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P2P trading mode for real-time coupled electricity and carbon markets based on a new indicator green energy

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A R T I C L E I N F O

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A B S T R A C T

The carbon trading market has introduced new opportunities for the low-carbon transformation of China's power industry. To realize real-time coupling of the electric–carbon market at the mechanism level, this study constructs a P2P trading mode that improves economic and environmental benefits through innovative mechanisms. First, we propose a novel indicator, Green Energy, which has multidimensional composite attributes and accurately characterizes the supply of clean and low-carbon energy. Green Energy is used as a matchmaking indicator in the P2P electricity market to increase the rate of renewable energy consumption and encourage emission reduction of fossil energy suppliers. Second, the carbon price is dynamically adjusted according to real-time electricity consumption information and it is transmitted to the electricity market through Green Energy. Third, blockchain cross-chain interoperability technology is introduced to establish a real-time data-sharing network for electricity and carbon co-trading. Moreover, a case study is conducted, and the simulation results show that the proposed method improves social welfare by over 18% compared to the traditional trading mode. And it can improve renewable energy utilization efficiency by 26.78% and reduce carbon emissions by more than 17%. This study provides a reference for the real-time coupled electricity and carbon markets.

1. Introduction

1.1. Background and motivation

According to the Special Report on Global Warming of 1.5 °C released by IPCC, only by achieving global carbon neutralization in the middle of the 21st century can the extreme harm caused by climate change be mitigated [1]. Carbon emissions from energy activities account for approximately 87% of the global carbon emissions, more than half of which originate from electricity production [2]. Humans have attempted to solve the adverse effects of fossil fuels using inexhaustible renewable energy sources [3]. In a low-carbon transition environment, carbon constraints would permeate all aspects of the electricity industry [4]. As basic participants in the carbon market, the degree of participation of electricity enterprises in the carbon market is not only related to the enterprise's operation but also to the healthy and stable development of this market. The coordinated development of electricity and carbon markets is crucial for achieving emission reduction goals [5].

The construction of incentive-compatible electricity–carbon coupling systems has gradually become a research direction worthy of attention. Early research on electricity–carbon coupling focused on the technical level, especially on the coupling of electric power and low-carbon technologies. Examples include the flexible control of renewable energy power generation [6], security and stability of power electronics [7], and application of carbon capture technology [8]. Although some scholars have designed electricity market mechanisms to promote carbon emission reduction, the correlation between electricity and the carbon market is weak; therefore, a real-time coupled trading mode is urgently needed [9]. Consequently, this study explores the trading mode and information interaction method of integrated electricity and carbon

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markets at the mechanism level.

1.2. Literature review

(1) Trading mode for electricity–carbon market

Research on the interaction and integration between the electricity and carbon markets helps reduce carbon emissions [10]. Scientific and reasonable trading modes can effectively strengthen the correlation between the two markets [11]. In terms of trading modes, traditional centralized trading methods are not conducive to stimulating the enthusiasm of all stakeholders to participate simultaneously in electricity and carbon markets [12]. Meanwhile, many prosumers cannot adapt centralized methods in the trading market to practical-scale distribution networks [13]. Therefore, peer-to-peer (P2P) trading involving a large number of prosumers is becoming a promising trend in electricity and carbon markets. Some scholars have proposed a P2P electricity-trading mode and have verified its advantages [14,15]. A P2P electricity trading platform is a virtual trading platform [16]. Consumers can use their account balance to directly offset electricity consumption or trade with other consumers [17] to achieve a local balance between electricity demand and distributed renewable energy (DRE) [18]. The P2P trading mode is also conducive to energy trading among multi-energy systems such as electricity, heat, and cold systems and to further expand the consumption channels of DRE [19]. Additionally, carbon trading generally adopts the P2P mode [20], and some participants sell excess carbon emission rights to those with insufficient carbon emission rights [21]. Although the P2P trading mode has been applied in the electricity and carbon markets, it is usually used in a single market. Further research is required to effectively combine these two distributed trading markets.

(2) Price strategy

The price strategy is the most sensitive and effective regulatory mechanism in the market. The change in carbon or electricity prices would cause a change in the supply and demand relationship and affect the emission reduction intention of the electricity–carbon market [22]. Carbon price is affected by the complex external environment and energy policies, which involve economic, energy, and climate factors, and is nonlinear, nonstationary, and multi-frequency [23]. However, obtaining accurate prices under fluctuating conditions is difficult. Considerable research has been conducted on the calculation of carbon prices. The marginal cost method reflects the cost of carbon emission reduction to a certain extent [24]. It is also a common carbon pricing method used to comprehensively analyze the influencing factors and sensitivity of the carbon market [25]. This method can provide guidance for policy formulation but cannot calculate the optimal carbon price [26]. In the electricity production scenario, some factors increase the volatility of carbon emissions, such as renewable energy generation, power load, and use of carbon reduction technologies [27,28]. In view of the particularity of electricity systems, methods to accurately account for real-time carbon emissions and realize optimal carbon prices need to be further investigated.

In terms of electricity pricing, bidding strategies with dynamic learning abilities are expected to become one of the methods to promote carbon emission reductions in the electricity market [29]. The adaptive aggressiveness strategy enables the buyer and seller to update the quotation independently to obtain a higher transaction rate based on the operational fluctuations of the energy system [30]. Decentralized bidding strategies are also used in the distributed electricity market, in order to enable renewable energy suppliers to obtain higher trading returns [31,32]. Wang et al. [33] designed a blockchain-based electricity–hydrogen coupling system using an adaptive bidding strategy to improve renewable energy utilization and reduce regional carbon emissions. Although the adaptive learning bidding strategy provides opportunities for distributed electricity markets, it has not shown technical advantages in electricity and carbon co-trading markets.

(3) Blockchain technology application

Electricity and carbon co-trading require infrastructure for data to interact effectively. Blockchain is a new generation of information technology. The basic features of blockchain technology, including decentralization, fairness, and expansibility, are consistent with P2P trading [34]. In a blockchain trading environment, information is updated in real time and stored in a distributed manner across the participating nodes [35]. This distributed storage method enhances the mutual trust among participants and provides a collaborative network platform for electricity and carbon emission trading [36]. However, there are differences in the data structure, update rate, and relative freedom between electricity trading and carbon emission information [37]. A single-chain structure cannot satisfy the effective interaction between electricity trading data and carbon emission data among multiple agents.

Several conclusions can be drawn from this review. First, the existing P2P trading mode is only for a single commodity, electricity or carbon, and it cannot adapt to the diversified and large-scale development trends of electricity–carbon markets. Moreover, electricity and carbon trading are mutually coupled, and traditional pricing strategies do not consider the real-time interaction between the two commodity transactions. Finally, existing projects do not include the use of an electricity–carbon market in implementation scenarios. A research gap exists in the implementation of a blockchain-based trading mode for real-time coupled electricity and carbon markets.

1.3. Contributions and article structure

Considering the shortcomings of existing research, this study further examines the trading mode for real-time coupled electricity and carbon markets based on previous research. To strengthen the correlation between the two markets, a new indicator is proposed, Green Energy (GE), which has multidimensional composite attributes and more accurately characterizes the supply of clean and low-carbon energy. The P2P electricity market uses GE as a matchmaking indicator, and the carbon price is transmitted to the electricity market through GE. The prices of electricity and carbon interact through GE, and real-time information exchange is enhanced through a double-chain blockchain network. The effectiveness of this method was analyzed in the context of China's coupled electricity and carbon markets. Compared to existing studies, the main contributions of this study can be summarized as follows:

- Energy indicator: An original indicator GE is proposed for the electricity–carbon market. GE can not only characterize the total amount of energy, but also measure the supply of clean and low-carbon energy. With its multiple attributes, GE is influenced by both electricity and carbon trading and effectively transmits real-time information on both types of transactions.
- Trading mode: A P2P electricity trading mode with learning ability that uses GE as a matchmaking indicator is proposed. Meanwhile, based on real-time electricity consumption data, the carbon accounting timescale is refined to optimize the carbon shadow price.
- Blockchain integration: A double-chain system was designed to store electricity trading and carbon emission data using blockchain cross-chain interoperability technology. The system shares market information in real time to enhance the coupling of electricity and carbon markets.

The remainder of this paper is organized as follows: Section 2 introduces the GE-based market framework for electricity and carbon co-trading. Section 3 describes the dynamic pricing strategy, which includes carbon pricing and electricity bidding strategies. Section 4 demonstrates the feasibility of the proposed method using a case study. Finally, Section 5 presents the conclusions and future work.

2. Green energy-based market framework

This section first describes the basic concepts and calculation methods for GE. Then, GE is used as a matchmaking indicator to establish the electricity and carbon co-trading market framework. Finally, we describe the double-chain system.

2.1. Green energy: concept and calculation

An energy measurement indicator is used to measure the energy quantity within a unit of time. At present, the main energy measurement indicators are joules (J), kilowatt hours (kWh), and calories (Cal). These indicators represent the use of energy in production, transmission, conversion, and utilization, and have been used until now. Indicators can be designed to quantify the relationship between the energy consumption and carbon emissions. Lewis et al. [38] proposed an 'energy-return-on-carbon' indicator to maximize the net energy from the remaining carbon budget. This indicator integrates the cost of fossil fuel energy with the biological differences. Wang et al. [39] used the co-benefit value of per-ton CO_2 reduction and the carbon emission price as a unified indicator. This study quantified the environmental costs of carbon dioxide and air pollutants, enabling policymakers to understand the social costs of coal-fired power generation more accurately. These conceptualized and quantified indicators help us understand the role of technological capabilities in social and economic development [40,41]. However, to the best of our knowledge, there is no indicator for integrating electricity and carbon markets.

With the urgent demand for clean and low-carbon renewable energy, there is a need for an indicator that not only represents the total amount of energy but also represents the clean, low-carbon, stable, efficient, and other attributes of energy. In view of this demand, this study proposes an energy measurement and matchmaking indicator, GE.

