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Analysis of carbon electricity coupled market modeling method based on carbon credit trading mechanism

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ABSTRACT

Due to the increasing problems of global warming and the gradual depletion of non-renewable energy sources, how to achieve low-carbon energy transition has become the focus of the entire energy industry. The article combines the policies related to carbon emission quotas and certified emission reductions in China, and designs a carbon credit trading mechanism that takes into account the synergy between electricity trading and carbon trading, based on which a carbon and electricity coupling market model is established with a carbon credit trading center as the core. Firstly, the carbon credit trading rules are prospectively formulated for the new power system, which connects power suppliers and power load users to form a diversified organic whole; secondly, the carbon credit management center is built with blockchain technology, which aims to shape the power spot market, power futures market and carbon trading market into a composite coupling, forming a new carbon and power coupled market with the carbon credit management center as the core, and the business interconnection and synergistic clearing of each market. Finally, a new carbon market model with carbon credit mechanism is established, and the components of nodal electricity prices are explored to quantify the impact of introducing carbon credit constraints on nodal marginal electricity prices. The results of the algorithm analyze the economic efficiency and social welfare of the electricity suppliers and load users, illustrate the necessity of introducing the carbon credit trading mechanism, and analyze the impact of the high proportion of renewable energy access on the carbon electricity coupling market.

1. Introduction

The convening of the 75th United Nations General Assembly in September 2020 has brought the issue of carbon emission reduction back to the center of attention of countries around the world. A series of environmental problems caused by large-scale greenhouse gas emissions have led governments to increase their efforts to promote energy-saving and carbon-reducing policies. At the same time, academic pioneers have been exploring ways to reduce greenhouse gas emissions in their own fields of specialization.

In many fields of scientific research, as the mainstay of clean energy, electric energy has gradually been noticed by the world, and in order to further realize the global goal of energy saving and carbon reduction [1], renewable energy power generation has gained great development in recent years in the world. Although the replacement of traditional energy sources by electricity has made a significant contribution to the world's carbon reduction problems, but part of the electricity production chain still exists in the excessive use of fossil energy problems, making the electricity market non-renewable energy power accounted for a high proportion of the electricity [2]. In addition, the power load user habits and power market mechanism of non-renewable energy power relies on a high degree of new energy power consumption ratio has always been at a low level, so the diversification of the power system reform and cleaner transformation can not be delayed, improve the power market system, standardize the user habits of electricity is also very significant.

The literature [3] concluded that carbon trading market can be used as an auxiliary market with both social welfare and electricity economy.

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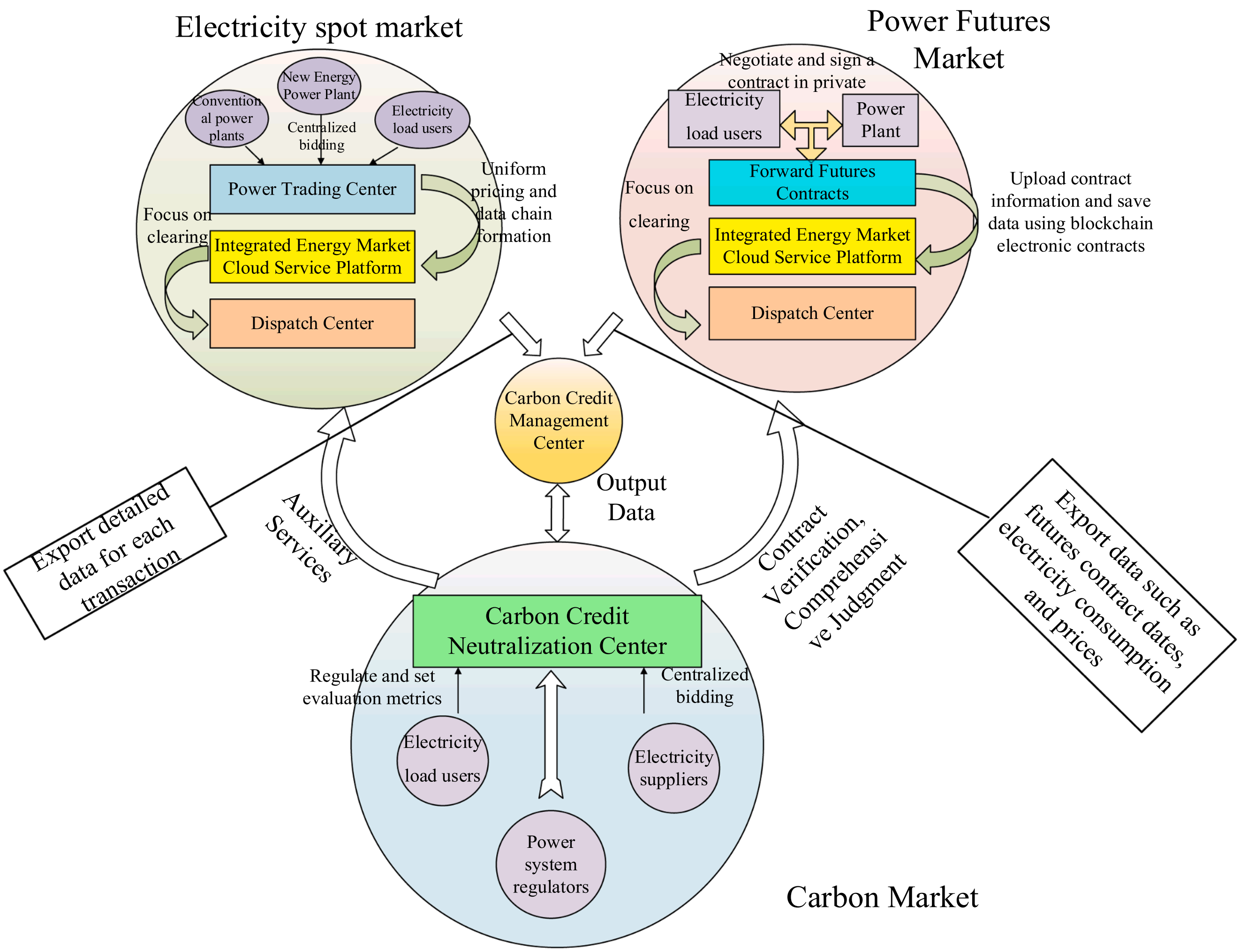

Fig. 1. Structure of carbonelectric coupling market.

In the literature [4–6], carbon trading and electricity trading are centralized and aggregated through blockchain technology, and buyers and sellers realize the flow and storage of data through the platform. Literature [7] proposed a carbon market framework design scheme based on categorical regulation and equivalent synergy. Most of the above studies are limited to the interaction between the electricity futures market and the carbon market, and the feedback from the carbon market to the electricity market clearing status lacks timeliness and accuracy, and the radiation ability of the electricity market to the influence of the carbon market is weak.

At this stage, the carbon market generally adopts a carbon quota system, but due to the long carbon compliance period of enterprises in the carbon quota mechanism, which is often measured in years, the carbon price fluctuates significantly in the short term, especially near the compliance period [8,9]. Therefore, existing studies focus on enhancing the coupling of carbon and electricity markets and the time-scale regulation of carbon prices. In [10], a step-scale carbon trading model is designed to replace the constant carbon price, and in [11], an example simulation of the equilibrium between the power generation market and the carbon market is proposed with a monthly time scale. In [12], an integrated energy system model that takes into account a stepped carbon trading mechanism is developed. The above-mentioned studies only incentivize electricity users to change their energy use characteristics through a one-way transmission price mechanism to strengthen the carbon-electricity market coupling, but do not fully consider the interactive coupling between the carbon-electricity market at multiple time scales.

Literature [13] studied the relationship between carbon quota bargaining model and carbon emission flow, and designed an optimal dispatching model of integrated energy park taking into account the carbon quota bargaining mechanism; literature [14] established a new optimal dispatching model of integrated energy system considering carbon cost under the carbon quota mechanism, and added carbon cost into the composition of nodal marginal tariff; The literature [15–17] designed a model and parameters related to the carbon electricity market, mainly based on the mechanism related to carbon quotas, and studied the effectiveness of carbon quotas for energy saving and carbon reduction; the literature [18] proposed a dynamic carbon trading curve based on the principle of supply and demand, and constructed a nodal marginal electricity price decomposition model using Lagrangian functions, and analyzed the relationship between the nodal marginal electricity price and the carbon quota mechanism.

However, there are three aspects of the carbon quota mechanism, which is the basis of the above study, that need to be improved: firstly, The existing mechanism has set a cap on the amount of carbon allowances for new energy power plants that emit less carbon, and since new energy power plants do not use carbon allowances to produce electricity, the profit they make from selling carbon allowances depends only on the total amount of carbon allowances allocated under the existing mechanism, and such a “birth-based” allocation method cannot realize the goal of “carbon profit”, and is not conducive to mobilizing production incentives. This “birth-based” distribution method fails to realize the “carbon profit” of “more work, more pay”, and is not conducive to mobilizing production enthusiasm; secondly, the existing mechanism

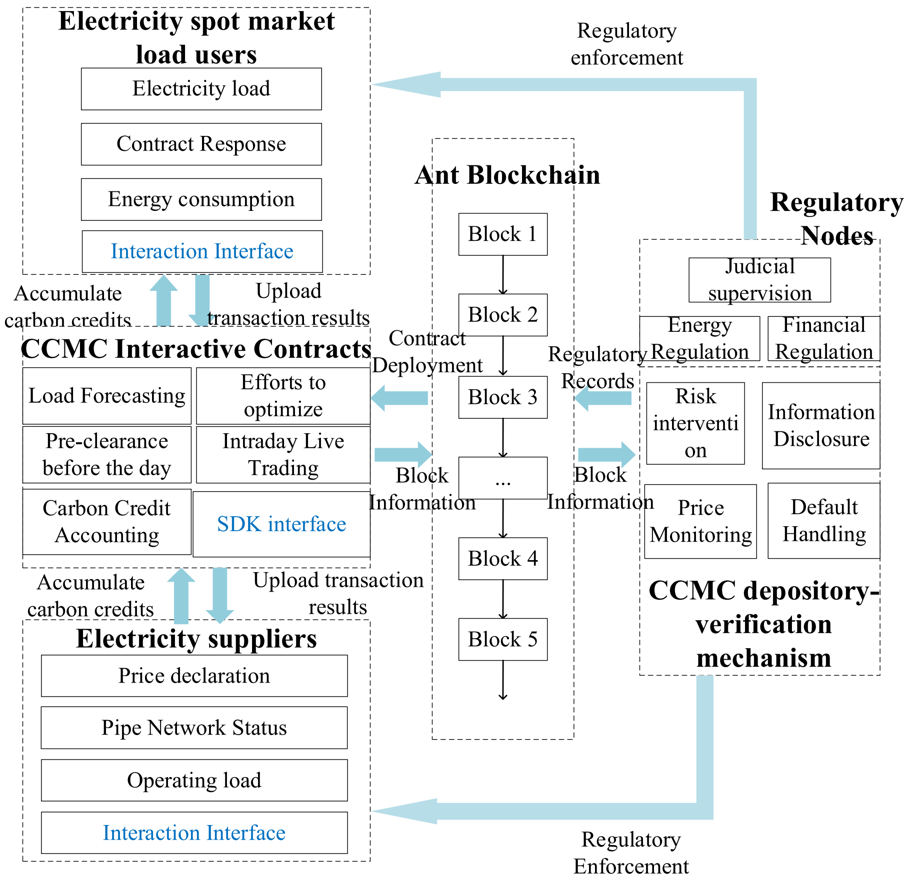

Fig. 2. CCMC and power spot market coupling structure.

attributes all carbon emissions to traditional energy plants, which is unreasonable. Thirdly, the existing mechanism cannot fundamentally solve the problem of carbon emission limit for power users, with the promotion of electric energy substitution, a large number of high-energy-consuming enterprises turn to electricity to reduce carbon emission, avoiding the high penalties.

