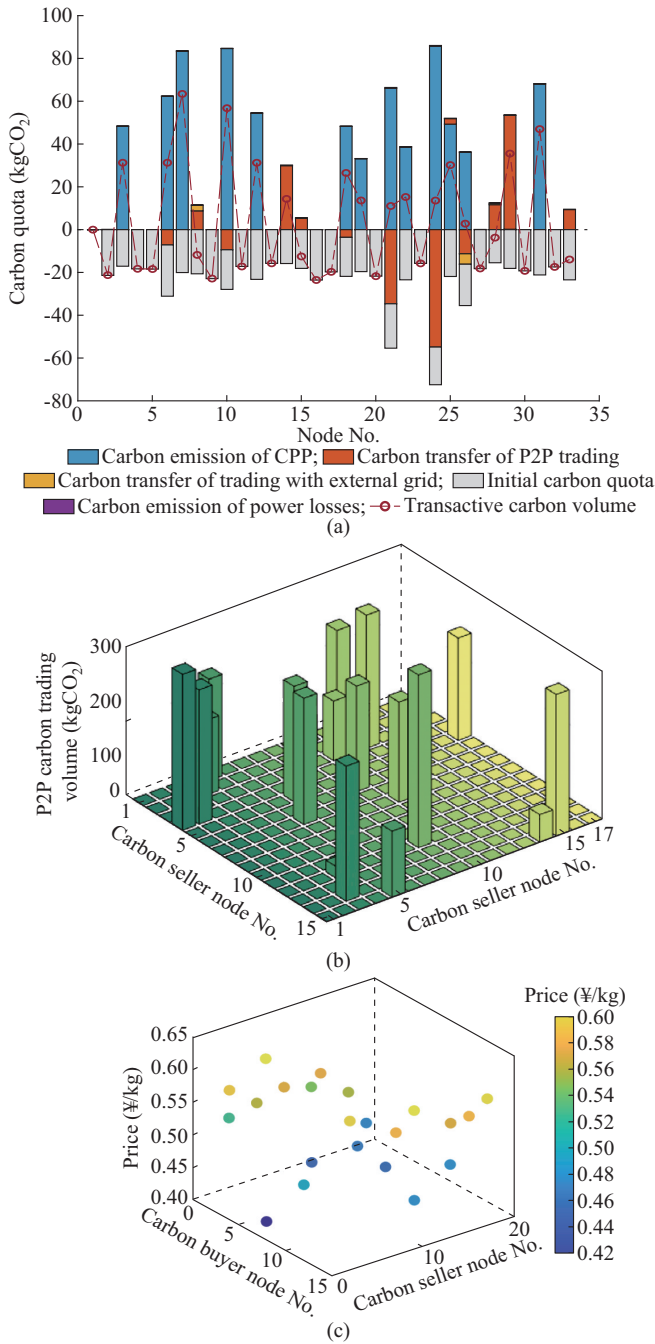


Fig. 8. P2P carbon sharing results. (a) Carbon quota balance strategies of prosumers. (b) P2P carbon trading volume of prosumers. (c) P2P carbon sharing price of prosumers.

Case 2: economy-based and low-carbon preferences are considered, without considering social behavior.

Case 3: economy-based preferences and social behavior are considered, without considering low-carbon preferences.

Case 4: three kinds of preferences (hybrid) are considered.

Table III shows the performance comparison of the proposed matching-based energy and carbon sharing scheme with hybrid preferences (Case 4) with other cases. For the total P2P energy sharing volume and the energy trading with the external grid, the sum of the total P2P energy sharing volume and that of the energy sold to the external grid in four cases are the same, which equal the total energy surplus of all sellers.