GE is defined as the total amount of green and low-carbon energy contained in any flow or stored energy source. GE is an indicator obtained by removing the cost of loss, carbon, and pollutants and weighting the reliability and comfort of the supplied electric power. Therefore, GE can be compared with electrical power "W." Here, we define its basic unit as "GrW." The calculation principle of GE is shown in Fig. 1; it is the amount of energy supply per unit time after deducting the transmission loss, carbon, and pollutant emission costs, and considering the reliability and comfort of energy use. It is formulated as Eq. (1):

$$GE = k_{r,i,t} \bullet k_{c,i,t} \bullet \left(Q_{i,t}^{basic} - Q_{i,t}^{tra} - Q_{i,t}^{car} - Q_{i,t}^{pol}\right) \tag{1}$$

$Q_{i,t}^{tra}$ refers to the electricity loss from the production to the consumer side. Generally, distributed renewable energy is closer to the consumer side and results in fewer transmission losses. The transmission loss can be calculated using Eqs. (2) and (3):

$$Q_{i,t}^{tra} = Q_{i,t}^{basic} \bullet \left(1 - \eta_i^{tra}\right) \tag{2}$$

$$\eta_i^{tra} = W_i^{pro} / W_i^{con} \tag{3}$$

$Q_{i,t}^{car}$ refers to the impact on the environment of the carbon dioxide generated during the process of supplying electricity. After deduction, it is the part of electricity consumption that does not generate additional carbon emissions. Wind power plants (WPPs), photovoltaics (PVs), hydroelectric power generation (HP), and other renewable energy sources do not generate carbon emissions during their operation. Therefore, the carbon conversion cost of renewable energy is zero. For fossil fuels and distribution networks (DNs) containing fossil fuels, the carbon conversion cost can be calculated as follows:

$$Q_{i,t}^{car} = C_{i,t}^{car} \bullet Q_{i,t}^{basic} \tag{4}$$

$$C_{i,t}^{car} = E_{i,t}^{car} \bullet P_t^{car} \Big/ P_t^{re} \tag{5}$$

$$P_t^{re} = \left(P_t^{WPP} + P_t^{PV} + P_t^{HP}\right) / 3 \tag{6}$$

$Q_{i,t}^{pol}$ refers to the impacts of various pollutants generated during the energy supply process on the environment, and their deduction can be regarded as the part that does not generate additional pollutants during the energy utilization period. The pollution conversion cost is calculated as follows:

$$Q_{i,t}^{pol} = C_{i,t}^{pol} \bullet Q_{i,t}^{basic} \tag{7}$$

$$C_{i,t}^{pol} = \sum_{m=1}^{M} \left(e_{i,t,1} \bullet f_1 + e_{i,t,2} \bullet f_2 + \cdots + e_{i,t,m} \bullet f_m\right) / P_t^{re} \tag{8}$$

$k_{r,i,t}$ refers to the probability of trouble-free equipment operation during the energy supply process, as formulated in Eq. (9):

$$k_{r,i,t} = \sum_{y=1}^{Y} \omega_{y,i,t} / T \tag{9}$$

$k_{c,i,t}$ refers to the comfort of energy provided by energy supply facilities and can also be regarded as the response speed of energy supply facilities to meet the energy demand of users quickly and effectively. It is calculated as follows:

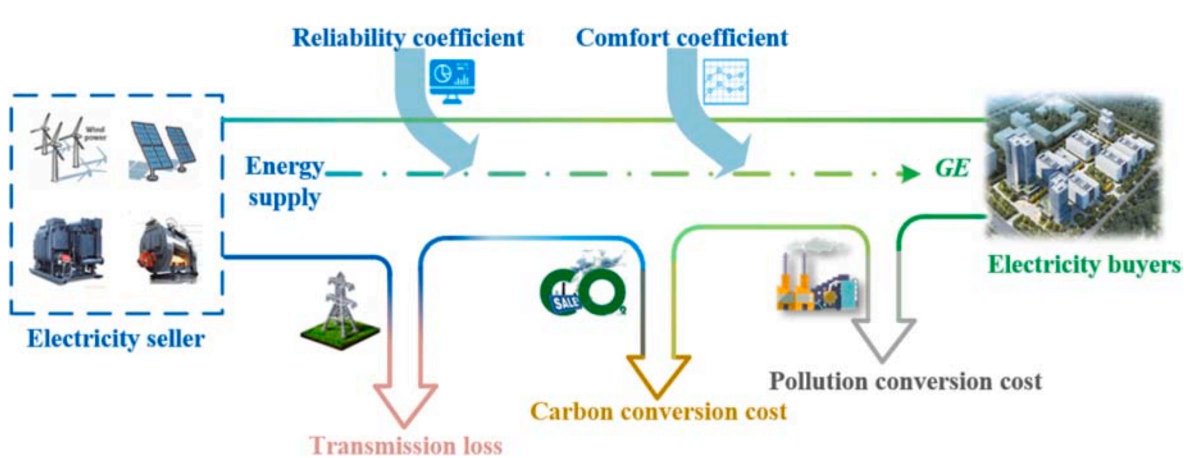

Fig. 1. Calculation principle of GE.

$$k_{c,i,t} = 1 - e^{-\left(W_{i,t} - W_{i,t-1}\right)} \quad (10)$$

2.2. Market framework based on green energy

The proposed real-time coupled electricity and carbon markets comprise a P2P electricity-trading market and a dynamic pricing carbon market. In P2P trading in the electricity market, GE is used as an indicator to replace electricity quantity. The GE value of each electricity supplier is affected by fluctuations in real-time carbon prices. Carbon accounting is conducted based on real-time electricity consumption data, and the shadow price of the carbon market is calculated using real-time carbon accounting. Therefore, GE, real-time carbon accounting, and dynamic carbon pricing integrate the electricity and carbon markets. The market framework is illustrated in Fig. 2.

In the electricity market, energy suppliers and consumers conduct matching trading and market clearing in the P2P mode. Electricity suppliers generally include WPPs, PVs, HP, gas-fired power plants (GPPs), coal-fired power plants (CPPs), and DNs, which ensure power supply and demand balance. Consumers of electricity actively participate in P2P trading. Each participant conducts matching transactions through a double auction and publishes information such as supply and demand type, bidding price, and GE of the $t+1$ time slot in time slot t. The electricity market ranks the bidding price of suppliers' GE from low to high and ranks the bidding price of consumers from high to low. The lowest bidding price of suppliers is matched with the highest bidding price of consumers, and the transaction price is the average bidding price. Finally, according to the actual electricity data of the smart meter and the transaction price, the electricity fee is determined.

The carbon market performs two functions: real-time carbon accounting and dynamic carbon pricing. In carbon accounting, the carbon emission factors of different time slots are calculated according to the electricity consumption data. The refined carbon emissions can be obtained by combining the power intensity and activity levels of consumers. Shadow prices are introduced to dynamically adjust carbon prices. This carbon pricing is based on total quantity control, carbon emission statistics, and the Chinese certified emission reduction (CCER) impact, combined with the power supply data for each time slot. The purpose of carbon pricing is to ensure that total carbon emissions do not exceed the standard and feed back to the electricity market to change the GE of electricity suppliers.

2.3. Double-chain system

The electricity and carbon markets involve some aspects of the energy sector. The trading areas, modes, and objects in each link are different, and electricity and carbon quota trading are both independent and coordinated. Therefore, two types of blockchain can be constructed: an electricity trading chain and a carbon trading chain. When a user uses a double-chain system for the first time, their basic identity information must be registered, authenticated, and verified. After all processes are completed, the trading model generates the public and private keys of the user according to the identity information provided by the user, which can be used to trade electricity or carbon quota indicators. To manage users efficiently and credibly, electronic credentials are introduced, and their information of electronic credentials is saved behind the blockchain to protect the rights and interests of users. If the user performs a malicious transaction, the double-chain system deducts points accordingly. If the score is below the set threshold, it is excluded from the analysis.

As shown in Fig. 3, the transactions in a double-chain system are primarily handled through blockchain smart contracts. When the selling

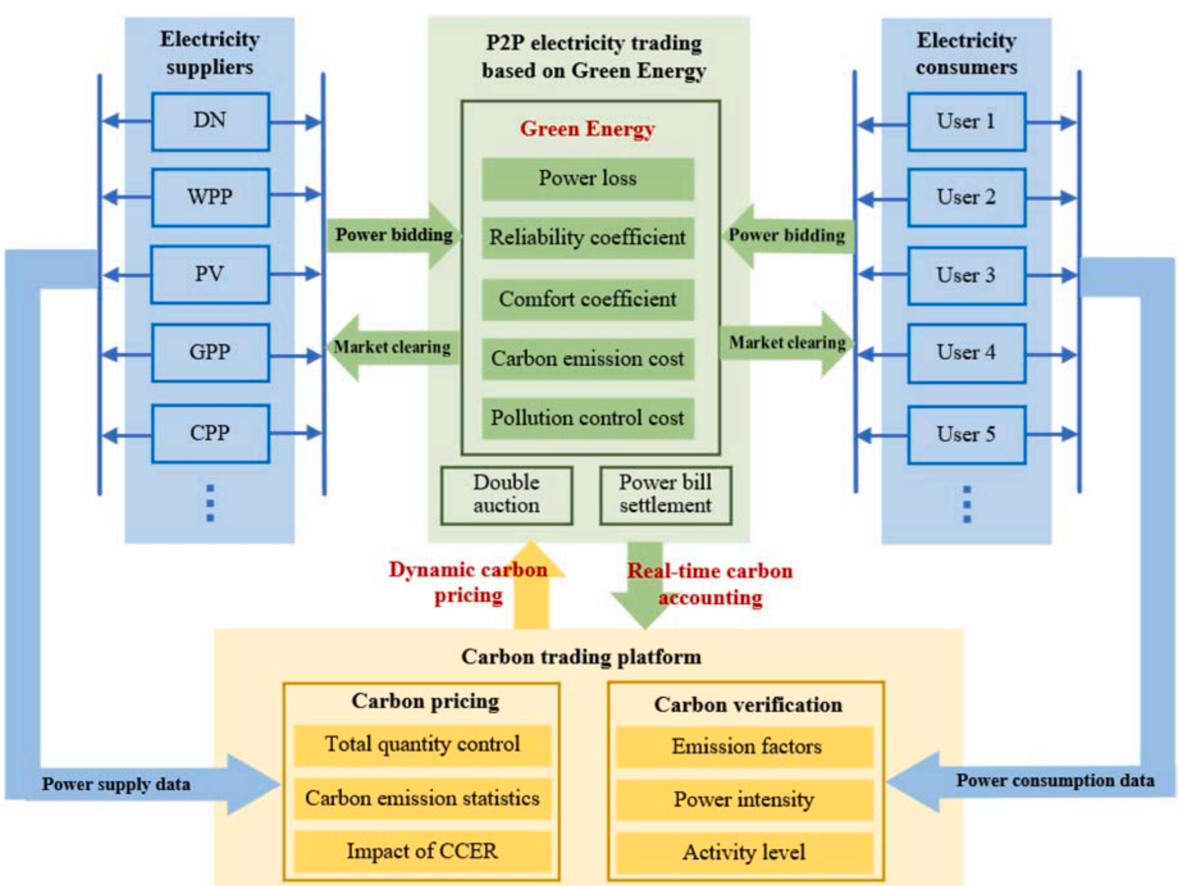

Fig. 2. Market framework for electricity and carbon co-trading.

