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Joint Operation Mechanism of Distributed Photovoltaic Power Generation Market and Carbon Market Based on Cross-Chain Trading Technology

HOUYU HE[1], ZHAO LUO[2], QIAN WANG[2], MAOXIN CHEN[1], HUAQIN HE[1], LINGJUN GAO[1], AND HAIXIANG ZHANG[3]

[1]Quanzhou Electric Power Supply Company, State Grid Fujian Electric Power Company, Quanzhou 362000, China
[2]Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming 650500, China
[3]College of Energy and Electrical Engineering, Hohai University, Nanjing 210098, China

Corresponding author: Zhao Luo (waiting.1986@live.com)

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ABSTRACT The rise of blockchain technology has injected new vitality into the energy market. At present, blockchain projects for distributed photovoltaic power generation and carbon trading are rapidly emerging, but due to the barrier of two markets and the independent operation of such projects in two chains, the two market values cannot be two-way circulation, which is not conducive to the expansion of power trading business and the scale of carbon market. This paper proposed a joint operation mechanism of cross-chain trading, combined distributed photovoltaic power generation market and the carbon market by the blockchain technology. The novelty is to construct two chains which includes the mainchain and sidechain that enables the two markets to share data and circulate value, and to design a two-way anchoring method that achieves equating between carbon trading and electricity trading by cryptocurrency. The simulation studies took the improved IEEE 33 system as an example to simulate transactions on the Ethereum platform, and technically verify the feasibility of cross-chain transactions in these two markets, and use Ether as the settlement currency.

INDEX TERMS Distributed photovoltaic power generation market, carbon market, cross-chain transaction, blockchain.

I. INTRODUCTION

Distributed photovoltaic power generation uses clean solar energy resources to complete the production and consumption of electricity nearby, which has the advantages of high utilization rate and low level. Especially the users represented by PV Prosumer (**PVP**) accelerate the process of distributed generation but also put forward new requirements for the management and trading of the electricity market. In recent years, great progress has been made in distributed photovoltaic power generation in China. Distributed photovoltaic power generation has gradually moved from policy subsidies to market competition. It is proposed to appropriately reduce the standard of distributed photovoltaic subsidies and gradually allow distributed photovoltaic power generation projects to enter the market [1]–[3], but it is still restricted by factors such as low degree of marketization, lagging public services and imperfect management system. The degree of market-oriented transactions still needs to be improved [4]. Distributed photovoltaic projects continue to grow all over the world. However, there are few types of transactions and low flexibility.

There are fewer subsidies and lower return on investment for distributed generation projects, which has affected the

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enthusiasm of the power generation side to invest in such projects. Now, some researchers are gradually focus on the economy in the field of distributed photovoltaic power generation market. An evaluation method to estimate the marginal value of distributed household photovoltaic power generation in the Australian power market environment, and carried out relevant evaluation in Sydney is proposed by Oliva *et al* in [5]; Guo Liang Luo *et al.* Analyzed the distributed photovoltaic power generation in combination with China's policies, the financial risks of power generation and the suggestions for market-oriented reform is given [6]; The distributed photovoltaic power generation business needs to be expanded urgently in [7]. In order to expand PVP's profit path, renewable energy investors can earn revenues from avoided carbon emissions, enabling partial compensation for the higher electricity production cost [47]. Revenues from the Clean Development Mechanism (CDM) and later from the Chinese Certified Emission Reduction Exchange (CCERE) system were thought to be compensating for PVP [48], [49]. However, there is a lack of practical trading system and settlement methods. More importantly, when the return on investment of distributed photovoltaic power generation is declining, few literatures provide feasible measures to achieve the multi-market transactions.

With the rapid development of blockchain technology, on the one hand, it has been applied in the field of energy, such as Brooklyn microgrid, solarcoin (SLR), grid +, energy blockchain labs, etc. The Brooklyn microgrid project has developed the energy platform on which distributed photovoltaic power producers can trade energy, and there is no agent in this transaction mechanism [8]. The big grid allows distributed generators to refer to time-varying tariffs and use blockchain-based payment technologies [9]. Energy blockchain lab provides a blockchain based platform for carbon owners [10]. The introduction of blockchain-based solutions aims to serve the photovoltaic production and consumption group in the energy sharing community [11]. The foundation of the P2P energy trading market is established, and the bidding mechanism and strategy of P2P solar power exchange are compared and analyzed from market demand and supply index [12].

The blockchain technology has also been applied in the carbon trading market [44]–[46]. Qu, Kaiping and others have proposed a decentralized optimization method for multi-energy flow of wide-area integrated energy system in the context of carbon trading [13]; Nurulkhaqqi and others have adopted blockchain technology to solve the management and fraud problems of ETS (emission trading scheme), and at the same time, the reputation system has been used to improve the effectiveness of ETS Rate [14]. Sam Hartmann and others have made important research contributions to carbon market policy-making by developing a blockchain design that can improve the functions of the existing carbon market [15]. But the block chain of distributed photovoltaic power generation market and carbon market operates independently, which has become a technical barrier for mutual trading between the two markets. However, the current carbon trading is usually carried out in the carbon exchange, which is inefficient and has a high threshold fee, so it is not suitable for small users.

Due to the profit path of the distributed PV generation is single, high threshold cost of carbon trading, unable to clear small carbon trading volume and other issues a considerable number of users consume both carbon and electricity. We propose a joint operation mechanism of the carbon market and distributed photovoltaic power generation market based on blockchain technology. Market access targets are the PVP and the CEC (carbon and electricity consumers). In this study, the conversion method from clean power generation to carbon quota of distributed photovoltaic is designed. The PVP can participate in carbon trading. Based on power trading and carbon trading running in their own blockchain, the capital circulation and data sharing of these two markets are realized through cross chain trading technology.

The organization of this paper is as follows. The second section will introduce the market mechanism of distributed photovoltaic power generation and carbon trading in China, and propose a system of electricity and carbon joint trading based on blockchain technology in combination with the power consumption characteristics of photovoltaic producers and consumers; the third section will focus on the cross-chain trading technology in blockchain, and analyze the adaptability of the technology in the two markets; the fourth section will build a double chain of the main chain and the secondary chain In the fifth section, based on the cross-chain trading technology, an example is analyzed. Finally, the conclusions are presented in Section VI.

II. DISTRIBUTED PHOTOVOLTAIC POWER GENERATION MARKET AND CARBON MARKET TRADING SYSTEM

A. DISTRIBUTED PHOTOVOLTAIC POWER GENERATION AND CARBON TRADING RULES

1) DISTRIBUTED PHOTOVOLTAIC POWER GENERATION TRANSACTION

According to the current market situation in China, there are three main trading modes of distributed photovoltaic power generation: ‘‘self-generation, self-use, Surplus power is supplied to the main grid ’’, ‘‘All electricity is supplied to the main grid ’’, ‘‘market-oriented trading’’:

1) For the mode of ’’Self-generation, self-use, Surplus power is supplied to the main grid ’’, the distributed photovoltaic power generation shall be provided with a certain amount of economic compensation in accordance with the policy of full power subsidy; among which, the surplus power of the distributed photovoltaic power generation system shall be purchased by the grid enterprise according to the benchmark on-grid price of the local coal-fired unit. In addition, all kinds of government funds and surcharges, system reserve capacity fees and other related grid connection service fees levied along with the electricity price are exempted from distributed photovoltaic self-consumption [16].

TABLE 1. Differences between China, EU and U.S. carbon emissions system.

	China's pilot carbon market							Europe	America
	Shenzhen	Beijing	Tianjin	Guangdong	Shanghai	Hubei	Chongqing	EU ETS	CA CAT
trader	Emission reduction units, investment institutions, individuals	Emission reduction units, investment institutions, natural person transactions allowed since 2014	Emission reduction units, domestic and foreign institutions, other organizations and individuals	Emission reduction units, investment agencies, other organizations and individuals	Emission reduction units, other organizations and individuals	Domestic and foreign institutions, enterprises, organizations and individuals	Emission reduction units, other organizations and individuals	Emission reduction units, investment institutions, individuals	Unlimited
Quota	√	√	√	√	√	√	√	√	√
New quota	√	√	√	√	√	√	×	√	√
Adjust quota	√	√	×	×	×	√	×	×	√
Aggregate segmentation	Benchmark method + multi-round game	Historical method + benchmark method	Historical method + benchmark method	Same industry historical method + benchmark method & rolling base year	Historical method + benchmark method & advanced emission reduction + rolling base year	Industry History + Benchmarking & Rolling Base Year	Self-declaration	Ⅰ、Ⅱ：Historical method Ⅲ：Benchmark method	Benchmark method
Quota allotment	⩽95%free+⩾3%bid+⩾2%pricing for sale	⩾95%free+<5%auction+<5%pricing for sale	100%free	⩽97%free+⩾3%auction	100%free	⩾90%free+⩽3%auction+<7%auction	100%free	free+auction	free+auction +pricing for sale
Quota adjustment	Adjust the quota based on the actual industrial added value multiplied by the industry's carbon intensity	Ex-post quota adjustment (details not specified)	Ex-post quota adjustment (details not specified)	Ex-post quota adjustment (details not specified)	Ex-post quota adjustment (details not specified)	Adjust the quota when the annual output changes by 20% or more	Quota reduction for over-declared enterprises, and quota reissuance for enterprises below 80%	Mainly determined in advance	Mainly determined in advance

2) For the ''All electricity is supplied to the main grid'' mode, the distributed photovoltaic power generation project shall be implemented according to the benchmark price of the photovoltaic power station in the resource area.

3) For the ''Market-oriented transaction'', China has opened the pilot market-oriented transaction of distributed generation at the end of 2017, allowing the ''partition power sale'' of distributed photovoltaic power generation projects. When the distributed generation project deals with the power users directly, it should pay the ''network fee'' to the power grid enterprises. First, the transaction scope shall be realized nearby, and the network fee shall be borne by the power users [17].