In order to solve the above problems, this paper constructs a coupled carbon-electricity market model with carbon credit management center as the hub, which realizes the organic coupling of electricity spot market, electricity futures market and carbon market. For the market players, the more new energy is produced or consumed, the more negative carbon credits are accumulated, and the positive cycle of new energy consumption is achieved by the carbon market's realization mechanism. In addition, carbon credits are not only an indicator of carbon emission delivery at a specific time and place in the future, but also a virtual currency circulating in the carbon market, and can be used as a kind of green energy credentials, so that users can enjoy additional rights and benefits.

2. Carbon credit trading mechanism and carbon-electric coupling market structure

2.1. Overview of carbon-electric coupling market structure and framework

The carbon-electric coupled market based on carbon credit trading mechanism is centered on Carbon Credit Management Center (CCMC), whose framework is shown in Fig. 1.

The power market is indirectly linked to the carbon market through CCMC, which imports the detailed data of each transaction into the carbon market and calculates the total carbon emissions of each market player precisely and efficiently. The carbon market is directly linked to the power market through negative feedback, providing electricity auxiliary services to the spot market and influencing the nodal load marginal price (carbon emission trading scheme embedded locational compound marginal price, CETS- (LCMP)[19]; on the other hand, it reviews and integrates the energy contracts uploaded in the electricity futures market and rejects those that do not meet the energy efficiency and low carbon requirements.

CCMC is born from the comprehensive energy cloud service platform, The construction, operation and joint functioning of the platform with the electricity market are described in detail in the literature [20], so it not only has the functions of data accounting, data storage, smart contract and information transmission of traditional cloud platform, but also can realize the centralized bidding and optimal clearing of electric power load users (EPU) and electric energy suppliers (EPS). In addition, CCMC plays the role of a core hub in the coupled carbon-electricity market system, optimizing the coordination of the spot market, futures market and carbon market.

For the power spot market, CCMC provides a cloud platform for peer-to-peer trading between EPUs and EPS through blockchain and smart contract technology, and assists the efficient operation of the power spot market through load forecasting, power output optimization, and carbon credit verification, as shown in Fig. 2.

In the process of pre-clearance and intraday real-time trading in the spot market, CCMC provides a series of services from price declaration to contract response for EPU and EPS, and uses blockchain technology to realize contract deployment, block information transfer and carbon credit verification and accumulation. In terms of security, CCMC ensures the safe and stable operation of the spot market by setting up regulatory nodes to control spot transactions in various fields such as justice, energy and finance. Meanwhile, CCMC depository verification mechanism can evaluate and intervene in trading risks, disclose and publicize illegal information, monitor and manage price fluctuations, and punish and control violations, which protects the practical interests of spot market users from multiple dimensions.

Compared with the spot market, CCMC focuses more on evaluating and managing customers' energy consumption treaties in the futures market. The reliability of energy supply and the efficiency of fund clearing are important indicators to evaluate the execution of contracts in the futures market. Therefore, when conducting futures trading, EPU and EPS will negotiate on the contract content and upload the formed written treaty to CCMC. After carbon credit accumulation, power system stability analysis and carbon-electric coupling market balance evaluation, CCMC will store the data in the form of smart contract and supervise EPS to clear the funds. During the effective period of the contract, CCMC will continuously monitor the EPS contract response and contract performance.

2.2. Carbon credit trading rules

Attachment A shows the correlation between the carbon-electricity market under the carbon credit trading mechanism from five aspects, including carbon-electricity system construction, trade release declaration, trade clearance, trade execution and trade settlement. The basic principles of carbon credit trading are as follows:

(1) CCMC accounts for the non-renewable energy or non-renewable energy electricity consumed by EPUs and accumulates positive or negative carbon credits for them respectively, and CCMC sets the carbon credit threshold for each EPU as shown in Eq. (1) based on the EPU's past trading data, carbon market supply and demand, and the proportion of renewable energy electricity and non-renewable energy electricity consumed.

$$T_{U,j} = \alpha_Q \sum_{j}^{t} (Q_{NR,j,t} - Q_{R,j,t}) + \beta_C I_t^{CCP} + \delta_E \frac{E_R}{E_{NR} + E_R} \tag{1}$$

where, $T_{U,j}$ is the carbon credit threshold of the *jth* EPU, α_Q is the electro-carbon conversion factor indicating the conversion of electricity into carbon credits, $Q_{NR,j,t}$ and $Q_{R,j,t}$ are the non-renewable electricity and renewable electricity consumed by the *jth* EPU at time *t, respectively*, βc is the dynamic carbon credit conversion factor, I_t^{CCP} is the carbon credit price at time *t*, δ_E is the electricity consumption ratio conversion factor, E_R and E_{NR} indicate the total amount of renewable electricity and non-renewable electricity consumed by the EPU in the market, respectively. The total amount of renewable and non-renewable generation consumed by EPU.

(2) When EPS produces non-renewable electricity, CCMC will account for and accumulate carbon credits for it, and when it produces renewable electricity, CCMC will accumulate negative carbon credits for it, and set carbon credit thresholds for EPS as shown in Eq. (2) based on the installed capacity, unit type, electricity turnover, and power system stability of EPS. In general, the carbon credit threshold for conventional energy power plants is much higher than that for new energy power plants of the same size.

$$\begin{aligned} T_{S,k} = {} & \eta_P \sum_{k} (P_{NR,k} - P_{R,k}) + \varepsilon_{NR} \sum_{k}^{t} Q_{NR,k,t} + \\ & \varepsilon_R \sum_{k}^{t} Q_{R,k,t} + \delta_E \frac{E_R}{E_{NR} + E_R} \end{aligned} \tag{2}$$

where $T_{S,k}$ is the carbon credit threshold of the *kth* EPS, η_P denotes the installed capacity conversion factor, $P_{NR,k}$ and $P_{R,k}$ denote the installed capacity of non-renewable units and renewable generation within the *kth* EPS, ε_R and ε_{NR} are the turnover conversion factors of non-renewable electricity and renewable electricity respectively, $Q_{NR,k,t}$ and $Q_{R,k,t}$ denote the turnover of non-renewable electricity and renewable electricity of the EPS in the market at time *t respectively*. The turnover of electricity from non-renewable and renewable sources in the market at time *t*.

(3) If the carbon credits of the electricity market players are always negative within a period of time, they can obtain Green Energy Incentives (GEI), and the coupled carbon-electricity market will give GEI users the following incentives: First, in the process of price and power declaration in the electricity spot market, they will enjoy the highest trading priority, and dispatching agencies and clearing management departments will give priority to GEI users. In the process of carbon market trading, GEI customers will enjoy priority when the carbon credit sellers offer the same price.

(4) After the EPU declares the required power and price is responded by EPS, CCMC will give a certain subsidy based on the amount of carbon credits of EPU at that time node and the current stage of CETS-LCMP, thus forming the electricity market price compensation mechanism related to carbon credits, which is calculated as shown in equation (3).

$$\Delta\pi = \begin{cases} \alpha_\pi \pi_t^l & N_{carbon} \leqslant 0 \\ \alpha_\pi \left(1 - \dfrac{N_{carbon,t}}{T_S}\right) \pi_t^l & 0 < N_{carbon} < T_S \\ 0 & N_{carbon} \geqslant T_S \end{cases} \tag{3}$$

where $\Delta\pi$ is the subsidized electricity price received by the EPU based on its carbon credit, $\pi l\ t$ is the CETS-LCMP at node *l* at time *t*, α_π is the price compensation factor based on the CETS-LCMP, and $N_{carbon,t}$ denotes the carbon credit held by the EPU at time *t*.

The closer the user's carbon credit is to the carbon credit threshold, the lower the subsidized electricity price is, which increases the electricity cost of EPU to a certain extent; when the user's carbon credit reaches or even exceeds the carbon credit threshold, the electricity price subsidy in the carbon-electric coupling market is 0, at which time the user needs to purchase electricity with CETS-LCMP, and the actual electricity fee paid by EPU is equal to the actual transaction price of its participation in the carbon-electric coupling market; when the user's held When the number of carbon tags held by customers is 0 or negative, the subsidized electricity price reaches the maximum, and the cost of electricity for EPU is significantly reduced and its reliability is guaranteed by GEI mechanism.

(5) When the amount of carbon credits exceeds the threshold at a certain point in time, the power market participant will not be able to make the next round of power market declaration, and then it will need to neutralize the over-limit carbon credits with the negative carbon credits purchased through the Carbon Credit Neutralization Center (CCNC). For the power futures market, the CCMC can calculate the amount of carbon credits accumulated by both parties to the contract when signing a forward power supply contract, and the data is transmitted to the CCNC for its final decision. Most of the contracts will be returned to the CCMC for supervision and management after passing the audit, and the CCNC has the right to reject a small number of contracts that have serious carbon credit overruns or that pose a certain threat to the security of the power system. The contracting parties are required to re-draft a more low-carbon and energy-saving power supply strategy.