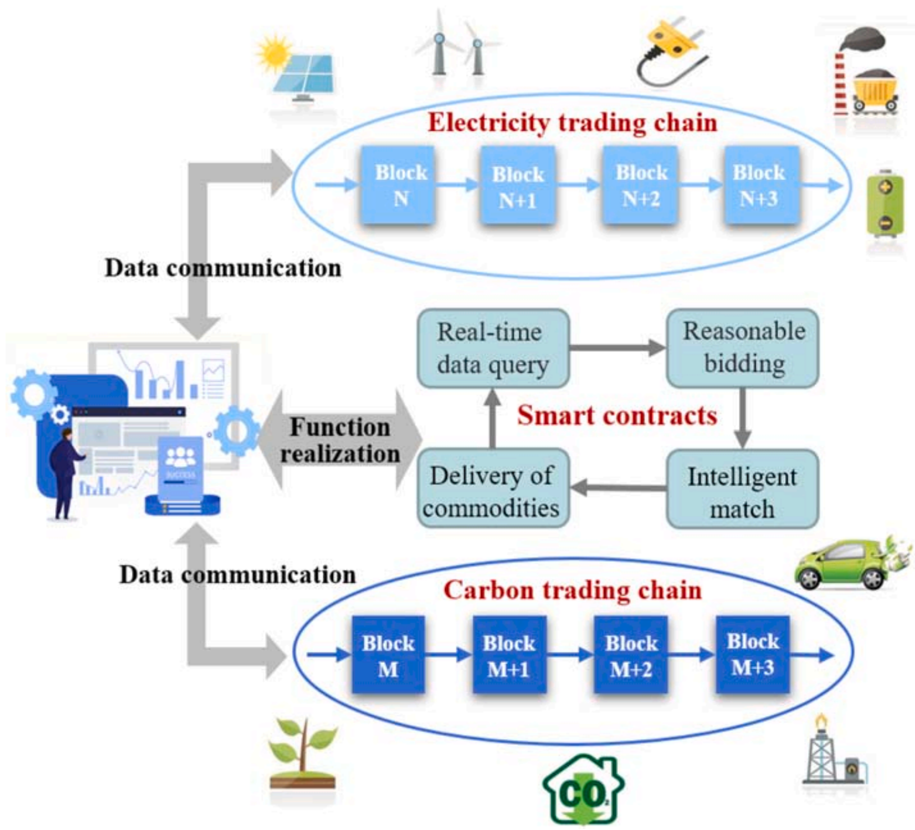

Fig. 3. Double-chain system operation mode.

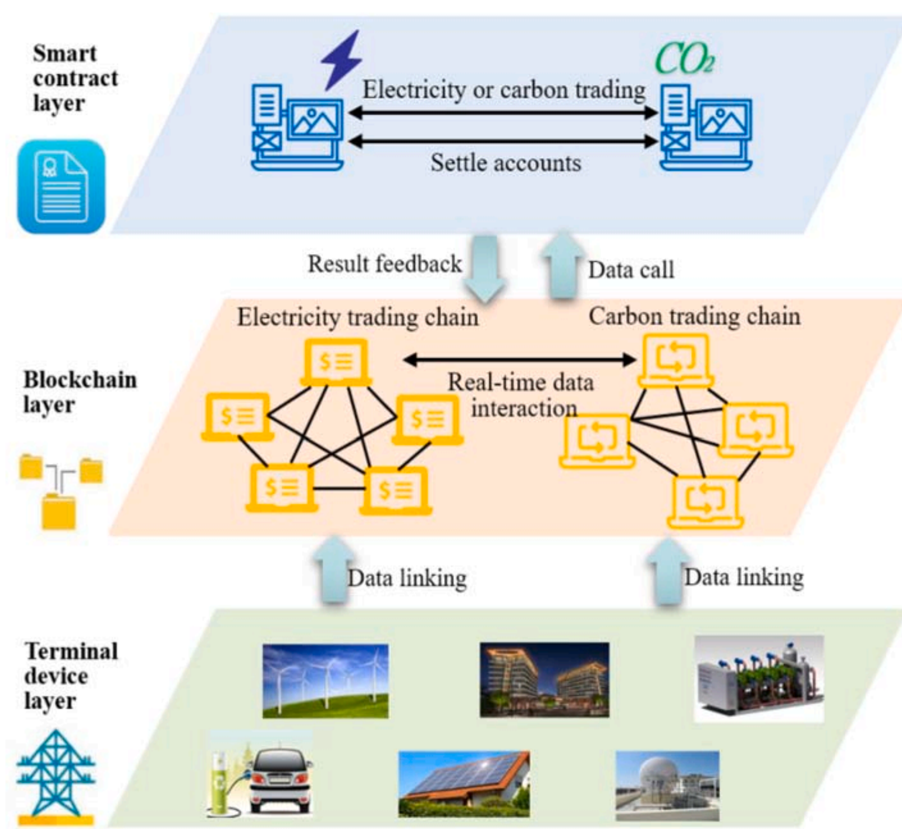

Fig. 4. Underlying architecture of dual-chain system.

and purchasing identities of users in the double-chain model are verified, the next step is to complete the trading of carbon quotas and electricity using the trading model. After the buyer and seller have paid the order deposit, they can place their respective demand orders reasonably, wait for the transaction chain to intelligently match the received purchase order with the sold order, and send a carbon quota or electricity order that is successfully matched to the buyer and seller. A smart contract is used to complete the transaction settlement of related commodities; the seller delivers commodities and the buyer confirms the delivery of commodities. After the smart contract is generated, it is saved in a transaction chain block. Each node in the network collects and retains its execution status and records the smart contract in real time.

According to the function settings of the double-chain system, it can be divided into three layers from the bottom up: the terminal device layer, blockchain layer, and smart contract layer, as shown in Fig. 4. The terminal device layer is primarily composed of massive terminal devices deployed in each domain to sense and collect the required data. The terminal device layer can be divided into different market domains according to its location and characteristics. The blockchain layer is mainly responsible for storing the perceived and collected data of the terminal device layer and realizing cross-domain access and communication interactions between the electricity and carbon trading chains. Smart contracts provide users with P2P electricity trading, dynamic carbon emission accounting, carbon pricing, real-time information queries, and other functions. In terms of the interactions between layers, the lower layer provides an interface to the upper layer that realizes real-time dissemination of information at these seven architecture levels. The terminal device layer transmits the power supply and demand data to the blockchain layer through smart meters. A distributed network unique to the blockchain layer delivers real-time data to various smart-contract applications. Meanwhile, the operational results of the smart contract are fed back to the blockchain layer through the Internet.

3. Dynamic pricing strategy

This section describes the dynamic pricing strategy for P2P trading based on GE. This pricing strategy includes carbon asset pricing and an electricity bidding strategy. The objective functions and constraints are presented in the following subsections.

3.1. Objective functions

In this study, the objective functions of electricity and carbon co-trading were set from two perspectives: economic and environmental benefits. The economic benefit adopts the objective function of social welfare (SW), which uses GE as a trading indicator. SW refers to the total amount of benefits created to society through each round of transactions, and can comprehensively evaluate the overall trading benefits of the supply and demand sides. This study adopted SW as an economic index to evaluate the pricing strategies. SW is the total revenue of the buyers and sellers in the electricity and carbon co-trading markets and is calculated as

$$SW=\sum_{t=0}^{T}\left(SW_t^{ele}+SW_t^{car}\right) \tag{11}$$

$$SW_t^{ele}=\sum_{i=1}^{I}\left(P_{i,t}^{sell}-RP_i^{sell}\right)\bullet GE_{i,t}+\sum_{j=1}^{J}\left(RP_j^{buy}-P_{j,t}^{buy}\right)\bullet GE_{j,t} \tag{12}$$

$$SW_t^{car}=\sum_{i=1}^{I}\left(P_t^{car}-RC_i^{sell}\right)\bullet E_{i,t}+\sum_{j=1}^{J}\left(RC_j^{buy}-P_t^{car}\right)\bullet E_{j,t} \tag{13}$$

In terms of environmental benefits, this study selected the renewable energy utilization rate, carbon emissions, and pollutant emissions as objective functions. As increased renewable energy consumption represents the low-carbon attribute of electricity systems, it is also the development direction of electricity markets. This study mainly evaluated the carbon and pollutant emissions of the electricity market. Pollutants from the electricity market primarily include SO_2 and NO_X.