2) CARBON TRANSACTION

The carbon emission trading rules of China, the European Union and the United States are shown in TABLE i1. At present, China has carried out carbon market trading pilot in seven cities, but the rules of carbon trading and the carbon punishment system are quite different. The EU carbon emission trading system (EU ETS and California carbon emission system, there are also differences in different degrees [18]–[22]. However, the trend of carbon trading marketization is gradually strengthened It can also be seen that the total cut-off benchmark method of carbon quota is widely used in the world. This paper adopts this method for the regulatory objects of carbon emissions, and CEC is part of carbon emission.

B. JOINT OPERATION MODE OF DISTRIBUTED PHOTOVOLTAIC POWER TRADING AND CARBON TRADING

Up to now, the profit channels of distributed photovoltaic power generation only sell electricity and participate in the auxiliary services of the grid [23], but in fact, the carbon emission reduction of the power generation project can not be ignored. Its clean power generation can be converted into the carbon emission of thermal power generation under the same power, so its carbon emission reduction can be used as a quota to participate in the carbon market transactions. Based on the above considerations and, Research on decentralized transaction of related PVP market [50]–[52], we have designed the following decentralized trading system:

The trading system in FIGURE. 1 is divided into two layers, the lower layer is the physical layer and the upper layer is the information layer. In terms of PV electricity trading, in the physical layer, the PVP can balance supply and demand with themselves and CEC. After being connected to the photovoltaic power supply, due to the reduction of transmission

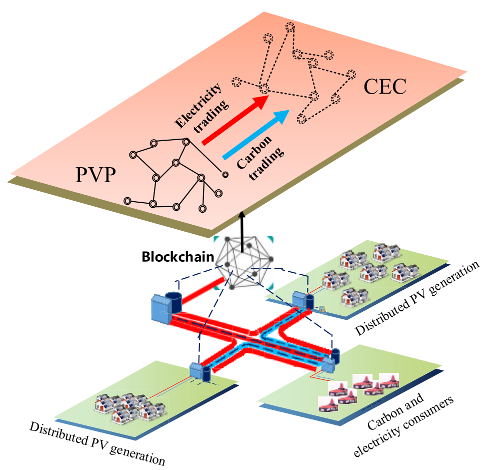


FIGURE 1. Structure of electricity and carbon joint transaction.

power on the feeder, the voltage at each load node along the feeder is raised, which may cause the voltage deviation of some load nodes to exceed the standard. The amount of voltage rise is closely related to the location and total capacity of the photovoltaic power supply. In general, the voltage offset of load nodes can be controlled within the specified range by setting on-load voltage regulating transformer, voltage regulator and other voltage regulating equipment in the medium and low voltage distribution network. And some PVP can transfer the redundant electricity to the nearby PVP and CEC through the method of nearby consumption, while the settlement needs to be realized in the information layer by relying on the blockchain technology, which can achieve P2P transactions within PVP and CEC instead of traditional aggregation based transactions [53], [54].

In terms of carbon trading, there are two kinds of trading channels: the first is the trading of carbon quota within the carbon emission regulatory group, and CEC that fail to meet the emission standard sell their excess carbon quota to the CEC that exceed the emission standard. The second is to assume that PVP can participate in carbon trading and sell their carbon quotas for clean power generation to nearby PVP with excessive carbon emissions. The sale and purchase of carbon quota can be conducted by bilateral auction [33].

Due to the lack of trading rules for PVP to enter the carbon market, we have designed a carbon quota calculation method for PVP as follow:

$$M_{\text{carbon quota}} = \delta \sum_{t=1}^{12} P_t \tag{1}$$

$M_{\text{carbon quota}}$ is the annual carbon quota value of the PVP, P_{t} is the monthly power generation, δ is the emission reduction conversion factor, that is, the amount of CO_2 emitted by the same 1kW·h power generation in the reduction of standard coal consumption of thermal power plants. It should be noted that our carbon quota calculation is not estimated, but calculated at the end of each year according to the total actual power generation of 12 months of a year by PVP.

The installed capacity of the distributed power generation project is different from that of the centralized photovoltaic power generation project. Its annual power generation capacity is small, so its converted carbon quota will not be too large. On the one hand, it will help to solve the problem of rising investment cost caused by the elimination of subsidies for PVP. On the other hand, a small amount of carbon quota will not cause too much fluctuation to the carbon market. Both types of transactions will be transacted and relevant data will be stored through the blockchain. Given the current application of the two types of transactions in the blockchain, usually two independent and non-interactive blockchains are running. Therefore, it is essential for the two markets to integrate to get through the two chain transactions.

III. CROSS-CHAIN TRANSACTION TECHNOLOGY

The biggest problem faced by the transaction system mentioned in section II B is how to make these two chains share data and trade with each other. The cross-chain technology of blockchain is an important technical means to realize data transfer and value circulate between blockchains, and can also be used to improve the scalability of blockchain.

A. TECHNICAL PRINCIPLE OF CROSS-CHAIN TRANSACTION

The asset transfer between blockchains is a difficult problem, especially the alliance chain and private chain, which leads to the inability of effective interconnection between blockchains and the formation of an ''island of value'' actively or passively. Therefore, cross-chain technology has also been concerned with and explored by people. Cross-chain technology can be widely used in cross-chain data interaction, asset transfer and other scenarios. At present, there are three mainstream cross-chain technologies: Notary mechanism, Hash locking and side chain / relay [24].

1) NOTARY MECHANISM

The notary mechanism is a centralized cross-chain model, and the two sides of the cross-chain blockchain build trust through a trusted third party. The notary is a node or organization with high credibility jointly selected by both parties of the transaction. The notary is only responsible for verifying the legitimacy and consistency of the transaction information, and does not participate in the transaction details. The biggest feature of the notarial mechanism is that it does not pay attention to the structure and consensus mechanism of cross-chain parties. The representative schemes are Interleaver and Corda [25].

2) HASH LOCKING

Hash locking technology realizes cross-chain interaction of different blockchains by setting triggers for mutual operation among different chains [29]; the basic process of hash locking is account an on-chain x generates random number and sends Hash (s) to account B on-chain Y; account a locks currency on-chain X and sets conditions. If chain x receives s in time ta (current time +2x), transfer If the account is sent to account B, it will be returned to account a; If account B receives Hash (s) and sees account A's lock and time setting, it will lock and set currency in chain Y, and set conditions. If it receives s in chain y within time T_A-x, it will be transferred to account a, otherwise it will be returned to account B; If account A sees account B is locked, it will send s to chain Y within time T_A-x to get currency in chain Y; If account B receives s, it will send currency in chain Y within time T_A Send s to chain x to get the coin of chain X. However, the information exchange cost of Hash locking technology is high, and the security is insufficient.

3) SIDECHAINS / RELAYS

The concept of the side chain and protocol implementation scheme was first proposed in enabling blockchain innovations with pegged sides in 2014 [27]. The original intention is to expand the function of blockchain. In essence, it is a

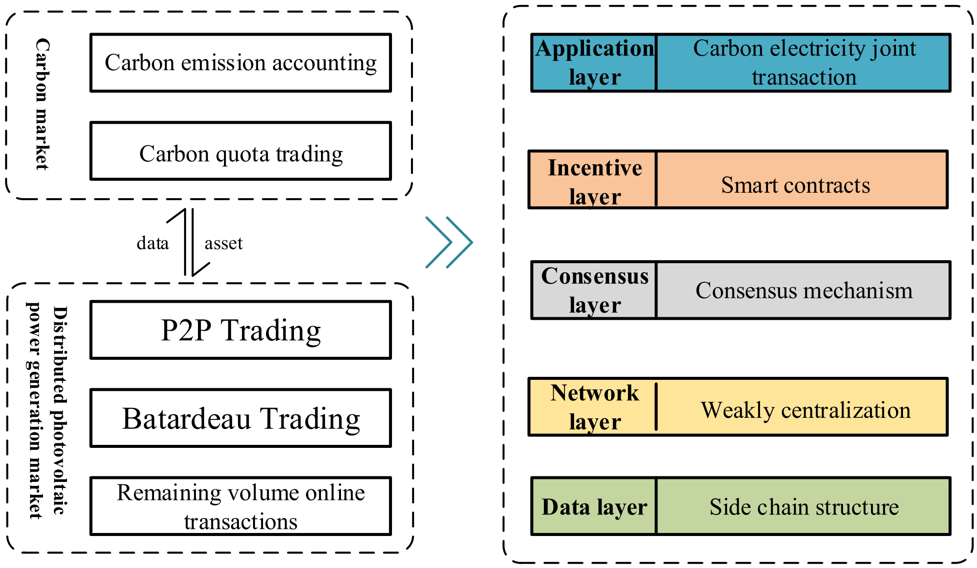


FIGURE 2. Adaptability analysis of side-chain technology in carbon electricity joint trading.

structure of one main blockchain plus one sub blockchain. The sub blockchain can view some information on the main blockchain to complete the asset transfer and circulation on the two blockchains. Besides, the technology divided into single custody, alliance anchoring, two-way anchoring and other modes [28].

B. ADAPTABILITY ANALYSIS OF SIDE CHAIN TECHNOLOGY IN CARBON AND ELECTRICITY JOINT TRADING

Considering the design requirements of distributed photovoltaic and carbon trading as well as the characteristics of blockchain, such as no tampering, distributed and intelligent, the technical route of establishing carbon electricity trading and side-chain trading is as follows:

In Figure 2, the multi-layer architecture of the blockchain can effectively solve the challenges of clearing and value circulation of PVP, and overcome the problems of carbon emission accounting consensus and carbon quota trading. Its main technical features are embodied in the following aspects:

1. Weak centralized trading network: there will be a big controversy in the realization of complete decentralized trading in China's energy market. Therefore, if the centralized trading form is adopted, the open account book of the whole network will be handed over to grid enterprises, energy regulatory departments, environmental protection departments and other institutions with a good reputation. In the power market and carbon market department, grid enterprises and carbon exchanges are completely relied on for photovoltaic Subsidy and carbon subsidy endorsement can promote more users to join these two markets.

