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Cooperative management of an emission trading system: a private governance and learned auction for a blockchain approach

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Abstract

Although blockchain technology has received a significant amount of cutting-edge research on constructing a novel carbon trade market in theory, there is little research on using blockchain in carbon emission trading schemes (ETS). This study intends to address existing gaps in the literature by creating and simulating an ETS system based on blockchain technology. Using the ciphertext-policy attributed-based encryption algorithm and the Fabric network to build a platform may optimize the amount of data available while maintaining privacy security. Considering the augmentation of information interaction during the auction process brought about by blockchain, the learning behavior of bidding firms is introduced to investigate the impact of blockchain on ETS auction. In particular, implementing smart contracts can provide a swift and automatic settlement. The simulation results of the proposed system demonstrate the following: (1) fine-grained access is possible with a second delay; (2) the average annual compliance levels increase by 2% when bidders' learning behavior is considered; and (3) the blockchain network can process more than 350 reading operations or 7 writing operations in a second.

Highlights

- Novel cooperative management of an ETS platform based on blockchain is proposed.
- The data access control policy based on CP-ABE is used to solve the contradiction between data privacy on the firm chain and government supervision.
- A learned auction strategy is proposed to suit the enhancement of information interaction caused by blockchain technology.
- This study provides a new method for climate change policymakers to consider the blockchain application of the carbon market.

Keywords: ETS, Blockchain, Smart contract, Supervision, Auction strategy

Introduction

Since the 1970s, global greenhouse gas emissions have doubled, and the current global temperature is 0.80–1.20 °C higher than that before industrialization (IPCC 2018). As a major amendment to the United Nations Framework Convention on Climate Change, the Paris Agreement proposes limiting temperature change to 1.5 °C to prevent severe climate change impacts (Oesingmann 2022). Due to greenhouse gas emissions, climate change and the transition to a low-carbon economy have become global problems that must be addressed (Lin and Jia 2020).

Carbon emissions trading aims to minimize global greenhouse gas emissions through the market mechanism (Liu et al. 2015) and is anticipated to become the largest commodity market (Kanter 2007). Carbon emissions trading originated from the 1997 Kyoto Protocol and intended to resolve the contradiction between greenhouse gas emissions and sustainable economic development to meet the goals of low-carbon emissions and control of global climate change (Al Sadawi et al. 2021). According to the report "State and Trends of Carbon Pricing 2021" published by the World Bank, there are 64 carbon tax and emission trading schemes (ETS), covering 21.5% of greenhouse gas emissions worldwide. European Union-ETS (Flachsland et al. 2020), China's pilot and national emission trading market (Feng et al. 2018; Wen et al. 2020; Zhang et al. 2021;), CCX (Gans and Hintermann 2013), RGGI (Fell and Maniloff 2018), and NSW-GAAS are among the more influential ones (Passey et al. 2008). ETS is playing an increasingly important role in improving the global climate (Bayer and Aklin 2020), thereby promoting the low-carbon transformation and economic growth of firms (Liu and Sun 2021; Marchewka-Bartkowiak and Jarno 2021) and increasing government public revenue and the implementation of climate change policy rules (Bayer and Aklin 2020; Liu and Sun 2021). According to the International Carbon Action Partnership's report, the transaction scale of the EU-ETS has surpassed $80 billion since its inception, and the monies acquired are mostly invested in low-carbon innovation, renewable energy, industrial decarbonization, and other areas.

In addition, other scholars have contributed to the research on ETS. This study focuses on four aspects—the design and construction of ETS, the evaluation and impact of ETS, the forecasting and implementation of ETS, and the conduct of firms and governments under ETS (Wadud and Chintakayala 2019; Leining and Kerr 2018; Zhang and Cheng 2021; Hassan et al. 2019). Although ETS brings great opportunities to the energy sector, there are still some problems in the operation process, such as a lack of information supervision and traceability mechanism (Skene and Murray 2017), a complex transaction process (Ellerman 2010), low degree of information sharing (Al Sadawi et al. 2021), and market opacity (Skene and Murray 2017). These problems affect the fairness and security of the trading mechanism and reduce ETS's operating efficiency.