3.2. Carbon pricing mode

Based on the IPCC carbon emission accounting methodology, the total carbon emissions and carbon emissions from electricity consumption in time slot t were calculated using real-time carbon emission factors, as shown in the following Eqs. (14) and (15):

$$E_{total}=E_{burn}+E_{heat}+E_{ele} \tag{14}$$

$$E_{ele,t}=f_t^{car}\bullet Q_t\bullet\left(1-R_{i,t}^{cap}\right)+f_t^{cor} \tag{15}$$

As individual electricity use behavior is significantly affected by many factors such as renewable energy procurement, carbon capture technology application, and electricity market fluctuations, this study focused on the real-time carbon emission factors of the electricity use behavior. The real-time carbon emission factor was calculated using Eqs. (16)–(18). The carbon emission coefficient and capture efficiency of seller i can be calculated using Eqs. (19) and (20), respectively.

$$f_t^{car}=\sum_{i=1}^{I}E_{i,t}^{ele}\Big/Q_{total,t} \tag{16}$$

$$Q_{total,t}=Q_t^{gen}+Q_t^{buy}-Q_t^{sell} \tag{17}$$

$$\sum_{i=1}^{I}E_{i,t}^{ele}=\sum_{i=1}^{I}F_{i,t}\bullet f_{i,t}^{ful}+\left(P_{all,t}^{buy}-P_{all,t}^{sell}\right)\bullet f_t^{reg} \tag{18}$$

$$f_{i,t}^{ful}=\frac{44}{12}hV_f^{low}\bullet R_f^{oxi}\bullet CV_f^{car} \tag{19}$$

$$R_{i,t}^{cap}=E_i^{cap}/E_i^{fuel} \tag{20}$$

Based on carbon accounting, the shadow price method was introduced to dynamically price the carbon. The shadow price refers to the price that reflects the consumption of social labor, scarcity of resources, and demand for final products when the social economy is in an optimal state [42]. The shadow price of carbon emission rights is the profit and loss caused to users by each unit of carbon dioxide emission reduction [43]. Therefore, users would determine the increase or decrease in production scale according to the relationship between the transaction price in the carbon emission rights market and the shadow price in the region.

It is assumed that the total carbon emissions of the region are controlled by M and that there are n carbon emission users in this region. The carbon emission of each user is $M_i(i=1,2,\cdots,n)$. Moreover, it is assumed that the profit rate of unit output value in the region is $A_i(i=1,2,\cdots,n)$ and the annual output value is $X_i(i=1,2,\cdots,n)$. There is a certain proportion between the annual output value and the carbon emission from fossil fuel combustion and purchased heat, and the average proportion coefficient is assumed to be γ. Therefore, the carbon emissions of user n from fossil fuel combustion and purchased heat are

$$E_{burn,heat}=\gamma\bullet X_i \tag{21}$$

A proportional relationship exists between the average output value and carbon emissions from electricity use. Assuming that the proportion coefficient is g, Eq. (22) can be established as follows:

$$X_i=g\bullet E_{ele} \tag{22}$$

The objective function of carbon pricing is to maximize the profit rate, and the boundary condition is to limit the total amount of carbon emissions, formulated as Eqs. (23) and (24):

$$\max\ V=\sum_{n=1}^{N}(A_i\bullet X_i)=\sum_{n=1}^{N}(A_i\bullet E_{burn,heat}/r) \tag{23}$$

$$E_{burn,heat}+E_{ele,t}\le M \tag{24}$$

The Lagrange equation is set as follows, where λ is the Lagrange multiplier (Eq. (25)):

$$L=\sum_{n=1}^{N}(A_i\bullet X_i)+\lambda\bullet(M-E_{burn,heat}-E_{ele}) \tag{25}$$

The first-order partial derivative of the Lagrange equation is given in Eqs. (26) and (27):

$$\partial L\Big/\partial X_i=\sum_{n=1}^{N}\left\{A_i-\lambda\bullet\left[\sum_{n=1}^{N}\gamma+\sum_{n=1}^{N}f_t^{car}\bullet(1-R_i^{cap})/g\right]\right\} \tag{26}$$

$$\lambda=\sum_{n=1}^{N}A_i\Big/\left[\sum_{n=1}^{N}\gamma+\sum_{n=1}^{N}f_t^{car}\bullet(1-R_i^{cap})/g\right] \tag{27}$$

The λ derived from the above formula is the marginal contribution of carbon emissions in the region, that is, the shadow price. This value means that the optimal price of carbon emission rights can be achieved through the optimal allocation and use of resources under the premise that carbon emissions in the region are within a certain range. Because the carbon market requires government regulation, the final carbon price is calculated as

$$P_t^{car}=\lambda+f_{con,t}^{car} \tag{28}$$

3.3. Electricity bidding strategy

The designed electricity bidding strategy has a dynamic learning ability, which dynamically adjusts the bidding trading according to the real-time information of the coupled electricity and carbon markets. It is conducted in a decentralized mode and is completed under constraint conditions. Participants who fail to make a deal within the time slot can adjust their bidding to meet the electricity trading demand. It submits updated transaction data to the electricity market in the next time slot.

The P2P electricity market provides bidding decision-making rights to each participant. These participants must consider real-time market information for bidding in each round of matching trading. This study characterizes the information to be considered as a bidding factor and obtains the bidding price for each buyer or seller by calculating multiple bidding factors. The trading process for the electricity market is illustrated in Fig. 5.

In each round of matching trading in the electricity market, sellers not only submit the available GE to the electricity market but also submit their own bidding price. These sellers comprehensively consider three factors: GE demand, GE supply, and the relationship between supply and demand. These factors can be characterized as bidding coefficients and are calculated as follows:

$$\varepsilon_{i,t,1}^{sell}=\left[sum\left(GE_t^{buy}\right)-max\left(GE_t^{buy}\right)\right]\Big/max\left(GE_t^{buy}\right) \tag{29}$$

$$\varepsilon_{i,t,2}^{sell}=GE_{i,t}^{sell}\Big/\left[sum\left(GE_t^{sell}\right)-GE_{i,t}^{sell}\right] \tag{30}$$

$$\varepsilon_{i,t,3}^{sell}=sum\left(GE_t^{buy}\right)\Big/sum\left(GE_t^{sell}\right) \tag{31}$$

The three bidding coefficients are integrated to obtain the seller's comprehensive bidding coefficient. We then calculate the final bidding price of the electricity sellers:

$$\varepsilon_{i,t}^{sell}=\varepsilon_{i,t,1}^{sell}\bullet\varepsilon_{i,t,2}^{sell}\bullet\varepsilon_{i,t,3}^{sell} \tag{32}$$

$$P_{i,t+1}^{sell}=max\left(P_i^{sell}\right)-\left[max\left(P_i^{sell}\right)-min\left(P_i^{sell}\right)\right]\Big/e^{\varepsilon_{i,t}^{sell}} \tag{33}$$

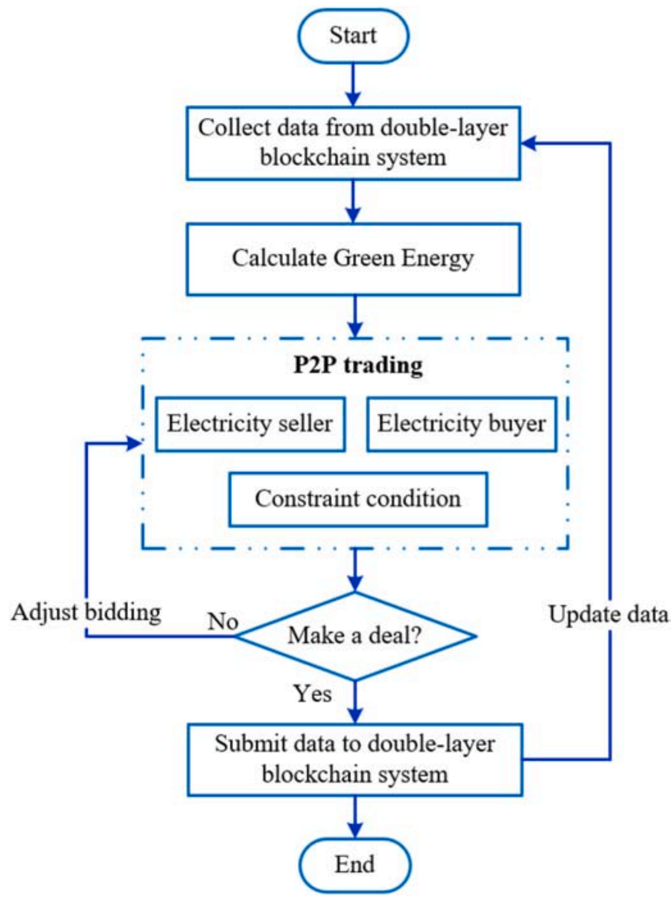

Fig. 5. Trading process of the electricity market.

The electricity buyer can freely choose the electricity seller to provide GE with real-time information on the electricity market. For a buyer who automatically executes matching trading, the final bidding price can also be determined according to historical bidding and Eqs. (34) and (35). Note that the agreed GE price is the average price between the buyer and seller in a P2P trading agreement. In addition, the final cost settlement still uses the quantity of electricity as a matchmaking indicator.

$$\varepsilon_{j,t}^{buy}=\left[1-\left(GE_t^{buy}\right)^2\right]\Big/\left[max\left(GE_t^{buy}\right)\right]^2 \tag{34}$$

$$P_{j,t+1}^{buy}=min\left[min\left(SP_t^{buy}\right)\bullet\varepsilon_{j,t}^{buy}+max\left(SP_t^{buy}\right)\bullet\left(1-\varepsilon_{j,t}^{buy}\right)\right] \tag{35}$$

3.4. Constraint condition

During the operation of the electricity market, it is necessary to consider the boundary conditions of the physical characteristics and P2P trading. Electric energy and GE must satisfy the limit of the supply and demand balance, and the following formula is established:

$$W_{re}+W_f+W_{DN}=\sum_{j=1}^{J}W_{j,user} \tag{36}$$

$$GE_{re}+GE_f+GE_{DN}=\sum_{j=1}^{J}GE_{j,user} \tag{37}$$

Operational security constraints mainly consider the upper and lower limits of electricity and the climbing efficiency of various types of equipment. The equipment includes fossil energy power generation units, such as coal- and gas-fired power plants. The boundary conditions are calculated as follows:

$$W_{i,min}^{ele} \le W_{i,t}^{ele} \le W_{i,max}^{ele} \tag{38}$$

$$W_{i,t+1}^{ele} - W_{i,t}^{ele} \le Climb_i^{ele} \tag{39}$$

$$E_{i,t}^{ele} = W_{i,t}^{ele} \bullet t \tag{40}$$

Based on the above constraints on the electricity market, operational safety, coupled electricity–carbon market, and the objective function described in Section 3.1, the maximization problem to be solved in this study is shown in Eq. (41). To maximize the overall SW, the welfare values of the involved electricity and carbon markets are given by Eqs. (12) and (13), respectively.

$$max\{SW\} = max\left\{\sum_{t=0}^{T}\left(SW_t^{ele} + SW_t^{car}\right)\right\} \tag{41}$$

For the objective function of SW, it is necessary to restrict trading prices to ensure orderly trading of both electricity and carbon commodities. In terms of electricity and carbon co-trading, this study considered the limitations of electricity bidding and carbon prices. These constraint conditions can be calculated using Eqs. (42)–(44). Eqs. (43) and (44) indicate that the bidding price of the electricity trading seller or user cannot exceed its reserve price to ensure basic trading profit.

$$P_{min}^{car} \le P_t^{car} \le P_{max}^{car} \tag{42}$$

$$RP_i^{sell} \le P_{i,t}^{sell} \tag{43}$$

$$P_{j,t}^{buy} \le RP_j^{buy} \tag{44}$$

4. Case study

This study considered a typical coupled electricity and carbon market scenario to simulate the SW, renewable energy consumption, and carbon and pollutant emissions of the different bidding strategies. Subsequently, the advantages of the proposed method were analyzed and verified.