2. Value flow of side chain technology: at present, there has been relevant research on distributed photovoltaic trading and carbon trading based on blockchain technology. The value flow between the two markets has a large space, but there is no bridge for the flow. Therefore, the side chain technology just meets the demand for a two-way flow of the distributed generation market and carbon market value. At the same time, the carbon market has small transaction volume and low data throughput, which just meets the technical characteristics of frequent side chain technology processing and small transaction. By designing the corresponding anchoring method, the data sharing and asset transfer between the power market and the carbon market can be realized, which can expand the business scope of the power market and increase the generation dividend for the PVP.

3. Transaction calculation of smart contract: Smart contract is a program, which realizes the automatic processing of the traditional contract by means of computer instructions. In short, a smart contract is a code that triggers execution when both parties trade on blockchain assets. This code is a smart contract. "Smart contract program is not only a computer program that can be executed automatically, but also a system participant. It can respond to the received information, receive and store the value, and also send out the information and value. This program is like a person who can be trusted, who can temporarily keep assets and always perform operations according to prior rules [38], [42].

The transaction situation of the carbon market and distributed photovoltaic market is complex. Adding smart contract in the block and coding the contract and transaction rules can ensure the effectiveness of power transaction and carbon transaction. Besides, considering that the mechanism of these two markets is not yet perfect, the plasticity of smart contracts can be updated and upgraded simultaneously with policy reform.

Smart contracts can also realize transaction clearing between nodes, so that point-to-point transactions can be carried out between different trading entities such as different PVP and CEC, and consensus incentive and photovoltaic scheduling in the day market can also enter the application of smart contracts.

IV. JOINT TRADING MODEL OF DISTRIBUTED OPTICAL POWER GENERATION MARKET AND CARBON MARKET

There are many researches on the separate operation of carbon trading chain and electricity trading chain. In the following scenarios where there are asset transfer and data sharing between them, a joint trading model of distributed photovoltaic power generation market and carbon market is constructed to research the underlying technology of the chain structure. In addition, a two-way anchoring technology of carbon trading chain and electricity trading chain designed by us is also introduced.

A. PRIMARY AND SECONDARY CHAIN TRANSACTION STRUCTURE

According to the double chain structure of the side chain, the trading data of PVP is stored in the main chain, and the data of carbon trading is stored in the side chain, aiming to expand its functions without changing the parameters and structure of the main chain. The main chain and side chain structure are shown in the following figure:

In FIGURE 3, the main chain of block chain is the electric energy trading chain, and the side chain is the carbon trading chain. The electricity trading chain mainly records the trading information of the PVP market in a certain region, and the carbon trading chain records the carbon emission situation and carbon trading information of the carbon emission regulatory objects in that region. The generation time scale of blocks in the two chains is different. The electric trading chain generates blocks in a short time step, such as seconds or minutes, while the block generation speed of the carbon trading chain may be days/ blocks or weeks/blocks. The electricity trading chain is generated according to the real-time scheduling of the day ahead market of electricity, and the carbon trading chain block is generated according to the clearing cycle of the regulatory authority. At present, the block generation rate of the mainstream blockchain platform can meet the time requirements of the clearing process of these two markets. The data and value exchange between the carbon trading chain and the electricity trading chain needs specific anchoring mechanism.

The specific block information is shown in the FIGURE 3. The blockheads of both blocks contain the Hash value of the previous block, that is, the length of the previous block is 256 bits except for the block area, the timestamp is the block time information, and the nonce is the account transaction serial number. The difference is that there is a Meckle tree in the electricity trading chain, and there are photovoltaic trading subtrees and cross-chain trading subtrees below. There are two subtrees in the carbon trading chain, root EOC is the subtree used to record carbon emission data, and root TOC is the subtree used to record carbon trading information.

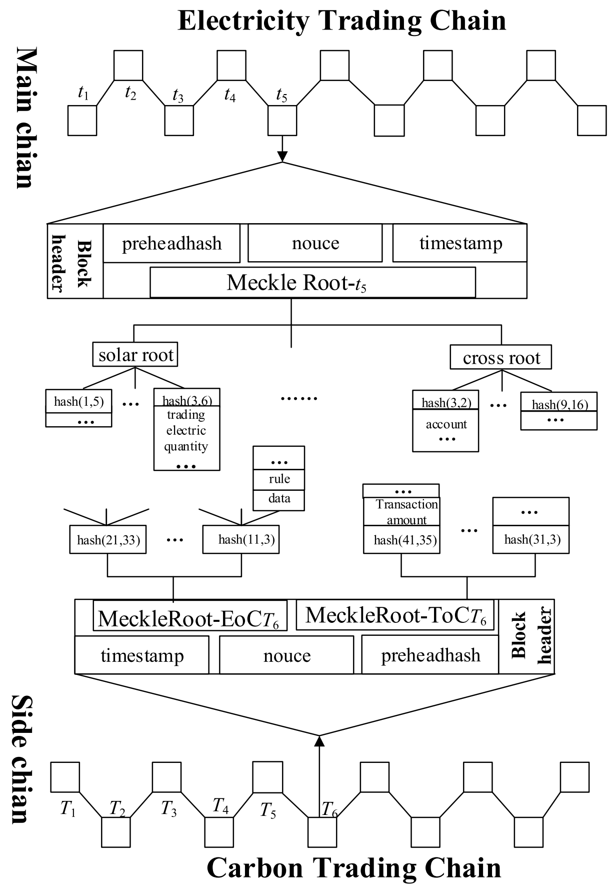


FIGURE 3. Double chain structure and block information.

The EOC root in the carbon trading chain represents the carbon emission accounting information, specifically the carbon emission of the carbon regulatory object in different unit time. The TOC root includes the carbon trading information, and the Hash (x, y) represents the carbon quota sold by the carbon regulatory object x to y and calculates the Hash value of the transaction. The tree structures in both chains are encrypted by the Hash algorithm to ensure that the data of the transaction and the record are not tampered with.

B. UNDERLYING TECHNOLOGY ARCHITECTURE

This section introduces the blockchain technology architecture of the joint trading model of the markets, including the reading and analysis of data across the chain, and the two-way anchoring technology of carbon and electricity prices to realize the transfer of assets on the two chains, the base layer of the consensus layer and the data layer is also specified.

✓ A Data cross-chain reading and analysis

The data reading process of the carbon trading chain and the electricity trading chain is shown in the figure:

As shown in the FIGURE 4, it is assumed that Node A in the carbon trading chain sends a data retrieval request with signature to the full Node B in the electricity trading chain [39]. The full Node B includes all power transaction

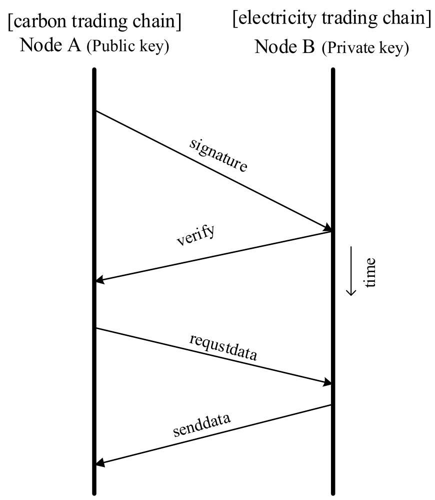


FIGURE 4. Cross-chain data reading.

information. In order to ensure the security of communication, the Elliptic curve digital is used between the Nodes signature algorithm [30]. Node A sends a signature and data request. By default, the data calls all transactions in the PVP market that contain Node A on the electricity transaction chain. B verifies that A's signature is sent to A, and B retrieves it. The transaction data related to A in its own Merkle tree is packaged and sent to A.

After Node A gets its own transaction data, it can broadcast it to the Nodes in the entire network, and the miner establishes the correlation analysis between the electricity price and the carbon price according to the Copula function theory.

Copula function can be uniquely determined by the joint probability distribution between random variables. It describes the information of the dependency structure between random variables in addition to variable edge distribution information in the multivariate joint probability distribution [31], [32]. The steps are briefly described as follows:

i. Determine the cumulative distribution function of carbon and electricity prices and calculate the kernel density.

$$\begin{aligned} &\mathrm{X} \in (x_1, x_2, \cdots, x_n, x \in X) \\ &\mathrm{Y} \in (y_1, y_2, \cdots, y_n, y \in Y) \end{aligned} \tag{2}$$

In formula (2), X and Y denote that the electricity market clearing price and carbon trading price are random variables, $(x_1, x_2, \ldots x_n)$ and $(y_1, y_2, \ldots y_n)$ are the sample space of electricity price and carbon price, n is the sample size.

$$\begin{aligned} H(x_1, x_2, \cdots, x_n, y_1, y_2, \cdots, y_n) \\ = C\left[F_{x1}(x_1), F_{x2}(x_2), \cdots, F_{\mathrm{yn}}(y_n)\right] \end{aligned} \tag{3}$$

In formula (3), C is a Copula function of electricity price and carbon price, F_{x1} (x_1) is an edge distribution function, $H(x_1, x_2, \ldots x_n, y_1, y_2, \ldots y_n)$ is a joint distribution function.

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K(\frac{x - x_i}{h}) \tag{4}$$

In formula (4): h is a smoothing coefficient; K $(\cdot)$ is a kernel function, and the symmetric unimodal probability density function centered on 0 is usually selected.

ii. Distribution transformation.

The edge distribution F $_{(\mathrm{X})}$ is transformed into a uniform distribution U, for r has:

$$P_{(F(x) \le r)} = P_{[x \le F^{-1}(r)]} = r \tag{5}$$

$$X = F_x^{-1}(U) \Leftrightarrow U = F_{(x)} \tag{6}$$

where P $[\cdot]$ represents the probability of $\cdot$.

iii. Find the joint probability density of electricity price and carbon price.