(6) CCMC outputs to CCNC in real time the amount of carbon credits accumulated by the current market players, CCNC assumes the role of the main body of the carbon trading market operation, where the negative value users make quotations, and then the carbon credits over the limit of the user centralized bidding, the price of carbon credits fluctuates due to a variety of factors, and CCNC imposes constraints on the marginal price of carbon

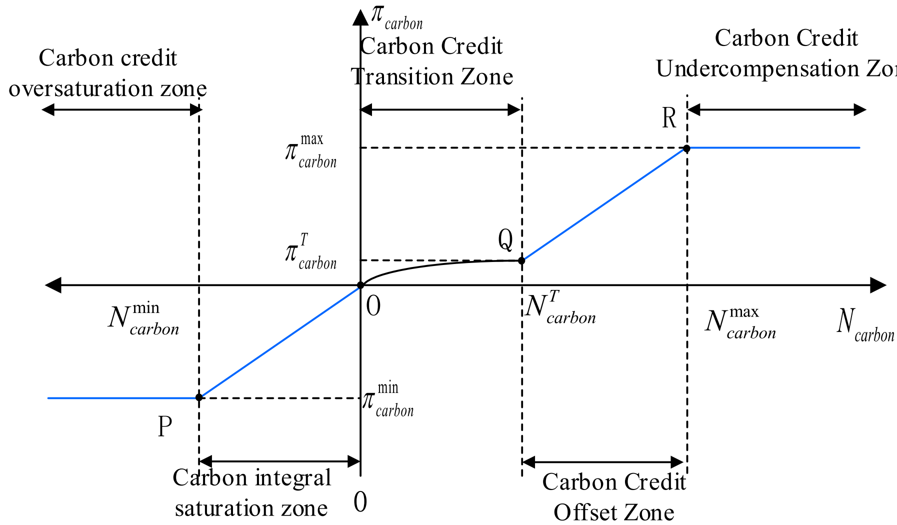

Fig. 3. Dynamic carbon credit price curve.

credits, and collects the "carbon tax" as a percentage of the successful outcome of each transaction as a fund for the maintenance and operation of the entire carbon power coupling market, and adopts a tax exemption policy for the users of the GEI.

(7) Binding electricity auxiliary services as a business to the carbon-electricity coupling market. The general customers can participate in demand response by changing their own energy consumption habits, so as to obtain subsidies for energy consumption costs; GEI customers enjoy free auxiliary services provided by the carbon-electricity coupling market to ensure their energy consumption safety and stability because they consume more new energy, and non-renewable power plants can participate in auxiliary services to reduce the negative impact of carbon credit mechanism on their daily Non-renewable power plants can reduce the negative impact of carbon credit mechanism on their daily production by participating in auxiliary services.

3. A carbon price model based on dynamic carbon credit supply and demand

3.1. Carbon credit price sensitivity analysis

Based on the above analysis, a Carbon Credits Price (CCP) sensitivity model is constructed, The analysis of the CETS-LCMP builds on the previous analysis by adding a dynamic carbon credit supply and demand impact component.. CCMC calculates carbon credits for each transaction in the coupled carbon-electricity market as shown in equation (4):

$$N_{carbon,i} = \alpha_1 Q_{NR} - \alpha_2 Q_R \tag{4}$$

where, $N_{carbon,i}$ denotes the amount of carbon credits accumulated after the completion of the *ith* transaction, α_1 *and* α_2 are the electricity and carbon conversion factors of non-renewable electricity and renewable electricity respectively, Q_{NR} *and* Q_R are the turnover amount of non-renewable electricity and renewable energy in the transaction respectively.

The carbon credits accumulated in the coupled carbon-electricity market increase as the electricity market turnover increases, and after reaching the carbon market threshold.

Before the cap, the CCP supply and demand components grow at a slow rate; after reaching this threshold cap at a faster rate, Eq. (5) gives the threshold cap for the carbon market:

$$N^{T}_{carbon} = \phi \sum_{i}^{t} (T_{U,j} + T_{S,k}) \tag{5}$$

where: ϕ is the carbon credit threshold factor and *NT carbon* indicates the carbon market threshold cap.

The greatest impact on the carbon credit transaction price occurs when the carbon credit reaches the limit value, and this saturation value is obtained from Equation (6):

$$N^{max}_{carbon} = \varphi \sum_{i}^{t} N_{carbon,i} \tag{6}$$

where: φ is the carbon integral saturation factor and *Nmax carbon* denotes the total carbon integral corresponding to the saturation of the market over-limit carbon integral.

The pricing of carbon market flow commodities is affected by supply and demand, which is generally expressed as a linear function in previous studies [21], however, such studies simply identify the supply and demand influence curve when the market tends to equilibrium as a linear relationship is inaccurate, and also can not more accurately elucidate the threshold for the carbon market to reach the tipping point, so a more efficient and effective method is needed to reconstruct the supply and demand influence curve of carbon price.

After the introduction of the carbon credit mechanism, the expression of the CCP supply and demand components affected by the supply and demand relationship is shown in equation (7), and its change curve is shown in Fig. 3.

$$\pi_{CSD} = \begin{cases} \pi^{min}_{carbon} & N_{carbon,v} \leqslant -\dfrac{(N^{max}_{carbon} - N^{T}_{carbon})}{\pi^{max}_{carbon} - \pi^{T}_{carbon}} \pi^{min}_{carbon} \\ -\dfrac{(\pi^{max}_{carbon} - \pi^{T}_{carbon}) N_{carbon,V}}{N^{max}_{carbon} - N^{T}_{carbon}} & -\dfrac{(N^{max}_{carbon} - N^{T}_{carbon})}{\pi^{max}_{carbon} - \pi^{T}_{carbon}} \pi^{min}_{carbon} \leqslant N_{carbon} \leqslant 0 \\ -\dfrac{\pi^{T}_{carbon}}{1 - e^{-N^{T}_{carbon}}} e^{N_{carbon,v}} + \dfrac{\pi^{T}_{carbon}}{1 - e^{-N^{T}_{carbon}}} & 0 < N_{carbon} < N^{T}_{carbon} \\ \pi^{T}_{carbon} + \dfrac{\pi^{max}_{carbon} - \pi^{T}_{carbon}}{N^{max}_{carbon} - N^{T}_{carbon}} N_{carbon,V} & N^{T}_{carbon} < N_{carbon} < N^{max}_{carbon} \\ \pi^{max}_{carbon} & N^{max}_{carbon} \leqslant N_{carbon} \end{cases} \tag{7}$$

where, $N_{carbon,V}$ represents the total carbon integral, π_{CSD} is the supply and demand components affecting CCP, *πmax carbon* and *πmin carbon* are the compensation and saturation extremes of CCP supply and demand components, respectively.

In Fig. 3, the horizontal coordinate represents the total amount of carbon credits; the vertical coordinate represents the degree of influence of the supply and demand of carbon credits on CCP;

When the total amount of carbon credits in the carbon market is negative, the curve is in the carbon credit oversaturation zone, which is equivalent to lowering CCP; as the total amount of carbon credits is elevated, the curve goes through the saturation zone close to the origin O, and the supply and demand balance has the least impact on CCP; when the total amount of carbon credits crosses the zero point into the carbon credit transition zone, the carbon emission of the main body of the power market increases, but it has not yet exceeded the carbon credit threshold, so the curve has a slow growth trend; Once the total amount of carbon credits exceeds the upper limit of carbon market threshold, which means most users' carbon credits have exceeded the threshold, CCP increases with the rise of carbon credits demand, and the curve enters the linear growth of carbon credits compensation zone; when the total amount of carbon credits reaches the undercompensation point, the curve stops growing, market demand reaches the peak, and CCP reaches the maximum.

3.2. CCP-based trading model

CCNC has improved the uniform carbon trading approach in the international market[22].by adjusting the original unchanging carbon price to a real-time carbon price influenced by the synergy of CCP supply and demand components and quotes from both sides of the transaction.

Both sides of the transaction are traded freely based on the carbon credit mechanism, and their declared prices are shown in equation (8):

$$\begin{cases} \pi_{i,s}(r) = (1-\beta_i(r))\pi_{i,\max} \\ \pi_{i,b}(r) = (1+\gamma_i(r))\pi_{i,\min} \end{cases} \tag{8}$$

where: $\pi_{i,s\ (r)}$ and $\pi_{i,b\ (r)}$ are the quotes of sellers and buyers in the *ith* market body, respectively, $\beta_{i(r)}$ and $\gamma_{i(r)}$ are the price correction factors for the *rth* round of trade declarations of sellers and buyers in the *ith* market body, respectively, and $\pi_{i,\min}$ and $\pi_{i,\max}$ are the minimum and maximum acceptable prices for market body *i,* respectively.

In order to prevent manipulation of CCP by both sides of the transaction, CCNC makes the following restrictions on market participants' quotes, drawing on the stock market's stop-and-go mechanism.

$$\Delta\pi(r)_{\min} \leqslant |\pi_i(r+1) - \pi_i(r)| \leqslant \Delta\pi(r)_{\max} \tag{9}$$

where $\Delta\pi(r)_{\min}$ and $\Delta\pi(r)_{\max}$ denote the lower and upper bounds of the absolute value of the increase or decrease in the quotes of market participants per round, respectively.

After several rounds of quotations, both sides of the carbon market transaction reach an agreement on CCP and make a final price declaration to CCNC. After the calculation of equation (10), the carbon market records and uploads the transaction data to CCMC, which finally centralizes the clearing of the transaction results according to the principle of priority of GEI users.

$$\pi_i = \frac{1}{2r}\sum_{i=1}^{r}\left[\pi_{i,s}(r) + \pi_{i,b}(r)\right] + \pi_{CSD} \tag{10}$$

where, π_i denotes the carbon credit transaction price.

4. Carbon - electricity coupled market trading method and clearing model

4.1. Carbon-electric coupled market players profit of electricity sales and cost of electricity consumption model

The main body of the carbon-electric coupling market consists of EPS and EPU, assuming that the offer of EPS is influenced by the cost of generation, the cost of carbon credits, and the guarantee of full consumption of declared electricity[23]; the energy cost of EPU is determined by the offer of EPS and influenced by CCP[24].

4.1.1. Non-renewable power plants profit from electricity sales

Most non-renewable energy plants at this stage are thermal power plants, whose consumption characteristics can be expressed by the following equation[25]:

$$N_{j,t}(P_{Aj,t}) = a_j P_{Aj,t}^2 + b_j P_{Aj,t} + c_j \forall \mathrm{j} \in \mathrm{A} \tag{11}$$

where, $N_{j,t}(P_{Aj,t})$ and $P_{Aj,t}$ denote the total fuel consumption and power generation of non-renewable power plant *j* at time *t*, respectively, a_j, b_j, c_j denote the coefficients of consumption characteristics, respectively, and the set A denotes the set of all non-renewable power plants.

Equation (11) is differentiated to obtain Equation (12):

$$n_{j,t}(P_{Aj,t}) = \frac{dN_{j,t}(P_{Aj,t})}{dP_{Aj,t}} = a_j P_{Aj,t} + b_j \forall \mathrm{j} \in \mathrm{A} \tag{12}$$

where $n_{j,t}(P)_{Aj,t}$ denotes the marginal fuel consumption of the non-renewable power plant j at moment t.

In the carbon-electric coupled market bidding model, the non-renewable power plant offer is an affine function of its marginal cost of generation, which is expressed as follows:

$$\pi_{j,t}^{NR,S}\quad(P_{Aj,t}) = \frac{n_{j,t}(P_{Aj,t})\gamma_N}{\varepsilon} \forall \mathrm{j} \in \mathrm{A} \tag{13}$$

where γ_N denotes the unit fuel cost; *πNR,S j,t*$(P)_{Aj,t}$ denotes the marginal cost of electricity generation at moment *t for* non-renewable plant *j*.