Similarly, the sum of the total P2P energy sharing volume and that of the energy purchased from the external grid in four cases are also the same, which equal the total energy deficit of all buyers. The reason is that the total trading volume is decided in *Step 1* of Algorithm 1, and the specific sharing results (with other prosumers or external grid) are optimized in *Step 2* of Algorithm 1. The results also show that solutions taking social behavior into account can significantly promote the involvement of prosumers in P2P energy sharing, which then reduce the trading with external market by comparing Cases 3 and 4 with Cases 1 and 2. For the total P2P carbon sharing volume and the carbon trading with the external market, it is noted that the sum of these two numbers and the total carbon emissions of three cases are different. The reason is that the carbon intensity of different prosumers (see Fig. 7(a)) and external energy (0.15 kgCO₂/kWh for this time slot) vary, and therefore, different energy sharing strategies correspond to different carbon emissions.

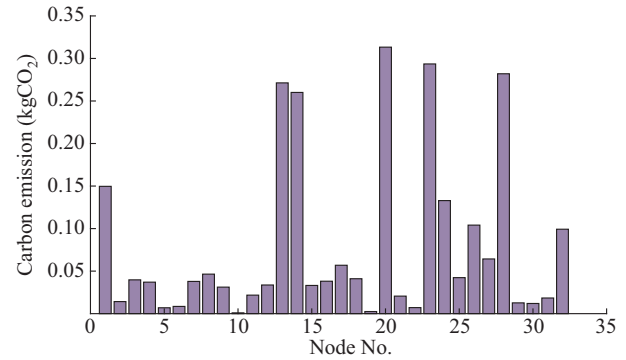


Fig. 9. Carbon emissions of power losses.

For the total carbon emissions of all prosumer clusters, Case 1 has the highest value. By comparing Case 1 and Case 2, it can be observed that schemes considering low-carbon preferences encourage prosumers to trade with external grid since the carbon intensity of external energy is lower than that some prosumers. This stimulates the prosumer with high carbon intensity to sell their energy to external grid instead of P2P sharing within prosumer cluster, and then reduces the total carbon emission, as shown in Fig. 10(a) and (b). And the similar situation can also be observed in Fig. 10(c) and (d).

For the average weighted utilities calculated by (34), the results show that Case 4 outperforms other cases.

5) Performance Comparison with ADMM-based Market Clearing Scheme

To illustrate the performance of the proposed matching-based energy and carbon sharing scheme, the ADMM-based market clearing scheme in [15] is used as the comparison case.

Case 5: prosumers conduct P2P energy and carbon sharing with the consideration of social behavior, but the product differentiation for sharing preferences is expressed as bilateral carbon sharing cost via carbon sharing coefficients, and ADMM algorithm is utilized to solve the problem.

The reason for this comparison is that both matching-based and ADMM-based market clearing schemes can obtain the specific P2P transaction results as well as the according price of each transaction.

TABLE III
PERFORMANCE COMPARISON OF CASE 4 WITH OTHER CASES

Case	Preference			Total P2P energy sharing volume (kW)	Energy trading with external grid (kW)		Total P2P carbon sharing volume (kgCO ₂)	Total carbon trading with external market (kgCO ₂)	Total carbon emission (kgCO ₂)	Average weighted utilities of all prosumers
	Economic-based	Social behavior	Low-carbon		Selling	Buying				
Case 1	√	×	×	1527.6	173.8	133.2	271.3	159.5	771.2	0.42
Case 2	√	×	√	1473.2	228.3	187.6	268.3	157.4	760.9	0.48
Case 3	√	√	×	1660.8	40.7	0.0	280.9	143.4	756.9	0.59
Case 4	√	√	√	1638.2	63.3	22.7	291.2	132.7	755.8	0.67