Under the premise that the random variable obeys the normal distribution, the Pearson linear correlation coefficient $\rho_{\,(\mathrm{x,y})}$ is a measure of the correlation between the carbon price and the electricity price, which is defined as follows:

$$\rho_{(x,y)} = \frac{C_{(x,y)}}{\sqrt{\delta_{(x)}^2 * \delta_{(y)}^2}} \tag{7}$$

In formula (7): $C_{(x,y)}$ is the covariance; $\delta_{(x)}$, $\delta_{(y)}$ are the variances; it is more reasonable to use the Spearman rank correlation coefficient ρ_{spearman} with better performance to reflect the dependence of random variables. For a random variable with a cumulative distribution function of F $(\cdot)$, P is a non-parametric rank statistical parameter that is equivalent to the Pearson linear correlation coefficient of the respective ranks of the random variables after the ranking. For a random variable with a normal joint distribution, there is a definite relationship between ρ_{spearman} and ρ. The calculation method for ρ_{spearman} (x, y) is as follows:

$$\begin{aligned} \rho_{spearman}(x, y) &= \rho\left[F_X(x), F_Y(y)\right] \\ &= \rho_{s(X,Y)} = \frac{6}{\pi}\arcsin\frac{\rho}{2} \end{aligned} \tag{8}$$

In formula (8), Calculate the Spearman rank correlation coefficient ρ_{spearman} of the electricity price and the carbon price and use the maximum likelihood estimation method to obtain the unknown parameters of the Copula function, so as to obtain the joint probability density of the electricity price and the carbon price. Aiming at the Copula function, finally, the Monte Carlo simulation sampling is used to obtain the correlation in electricity and carbon price random vectors. After the correlation analysis of Node A on the carbon trading chain, the carbon price is more targeted in the bilateral auction.

✓ CONSENSUS LAYER OF CARBON-ELECTRICITY JOINT TRADING

The current mainstream consensus mechanisms include POW, POS, DPOS, etc. [34], [35]. The consensus mechanism represented by POW consumes a lot of energy, and the calculation results have no meaning and are criticized. In the joint trading model of the PVP market and the carbon market, we designed a consensus mechanism for carbon price copula function analysis and POW fusion. The competition algorithm for the bookkeeping rights of each node is as follows:

$$A_{\mathrm{C\cdot H}} = (v, R_i, k_i) \leq d_v + d_{\mathrm{base}} \quad (9)$$

In formula (9), $A_{\mathrm{C\cdot H}}$ is the Hash and copula correlation function, v is the dimension of the correlation analysis variable, R_i is the root Hash of all the data packed into the block by Node i, K_i is the random number that Node i needs to find, and d_v is the calculation difficulty of the correlation analysis, d_{base} is the default base difficulty of the system. Under the competitive accounting right algorithm proposed by formula (9), the rules for a Node to obtain a complete accounting are as follows:

1) Node i first packs all the data and calculates the root Hash R_i of the transaction data;

2) Node i finds random numbers that meet the requirements in an enumerated manner. When it is found that $\mathrm{k}_i = \mathrm{k}_{i'}$ makes formula (9) true, k_i is recorded in the block and the block is broadcast to the entire network;

3) After the other Nodes receive the block broadcasted by Node i, according to the legality of formula (9), and verify the correctness of the data contained in the block. If the verification is passed, the block is added to the blockchain, and Node i obtains the transaction fee for all transactions in the block to compensate for the electricity cost caused by its mining and obtain a certain income; otherwise, the block was abandoned.

The above consensus mechanism has the following advantages: On the one hand, Node A can broadcast the data it obtains, and the Nodes on the entire network carry out calculations, avoiding the waste of computing power of POW. On the other hand, it is appropriate to reduce the difficulty of POW's target calculation, aiming to distinguish the computing power of Nodes in the entire network, to avoid the difficulty of distinguishing the accounting rights caused when the calculation target of copula association analysis is too simple.

✓ NETWORK LAYER

In order for all nodes in the system to reach a consensus on the results of bookkeeping rights, the POW verification mechanism remains unchanged, What needs to be explained is the verification method for copula association analysis:

$$AIC = -2 * A + \frac{2}{T} * P \quad (10)$$

In formula (10), We use the AIC criterion for correlation testing [36]. Where A represents the maximum likelihood function, T represents the sample size, and P represents the number of parameters of the fitting function. AIC contains information about model and parameter estimates. The smaller the value, the better the fitting effect. If the AIC of the new block calculated by the node is the smallest and the POW completion speed is the fastest, all nodes confirm the block. Complete network analysis and POW nodes in the network as a priority. They will obtain accounting rights, package transaction information into blocks, and broadcast transactions.

C. TWO WAY PEG TECHNOLOGY FOR CARBON TRADING CHAIN AND ELECTRICITY TRADING CHAIN

The carbon and the PVP market have value circulation in the following scenarios:

1. Carbon trading internal clearing: that is, the buyer and seller is CEC, and the carbon quota sold by the seller can be settled in the form of electricity fees on the electricity transaction chain, And pay electricity charges for the electricity used by the seller in the future, and can also be transferred back to the carbon trading chain;

2. Cross-market clearing, the buyer is a CEC, and the seller is a PVP. Similarly, the seller can choose to settle on the trading chain, or return to the carbon trading chain for settlement; buyers and sellers can complete carbon trading without entering the carbon exchange to pay handling fees. Realizing the above value circulation requires the two-way anchoring technology in the side chain.

It should be noted that the distributed photovoltaic power generation market and the carbon market are jointly cleared. The order of clearing is that the carbon market is prioritized internally, and the surplus carbon quota is cleared with the distributed power generation market.

The two-way peg process is as follows:

After the trading entities A and B successfully complete the auction, the smart contract is started to lock the carbon trading funds that A will pay to B. At the same time, the carbon trading chain sends a certificate with SPV to the electricity trading chain and verifies the carbon trading chain. The funds on the account have been locked, and digital assets with the same value are opened on the electricity trading chain. On the electricity trading chain, obtains assets equivalent to the carbon transaction amount. B will choose whether to accept the electricity fee withholding service. If accepted, The transaction deduction of B in the electricity market will be paid by this part of the fee first; if it is rejected; the electricity trading chain will send a rejection message with an SPV certificate, and at the same time lock the electricity fee asset of B on the electricity trading chain, and zero the asset, the carbon trading link After the proof of rejection is reached, the transaction amount will be unlocked, the contract will be started, and A will pay the funds to B.

V. TRANSACTION PROCESS

Carbon and electricity's cross-chain transactions are mainly completed by smart contracts [38]. The smart contracts are based on the Ethereum platform, and the platform is open-source and has strong development ability. It can develop and apply personalized solutions for different projects. By allowing the full language to be used on the blockchain, Ethereum has created a platform to run more complex contracts on the network. In many cases, third-party services are not required. This makes Ethereum a complete package, different from other blockchains [40], [41]. And are deployed on two blockchains after being compiled and tested for security and other conditions.

The TABLE 2 compares the features of the Ethereum with other cryptocurrencies:

TABLE 2. Comparison of features in existing blockchain platform.

Platform	Environment	Language	Consensus	Turing-complete
Bitcoin	-	Scirpt	PoW	No
Fabric	Dockers	Go, Java	PBFT, Kafka	Yes
Ethereum	EVM	Go, Solidity	PoW, PoS	Yes

The following is the pseudo-code of the main algorithm for carbon-electricity joint trading:

Algorithm 1 Carbon and Electricity Joint Trading Algorithm

Carbon trading blockchain: **C**, Electricity trading blockchain: **E**;
Associated Node: i, $i \in$**C**;
Data(i): Electricity trading related i;
if (cross-chain trading is valid) **then**
  SendRequest_ Data (i) $\rightarrow$**E**;
  Package_ Data (i) $\leftarrow$ Data (i), Run cross-chain data smart contract;
  PublicNetwork{Package_ Data (i),POW($diff$)};
  PublicNetwork{carbon emiss(i)};
  miner check(value){carbon emiss(i)}; return(value));
  miner calculate{Package_ Data (i),POW($diff$)};
  if(HeadHash<TargetValue & Min[AIC]& carbon emiss(i)== value);
    publish the data to blockchain;
    return block Number;
  else
    return: "Error Message";
  end if
else
  return "Blockchain runs respectively";
end

1) When cross-chain transactions are legal, Node i on carbon trading chain C sends a data request to electric transaction chain E. The consensus is achieved by the oracle which deployed on every Node. More than 51% the oracle voted the requirement through, Node i can access to data;

2) E will retrieve the transaction history related to i on the entire chain, and package and send related data to it, and start the smart contract for data transmission;

3) Broadcast the data of i to the Nodes of the whole network, and the difficulty of broadcasting POW at the same time. The algorithm of POW can be described as follows: in a period of time, there are multiple servers to package the transactions in this period of time, and after the completion of the package, the block header information is combined with the SHA 256 algorithm for operation. There is a variable nonce in the block header and the reward transaction coinbase. If the result of the operation does not meet the difficulty requirements, adjust the value of nonce to continue the operation. If a server is the first to calculate a block that meets the difficulty value, it can broadcast the block. After other servers are verified to be corrected, they can be added to the existing blockchain, and then we can compete for the next block together. This process is also known as mining [43].

4) Node i broadcasts its own carbon emission data, and the miners verify the carbon emission data and return a verification value;

5) The entire network of miners began to perform copula analysis and proof of workload for carbon and electricity prices.

6) If the proof of work and the AIC value calculated by the miner is the smallest, it is also necessary that the carbon emissions of Node i need to be consistent with the check value, and then a block can be generated and connected to the chain; otherwise, a report of information error needs to be returned.