For non-renewable power plants, their carbon credits may have an over-limit problem, so their profits can be expressed by equation (14):

$$\begin{aligned} \pi_{j,profit}^{NR,S} = (\lambda_j - 1)\sum_{t=1}^{T}\pi_{j,t}^{NR,S}(P_{Aj,t})Q_{j,t} - \\ \sum_{t=1}^{T}(\alpha_1 Q_{j,t} - N_{carbon,j}^{T})\pi_j \forall \mathrm{j} \in \mathrm{A} \end{aligned} \tag{14}$$

where *πNR,S j,profit* is the total profit of non-renewable power plant *j* at time scale *T*; λ_j, π_j and *NT carbon* are the offer factor, carbon credit transaction price and carbon credit limit of non-renewable power plant *j,* respectively; $Q_{j\ ,\ t}$ is the non-renewable electricity sold by non-renewable power plant *j* at time *t*.

4.1.2. Renewable energy power plants profit from electricity sales

The production costs of renewable energy plants are mainly composed of daily operation and maintenance costs. At this stage, the cost of renewable energy generation is generally measured using the levelized cost of electricity (LCOE) method[26], from which the LCOE of renewable energy generators can be obtained as follows:

$$\pi_k^{R,S} = \frac{I_k\theta_{CER} + M_k^T + O_k^T}{W_k^{R,T}} \forall k \in B \tag{15}$$

where, $\pi R,S$ $k$and I_k denote the marginal generation cost and initial investment of renewable energy plant k, respectively, θ_{CER} denotes the initial capital recovery factor, *MT k denotes the* maintenance cost of renewable energy plant *k over* a certain time scale *T, OT k denotes the* operating cost of renewable energy plant *k over* a certain time scale *T, WR,T k denotes the* generation capacity of renewable energy plant k over a certain time scale *T*, and *B denotes the* set of renewable energy plants.

The cumulative carbon credit for renewable energy plant *k* may be negative, at which point the profit model is as follows:

$$\pi^{R,S}_{k,profit} = (\lambda_k - 1)\sum_{t=1}^{T}\pi^{NR,S}_{j,t} + \sum_{t=1}^{T}\alpha_2 W^{R,T}_k \pi_k \forall \mathrm{j} \in B \tag{16}$$

where *πR,S k,profit* denotes the total profit earned by the non-renewable power plant *k in* time scale *T*, λ_k is the offer factor of the non-renewable power plant *k*, and π_k denotes the carbon credit transaction price of the non-renewable power plant *k*, which can be calculated by Equation (10).

4.1.3. Cost of electricity for EPU

When EPU is a negative carbon credit user, as the main consumer of renewable energy, it can enjoy the tariff subsidy from the coupled carbon-electricity market, and at the same time, it can further reduce the cost of electricity by selling negative carbon credits.

When the EPU carbon credits are between 0 and the carbon credit threshold, it will lose the way to sell carbon credits to the carbon market, and the subsidy of the carbon-electric coupling market will be reduced accordingly, and the cost of electricity for EPU will continue to rise.

$$\pi^{U}_{\mathrm{cost}} = \begin{cases} \begin{matrix}[\pi^{NR,S}_{j,t} \quad (P_{Aj,t}) - \triangle\pi]Q_{NR} + \\ [\pi^{NR,S}_{j,t} - \triangle\pi]Q_R - \pi_i \mathrm{N}_{carbon,i}\end{matrix} & \mathrm{N}_{carbon,i} \leqslant 0 \\ \begin{matrix}[\pi^{NR,S}_{j,t} \quad (P_{Aj,t}) - \triangle\pi]Q_{NR} + \\ [\pi^{NR,S}_{j,t} - \triangle\pi]Q_R\end{matrix} & 0 < \mathrm{N}_{carbon,i} \leqslant \mathrm{N}^{T}_{carbon} \\ \begin{matrix}\pi^{NR,S}_{j,t} \quad (P_{Aj,t})Q_{NR} + \\ \pi^{NR,S}_{j,t} Q_R + \pi_i \mathrm{N}_{carbon,i}\end{matrix} & \mathrm{N}^{T}_{carbon} < \mathrm{N}_{carbon,i} \end{cases} \tag{17}$$

where *πU cost* represents the cost of electricity used by the EPU.

4.2. Carbon-electric coupled market joint trading model

4.2.1. Carbon - electricity coupled market trading process

Attachment B shows the flow chart of the carbon - electricity coupling market transaction. In the spot transaction, CCMC announces the D-day demand plan on D-2 according to the load forecast, equipment optimization and energy purchase proposal, and then discounts the price price curve of the price of electricity to each EPS after considering all kinds of transportation losses, and the EPS responds to EPUs according to the balance of the electricity output in order from the highest to the lowest, and then CCMC executes the transaction continuously in a cyclical manner according to the principle of highest priority of the GEI users, followed by the principle of price priority and time priority. After that, CCMC executes the transactions periodically and continuously according to the highest priority of GEI users, followed by the principles of price priority and time priority. After the completion of each cycle of transaction, CCMC will update the price in real time, deduct the available transmission capacity of the transaction path and the corresponding declared quantity of EPU, and then deposit the pre-clearing contract reached by both parties into SPM blockchain, and then finally follow the SPM compliance review and the pre-clearing result of the formula on the D-1 day.

In the case of futures transaction, firstly, the EPU will send the application for forward transaction to the EPS through the CCMC, then the CCMC will send the application for forward transaction to the EPS through the CCMC, and then the CCMC will send the application to the EPS through the CCMC. In futures trading, firstly, EPU will send forward transaction application to EPS through CCMC, then CCMC will propose reference price to IEU based on energy output and market conditions, then EPS will dock with EPU and prepare contract for transmission to CCMC and submit it to CCNC for review and approval, and after passing the review and approval, EPU will pre-deposit the forward transaction fee to CCMC, and the transaction will be completed. During the energy delivery period, EPS provides EPU with stable electricity at regular intervals according to the content of the contract, and SPM automatically examines whether both parties have completed the contract, and finally SPM deducts a certain amount of transaction service fees and transfers the prepaid fees from IEU to the accounts of IES and IESP.

4.2.2. Objective function

Based on the influence of carbon credit trading mechanism on the transaction price of the carbon-electricity coupling market, and combined with the influence of dynamic carbon credit supply and demand curves on CCP, the lowest carbon credit amount accumulation $N_{carboin}$, i.e., the lowest carbon emission *πNR,S i,profit*, the highest social welfare *πR,S k,profit*; the lowest EPU electricity cost; and the highest EPS participation in the market profit *πU cost,* respectively, are objective function.

4.2.3. Constraints

1) Node power balance constraint.

$$\sum_{m\in M_l} Q_{Dm,t} = \sum_{j\in J_l} P_{Aj,t} + \sum_{j\in J_l} P_{Bj,t} - \sum_{n} \frac{\theta_{l,t} - \theta_{n,t}}{X_{\ln}}\ , \forall l \in \mathrm{L} \tag{18}$$

where: M_l is the set of load nodes connected to node l; J_l is the set of EPS nodes connected to node l; $P_{Bj\ ,\ t}$ denotes the power generated by renewable energy plant j at moment t; n is any node connected to node l; $\theta_{l,t}$ and $\theta_{n,t}$ are the voltage phase angles of nodes *l and k* at moment *t, respectively;* X_{ln} denotes the reactance value of branch ln*;* L denotes the set of all available nodes.

2) Renewable energy power plant capacity constraints.

$$P^{\min}_{Bj,t} \leqslant P_{Bj,t} \leqslant P^{\max}_{Bj,t} \tag{19}$$

Where *Pmax Bj,t* and *Pmin Bj,t* represent the maximum and minimum values of the output of renewable energy plants under the premise of maintaining the safety and stability of the power system.

3) Non-renewable power plant capacity constraints.

$$P^{\min}_{Aj,t} \leqslant P_{Aj,t} \leqslant P^{\max}_{Aj,t} \tag{20}$$

Where *Pmax Aj,t* and *Pmin Aj,t* represent the maximum and minimum values of the power output of non-renewable energy plants under the premise of maintaining the safety and stability of the power system.

4) Bypass tidal current constraint.

$$-L_{\ln,\max} \leqslant \frac{\theta_{l,t} - \theta_{n,t}}{X_{\ln}} \leqslant L_{\ln,\max}, \forall \ln \in C \tag{21}$$

Where, $L_{ln,\max}$ denotes the capacity limit of the whole ln line, and C is the set of branches where the line is located.

5. System test and results

To verify the effectiveness of the coupled carbon-electricity market operation based on the carbon credit trading mechanism, the carbon credit transaction price model is programmed using MATLAB R2022b in a laboratory environment and solved using Nash bargaining and accelerated-adaptive alternating direction multiplier method [27]. For the non-renewable power plant, its fuel cost is set at yuan725 per ton according to the WTO unified standard, the user offer factor in carbon trading is set at 0.15 according to the Nash bargaining rule, and the base value π(r) per unit carbon credit offer is set at yuan162 with reference to

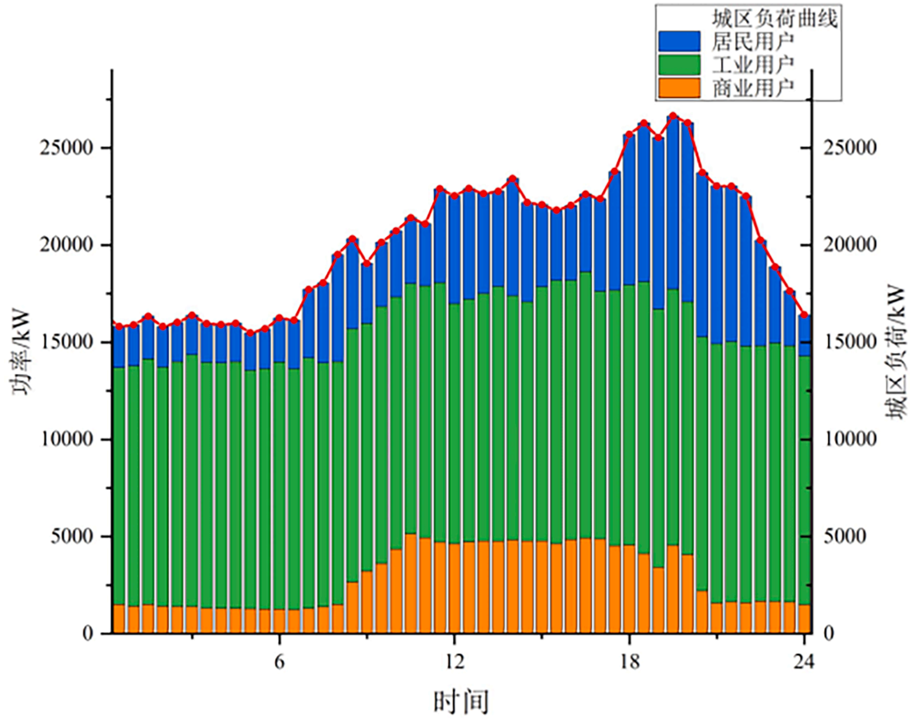

Fig. 4. Customer load curve of an urban area.