Blockchain technology, which is one of the most prominent digital economy technologies (Kakavand et al. 2017; Burniske and Tatar 2018), can be used to solve the problems above (Shu et al. 2022). Blockchain is distinguished by its traceability, time-stamped ledger, and immutable ledger (Aste et al. 2017), as well as its extensive application in the domains of energy, finance, healthcare, supply chain, public services, information security, Internet of things, etc. (Al Sadawi et al. 2021; Sahebi et al. 2022; Harwick and Caton 2020; Ølnes et al. 2017). Due to the advantages and potential of blockchain, in recent years, new application cases are being encouraged, including the electricity and carbon markets (Diestelmeier 2019). Unfortunately, most current research is devoted to distributed energy systems and technology to support the new economic model for power generation and consumption (Green and Newman 2017; Burger and Luke 2017).

Blockchain technology's applicability to the carbon trading market is just beginning to be investigated (Hartmann and Thomas 2020). Specifically, the accounting systems, rules, and institutions enabled by blockchain technology may be used to support the carbon trading market (Dong et al. 2018). The benefit of blockchain includes the following. First, the consensus mechanism ensures that all participants reach an agreement on the transaction results and then record them in the chain to ensure the integrity of the transaction data. Second, a blockchain's chain data storage structure can correctly track all past transaction data. These two characteristics offer exceptional technological support for validating and monitoring carbon trading data (Wen et al. 2021). Blockchain is a network system of peer-to-peer (P2P) value exchange (Mougayar 2016), enabling firms to conduct transactions directly without needing middlemen. This strategy simplifies and expedites the transaction process and eliminates the need for costly intermediaries. Third, because the entire network broadcasts the data stored in the chain, blockchain technology can increase the level of information exchange and provide a more transparent mechanism for a carbon trading market (Pigeolet and Van Waeyenberge 2019). According to climate chain coordination, the use of blockchain will increase capital market confidence and assist in achieving the goals of combating climate change at both the local and global levels through consultation methods and interoperability.

Despite the huge potential, there are obstacles to integrating ETS and blockchain. In this study, we propose an ETS system based on blockchain. This study improves the supervision and auction process by incorporating the ciphertext-policy attributed-based encryption (CP-ABE) algorithm and learning behavior instead of modifying the existing systems. This study's contributions are as follows:

1. It offers a unique ETS system based on blockchain technology to overcome privacy issues and improve annual auction compliance. We assessed the performance of the proposed system during sensitive data access, auction, and smart contract processes. The pertinent experimental outcomes suggest that our proposed system is practicable, secure, and effective.
2. Compared to existing ETS systems, our model not only resolves the contradiction between firm data privacy protection and government information verification but also eliminates "trusted third party"—a common practice in privacy protection—to reduce potential privacy risks from additional assumptions.
3. Based on the features of blockchain technology, we combined the particle swarm optimization (PSO) algorithm to optimize the uniform price auction system. The results contribute to the climate change policy on the carbon market and can be used as a future reference for the current carbon market, new technologies, and the carbon market plan under the Paris Agreement.
4. In addition to the theoretical study, we implemented and evaluated the functioning of the proposed blockchain network from a reading and writing perspective. This can assist in validating the practicability of the suggested paradigm.

Based on the above research needs and objectives, this study is organized as follows: "Literature Review" section presents the literature review. This section offers a summary of the practical application platform of blockchain technology in the energy sector, followed by a discussion and analysis of pertinent research. "Introduction and Application of Blockchain-based ETS System" section elaborates on the model suggested in this study from the perspective of blockchain technology's infrastructure and introduces the model's function and how blockchain technology operates. Then, "Problem Definition and Model Construction of Blockchain-based ETS System" section includes two fundamental components of the model—a carbon emission supervision approach based on the privacy protection of firm-sensitive data and a learning quotation auction strategy. "Case Study" section is a case study. In this section, simulation tests are conducted from three perspectives—the security of the model privacy protection scheme, the performance of the blockchain system, and the efficacy of auction strategies. Finally, "Conclusion" section provides a summary of the study's contents.