The above code completes the main framework of cross-chain transactions, but the specific transfer of assets in cross-chain transactions require further analysis. The following is the pseudo-code of the asset transfer algorithm for carbon and electricity transaction chains in cross-chain transactions:

Algorithm 2 Cross-chain trading Smart Contract Algorithm

Carbon seller: x, number of seller: N, Carbon buyer: y, number of buyer: M.
Carbon trading blockchain: C, Electricity trading blockchain: E;
Initial cross-chain data smart contract;
for ($x \leq N$ & $y \leq M$)
$i \leftarrow$ copula function(x, E);
x quote, y quote;
x++, y++,Bid Matching(x, y)
  if(carbon quote is clear out)
  initial payment;
  if (x send transfer request & SPV)
    initial payment;
    lock asset of x in C;
create asset of y in E, amount of money: G(x);
    while (**G**(x) $\geq$0 or cancel is null) **do**
    x has the priority to use the amount to pay electricity
    end while
  if (SPV of cancel is valid)
    $G(x) = G(x, T)\text{-}G_{used}(x, T{+}n,)$
    lock asset of y in E;
    unlock asset of x in C, update G(x).
  end if
end

Through the above algorithm, the asset transfer between the carbon trading chain and the electricity trading chain-chain can be summarized as the following process:

1) After launching a smart contract for cross-chain trading in the previous main algorithm, initialize the contract;

2) Call the copula function and return the analysis result to Node *i*.

3) The members of seller set *N* and buyer set *M* begin to perform bilateral transaction auction matching;

4) If the carbon transaction has been cleared, start the payment process;

5) Otherwise, if seller *x* submits an asset transfer request and the SPV proves legal [37], the payment is locked and the carbon transaction amount obtained by *x* on the carbon trading chain is locked. At the same time, a corresponding account is generated on the electricity trading chain and an equivalent amount is generated. Currency anchoring

6) When the amount on the electricity trading chain has not been cleared or the asset cancellation order is illegal, the user of *x* and the priority use this amount to pay electricity fees on the electricity trading chain

7) If the SPV certificate of the cancellation order is passed, the balance is settled and the assets on the electricity trading chain are locked at the same time.

8) Settle the assets on the carbon trading chain, but the asset value of seller *x* on the carbon trading chain needs to be updated.

Through the above algorithm, the security of funds on the two chains can be guaranteed. It has the following two advantages. On the one hand, it is the sharing of carbon price and electricity price data. Bids are more effective; on the other hand, the transfer of funds back and forth gives carbon trading parties more choices, making transactions more flexible, and expanding the business scope of the PVP market.

VI. CASE STUDY

In order to verify the effectiveness of the cross-chain transaction mechanism proposed in this article, tests were conducted on the Ethereum platform, and smart contract deployment tests were conducted through the Metamask and remix. Core CPU, 16GB memory server, test network is Ropsten and local private chain. In this section, the improved IEEE33 node system such as FIGURE 6 is used to simulate the transaction process. With the original load and line parameters unchanged, CEC are added at Nodes 5, 11, 12, 22, and PVP are added at Nodes 6, 14, 18, 20, 24 32. The historical transaction data of electricity and carbon prices in China's Fujian Province is shown in FIGURE 7.

From the FIGURE 13, the sidechain is initialized. The initialization of side chain includes starting P2P nodes, allocating memory and files, initializing the structure of blockchain and initializing the contracts in Ethereum. It can be seen that the P2P network has been started and the terminal of IPC has been opened

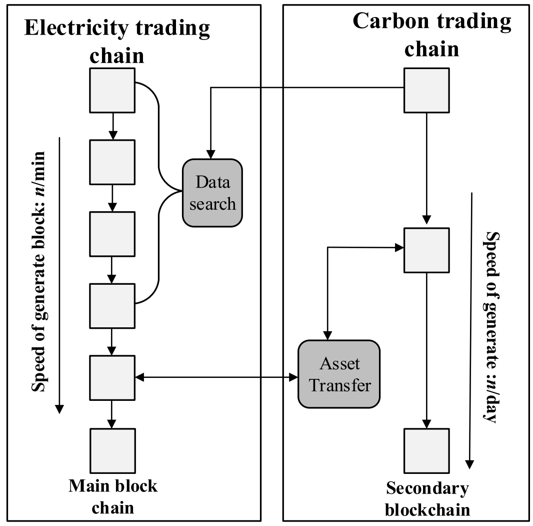


FIGURE 5. Two-way anchoring technology.

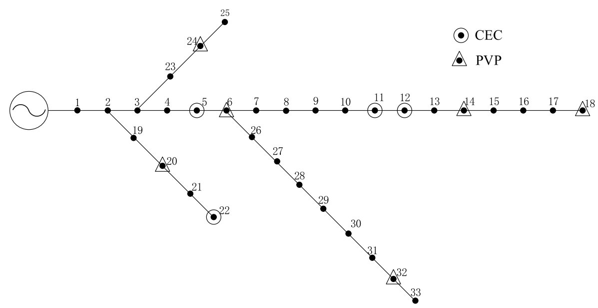


FIGURE 6. The improved IEEE33 node system.

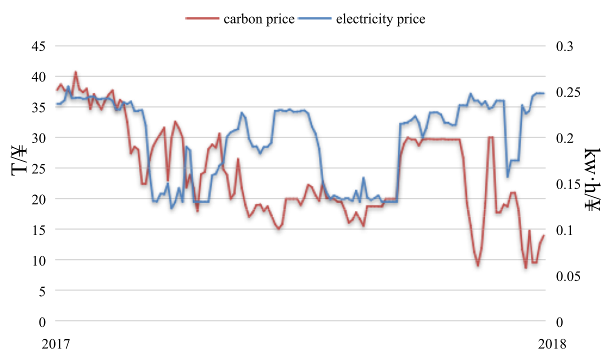


FIGURE 7. Historical data on electricity and carbon prices.

A. CORRELATION ANALYSIS BETWEEN CARBON PRICE AND ELECTRICITY PRICE

The data of carbon price and electricity price come from the historical data of a carbon trading market and distributed power generation transactions in a certain province in China. After obtaining data from a certain node, the data is broadcast to the nodes in the entire network. Copula correlation test result of the lowest AIC value:

In the FIGURE 8 and FIGURE 9, the correlation between the carbon price and the electricity price historical data

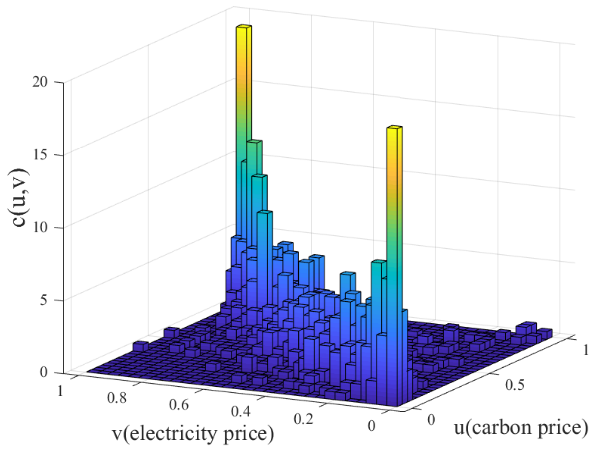


FIGURE 8. Sample Frequency Histogram.

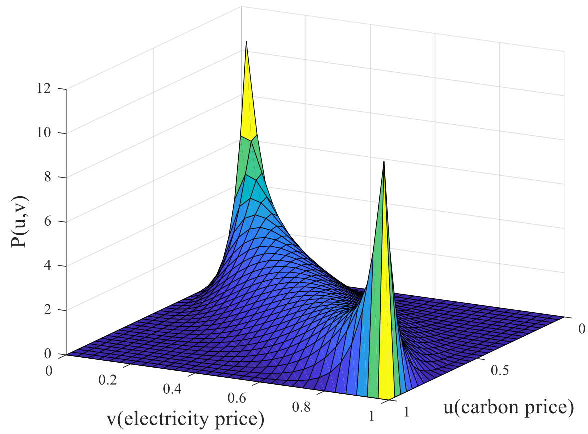


FIGURE 9. Joint Frequency Density Function Graph.

samples at the corresponding time is large. The distribution of the carbon price and the electricity price is U-shaped, with a top-bottom correlation, and its joint density function has an approximately symmetrical tail. Copula correlation analysis Recommendations for effective carbon price bidding can be given for the blocks on the current carbon trading chain.

TABLE 3. Market member information.

Node number	Estimated carbon quota	Consensus check value
5	-1532	-1455
11	341	341
12	-265	-261
22	154	134
6	213	213
14	456	456
18	99	94
20	36	41
24	87	87
32	395	350

B. CARBON AND ELECTRICITY JOINT TRADING PROCESS AND RESULTS

1) BEFORE CROSS-CHAIN TRANSACTIONS

Take a carbon quota clearing process as an example to simulate the cross-chain transaction process. A negative sign indicates that the carbon emissions exceed the standard, and a positive sign indicates that the converted carbon quota of the PVP does not exceed the benchmark. To participate in the sale. Each node publishes an estimated carbon quota value, and other nodes in the network check to get a consensus check value. The information of market members before cross-chain transactions is as the TABLE 3.