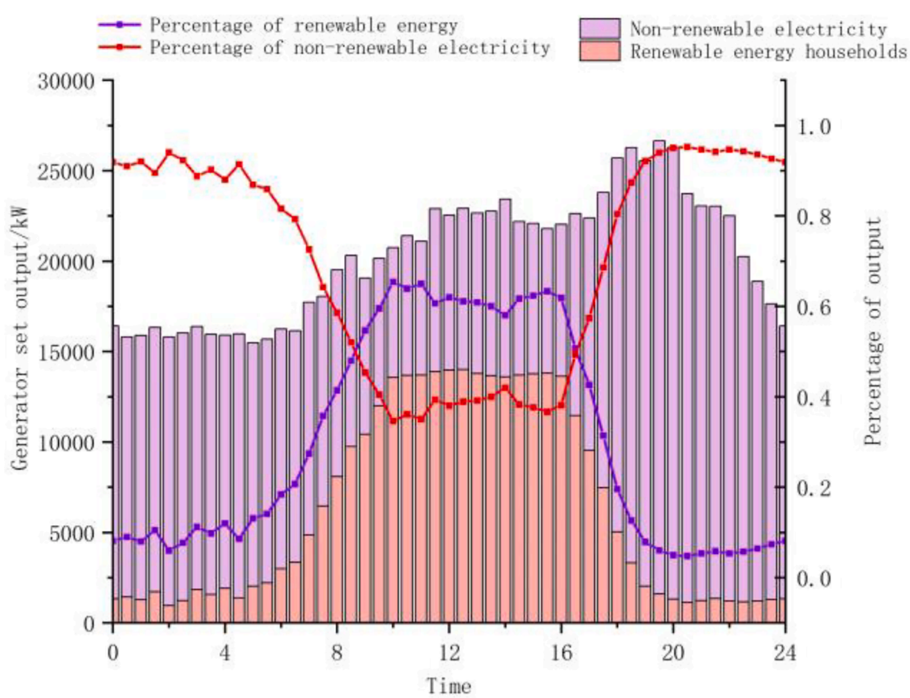

Fig. 5. The output and percentage of generating units in an urban area.

the forecast of the 2022 International Carbon Trading Price Report, and the fluctuation $\Delta\pi(r)$ per offer round is set at 20 %.

5.1. Analysis of the impact of carbon credit supply and demand curves on CCP

The residential electricity load curve of an urban area during a 24-hour period measured on a summer day is shown in Fig. 4.

As can be seen from the curves, industrial users in the urban area account for half of the total load in the urban area, with a high proportion of rigid load, and their energy consumption is more stable throughout the day than that of residential and commercial users, which is less responsive to the carbon credit trading mechanism; commercial users account for about 20 % of the total electricity consumption, and their flexible load mostly changes with time, and their energy consumption is lower at night, so they can better respond to the carbon-

Table 1
Statistics of unit output in an urban area.

	Maximum daily energy supply/kW	Minimum daily energy supply/kW	Average daily energy supply/kW	Peak-to-valley difference/kW
Renewable energy units	13995.64	948.17	6267.12	13047.47
Non-renewable energy units	25045.17	7174.21	13978.87	17870.96

electric coupling market trading mode. Residential users account for about 30 % of the electricity consumption in urban areas, and their energy consumption is more regular, with daily peaks mainly in the afternoon and evening.

Fig. 5 shows the change curve of the proportion of renewable energy and non-renewable energy to the total energy consumption in the urban area, it can be seen that only a few wind turbines and biomass units generate electricity at night, so the output of non-renewable energy units is high, the supply of renewable energy electricity has a more obvious rising trend at the beginning of sunrise, at this time the output of non-renewable energy units decreases; with the peak of photovoltaic power generation, at 10 am However, with the continuous growth of customer's power load, the new energy power is not enough to supply completely, and the output of non-renewable energy units rebounded slightly; near the sunset, the load in the city reached the peak, and the non-renewable energy units regained the dominant position because the output of new energy units dropped rapidly.

Table 1 is the integrated data of the power output of the units in this urban area. Combining with the power output curve of the generating units, it can be seen that the overall power output of renewable energy units is still at a low level compared with that of non-renewable energy units, and only the time period when the photovoltaic power is in full bloom or the hydrothermal conditions are good can reach 60 %, and whenever night falls, only a small number of units such as wind power and biomass power generation work normally, and the power output of non-renewable energy units is as high as 90 % at this time. 90 %.

Through the analysis of Fig. 6, it can be seen that at the time nodes with a high proportion of renewable energy unit output, such as between 10 a.m. and 4 p.m. daily, the carbon-electric coupling market consumes more renewable energy electricity, and the accumulated amount of negative carbon credits is greater than the positive carbon credits, at which time the dynamic carbon credit price impact curve is in the saturation zone, thus the CCP drops below the carbon credit offer benchmark value, and when the dynamic carbon credit supply and demand impact factor reaches −0.24 and below, CCP reaches a trough of 97.2 yuan; located in the time node when the output ratio of renewable energy units is low, such as in the evening and night time, the carbon-electric coupling market consumes more non-renewable power, and users accumulate a large amount of positive carbon credits, at this time the dynamic carbon credit price impact curve is in the compensation zone, thus making CCP rise above the carbon credit offer benchmark, when the dynamic carbon When the dynamic carbon credit supply and demand impact factor reaches 0.9 and above, CCP reaches a peak of yuan226.8.

5.2. Analysis of the operation effect of carbon-electric coupling market under different scenarios

5.2.1. Analysis of the impact of carbon-electric coupling market development stage on the outcome of clearing

Based on the international development law of the carbon-electric coupling market and the different characteristics presented by the future development plan of an urban area, the parameters of different stages of the carbon-electric coupling market construction are set, as shown in Table 2.

Assuming a 24-hour-a-day clearing for this urban area, the variability in the stages of development of the carbon-electric coupling

Table 2
Parameters related to the different development stages of the carbon-electric coupling market.

	Carbon credit price benchmark/yuan	Electro-carbon conversion factor	Degree of economic and social development/kW
Start-up period	162	0.15	20132.13
Development Period	174	0.33	43161.78
Maturity	202	0.54	69561.15

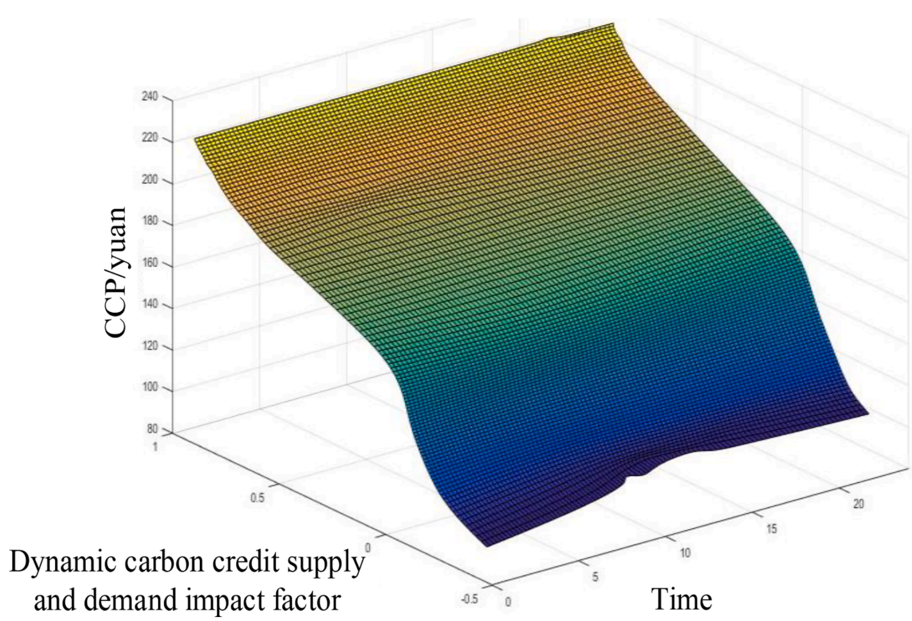

Fig. 6. CCP and dynamic carbon credit supply and demand diagram.

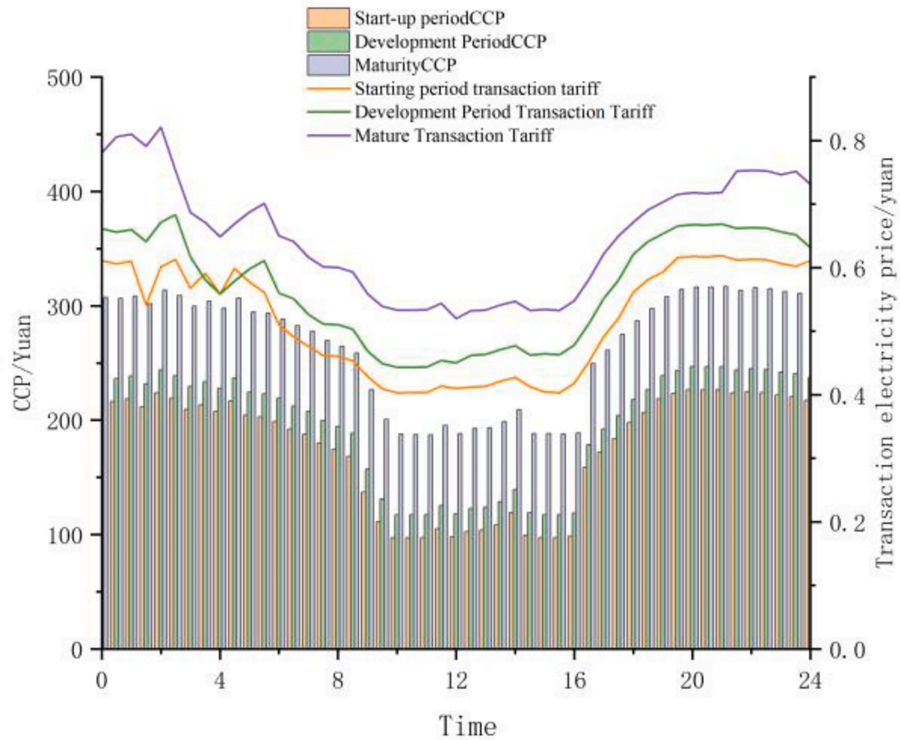

Fig. 7. Relationship between CCP and transacted electricity price at different development stages.