4.1. Scenario description

The scenario of the coupled electricity and carbon market was constructed based on a typical Chinese integrated P2P electricity market and a dynamic pricing carbon market. The electricity market contains six electric power suppliers and five users. The suppliers included distributed WPP projects of 5 and 3 MW (WPP1 and WPP2), distributed PV projects of 3 and 2 MW (PV1 and PV2), a GPP of 2 MW, and a CPP of 6 MW. The power outputs of the WPPs and PVs for one day are shown in Fig. 6. The GPP and CPP participate in the electricity market at 75% of the rated power, thus providing 1.5 MW and 4.2 MW tradable power, respectively. On the electricity demand side, two industrial users (users 1 and 2), two residential communities (users 3 and 4), and one commercial user (user 5) were selected [31]. The power inputs are shown in Fig. 7.

The carbon market conducts real-time carbon accounting for electricity market participants. The fossil energy suppliers, GPP and CPP, must purchase carbon assets from renewable energy suppliers. We refer to the operation of the carbon emission trading market in Beijing, China, to set the carbon price and fluctuation range. The initial carbon price was calculated according to the benchmark carbon price of China's current CCER, 8.50 USD·t^{-1}. Under the macro control of government departments, the carbon price fluctuates between 7.00 and 15.00 USD·t^{-1}. The system is linked to a distribution network to provide a reliable electric power supply for users.

To enhance the application performance of the proposed double-chain system further, an electricity and carbon coupling trading mode was developed and deployed on a blockchain network platform. Go was selected as the main programming language, and simulation experiments were conducted using the Hyperledger Fabric platform. Hyperledger Fabric is an open-source enterprise-permissioned distributed ledger technology platform built by the Linux Foundation. It has a highly configurable architecture that can provide diverse services to various types of businesses. The operating interface is illustrated in Fig. 8. This model tests a blockchain network running on a single host. The electricity-trading chain includes six power suppliers and five power users who simultaneously participate in the carbon-trading chain. The power and carbon emission data in the double-chain system are distributed and stored in each participating node so that all nodes can obtain real-time information.

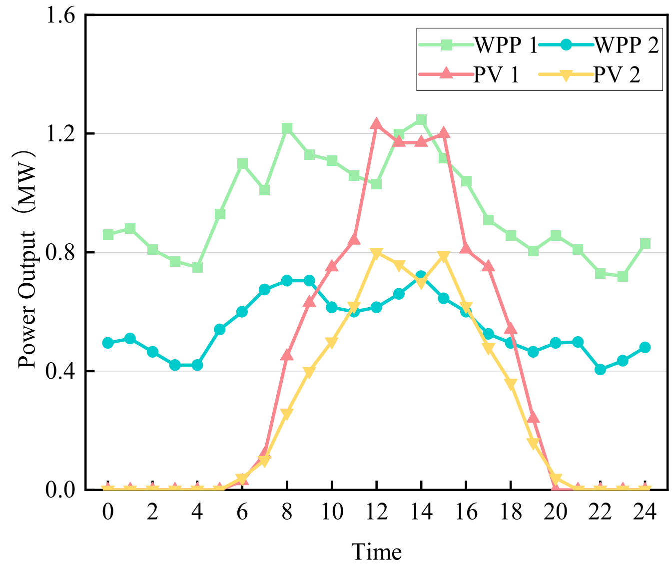

Fig. 6. Power output of wind power plants (WPPs) and photovoltaics (PVs).

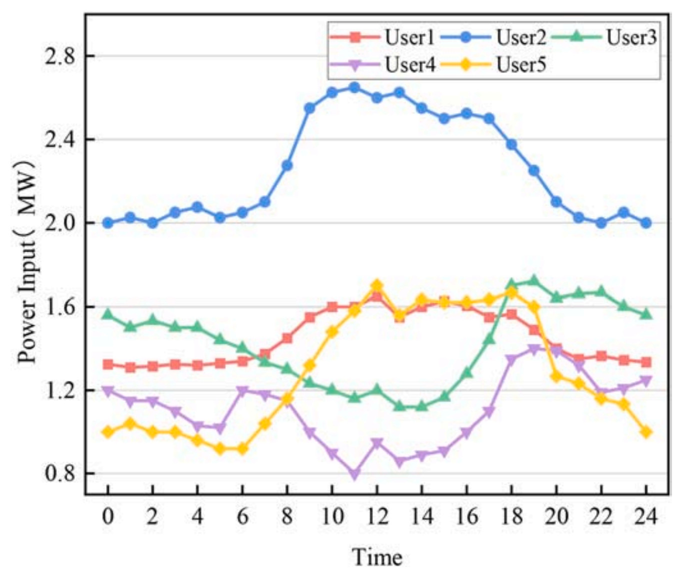

Fig. 7. Power input of electricity users.

4.2. Calculation of green energy for electricity suppliers

The GE of each electricity supplier can be calculated before the electricity and carbon co-trading. The basic parameters of the different

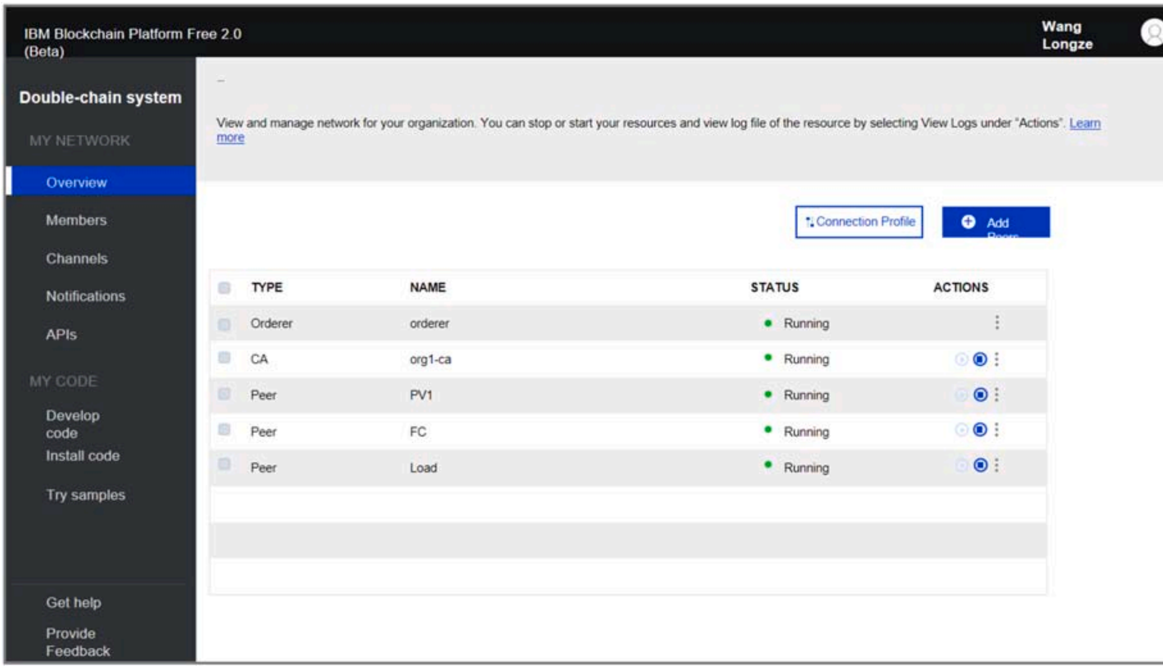

Fig. 8. Double-chain system operation testing interface.

energy-supply modes are listed in Table 1. The structure of a renewable energy system is simpler than that of fossil energy; however, it is volatile owing to weather. Therefore, compared with the GPP and CPP, the k_r of the WPP and PV is larger, and k_c is smaller. Distributed renewable energy is closer to the demand side, making their η^{tra} smaller. No carbon or pollutant emissions were observed during the operation of the WPP and PV systems. Other energy supply facilities primarily consider carbon, SO_2, and NO_X pollutants.

The governance cost of carbon emissions is equal to real-time carbon prices in the carbon market. The environmental governance costs of SO_2 and NO_X were 170 USD·t^{-1} and 320 USD·t^{-1}, respectively, according to typical cities in China. The renewable energy prices P_t^{WPP}, P_t^{PV}, and P_t^{HP} are respectively set at 133.5, 125.9, and 95.6 USD·MWh^{-1}. That is, the P_t^{re} was 118.3 USD·MWh^{-1}. Based on these parameters, the GE of renewable energy suppliers can be calculated as shown in Fig. 9. The GE of fossil fuel energy suppliers is shown in Fig. 10. The tradable electricity of the GPP and CPP is constant, but different carbon prices can affect GE.

4.3. Results and discussion

To verify the rationality of the electricity–carbon co-trading framework proposed in this study, a comparative analysis of the following four bidding strategies was conducted. The initial bidding and reserve prices of the participants in the electricity and carbon co-trading markets are listed in Table 2. The initial carbon price is 8.50 USD·t^{-1}, and the bidding prices and reserve prices can be calculated using GE as the matchmaking indicator for the electricity matchmaking trading. The simulations were performed using the MATLAB platform, with a focus on day-ahead bidding scenarios in 1 h increments. The scenarios set four bidding strategies, namely, Case 1 to Case 4.

Table 1
Basic parameters of different energy supply modes.