It can be seen from the TABLE 4. that compared to the quotation on the traditional carbon trading, on the blockchain platform, the buyer nodes 5 and 12 have undergone copula correlation analysis, and the carbon quotation is more reasonable, that is, the difference between the price quoted by the seller and the seller is smaller. At the same time, it can be seen that the bidding space offered by the buyer is more stable, and the matching of the seller's bid is better. The subjects of transactions with different attributes obviously need to conduct cross-chain transactions, and node 5 and Node 11 both belong to the carbon trading chain, and Node 11 still sends an application for cross-chain transactions in this transaction,

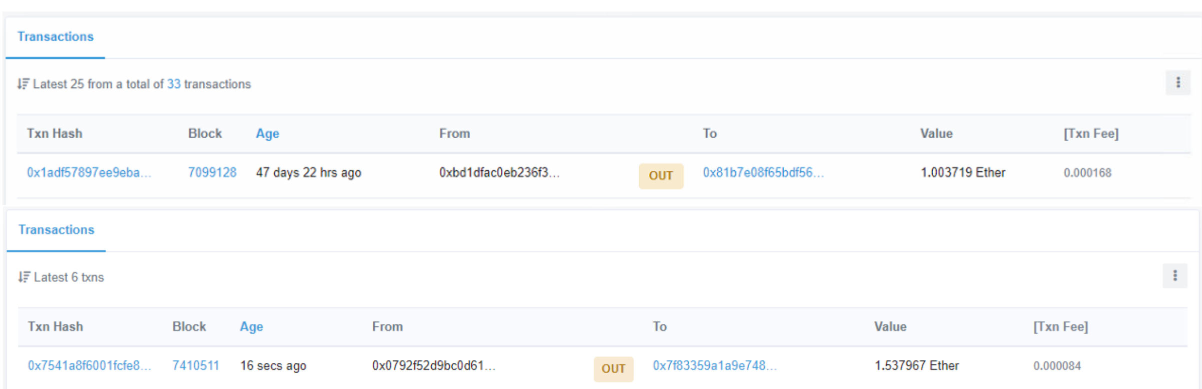
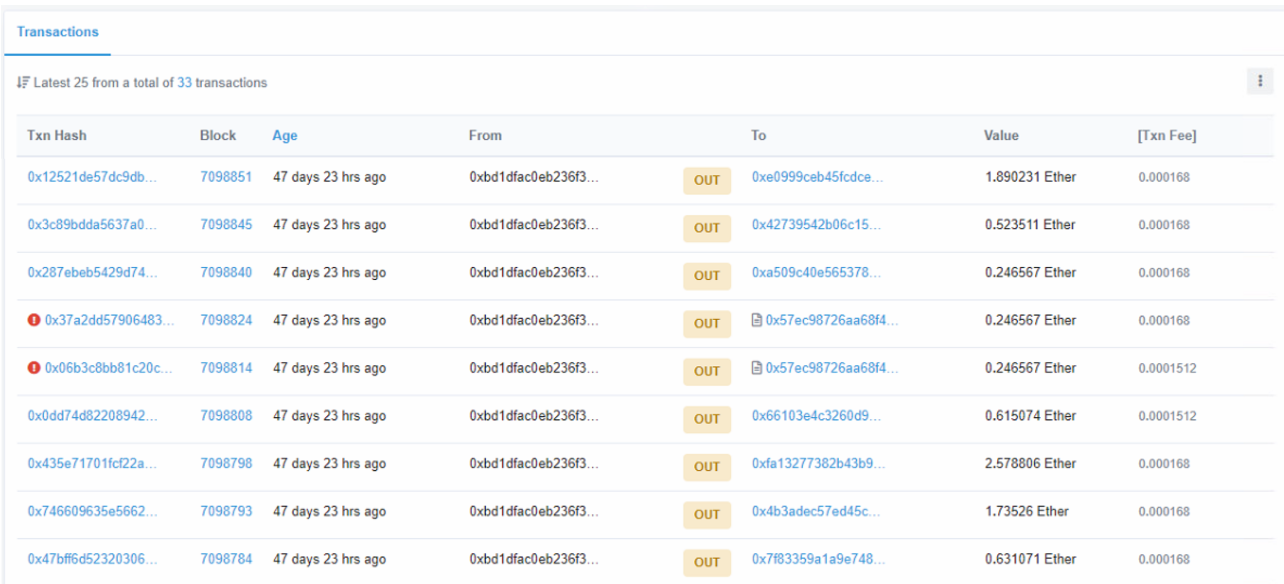


FIGURE 10. Transaction without submitting a cross-chain request.

TABLE 4. Carbon trading clearance results.

Counterparty		Carbon turnover (T)	Quotation (Carbon trading) (USD)		Quotation (Blockchain) (USD)		Final price (USD)	Turnover (USD)	Whether Node can make cross-chain requirements
Buyer	Seller		Seller	Buyer	Seller	Buyer			
5	11	85	5.05	7.06	6.26	6.98	6.06	515.32	yes
5	22	134	5.54	6.69	6.26	6.73	6.11	819.61	no
5	6	213	7.84	6.89	5.97	7	6.65	1416.98	yes
5	14	456	4.35	4.88	4.92	5.63	4.61	2105.8	yes
5	18	94	4.99	5.69	6.07	6.85	5.34	502.257	yes
5	20	41	4.04	5.77	4.97	7.12	4.91	201.342	yes
5	24	87	4.24	5.58	6.31	6.81	4.91	427.48	yes
5	32	350	4.05	4.76	6.06	6.16	4.41	1543.52	yes
12	11	256	4.68	5.12	6.32	6.57	4.9	1255.87	no


Transactions

Latest 25 from a total of 33 transactions

Txn Hash	Block	Age	From		To	Value	[Txn Fee]
0x12521de57dc9db...	7098851	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0xe0999ceb45fcdce...	1.890231 Ether	0.000168
0x3c89bdda5637a0...	7098845	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x42739542b06c15...	0.523511 Ether	0.000168
0x287ebeb5429d74...	7098840	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0xa509c40e565378...	0.246567 Ether	0.000168
0x37a2dd57906483...	7098824	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x57ec98726aa68f4...	0.246567 Ether	0.000168
0x06b3c8bb81c20c...	7098814	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x57ec98726aa68f4...	0.246567 Ether	0.0001512
0x0dd74d82208942...	7098808	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x66103e4c3260d9...	0.615074 Ether	0.0001512
0x435e71701fcf22a...	7098798	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0xfa13277382b43b9...	2.578806 Ether	0.000168
0x746609635e5662...	7098793	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x4b3adec57ed45c...	1.73526 Ether	0.000168
0x47bff6d52320306...	7098784	47 days 23 hrs ago	0xbd1dfac0eb236f3...	OUT	0x7f83359a1a9e748...	0.631071 Ether	0.000168

FIGURE 11. Transaction with submitting a cross-chain request.

that is, to start the smart contract for electricity fee generation. In the transactions of Nodes 12 and 11, Node 11 did not send a request because the cross-chain transactions with relatively small transaction amounts are more secure, and the local preservation of large amounts of funds can improve its own capital circulation.

2) CROSS-CHAIN TRANSACTION RESULTS

The main chain (electricity trading chain) runs in the Ropsten test environment, and the side chain (carbon trading chain) runs in the loom API. Due to the limited Ethereum resources in the current Ropsten test environment, we selected 2018.5.5 USD and Ethereum. The conversion rate 1Eth = 816.58USD is the settlement exchange rate. The trading results are shown in the figure below:

From FIGURE 10 and FIGURE 11, it can be seen that the buyer and seller of each transaction have unique Hash addresses, and each transaction requires an additional handling fee, every transaction has its own Hash address, the amount of transaction and height of block are also known, height of block represents the order of the block.

The transaction on Ethereum, which is called gas, is not an integer. It also provides monetary support for accurate settlement in transactions. FIGURE 10 shows two transactions for which no cross-chain transaction request was provided, Node 5 and Node 11, and Node 12 and Node 11. Both transactions were performed on the carbon trading chain.

In the FIGURE 11, an application for cross-chain transaction was submitted. Node 5 submitted 7 cross-chain transactions, and two of the cross-chain transactions failed when transferring to a smart contract. The third transfer was successful, because loom network may be delays in the test network, resulting in unconfirmable transactions. Therefore, the stability of the test network needs to be further strengthened.

C. CROSS-CHAIN TRANSACTION FEES

Each transaction on the Ethereum platform costs gas, that is, the handling fee of the transaction and the payment by the transaction initiator. In addition, we also perform a lot of cost statistics of cross-chain transactions and on-chain transactions. The statistical results are shown in the following figure:

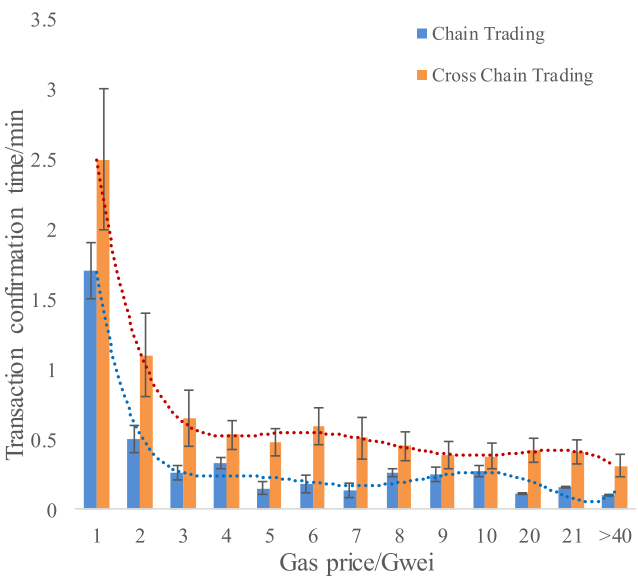


FIGURE 12. Cross-chain transaction fees.

Both types of transactions in the FIGURE 12. consume gas, and a unit of gas price is GWei [55]. It can be seen that the high amount of fees will speed up the block confirmation speed and allow miners to package transactions into the block earlier, but there is a bottleneck in the increase in transaction speed, even if the fees are too high. The amount of handling fee cannot greatly shorten the confirmation time of the transaction. In addition, the block confirmation time of cross-chain transactions is significantly longer than that of on-chain transactions. Furthermore, the time fluctuation range under the same transaction fee is also larger than on one chain. However, for the transaction time requirements of carbon and electricity trading chains, such cross-chain transaction time is acceptable.

We recommend that sellers on small carbon trading chains do not need to conduct cross-chain transactions, because higher transaction fees will reduce the economics of the transaction. There is not a systematic method of calculating the transactions cost, but it is very clear that the cross chain transaction needs to set a higher handling fee in order to allocate enough resources for the miner in the two chains to support the successful transaction, otherwise it will fail.