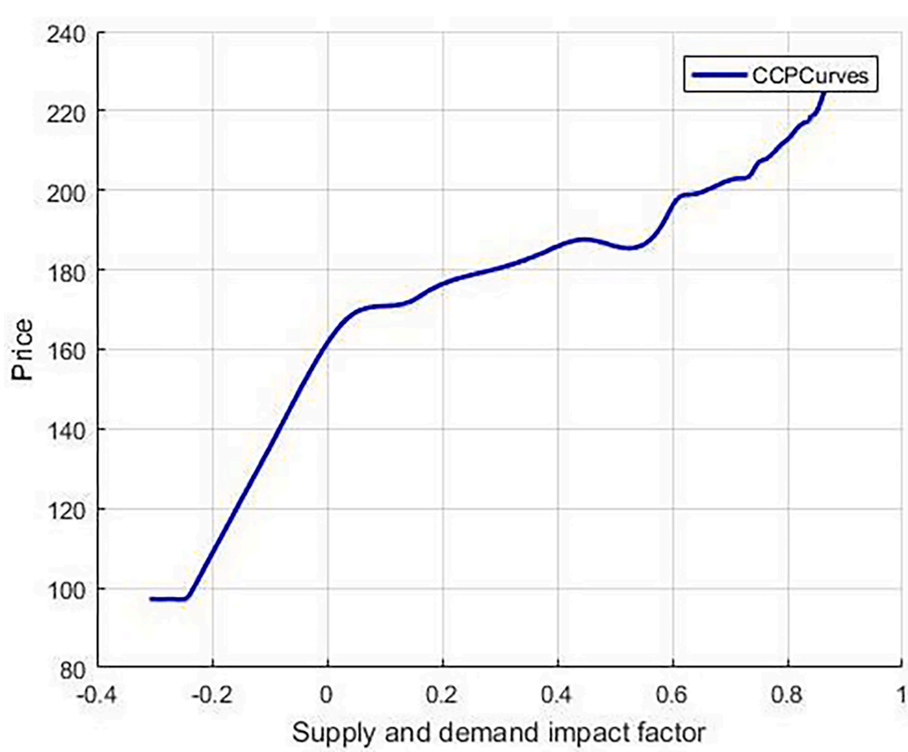

Fig. 8. Impact of high percentage of renewable energy access on dynamic carbon credit factor.

market is combined to produce the results shown in Fig. 7.

From the image, we can see that with the development of the carbon-electric coupling market and the further increase of the degree of economic and social development, CCP will be on a rising trend, and the rate of increase is large, even reaching yuan316.7 per unit of carbon credits in the peak period, which is due to the economic development to promote the rapid increase of energy consumption, the higher the demand CCP also rises, thus forcing high energy consumption enterprises to clean transformation and technological innovation Iteration. As another measure of the stability of the carbon-electricity coupling market, the transaction price of electricity also shows an upward trend, but the increase is small, which is in line with the basic law of

Table 3
Parameters related to the different development stages of the carbon-electric coupling market.

Degree of renewable energy access	Renewable energy consumption rate	Dynamic carbon credit factor	CCP/ yuan
Low level	20 %	0.6	194.231
Medium level	50 %	0	137.084
High level	80 %	−0.3	97.201

international electricity prices and protects people's livelihood.

5.2.2. *Analysis of the results of high proportion of renewable energy access on carbon-electric coupling market clearing*

In order to deal with the serious environmental problems, the future clean-up direction of the power industry is to increase the share of renewable energy consumption, and with the high proportion of renewable energy access, the dynamic carbon credit factor will change as shown in the table below.

From Fig. 8 and Table 3, it can be seen that as the proportion of renewable energy access gradually increases, the dynamic carbon credit factor decreases and CCP decreases, and the trend of the curve changes with Fig. 6 basically coincides.

5.3. *Analysis of the results of the joint application of CCNC and CCMC*

The simulation test was conducted in a laboratory environment with a user of an industrial-city integration zone in the urban area of subsection 5.1, and the structure diagram is shown in Fig. 9.

The upper end of the load aggregator is connected to the CCNC energy network and supplies energy to the EPUs through various energy transmission devices. 6 residential communities, 1 enterprise and 1 school are included in the EPU side, and all EPUs have been installed with intelligent energy terminals by the load aggregator. EPU D is an enterprise, EPU F is a school, and EPUs A, B, C, E, G, and H are residential communities. EPU B and EPU G have signed intelligent regulation contracts with load aggregators. The time share tariffs and CCPs agreed between the load aggregators and EPUs in this region are shown in Table 4.

To verify the stability of the operation of the coupled carbon-electricity market under the joint control of CCNC and CCMC, electricity settlement transactions and carbon trading are simulated in the following scenarios:

Scenario 1: The load aggregator reaches an energy use agreement with EPU D on June 22, 2023, and completes uploading the smart contract in the CCNC system to supply energy to EPU D during the time period of 10:00–13:00 on June 23, 2023, while completing the liquidation of funds.

Scenario 2: EPU D, as a high-energy consuming enterprise, has reached the market threshold for accumulated carbon credits, so it purchases negative carbon credits through CCNC to neutralize the over-

Table 4
Table of energy prices for load aggregators.

Energy Type	Electricity (yuan/ kWh)			Carbon credits (yuan/unit)		
	0 h-9 h	9:00–16:00	16 h00-0 h00	20:00–4:00	4 pm-12 pm	12:00–20:00
Price	0.45	0.74	1.12	196.4	162.7	107.2

Table 5
Profitability of thermal power plants in September.

	Carbon emissions/ million tons	Profit from electricity sales/ million yuan	Profit from auxiliary services/ million	Carbon cost/ million RMB	Total profit/ million
Current Market	96.72	71.74			71.74
Carbon quota market	61.62	67.40		12.17	55.23
Carbon-electric coupling market	59.98	66.26	20.17	3.14	83.29

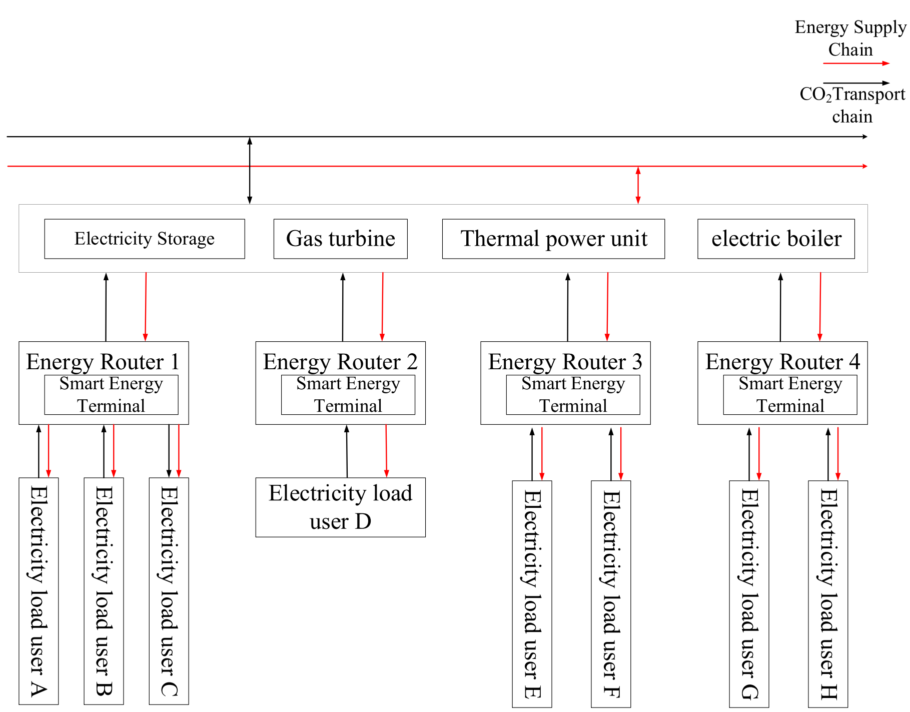

Fig. 9. User structure of the industrial-city integration zone.

Fig. 10. Scenario 1 blockchain deposition information.

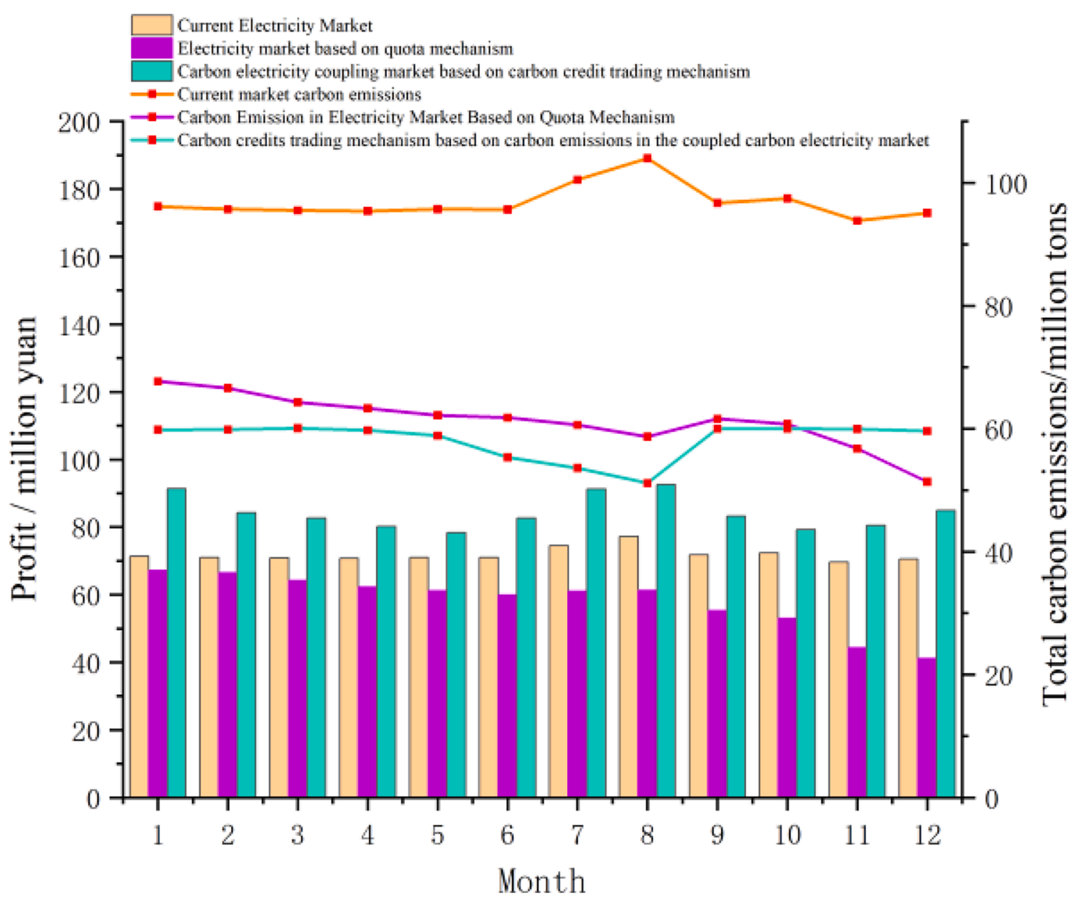

Fig. 11. Annual profitability status of thermal power plants and carbon emission changes.

limit carbon credits and signs a carbon trading contract (see Table 5).