Parameter	WPP	PV	GPP	CCP
k_r	0.97	0.98	0.95	0.97
k_c	0.94	0.96	0.98	0.98
η^{tra}	0.02	0.01	0.05	0.08
$E_{i,t}^{car}$ (t·MWh^{-1})	0	0	0.97	1.13
e_{SO_2} (t·MWh^{-1})	0	0	8.98×10^{-3}	9.61×10^{-3}
e_{NO_X} (t·MWh^{-1})	0	0	2.62×10^{-3}	2.83×10^{-3}

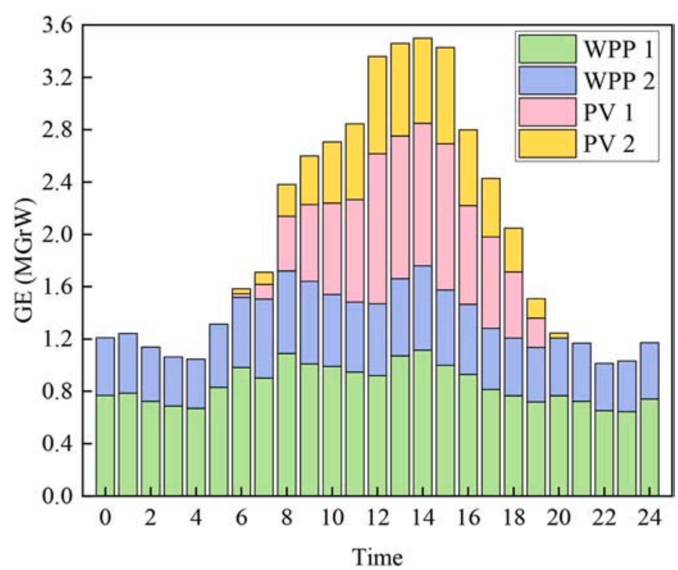

Fig. 9. GE of renewable energy suppliers.

Case 1. The matchmaking indicator is electric power, and the electricity and carbon prices are fixed.

Case 2. The matchmaking indicator is electric power, and the electricity and carbon prices are dynamically adjusted.

Case 3. The matchmaking indicator is GE, and the electricity and carbon prices are fixed.

Case 4. The matchmaking indicator is GE, and the electricity and carbon prices are dynamically adjusted.

(1) Economic benefit

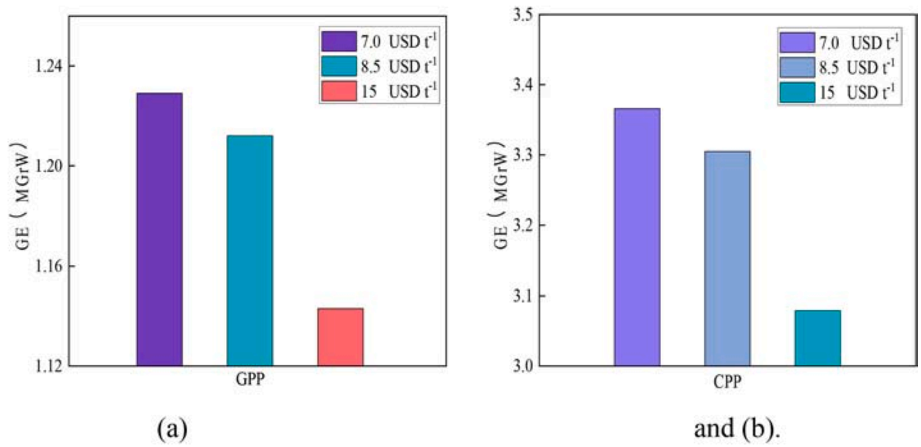

Fig. 10. (a) GE of gas-fired power plant (GPP) with different carbon prices; (b) GE of coal-fired power plant (CPP) with different carbon prices.

Table 2
Initial bidding prices and reserve prices of electricity and GE.

Participant	Electricity (USD·MWh^{-1})		GE (USD·MGrWh^{-1})	
	Initial price	Reserve price	Initial price	Reserve price
WPP 1	67.45	47.22	75.71	52.47
WPP 2	66.5	46.45	73.89	51.61
PV 1	70.63	49.5	78.48	53.51
PV 2	70.35	48.3	76.05	52.22
GPP	60.45	42.71	76.81	52.86
CPP	51.66	36.16	66.75	48.02
User 1	51.85	66.7	62.22	76.71
User 2	52	67.6	62.40	77.74
User 3	50	65	60.00	74.75
User 4	51	66.5	61.20	76.48
User 5	51.5	65	61.80	74.75

A comparison of the SW for the different cases in one day is shown in Fig. 11. It can be observed that the SW in Case 1 is the lowest. Because fixed electricity bidding and carbon prices cannot adjust the pricing strategy according to real-time information, the success rate of the matching transactions is reduced. In Case 3, GE is used as the matchmaking indicator of electricity P2P trading, that is, bidding is adjusted according to carbon market dynamics. However, the carbon price is a constant value that limits the adaptive learning ability of electricity trading. As a result, SW in Case 3 was only 5% higher than that in Case 1. Case 2 adopted flexible electricity bidding and carbon pricing, which increased SW by 14% compared with Case 1. Moreover, Case 4 uses GE to further integrate the electricity and carbon markets, making SW 18% higher than that in Case 1.

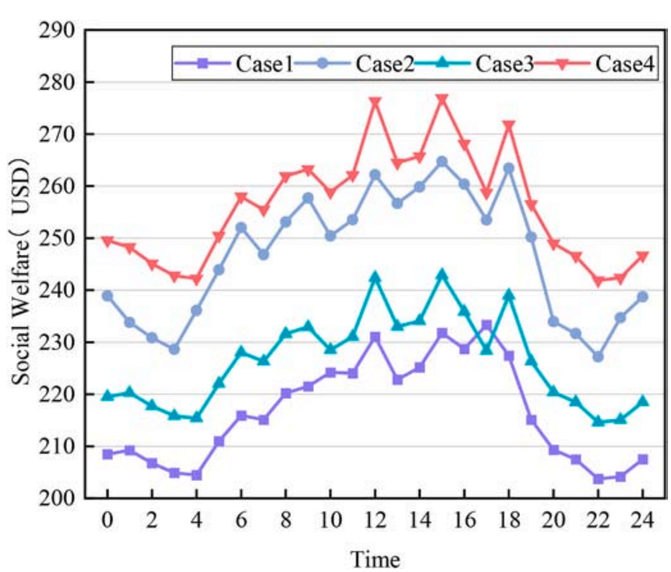

Fig. 11. Social welfare with different cases.

To further demonstrate the economic benefit of GE as a matchmaking trading indicator, this study uses electric power (EP) as a pairwise trading indicator representing traditional electricity trading to form a control group, which is simulated and compared with the experimental group in which GE is a pairwise indicator, and the results of the comparison of the electricity supply and the trading revenues of each producer-consumer under the two indicators mentioned above are given in Fig. 12. The trading benefits include both electricity and carbon benefits. Table 3 lists the total amount of power supply, electricity trading, and carbon trading benefits within a day under different trading modes, as well as the proportion of the differences. The simulation results demonstrated that using GE as a matching indicator for electricity trading improved the generation and trading returns of WPPs and PVs. Correspondingly, the proposed trading mode reduced the bidding advantages of the GPP and CPP, thereby reducing their power supply quantity and electricity-trading benefits. In terms of carbon trading benefits, a high proportion of renewable energy utilization can reduce carbon emissions factors and affect GE, thereby increasing the carbon trading benefits of fossil fuels.

(2) Environmental benefit

In this study, the renewable energy consumption, carbon emissions, and pollutant emissions in the different cases were compared to discuss the environmental benefits of the proposed method. Fig. 13 shows the consumption of renewable energy for different cases in a single day. The fixed-price mechanism limits the flexibility of the bidding strategy and restricts the transaction rates of WPPs and PVs with high power-generation costs. Although electricity bidding in Case 2 can be dynamically adjusted according to market information, fossil energy suppliers' synchronous adjustment of bidding still makes their price advantages obvious. Using GE as a matchmaking indicator reduces the tradable GE volume of fossil energy suppliers, resulting in an increase in prices during the bidding processes. This makes the bidding prices of renewable energy suppliers more competitive, and increases their consumption. Therefore, the consumption of renewable energy in Cases 3 and 4 was 17.45% and 26.78% higher, respectively, than that in Case 1.

Fig. 14 shows the emissions of CO_2 in one day for the four cases. The emissions of all three pollutants decreased. Because the consumption of renewable energy is improved by using GE, the energy supply quantities of the GPP and CPP were reduced correspondingly. The carbon emissions in Cases 3 and 4 were 12.11% and 17.48% lower, respectively,

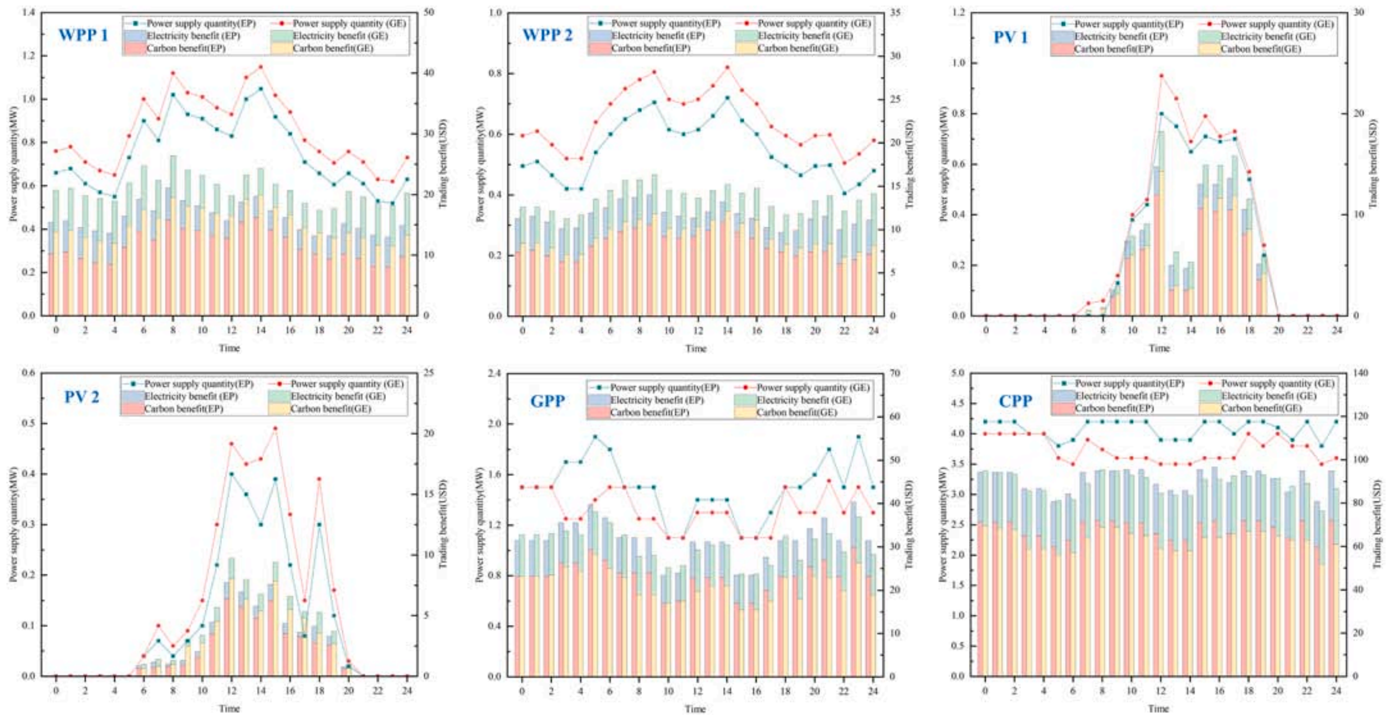

Fig. 12. Power supply quantity and trading benefit of prosumers.