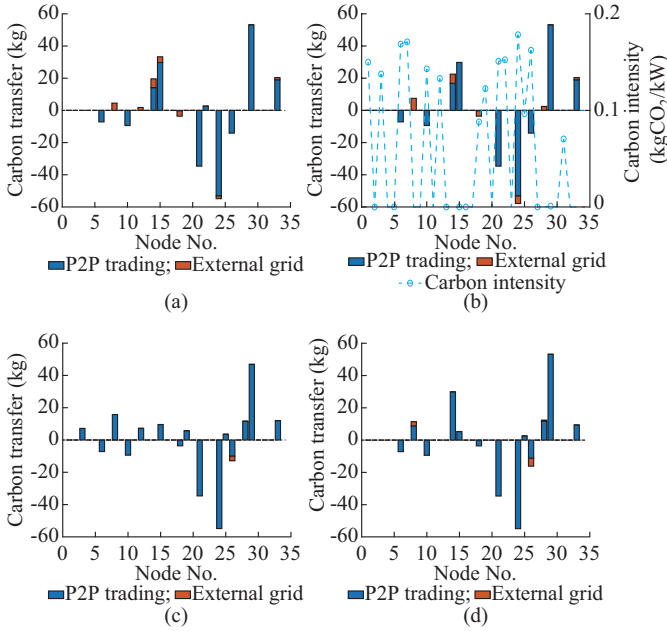


Fig. 10. Carbon transfer of energy sharing in four cases. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

The difference is that Case 4 is a two-step optimization process, where the specific P2P sharing results are decided in *Step 2* of Algorithm 1. While for ADMM-based market clearing scheme, the P2P energy and carbon sharing results are optimized via multiple rounds of information interaction and iteration.

Table IV presents the comparison between Cases 4 and 5, which shows that the social welfare in Cases 4 is higher than that in Case 5. And the average economic utilities of prosumers calculated via (11) in Case 4 is slightly less than those in Case 5. The analysis for these results is as follows. In ADMM-based market clearing scheme, the CPP generation as well as the energy and carbon transaction strategies is optimized synchronously in the distributed iteration process, and its optimization goal is to maximize individual utilities. While in this paper, the CPP generation, the total energy demands of buyers, and the total energy surplus of sellers are decided firstly with the goal of social welfare maximization, and then the energy and carbon transactions are sequentially optimized, which results in higher social welfare but lower average economic utilities of prosumers.

Table V shows the comparison results of computing time. It can be found that the computing time of Case 4 is much lower than that of Case 5.

TABLE IV
COMPARISON BETWEEN CASES 4 AND 5

Case	Total P2P energy sharing volume (kW)	Total P2P carbon sharing volume (kgCO ₂)	Total social welfare (¥)	Average economic utility of prosumers (¥)
Case 4	1638.2	291.2	23270.6	703.3
Case 5	1595.8	261.5	23105.2	721.4

Since for Case 4, its time complexity is $O(n^2)$, while for Case 5, its time complexity is $O(Kn^2)$, where K is the number of iterations. In distributed and large-scale cases, the number of iterations of Case 5 increases significantly.

TABLE V
COMPARISON RESULTS OF COMPUTING TIME

IEEE test system	Case 4 (s)	Case 5 (s)
IEEE 33-bus	10.3	69.4
IEEE 114-bus	27.7	198.4
IEEE 169-bus	40.5	300.8

VII. CONCLUSION

In this paper, the bidirectional carbon emission obligation transfer model is derived for P2P energy sharing among prosumers. Then, hybrid preferences are defined for prosumers, and are integrated into the proposed matching-based energy and carbon sharing scheme. Numerical results demonstrate that the proposed matching-based energy and carbon sharing scheme considering social behavior can enhance the P2P sharing involvements, and the consideration of low-carbon preferences can encourage prosumers to choose cleaner energy and then reduce the total carbon emissions of all prosumer clusters. Compared with ADMM-based market clearing scheme, the proposed scheme can significantly improve the computational efficiency while yielding only slightly lower economic benefits for prosumers. This paper is a fundamental study, and only the single-time-slot optimization results are considered. The main contributions of this paper lie in the effective clearing process while integrating hybrid preferences of prosumers. In the future, the interactions between optimizing the energy storage device or time-coupled loads and optimizing the process of matching theory will be further explored.

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