Literature review

Numerous businesses have confirmed the potential of blockchain technology for carbon trading (Hartmann and Thomas 2020; Shu et al. 2022). Although blockchain technology has enormous development potential in ETS and has progressed rapidly over the past few years, adopting new technologies has introduced the following two issues: carbon emission traceability and creating an auction mechanism for carbon emission rights. In recent years, an increasing number of carbon trading platforms utilizing blockchain technology have gone live, indicating the viability and efficacy of blockchain in enhancing carbon trading processes (Lu et al. 2022). Further, the confirmation of industry professionals has also encouraged research on using blockchain technology in carbon trading. Therefore, this study examines some common blockchain-based energy trading systems (Table 1).

Due to its transparency and decentralization, blockchain significantly impacts ETS's development and growth, especially in carbon emission monitoring and allowances auctions. We suggest a Hyperledger Fabric-based ETS system that focuses on carbon emission supervision and allowance auctioning to comprehend blockchain's potential for ETS. The following is a summary of recent studies on the impact of blockchain technology on ETS, carbon emission supervision, and carbon auction theory.

Blockchain's influence on ETS

Originally developed for Bitcoin, blockchain is regarded as a powerful and dependable technology that enables immutable and transparent data recording. Numerous studies have focused on the impact of blockchain technology on ETS; we present these studies and discuss their similarities and differences. For example, Fu et al. (2018) described a blockchain-based system for emission trading in the fashion manufacturing sector. They suggested a framework that comprises four entities—the auditor, authority, manufacturing firms, and individuals responsible for implementing the life cycle of garment manufacturing and promoting environmental sustainability. The primary purpose of blockchain technology is to develop an open, immune, and public-shared community that increases the level of trust between various institutions. In addition, they presented

Table 1 Blockchain-based energy trading system frameworks

Company	Website	Detail
Enerchain	https://enerchain.ponton.de/index.php/21-enerchain-p2p-trading-project	A blockchain-based infrastructure that can be used to execute the energy trade
PYLON	https://pylon-network.org/	A platform that sees decentralized energy as the essence of community
LO3ENERGY	https://lo3energy.com/	Integrated accounting tools for a distributed energy future
Powerledger	https://www.powerledger.io/	Powerledger is a software and technology company that is working towards making renewable energy work in a more stable way, by having more responsive markets
SPECTRAL	https://spectral.energy/	Spectral leverages support governments, energy utilities, and real-estate developers in realizing complex projects and executing ambitious energy transition strategies
GPX	https://www.gpx.energy/	The Green Power Exchange Platform is a blockchain-based P2Penergy trading platform, which enables simple Peer-to-Peer energy trading
Wepower	https://wepower.com	Wepower is a platform connecting energy suppliers, corporate buyers and energy producers for easy, direct green energy transactions
Suncontract	https://suncontract.org/	Suncontract is a blockchain-based P2P energy trading platform

a comprehensive case study and analyzed its environmental performance, political acceptability, and implementation ability. However, neither blockchain technology simulation nor carbon allowances auction was considered in their case study.

Khaqqi et al. (2018) proposed another framework by presenting a blockchain-enabled emission trading system that combines the digitalization and automation of Industry 4.0. They focused on resolving fraudulent encounters in managing the ETS and achieving long-term and sustainable emission production. Their proposed framework accomplishes these goals using blockchain technology and a reputation system. According to the multi-criteria analysis, the advantages of the suggested model exceed its disadvantages. However, neither the source nor the process of reputation is explained.

Later, Pan et al. (2019) validated the effectiveness of blockchain technology in carbon trading at both the individual and company levels. Blockchain technology promotes low-carbon behavior through more efficient and intelligent methods, and businesses can benefit from P2P information exchanges.

Moreover, Al Sadawi et al. (2021) offered a comprehensive carbon emission trading system based on hierarchical blockchain technology and smart contract. They provided detailed explanations of the shortcomings of the current ETS and how blockchain technology can remedy them. Their framework comprises three levels—the upper application, lower measurement, and cross-transfer levels. The first level is public, with the government issuing carbon permits and organizations trading carbon shares. At the second level, sensor data are received and stored on a permissioned blockchain safely. The third level will transfer required data from permissioned blockchain to public blockchain. The existing literature proposes a theoretical framework without case studies or smart contract specifics.