Scenario 3: EPU A residents are more aware of energy saving and emission reduction, and most of the time they consume new energy, so they belong to GEI users, and sell negative carbon credits to user D through CCNC and upload carbon credit trading contracts.

As shown in Fig. 10, every record of the carbon-electric coupling market is deposited by the blockchain to keep the contract information secure.

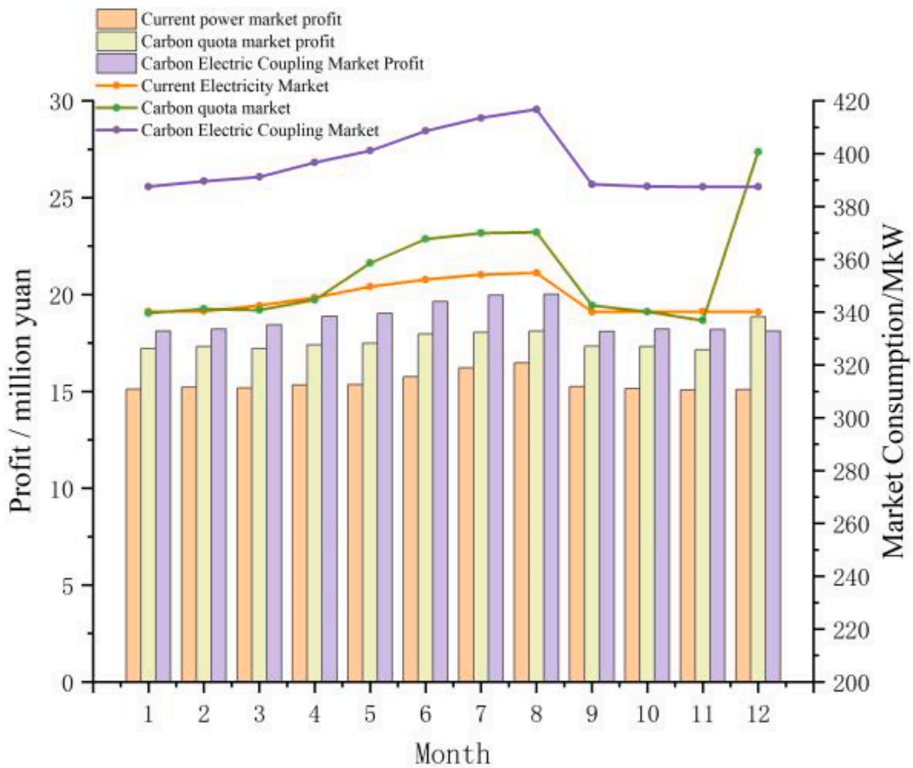

Fig. 12. Annual profitability status of new energy power plants and changes in market consumption.

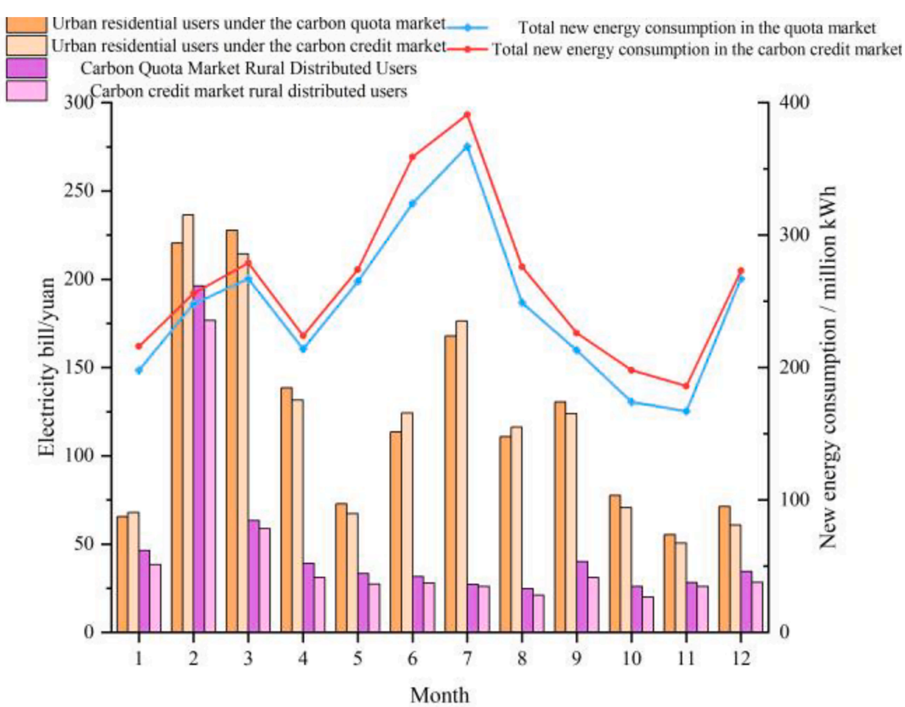

Fig. 13. Average annual electricity bill for residential customers and total new energy consumption in urban areas.

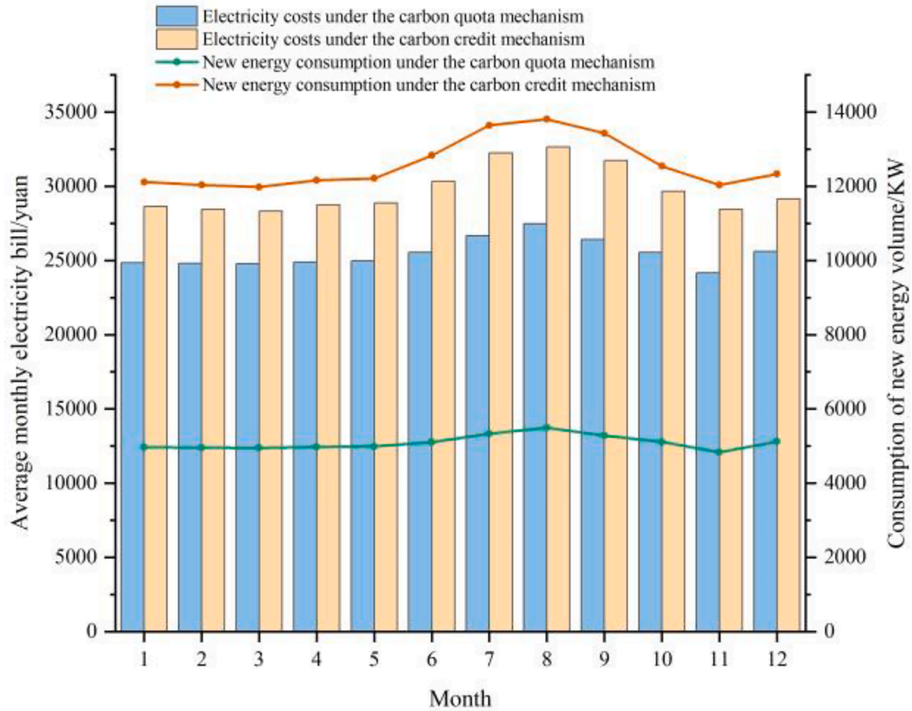

Fig. 14. Annual electricity bills of high-energy-consuming enterprises and the change of new energy consumption.

5.4. Analysis of economic benefits and social welfare of carbon-electric coupling market players

5.4.1. Conventional thermal power plants

The modeling simulation was conducted in a laboratory environment for one year for thermal power plants in an urban area. The following figure shows the trend of profit and total carbon emission of traditional thermal power plants in different markets over time, and the table shows the breakdown of profit composition and carbon emission of thermal power plants in September.

From the Fig. 11, we can see that the current electricity market has not yet made effective control on carbon emissions, so the amount of carbon emissions remains high, and at the same time, due to the low degree of marketization, the price of electricity is not time-series, resulting in thermal power plants to produce more electricity but lower profits; the electricity market with carbon quotas takes into account the cost of carbon compared with the current market, which has a significant effect on the reduction of emissions, however, there are still two problems, firstly, the carbon cost of energy use by users is imposed on thermal power plants. However, there are still two problems: firstly, the carbon cost of energy used by users is imposed on thermal power plants, so thermal power plants have to pay the cost of electricity production and bear the carbon cost of users and themselves, and the economic benefits are greatly reduced; secondly, the compliance date of carbon quota is December every year, so the carbon emission curve of thermal power plants is higher at the beginning of the year and plunges at the end of the year, which is not conducive to the stability of carbon price and also leads to the explosion of earnings of thermal power plants at the end of the year; compared with the other two, the carbon-electricity coupled market can reduce the carbon cost to a certain extent. Compared with the other two, the carbon-electricity coupling market can reduce the carbon emission of thermal power plants to a certain extent while ensuring that their economic benefits are not damaged, especially in July and August when the thermal conditions are favorable, further reducing the carbon emission of thermal power plants.

5.4.2. New energy power plants

Similarly, a new energy source in the jurisdiction is modeled and simulated, and the results are shown in Fig. 12.

The subsidies for new energy power plants in the current market are small, and new energy power plants handle more stable and average, and their profits are relatively small; after the introduction of the carbon quota mechanism, the profits of new energy power plants have increased significantly, however, on the other hand, the market new energy consumption has not increased in the same proportion, mainly due to the fact that new energy power plants do not need to emit carbon for their production, and the quota can be sold in full, but due to the quota mechanism when it was formulated However, due to the “originism” of the quota mechanism, new energy power plants are not motivated to produce; under the catalyst of carbon credit trading mechanism, new energy power plants can accumulate negative carbon credits for each transaction, and then realize them through CCNC, so the market efficiency of consuming renewable energy power is greatly improved, realizing the win–win situation of economic efficiency and social welfare. Therefore, the market efficiency of consuming renewable energy power is greatly improved, achieving a win–win situation in terms of economic benefits and social welfare.

5.4.3. Residential users

As the centralized embodiment of social welfare, it is the original intention of the carbon-electricity coupled market to reduce the energy cost as much as possible under the premise of meeting their energy demand.

As we can see from the Fig. 13, the average electricity cost of urban residential customers is slightly higher than that of the carbon quota market, because the accumulated carbon credits increase during the peak season, which affects the CCP and the energy cost of customers, but during the low season, the average monthly electricity cost of urban residential customers is lower than that of the carbon quota market. For rural distributed customers, they can save energy cost by self-sufficiency and accumulate negative carbon credits to realize, so the annual cost of electricity for rural distributed customers under the carbon credit mechanism is much lower than the carbon quota mechanism.

5.4.4. High energy consumption industrial users

As the main force of energy consumption and carbon emission, clean reform and production social renewal are imminent for high-energy-consuming enterprises. Fig. 14 shows the trend of annual electricity bill and renewable energy electric energy consumption of typical high-energy-consuming enterprises in this urban area.

However, for the society, the increase of energy consumption cost forces the high energy consumption enterprises to increase the proportion of renewable energy consumption and start the innovation of carbon reduction production technology, so the average monthly consumption of new energy by the enterprises is significantly increased and the social welfare is greatly increased. Therefore, the average monthly energy consumption of the enterprise is significantly increased, which is beneficial to the sustainable development of society and economy.