VII. CONCLUSION

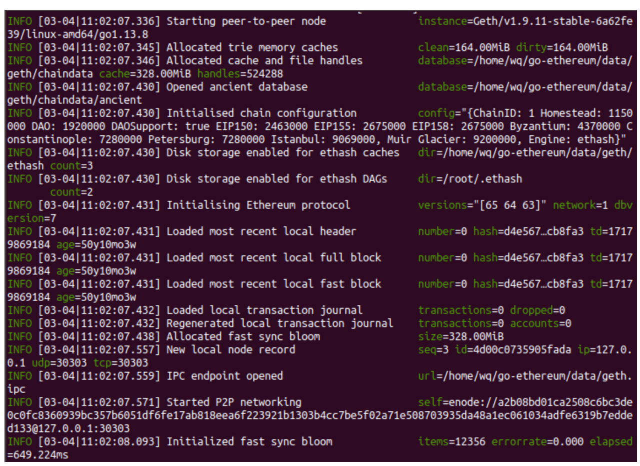
This paper proposed a operation mechanism of electricity and carbon trading market based on cross-chain trading technology. This mechanism is expected to be jointly traded in the carbon market and the distributed photovoltaic power generation market with the support of blockchain technology. We have also designed the underlying technologies of cross-chain transactions, including cross-chain data sharing and correlation analysis of electricity and carbon prices, and the coding of carbon and electricity joint transactions through smart contracts, and finally based on the Ethereum platform conducts simulated transactions and demonstrates the feasibility of two types of markets in cross-chain transactions.

Through the test of simulated transactions, joint trading of carbon and electricity markets is achievable, and cross-chain data sharing can make bilateral auctions in carbon trading more efficient, and the transaction costs of cross-chain transactions are higher than general on-chain transactions. This is also a problem that buyers and sellers should pay attention to when performing cross-chain transactions. The study strengthens the marketization degree of distributed photovoltaic power generation, reduces the dependence on government subsidies, widens the way to make profits. The study also confirmed that it is suitable to carry out pilot projects to explore the feasibility of electricity trading and carbon trading integration.

In future research, we will conduct transactions with greater throughput and expand the transaction volume of the two markets to meet the transaction needs of the larger market.

APPENDIX

See Figure 13.



```
INFO [03-04|11:02:07.336] Starting peer-to-peer node               instance=Geth/v1.9.11-stable-6a62fe
39/linux-amd64/go1.13.8
INFO [03-04|11:02:07.345] Allocated trie memory caches             clean=164.00MiB dirty=164.00MiB
INFO [03-04|11:02:07.346] Allocated cache and file handles         database=/home/wq/go-ethereum/data/
geth/chaindata cache=328.00MiB handles=524288
INFO [03-04|11:02:07.430] Opened ancient database                  database=/home/wq/go-ethereum/data/
geth/chaindata/ancient
INFO [03-04|11:02:07.430] Initialised chain configuration          config="{ChainID: 1 Homestead: 1150
000 DAO: 1920000 DAOSupport: true EIP150: 2463000 EIP155: 2675000 EIP158: 2675000 Byzantium: 4370000 C
onstantinople: 7280000 Petersburg: 7280000 Istanbul: 9069000, Muir Glacier: 9200000, Engine: ethash}"
INFO [03-04|11:02:07.430] Disk storage enabled for ethash caches   dir=/home/wq/go-ethereum/data/geth/
ethash count=3
INFO [03-04|11:02:07.430] Disk storage enabled for ethash DAGs     dir=/root/.ethash
      count=2
INFO [03-04|11:02:07.431] Initialising Ethereum protocol           versions="[65 64 63]" network=1 dbv
ersion=7
INFO [03-04|11:02:07.431] Loaded most recent local header          number=0 hash=d4e567…cb8fa3 td=1717
9869184 age=50y10mo3w
INFO [03-04|11:02:07.431] Loaded most recent local full block      number=0 hash=d4e567…cb8fa3 td=1717
9869184 age=50y10mo3w
INFO [03-04|11:02:07.431] Loaded most recent local fast block      number=0 hash=d4e567…cb8fa3 td=1717
9869184 age=50y10mo3w
INFO [03-04|11:02:07.432] Loaded local transaction journal         transactions=0 dropped=0
INFO [03-04|11:02:07.432] Regenerated local transaction journal    transactions=0 accounts=0
INFO [03-04|11:02:07.438] Allocated fast sync bloom                size=328.00MiB
INFO [03-04|11:02:07.557] New local node record                    seq=3 id=4d00c0735905fada ip=127.0.
0.1 udp=30303 tcp=30303
INFO [03-04|11:02:07.559] IPC endpoint opened                      url=/home/wq/go-ethereum/data/geth.
ipc
INFO [03-04|11:02:07.571] Started P2P networking                   self=enode://a2b08bd01ca2508c6bc3de
0c0fc8360939bc357b6051df6fe17ab818eea6f223921b1303b4cc7be5f02a71e508703935da48a1ec061034adfe6319b7edde
d133@127.0.0.1:30303
INFO [03-04|11:02:08.093] Initialized fast sync bloom              items=12356 errorrate=0.000 elapsed
=649.224ms
```

FIGURE 13. Initialize the sidechain.

REFERENCES

[1] *On Improving the Feed-in Tariff Mechanism for Photovoltaic Power Generation Notice of Issues*, Nat. Develop. Reform Commission, Beijing, China, 2019. [Online]. Available: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201904/t20190430_962433.html

[2] *Notice on the Price Policy of Photovoltaic Power Generation Projects in 2018*, Nat. Develop. Reform Commission, Beijing, China, 2017. [Online]. Available: https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171222_960932.html

[3] *Notice on Leveraging Price Leverage to Promote the Healthy Development of the Photovoltaic Industry*, Nat. Develop. Reform Commission, Beijing, China, 2019. [Online]. Available: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201308/t20130830_963934.html

[4] *Energy—Power and Energy Systems; Study Findings from Zhejiang University Broaden Understanding of Power and Energy Systems (Distributed Photovoltaic Generation in the Electricity Market: Status, Mode and Strategy)*. Atlanta, GA, USA: Energy Weekly News, 2019.

[5] S. Oliva H., I. MacGill, and R. Passey, "Estimating the net societal value of distributed household PV systems," *Sol. Energy*, vol. 100, pp. 9–22, Feb. 2014.

[6] G.-L. Luo, C.-F. Long, X. Wei, and W.-J. Tang, "Financing risks involved in distributed PV power generation in China and analysis of countermeasures," *Renew. Sustain. Energy Rev.*, vol. 63, pp. 93–101, Sep. 2016.

[7] C. Yang and L. Zuo, "Investment value analysis of household rooftop PV power generation project under carbon trading mode," in *Proc. 2nd Int. Conf. Inf. Manage. Manage. Sci. (IMMS)*, 2019, pp. 160–165.

[8] P. Siano, G. De Marco, A. Rolan, and V. Loia, "A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3454–3466, Sep. 2019, doi: 10.1109/JSYST.2019.2903172.

[9] *Energy Blockchain Labs*. Accessed: 2017. [Online]. Available: https://www.ibm.com/case-studies/energy-blockchain-labs-inc

[10] R. Brown. *A Simple Model for Smart Contracts*. Accessed: Apr. 21, 2019. [Online]. Available: https://gendal.me/2015/02/10/a-simple-model-for-smart-contracts/

[11] C. Plaza, J. Gil, F. de Chezelles, and K. A. Strang, "Distributed solar self-consumption and blockchain solar energy exchanges on the public grid within an energy community," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC /I CPS Eur.)*, Jun. 2018, pp. 1–4, doi: 10.1109/EEEIC.2018.8494534.

[12] J. Lin, M. Pipattanasomporn, and S. Rahman, "Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets," *Appl. Energy*, vol. 255, Dec. 2019, Art. no. 113687.

[13] K. Qu, T. Yu, L. Huang, B. Yang, and X. Zhang, "Decentralized optimal multi-energy flow of large-scale integrated energy systems in a carbon trading market," *Energy*, vol. 149, pp. 779–791, Apr. 2018.

[14] K. N. Khaqqi, J. J. Sikorski, K. Hadinoto, and M. Kraft, "Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application," *Appl. Energy*, vol. 209, pp. 8–19, Jan. 2018.

[15] S. Hartmann and S. Thomas, "Applying blockchain to the Australian carbon market," *Econ. Papers, J. Appl. Econ. Policy*, pp. 1–19, Aug. 2019.

[16] F. Zhang, H. Deng, R. Margolis, and J. Su, "Analysis of distributed-generation photovoltaic deployment, installation time and cost, market barriers, and policies in China," *Energy Policy*, vol. 81, pp. 43–55, Jun. 2015.

[17] Y. Pang, Y. He, and H. Cai, "Business model of distributed photovoltaic energy integrating investment and consulting services in China," *J. Cleaner Prod.*, vol. 218, pp. 943–965, May 2019.

[18] X.-G. Zhao, L. Wu, and A. Li, "Research on the efficiency of carbon trading market in China," *Renew. Sustain. Energy Rev.*, vol. 79, pp. 1–8, Nov. 2017.

[19] J. Jia, H. Li, J. Zhou, M. Jiang, and D. Dong, "Analysis of the transmission characteristics of China's carbon market transaction price volatility from the perspective of a complex network," *Environ. Sci. Pollut. Res.*, vol. 25, no. 8, pp. 7369–7381, Mar. 2018.

[20] "None. Partnership paves way for global carbon market," in *Nature*, vol. 450, no. 7167. Springer, 2007, p. 149.

[21] Z.-H. Feng, L.-L. Zou, and Y.-M. Wei, "Carbon price volatility: Evidence from EU ETS," *Appl. Energy*, vol. 88, no. 3, pp. 590–598, Mar. 2011.

[22] R. G. Newell, W. A. Pizer, and D. Raimi, "Carbon market lessons and global policy outlook," *Science*, vol. 343, no. 6177, pp. 1316–1317, Mar. 2014.

[23] S. Camal, A. Michiorri, and G. Kariniotakis, "Optimal offer of automatic frequency restoration reserve from a combined PV/Wind virtual power plant," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6155–6170, Nov. 2018, doi: 10.1109/TPWRS.2018.2847239.