In addition, compared to Fu et al. (2018), Shu et al. (2022) provided a blockchain-enhanced system for the construction business. They paid more attention to carbon emissions from the material phase than previous studies and designed blockchain-based building a product trading system and ETS. Detailed descriptions of the framework, operations, and pseudo-code were provided. According to a multi-criteria study, the proposed system outperforms conventional ETS in the construction industry. The system provides exhaustive building industry research.

Carbon emissions tracing

Carbon emission tracing has attracted the attention of researchers. Li et al. (2013) used the carbon flow tracing method to verify the power consumption energy of an entire network and indirectly determined the resulting carbon emissions. The effectiveness of this method was proved via case tests of the PJM 5-bus benchmark system and six regions of China. Similarly, Chen and Chen (2017) used a time-series dataset of 66 urban samples with different economic and geographical conditions to model urban scale and carbon metabolism from the perspective of a network and found a strong coupling relationship between them. Although the carbon emissions flow method can trace carbon emissions to a certain extent, it cannot trace them accurately nor can it deal with the complex situation in which some firms produce and sell their energy (Hua et al. 2020).

Blockchain technology can accurately record and trace the carbon emission records and carbon allowances circulation of firms, but some firm-sensitive data cannot be broadcast and synchronized in an entire network (Leng et al. 2018). To solve the problem caused by data transparency in a network, Hyperledger Fabric proposes using data encryption and chaining, that is, upload the encrypted data to the blockchain and only users who decrypt a key can obtain the corresponding plaintext data. Although this method solves the problem of data privacy protection to a certain extent, its efficiency in practical application is not high (Wang 2020).

To achieve secure access control, each encrypted data on the blockchain needs to have a corresponding key. The key needs to be distributed separately to users who can access the data; this involves a lot of key generation, distribution, and management. To solve the contradiction between data uplink supervision and privacy protection, some scholars have put forward solutions from the perspective of data access control. For example, similar to the government's regulation of carbon emissions, e-government systems also need to improve the degree of data sharing among departments to efficiently protect data privacy from providing services to individuals and organizations. Under the above background, Elisa et al. (2018) designed a P2P e-government system based on blockchain. This study analyzes the system's security from theoretical and experimental aspects. Piao et al. (2021) proposed the service-on-chain method to solve the data access problem among government departments. The service-on-chain method can effectively control data ownership and identify the data retrieval needs of different departments to realize data sharing between government departments and improve business efficiency while protecting government data. Truong et al. (2019) designed a unique data management platform in accordance with the general data protection regulation. The platform combines data use license, smart contract, encryption algorithm, and other contents to ensure that only the formulated talents can process personal data. Wang et al. (2016) designed a public data ownership certificate based on anonymous identity. Users can use this method to report the crimes anonymously, and those who report the correct information can receive government rewards without revealing their identity. Studying electric vehicles, Feng et al. (2021) used asynchronous accumulators to verify membership, avoid the time consumption of certificate verification, and use mutual authentication protocols to protect user privacy. In the case test phase, this method's member authentication time does not exceed 0.2 ms.

Traditional carbon emission flow can play a certain role in carbon traceability, but it cannot achieve accurate traceability at the firm level, and its usefulness for government supervision is very limited. Blockchain technology has distinct characteristics and powerful functions, but the problem of data privacy on the chain and the resulting efficiency delay must be solved in the application process.

Design of auction strategy

The application of new technology has changed the auction environment. In the blockchain system, the P2P interaction mode has greatly weakened the concept of "intermediary." Further, the "broadcast" stage in the consensus verification process has greatly promoted information transparency in the network. Therefore, it is necessary to design an auction mechanism in line with the characteristics of blockchain to deal with this change and achieve the goal of maximizing social profits.