Table 3
Economic benefit using electric power (EP) or GE as trading indicators.

Participant	Power supply quantity			Electricity trading benefit			Carbon trading benefit		
	EP	GE	Increase ratio	EP	GE	Increase ratio	EP	GE	Increase ratio
WPP 1	67.45	47.22	13.30%	291.21	380.61	30.70%	109.38	143.67	31.35%
WPP 2	66.5	46.45	18.20%	206.07	232.45	12.80%	81.1	107.8	32.92%
PV 1	70.63	49.5	11.28%	74.55	84.51	13.36%	23.64	29.91	26.52%
PV 2	70.35	48.3	31.87%	44.21	57.21	29.41%	10.88	14.2	30.51%
GPP	60.45	42.71	−5.65%	564.09	531.09	−5.85%	206.92	228.41	10.39%
CPP	51.66	36.16	−4.48%	1756.61	1677	−4.53%	568.08	646.59	13.82%

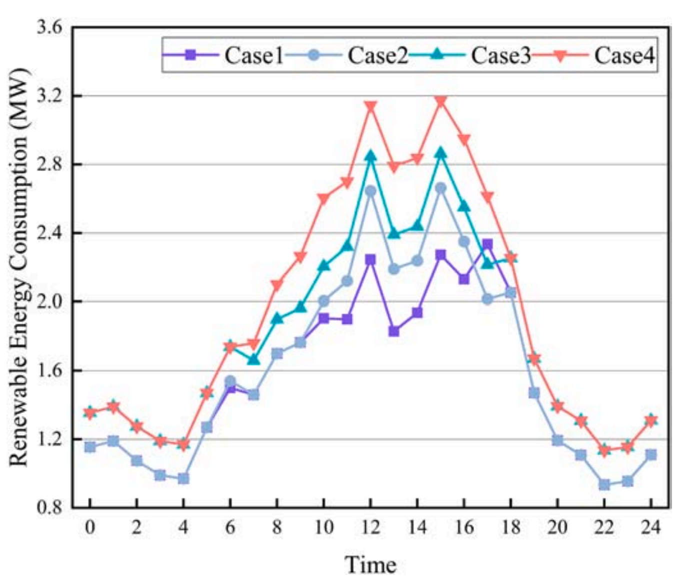

Fig. 13. Renewable energy consumption in different cases.

than those in Case 1. The percentages of pollutant reduction under different scenarios are shown in Fig. 10. We found that the magnitude of the emission reduction gradually increased with the adjustment of the bidding strategy. The simulation results show that dynamic bidding with GE can reduce SO_2 emissions by 15.04% and NO_X emissions by 18.91%, respectively. To demonstrate the environmental benefits of the proposed method, Table 4 presents the carbon and pollutant emission data for different cases within a single day.

(3) Blockchain implementation

Electricity and carbon co-trading modes have both economic and environmental benefits. Traditional centralized control is not conducive to mutual trust between participants, and the participation of third-party intermediaries increases the system operating costs. To effectively transmit real-time information such as GE in the two markets, this study introduces the blockchain cross-chain interoperability technology to build a double-chain system, the operation interface of which is shown in Fig. 15. Fig. 15(a) illustrates electricity bidding by various prosumers in the electricity trading chain. GE's price and sales are displayed in real time to users, making the transaction behavior transparent and trustworthy. The dynamic pricing method for the carbon trading chain is illustrated in Fig. 15(b). The real-time calculation of carbon emissions and the dynamic carbon pricing mode are embedded in the double-chain system, and users who need carbon indicators can

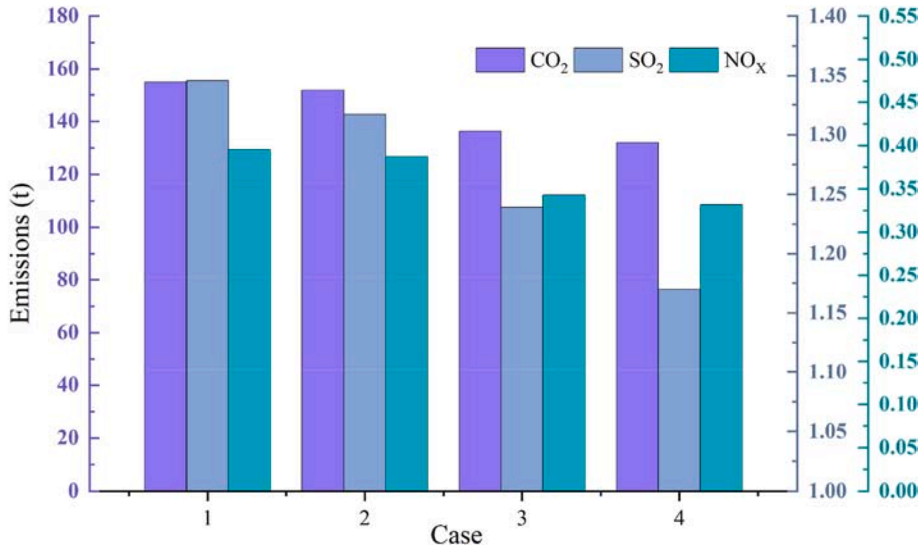

Fig. 14. CO_2, SO_2, and NO_X emissions in different cases.

Table 4
Daily emissions of carbon and pollutants in different cases.

Daily emissions	CO_2 (t)	SO_2 (t)	NO_X (t)
Case 1	155.03	1.35	0.40
Case 2	151.92	1.32	0.39
Case 3	136.27	1.24	0.34
Case 4	131.94	1.17	0.33

purchase carbon emission rights independently.

Notably, the proposed method is influenced by some external factors, such as government regulations, market volatility, technological advancements, and environmental awareness. First, the energy management department must allow market-oriented trading of electricity and carbon. Although this is feasible in China and most other countries, some regions restrict the market-oriented trading of energy and carbon emissions rights. Second, the level of competition in the market determines the price of electricity or carbon as well as their supply and demand relationship in the market. Thus, the proposed GE indicator is significantly influenced by external factors. For example, reducing the power supply volatility for renewable energy would increase GE, and fossil energy suppliers would also increase their GE value if they reduce their emissions of carbon and pollutants. In addition, with the increasing awareness of environmental protection in society, energy demanders are willing to purchase renewable energy, even if its price is slightly higher. Although these factors have an impact on the application of our study, the proposed trading mode can effectively improve the economic and environmental benefits for electricity and carbon markets. Blockchain technology applications also provide the infrastructure for the application of the proposed trading mode.

5. Conclusions

To achieve real-time coupling between the electricity and carbon markets, this study proposes a trading mode based on the GE indicator. Our simulation results show that GE can link the electricity and carbon markets in real time to improve economic and environmental benefits. Dynamic electricity bidding and carbon pricing based on GE improved the SW and renewable energy utilization efficiencies by 18% and 26.78%, respectively. The bidding strategy reduced carbon emissions by approximately 17.48% and emissions of other pollutants by more than 15%. Compared to EP, using GE as a matchmaking trading indicator significantly improves the economic benefits of renewable energy prosumers by 4.97%. Meanwhile, fossil energy suppliers' electricity trading benefits decreased, whereas proactive emission reductions increased their carbon trading benefits.

Following our key findings, the GE indicator consisted of two interaction dimensions. As a "quantity" metric, GE gives an environmental label to the traditional matchmaking indicator, and promotes the understanding of the low-carbon attributes of different electricity supply modes. As a "price" measurement, GE transmits carbon emission costs to the electricity market to guide the priority consumption of renewable energy. The designed double-chain system has a high degree of compatibility with electricity–carbon co-trading and can establish an executable infrastructure for the calculation and transmission of GE.

However, this study has some limitations. GE involves a clean, low-carbon, stable, and effective energy supply, among other attributes, and requires the approval of all consumers for its calculation methods and processes, which undoubtedly pose challenges to GE's promotion. Data such as that of GE are transmitted between the electricity and carbon trading chains, and the operational efficiency of the blockchain system directly affects the scalability of this study. Therefore, GE is still a long way from being proposed for application, and is still immature. In future research, further improvement of GE's computing process is required to enhance its recognition. The theoretical system around GE as the core should be further improved, and GE should be promoted and applied in additional scenarios.

Credit author statement

Longze Wang: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing, Data curation, Project administration. Yan Zhang: Writing – original draft, Writing – review & editing, Formal analysis, Funding acquisition, Investigation. Zhehan Li: Writing – review & editing, Investigation. Qiyu Huang: Writing – review & editing, Formal analysis, Investigation. Yuxin Xiao: Writing – review & editing. Xinxing Yi: Writing – review & editing. Meicheng Li: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Compliance with ethics guidelines

Longze Wang, Yan Zhang, Zhehan Li, Qiyu Huang, Yuxin Xiao, Xinxing Yi, Yiyi Ma and Meicheng Li declare that they have no conflict of interest or financial conflicts to disclose.