6. Conclusions

In order to promote the realization of the “double carbon goal”, the pace of clean-up in the power industry has been accelerating, and the carbon market, as a powerful helper on the road to carbon reduction in the power system, has gradually realized a natural coupling with the power market. To this end, this paper designs a carbon credit trading mechanism that combines carbon trading with the power market from the perspective of synergistic trading between the power market and the carbon market, incorporating the advantages of the carbon quota system and discarding the shortcomings of the traditional carbon trading market, and constructs a coupled carbon-electricity market model with a high degree of linkage and information interaction based on this model. On this basis, we analyze the factors influencing the transaction price of carbon credits, and study the trading model and profit realization mechanism of the main body of the coupled carbon-electricity market. Through a number of simulation experiments, the following conclusions are drawn:

(1) The supply and demand of carbon credits will affect the price of carbon credits in the carbon trading market. When the dynamic carbon credit factor is larger, the higher the price component of carbon credit supply and demand, which makes the trading price of carbon credits increase and raises the cost of energy use for users.
(2) Along with the development of the carbon-electric coupling market, the price of carbon credits will rise with the improvement of social and economic development, and eventually stabilize at a certain critical value, when the proportion of new energy consumed by society will be significantly increased, which will promote the realization of emission reduction targets.
(3) The process of achieving the carbon reduction target will definitely lead to the influx of high proportion of renewable energy into the power market, when the total amount of carbon credits in the market will continue to decline and eventually become negative, which means that the price of carbon credits will always remain at a low level, and the number of users with excessive carbon emissions will be drastically reduced, and the power system will take a key step towards cleanliness.
(4) In the carbon-electric coupled market model based on carbon credit trading mechanism, the carbon credit management center and carbon credit neutralization center can effectively guarantee the safety of users’ personal information through blockchain technology, ensure the accuracy and efficiency in the execution of contracts, and maximize the protection of the rights and interests of both users and suppliers in the transaction process.
(5) For the carbon - electricity coupling market main body, the non-renewable energy power plant in the social carbon reduction responsibility at the same time economic benefits are guaranteed; renewable energy power plant production enthusiasm has been greatly improved, the market renewable energy electricity consumption significantly increased; urban residential users received less impact, maintain the stability of the power system operation; rural distributed users to further reduce the cost of energy, to achieve electricity self-sufficiency at the same time can also feed the power system; high energy consumption enterprises by the market impact, forcing them to innovate the industrial technology chain, improve production equipment, so as to improve the social new energy consumption, to achieve the overall goal of energy saving and carbon reduction. High energy consumption enterprises are affected by the market, forcing them to innovate the industrial technology chain and improve the production equipment, thus increasing the amount of new energy consumption in society and achieving the overall goal of energy saving and carbon reduction.

By constructing a coupled carbon-electricity market based on the carbon credit trading mechanism, this paper hopes to minimize the total carbon emissions while ensuring that the energy-use characteristics of each market player remain unchanged, the cost of energy use is reduced, and the profit from electricity sales is increased.

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

Data will be made available on request.

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Appendix

Appendix A

See Fig. A.

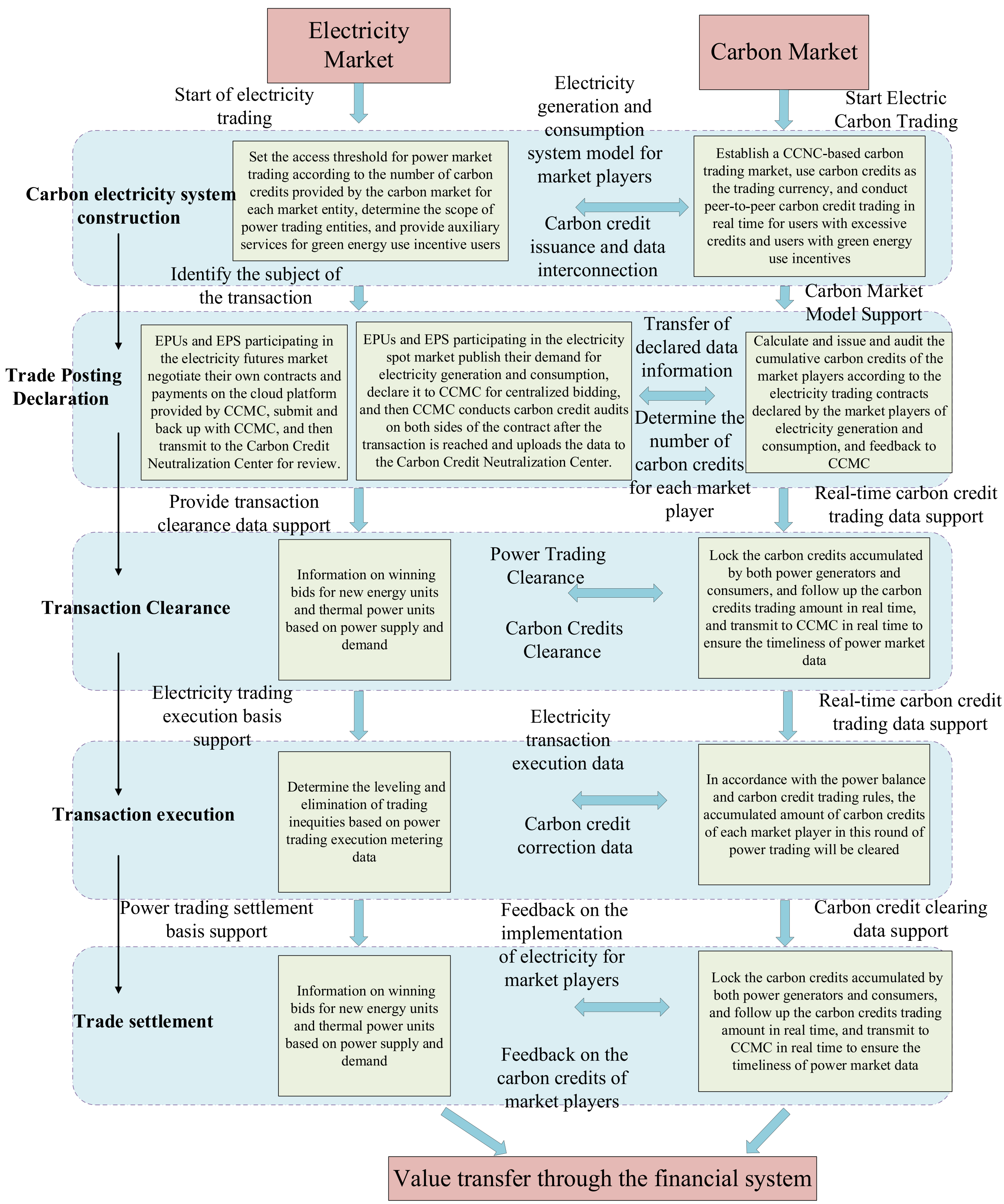

Fig. A. Coupling Structure of Electricity Market and Carbon Market.

Appendix B

See Fig. B.

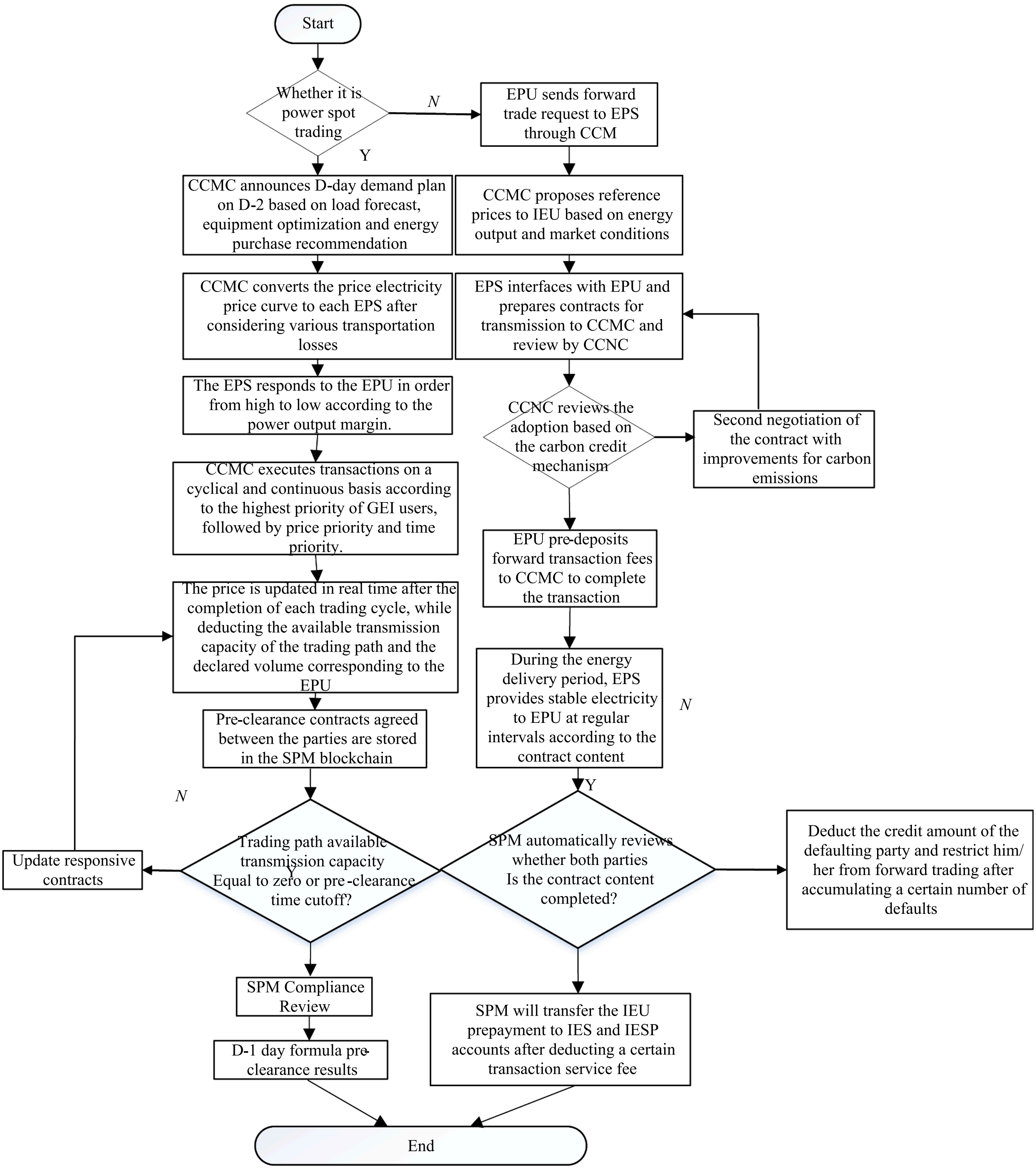

Fig. B. Carbon electricity coupling market trading flow chart.

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