To realize the price optimization problem in a distributed system, some scholars have improved the heuristic algorithm to optimize the auction process in a blockchain system. For example, Esmat et al. (2021) designed a decentralized ant colony optimization algorithm to improve market efficiency and protect user privacy. The specific process is that each node uses the local information to execute the local ant colony algorithm and then shares the information and adjusts the parameters of each round. This algorithm structure is well coupled with the proposed market model. Zaidi and Hong (2018) combined the PSO algorithm and genetic algorithm to optimize the price clearing process between multiple microgrids. Regarding auction strategy, continuous double-auction (CDA) is often used in P2P trading platforms recently (Foti and Vavalis 2019; Wang et al. 2017; Wang et al. 2018a, 2018b).

In CDA, traders can carry out two-way buying and selling operations. Both parties can put forward their quotation or accept the quotation of others during the operation of the market. Once both parties accept each other's quotation, they close the deal immediately (Friedman 1993), thus providing a fully competitive market environment for buyers and sellers. However, in the energy trading system, the CDA auction strategy cannot fully integrate energy products with time heterogeneity, which has certain limitations in practical application (Esmat et al. 2021).

In addition, scholars have considered the impact of the reputation effect, low-carbon incentives, market fairness, and other factors on the results of carbon emission auctions. For example, Wang et al. (2021) designed a distributed reputation system to enhance trust in the energy system based on blockchain and enhanced the fairness of the energy trading market. Similarly, Liang et al. (2019) allowed firms to improve their reputation by investing in emission reduction projects to encourage them to reduce carbon emissions. To realize low-carbon incentives, Hua et al. (2020) built a consumer-centered energy trading system to balance regional energy demand and mitigate carbon emissions. Al Sadawi et al. (2021) designed an ETS system based on blockchain technology with the goal of environmental protection but did not elaborate on specific technical details and algorithm ideas. Finally, Wang (2016) considered the fairness between non-cooperative users in the transaction process, designed an incentive algorithm to improve the participation of users, and then discussed the impact of market equity on renewable energy trading.

We discover that several aspects influence the impact of carbon allowances auctions, and the perspectives of the literature reviewed are expansive. However, most studies focused on the carbon trading mechanism between customers instead of the auction of carbon allowances in ETS.

In summary, although the above studies have made significant contributions to the research on carbon emission auction mechanisms based on blockchain technology, only a few focused on the information exchange effect of the transparent attribute of the blockchain network and the quotation learning behavior of the bidding subject when developing a model for the carbon emission auction system. Similarly, after the implementation of blockchain technology, more studies have focused on the auction of carbon emission rights on the secondary market, while a few have focused on the auction procedure on the primary market. This study investigates the implementation of blockchain technology in the ETS system from the perspective of carbon emission traceability and constructs an auction mechanism for carbon allowances.

Introduction and application of blockchain-based ETS system

From the perspective of blockchain's fundamental architecture, this section describes our proposed model in detail by covering essential blockchain technologies. From bottom to top, the fundamental blockchain architecture comprises a P2P network, a global ledger, and an application (Feng et al. 2019). In Fig. 1, the three levels of the structure of the ETS based on blockchain technology are depicted. This study selects the permissioned blockchain Hyperledger Fabric as the basic network framework of transactions