[24] V. Buterin. (2016). *Chain Interoperability*. [Online]. Available: https://www.r3.com/wp-content/uploads/2017/06/chain_interoperability_r3.pdf

[25] R. Brown. (2018). *Blockchain Interoperability: Towards a Simpler Debate*. [Online]. Available: https://medium.com/corda/blockchain-interoperability-towards-a-simpler-debate-5064d33e9d0c

[26] I. A. Seres *et al.* 2019. *Topological Analysis of Bitcoin's Lightning Network*. [Online]. Available: https://www.researchgate.net/publication/330409502_Topological_Analysis_of_Bitcoin's_Lightning_Network

[27] A. Back, M. Corallo, and L. Dashjr. (2014). *Enabling Blockchain Innovations With Pegged Sidechains*. [Online]. Available: https://blockstream.com/sidechains.pdf

[28] L. Deng, H. Chen, J. Zeng, and L.-J. Zhang, "Research on cross-chain technology based on sidechain and hash-locking," in *Proc. Int. Conf. Edge Comput.*, 2018, pp. 144–151.

[29] Bitcoin Wiki. (2015). *Hashlock*. [Online]. Available: https://en.bitcoin.it/wiki/Hashlock

[30] D. Fan, X. Meng, Y. Wang, X. Yang, X. Peng, W. He, G. Dong, and H. Chen, "Optical identity authentication scheme based on elliptic curve digital signature algorithm and phase retrieval algorithm," *Appl. Opt.*, vol. 52, no. 23, p. 5645, Aug. 2013.

[31] C. Jiang, W. Zhang, B. Wang, and X. Han, "Structural reliability analysis using a copula-function-based evidence theory model," *Comput. Struct.*, vol. 143, pp. 19–31, Sep. 2014.

[32] Z. Q. Xie, T. Y. Ji, M. S. Li, and Q. H. Wu, "Quasi-Monte Carlo based probabilistic optimal power flow considering the correlation of wind speeds using copula function," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 2239–2247, Mar. 2018, doi: 10.1109/TPWRS.2017.2737580.

[33] C. Du, X. Wang, X. Wang, and C. Shao, "A block-based medium-long term energy transaction method," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 4155–4156, Sep. 2016, doi: 10.1109/TPWRS.2015.2497965.

[34] Y. Jiao, P. Wang, D. Niyato, and K. Suankaewmanee, "Auction mechanisms in cloud/fog computing resource allocation for public blockchain networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 30, no. 9, pp. 1975–1989, Sep. 2019, doi: 10.1109/TPDS.2019.2900238.

[35] D. Liu, A. Alahmadi, J. Ni, X. Lin, and X. Shen, "Anonymous reputation system for IIoT-enabled retail marketing atop PoS blockchain," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3527–3537, Jun. 2019, doi: 10.1109/TII.2019.2898900.

[36] S. Sriboonchitta, J. Liu, A. Wiboonpongse, and T. Denoeux, "A double-copula stochastic frontier model with dependent error components and correction for sample selection," *Int. J. Approx. Reasoning*, vol. 80, pp. 174–184, Jan. 2017.

[37] W. Dai, J. Deng, Q. Wang, C. Cui, D. Zou, and H. Jin, "SBLWT: A secure blockchain lightweight wallet based on trustzone," *IEEE Access*, vol. 6, pp. 40638–40648, 2018, doi: 10.1109/ACCESS.2018.2856864.

[38] A. Pinna, S. Ibba, G. Baralla, R. Tonelli, and M. Marchesi, "A massive analysis of Ethereum smart contracts empirical study and code metrics," *IEEE Access*, vol. 7, pp. 78194–78213, 2019, doi: 10.1109/ACCESS.2019.2921936.

[39] Y. Cao, Y. Li, Y. Sun, and S. Wang, "Decentralized group signature scheme based on blockchain," in *Proc. Int. Conf. Commun., Inf. Syst. Comput. Eng. (CISCE)*, Haikou, China, Jul. 2019, pp. 566–569, doi: 10.1109/CISCE.2019.00131.

[40] Y. Yu, Y. Li, J. Tian, and J. Liu, "Blockchain-based solutions to security and privacy issues in the Internet of Things," *IEEE Wireless Commun.*, vol. 25, no. 6, pp. 12–18, Dec. 2018, doi: 10.1109/MWC.2017.1800116.

[41] S. Wu, Y. Chen, Q. Wang, M. Li, C. Wang, and X. Luo, "CReam: A smart contract enabled collusion-resistant e-auction," *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 7, pp. 1687–1701, Jul. 2019, doi: 10.1109/TIFS.2018.2883275.

[42] H. Cho, "ASIC-resistance of multi-hash Proof-of-Work mechanisms for blockchain consensus protocols," *IEEE Access*, vol. 6, pp. 66210–66222, 2018, doi: 10.1109/ACCESS.2018.2878895.

[43] D. Gupta, J. Saia, and M. Young, "Proof of work without all the work," in *Proc. 19th Int. Conf. Distrib. Comput. Netw. (ICDCN)*. New York, NY, USA: ACM, 2018, pp. 1–10.

[44] E. Al Kawasmi, E. Arnautovic, and D. Svetinovic, "Bitcoin-based decentralized carbon emissions trading infrastructure model," *Syst. Eng.*, vol. 18, no. 2, pp. 115–130, Mar. 2015, doi: 10.1002/sys.21291.

[45] W. Hua and H. Sun, "A blockchain-basED PEER-TO-PEER TRADING SCHEME COUPling energy and carbon markets," in *Proc. Int. Conf. Smart Energy Syst. Technol. (SEST)*, Porto, Portugal, Sep. 2019, pp. 1–6, doi: 10.1109/SEST.2019.8849111.

[46] A. Galenovich, S. Lonshakov, and A. Shadrin, "Blockchain ecosystem for carbon markets, environmental assets, rights, and liabilities: Concept design and implementation," in *Transforming Climate Finance and Green Investment with Blockchains*. New York, NY, USA: Academic, 2018, pp. 229–242.

[47] Q. Tu, R. Betz, J. Mo, and Y. Fan, "The profitability of onshore wind and solar PV power projects in China–A comparative study," *Energy Policy*, vol. 132, pp. 404–417, Sep. 2019.

[48] T. Tang and D. Popp, "The learning process and technological change in wind power: Evidence from China's CDM wind projects," *J. Policy Anal. Manage.*, vol. 35, no. 1, pp. 195–222, 2016.

[49] A. Murata, J. Liang, R. Eto, K. Tokimatsu, K. Okajima, and Y. Uchiyama, "Environmental co-benefits of the promotion of renewable power generation in China and India through clean development mechanisms," *Renew. Energy*, vol. 87, pp. 120–129, Mar. 2016, doi: 10.1016/J.RENENE.2015.09.046.

[50] S. Jiang, C. Wan, C. Chen, E. Cao, and Y. Song, "Distributed photovoltaic generation in the electricity market: Status, mode and strategy," *CSEE J. Power Energy Syst.*, vol. 4, no. 3, pp. 263–272, Sep. 2018.

[51] M. R. Alam, M. St-Hilaire, and T. Kunz, "An optimal P2P energy trading model for smart homes in the smart grid," *Energy Efficiency*, vol. 10, no. 6, pp. 1475–1493, Dec. 2017.

[52] J. Wang, Q. Wang, N. Zhou, and Y. Chi, "A novel electricity transaction mode of microgrids based on blockchain and continuous double auction," *Energies*, vol. 10, no. 12, p. 1971, 2017.

[53] T. Bo, T. Ishizaki, M. Koike, N. Yamaguchi, and J.-I. Imura, "Optimal bidding strategy for multiperiod electricity market with consideration of PV prediction uncertainty," in *Proc. 56th Annu. Conf. Soc. Instrum. Control Eng. Jpn. (SICE)*, Sep. 2017, pp. 293–298.

[54] J. S. John, "A how-to guide for transactive energy," Greentech Media, Boston, MA, USA, White Paper, Nov. 2013. [Online]. Available: https://www.greentechmedia.com/articles/read/a-how-to-guide-for-transactive-energy#gs.s1-G9Vhk

[55] V. Buterin, D. Reijsbergen, S. Leonardos, and G. Piliouras, "Incentives in Ethereum's hybrid casper protocol," in *Proc. IEEE Int. Conf. Blockchain Cryptocurrency (ICBC)*, Seoul, South Korea, May 2019, pp. 236–244.

HOUYU HE is currently with Quanzhou Electric Power Supply Company, State Grid Fujian Electric Power Company. His research interests include power system analysis and microgrid operation and control.

ZHAO LUO received the B.S. degree in electronic science and technology from the Nanjing University of Posts and Telecommunications, China, in 2008, and the M.S. and Ph.D. degrees in electrical engineering from Southeast University, China, in 2013 and 2018, respectively.

He is currently a Lecturer with the Faculty of Electric Power Engineering, Kunming University of Science and Technology. His research interests include distributed generations and microgrids, and active distribution networks.

QIAN WANG received the B.S. degree in electrical engineering and automation from the Shandong University of Science and Technology, China, in 2018. He is currently pursuing the master's degree with the Kunming University of Science and Technology.

His research interests include integrated energy systems and electricity market.

MAOXIN CHEN is currently with Quanzhou Electric Power Supply Company, State Grid Fujian Electric Power Company. His research interest is power system operation control.

HUAQIN HE is currently with Quanzhou Electric Power Supply Company, State Grid Fujian Electric Power Company. Her research interest is power system operation control.

LINGJUN GAO is currently with Quanzhou Electric Power Supply Company, State Grid Fujian Electric Power Company. His research interest is power system operation control.

HAIXIANG ZHANG received the B.S. degree in electrical engineering from Nanjing Normal University, in 2009, and the Ph.D. degree in electrical engineering from Southeast University, in 2014. He is currently an Associate Professor with the College of Energy and Electrical Engineering, Hohai University, Nanjing, China. His research interests include generation of renewable energy, and operation and control of power system.