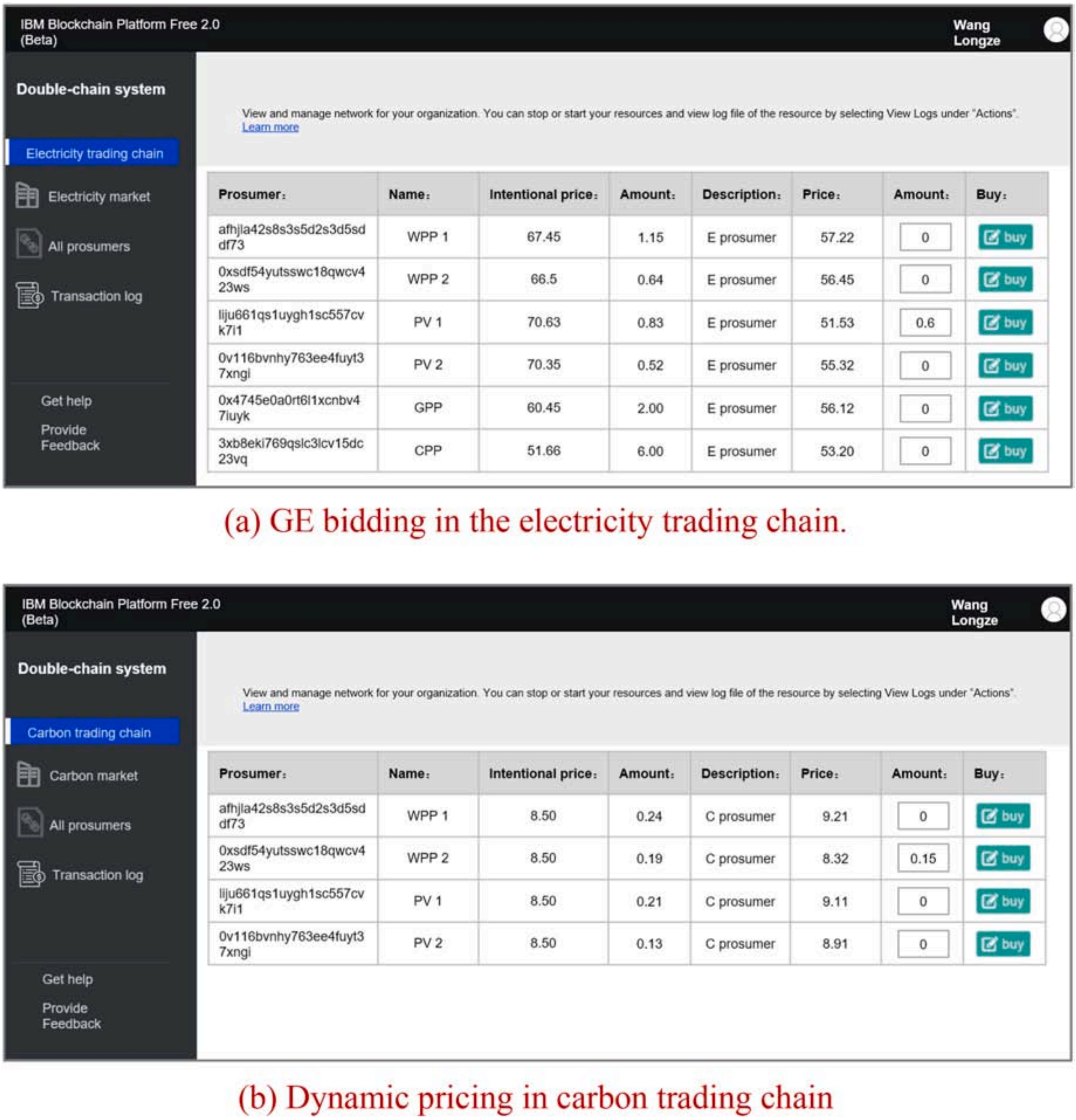

Fig. 15. Double-chain system operation interface for electricity and carbon co-trading.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Nomenclature

Acronyms

IPCC	intergovernmental panel on climate change
DSM	demand side management
DRE	distributed renewable energy

P2P	peer-to-peer
GE	Green Energy
J	Joule
KWh	Kilowatt hour
Cal	calorie
WPP	wind power plant
PV	photovoltaic
HP	hydroelectric power generation
GPP	gas-fired power plant
CPP	coal-fired power plant
DN	distribution network
CCER	Chinese certified emission reduction
SW	social welfare

Variables and Parameters

T	total duration of the statistical cycle
Y	number of presidential counts
M	total carbon emission of the region
M_i	carbon emission of each user
A_i	profit rate of unit output value
X_i	annual output value
γ	average proportion coefficient
g	proportion coefficient
V	profit rate of all users in the regional carbon market
λ	Lagrange multiplier
$k_{r,i,t}$	reliability coefficient of electricity seller i in time slot t
$k_{c,i,t}$	comfort coefficient of electricity seller i in time slot t
$Q_{i,t}^{basic}$	basic electricity produced by electricity seller i in time slot t
$Q_{i,t}^{tra}$	transmission loss of seller i in time slot t
$Q_{i,t}^{car}$	carbon conversion cost of seller i in time slot t
$Q_{i,t}^{pol}$	pollution conversion cost of seller i in time slot t
η_i^{tra}	electricity transmission efficiency of seller i
W_i^{pro}	production power of seller i
W_i^{con}	consumption power of seller i
$C_{i,t}^{car}$	carbon emission conversion factor of seller i in time slot t
$E_{i,t}^{car}$	carbon dioxide emission of 1 kWh energy supplied by energy supply facility i in time slot t
P_t^{car}	price of carbon emission in time slot t
P_t^{re}	price of renewable energy in time slot t
P_t^{WPP}	electricity price of WPP in time slot t
P_t^{PV}	electricity price of PV in time slot t
P_t^{HP}	electricity price of HP in time slot t
$C_{i,t}^{pol}$	pollution conversion factor of seller i in time slot t
$e_{i,t,m}$	pollutant quantity per unit energy supply m emitted by seller i in time slot t
f_m	environmental treatment cost of unit quantity m emitted
$\omega_{y,i,t}$	time between failures of the energy supply facility i for the y statistics in time slot t
$W_{i,t}$	power load at time t during climbing of energy supply facility i
$W_{i,t-1}$	power load at time t-1 during climbing of energy supply facility i
SW_t^{ele}	social welfare of electricity market in time slot t
SW_t^{car}	social welfare of carbon market in time slot t
$P_{i,t}^{sell}$	trading prices of electricity seller i in time slot t
$P_{j,t}^{buy}$	trading prices of electricity buyer j in time slot t
RP_i^{sell}, RP_j^{buy}	reserve prices in the electricity P2P trading of electricity seller i and buyer j
RC_i^{sell}, RC_j^{buy}	reserve prices in the carbon trading of electricity seller i and buyer j
E_{total}	total carbon emission
E_{burn}	carbon emission from fossil fuel combustion
E_{heat}	carbon emission of purchased heat
E_{ele}	carbon emission from electricity use
f_t^{car}	real-time carbon emission factor in time slot t
f_t^{cor}	correction factor in time slot t
Q_t	quantity of electricity i in time slot t
$R_{i,t}^{cap}$	carbon capture efficiency of seller i in time slot t

$Q_{total,t}$ total electricity consumption in the electricity market in time slot t
Q_t^{gen} quantity of generated electricity in time slot t
Q_t^{buy} quantity of buy electricity in time slot t
Q_t^{sell} quantity of sell electricity in time slot t
$F_{i,t}$ fuel consumption of seller i in time slot t
$f_{i,t}^{ful}$ carbon emission coefficient of seller i in time slot t
f_t^{reg} regional carbon emission factor in time slot t
$(P_{all,t}^{buy} - P_{all,t}^{sell})$ regional net purchased electricity in time slot t
hV_f^{low} average low calorific value of energy f
R_f^{oxi} carbon oxidation rate of energy f
CV_f^{car} carbon content per unit calorific value of energy f
E_i^{cap} amount of carbon captured of seller i
E_i^{fuel} amount of carbon using fossil fuels of electricity seller i
$E_{burn,heat}$ carbon emission of user n from fossil fuel combustion and purchased heat
$f_{con,t}^{car}$ real-time control coefficient of government on the carbon price in time slot t
$\varepsilon_{i,t,1}^{sell}$ bidding coefficient of GE demand of seller i in time slot t
$\varepsilon_{i,t,2}^{sell}$ bidding coefficient of GE supply of seller i in time slot t
$\varepsilon_{i,t,3}^{sell}$ bidding coefficient of supply and demand relationship of seller i in time slot t
$sum(GE_t^{buy})$ sum of GE purchases in time slot t
$sum(GE_t^{sell})$ sum of GE sales in time slot t
$max(GE_t^{buy})$ maximum GE purchases in time slot t
$GE_{i,t}^{sell}$ GE supply quantity of seller i in time slot t
$max(P_i^{sell})$ maximum historical price of seller i
$min(P_i^{sell})$ minimum historical price of seller i
$\varepsilon_{i,t}^{sell}$ comprehensive bidding coefficient of seller i in time slot t
$P_{i,t+1}^{sell}$ bidding price of the seller i in time slot t+1
SP_t^{buy} bidding price set of all buyers in time slot t
$\varepsilon_{j,t}^{buy}$ bidding coefficient of buyer j in time slot t
$P_{j,t+1}^{buy}$ bidding price of buyer j in time slot t+1
W_{re} electric power of renewable energy
W_f electric power of fossil energy
W_{DN} electric power of distribution network
$W_{j,user}$ electric power of buyer j at the user side
GE_{re} GE of renewable energy
GE_f GE of fossil energy
GE_{DN} GE of distribution network
$GE_{j,user}$ GE of buyer j at the user side
$W_{i,max}^{ele}$ maximum power load of electricity seller i
$W_{i,min}^{ele}$ minimum power load of electricity seller i
$Climb_i^{ele}$ climbing efficiency of equipment operation of electricity seller i
P_{max}^{car} maximum carbon price under government control environment
P_{min}^{car} minimum carbon price under government control environment

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