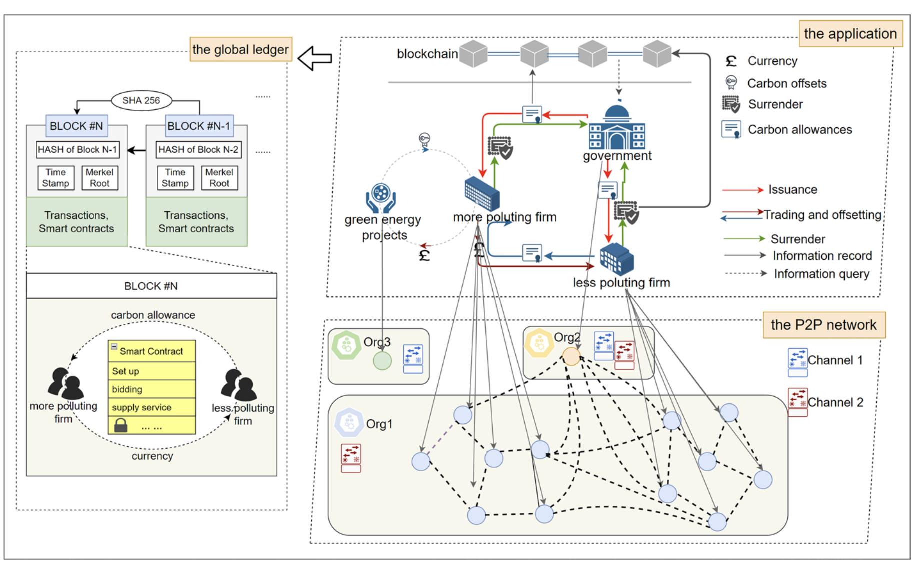


Fig. 1 The basic proposed framework of blockchain-based ETS

to achieve a balance between effective traceability and privacy protection, considering the peculiarities of ETS. Unlike public blockchains where all users have read-and-write access to the network, permissioned blockchains are only accessible to authorized users and restrict their read-and-write privileges (Behnke and Janssen 2020), which have become prevalent in business-to-business contexts to safeguard the manufacturing secrets of participating firms (Helliar et al. 2020). Also, permissioned blockchains are preferable to openly disclosed blockchains as it promotes system integrity as opposed to private blockchains in which the network's state is controlled by a central body, and transparency and efficiency are constrained.

P2P network

Through a flat structure, a P2P network can ensure that nodes in different geographical locations in a blockchain network exchange information equally and freely (Feng et al. 2019). Each node in a network is also responsible for network routing, verifying data blocks, maintaining connections with adjacent nodes, broadcasting block data, promoting the execution of transactions, and maintaining data consistency in the network. This feature can ensure that carbon trading is implemented well without intermediaries.

When using the Fabric network, according to the different roles of participants in the process of ETS, this study defines the corresponding nodes as three different organizations—government departments, carbon emission firms, and green energy projects. The definition of organization is similar to that of different departments in a company. Different organizations can perform endorsement and sorting operations in different types of transactions. Therefore, the division of organizations can promote the efficient and orderly process of consensus verification and transaction. In addition, Fabric supports a multi-channel mechanism. In this study, two channels (Channels 1 and 2) are designed to record the purchase of green energy projects and the transfer of the carbon emission rights of firms. Each channel maintains an independent blockchain ledger, and the data between different channels are completely isolated.

Global ledger

A global ledger uses the chain data structure to record a series of important information truthfully and reliably. It is an important tool for establishing a trust mechanism between nodes. A global ledger's work includes generating transactions, consensus verification, and updating the ledger. In this study, the transaction includes carbon emissions and the circulation of carbon allowances between firms. The procedure is as follows. Based on the details of the transaction, such as the seller's address, the number of carbon blocks, and the transaction volume, hash the content in the block body to generate a Merkel tree. Select the Merkel tree's root node, the current block's generation time, and the previous block's hash address to form a block header. The block body and the block header are combined to form a block. In essence, blocks record the generation of transactions. However, there is an automatically executed transaction in the blockchain called a smart contract. Smart contracts are predefined functions that automatically trigger execution when specific conditions are met (Wang et al. 2018a, 2018b). For example, after the auction mechanism is set, the smart contract will automatically complete the matching, cryptocurrency, and carbon allowances circulation based on the quotation of the buyer and seller.

When initiating a transaction, users need to specify the channel ID, sign the transaction proposal with their private key, and submit it to the endorsement node in the Fabric network. The endorsement node verifies the transaction proposal. The specific verification contents include whether the proposal format is correct, whether the signature is effective, and whether the proposal has been submitted multiple times. If the verification is passed, the endorsement node will simulate the execution of the transaction proposal and return the execution result to the user with the endorsement node signature. After collecting enough endorsements, the user needs to package the collected proposal information into transaction requests and send them to the sorting node. The sorting node sorts the received transaction requests, packages the sorted transactions into blocks, and sends them to the controller node of each organization in the channel. The controller node sends the blocks to other submission nodes in the organization. Finally, the submitting node verifies the transaction content contained in the block. Only blocks that pass the verification can affect the status of the ledger, and blocks that fail to pass the verification cannot be recorded in the ledger. Blocks that pass the inspection are connected chronologically to form a blockchain and cannot be changed at will. In this way, the contents recorded in the ledger are all transactions verified by P2P network consensus. The ledger can enhance the transparency of the carbon trading market and provide strong technical support for market supervision.

Application

In this context, the application is the physical application layer of the blockchain. In this layer, various participants of ETS, including government agencies and carbon emission firms, can directly interact with others without considering the underlying technical details of the blockchain. For example, users can query and confirm the transaction directly through tools provided by the carbon exchange without considering the protocol through which the information is transmitted in the network. Hyperledger Fabric offers a user-friendly software development kit to access a variety of resources in a blockchain, such as a ledger, transaction, chain code, and permission management, to help users interact directly with the Fabric blockchain network. Specifically, the application layer of ETS mainly includes three links—issue, trading, and regulator.

Issue: Currently, the most common initial carbon allowances allocation methods include free allocation, public auction, and a combination of the two. The mechanism for allocating carbon allowances is not fixed. For example, the EU has set four stages for the allocation mechanism, and it is currently in the last stage (2021–2030), where 57% of carbon allowances will be auctioned.

Trading: Carbon allowances can be traded between polluting firms. High-polluting firms can buy carbon allowances from low-polluting firms. If high-polluting firms cannot buy enough carbon allowances in the market, they can purchase carbon subsidies to offset the excess carbon emissions. Carbon subsidies are a way to fund green projects to reduce greenhouse gases.

Surrender: Polluting firms are obliged to regularly surrender their actual emission and the relevant number of permits during a certain period. Surrendering is essential to the monitoring, reporting, and verification system, which is the basic element of the construction and operation of the carbon trading mechanism.

Problem Definition and Model Construction of Blockchain-based ETS System

Data Governance method based on CP-ABE

Goyal (2006) originally proposed ABE to address the challenge of fine-grained access control and dynamic user expansion of data in cloud storage. ABE can be separated into KP-ABE and CP-ABE depending on various decryption strategies. The access policy of KP-ABE is associated with the key, while the access policy of CP-ABE is associated with the ciphertext content. We chose the CP-ABE algorithm to reconcile the contradiction between data privacy and government oversight as our approach requires data access to be tied to the user's identification.

The original CP-ABE algorithm comprises four fundamental algorithms—setup, keygen, encrypt, and decrypt.

Setup: $(PK, MK) \leftarrow Setup(\lambda)$. It is executed by a trusted third party such as the government. After passing in security parameters λ, the algorithm will generate the public key PK and the system master key MK.

KeyGen: $SK \leftarrow KeyGen(PK, MK, A)$. It is generally performed by a trusted third party. The KeyGen algorithm takes input as a set of attributes A and outputs private key SK that identifies with A.

Encrypt: $CT \leftarrow Encrypt\left(PK, M, A_{policy}\right)$. It is executed by an encryptor. Encrypt algorithm takes public key PK, plaintext message M, and access policy A_{policy} as input. It takes ciphertext CT as output, and CT can only be decrypted by users satisfied with A_{policy}.

Decrypt: $M \leftarrow Decrypt(PK, CT, SK)$. Decrypt is performed by a decryptor. It takes public key PK, ciphertext CT, and the user's private key SK as input. If the attribute set A in the user's private key SK is included in the user attribute set A_{policy} of CT, the plaintext M corresponding to CT is returned; otherwise, decryption fails.

Figure 2 depicts the carbon transaction tracing procedure in the Fabric network based on the CP-ABE algorithm. This procedure mostly consists of user registration, data submission, and data query. To aid comprehension of the privacy protection approach, a brief description of this scheme is provided. Institution 1 must upload data, and Institution 2 queries data over the Fabric network. The scheme's symbol description is presented in Table 2. Each step's operation is described in detail below.

(1) User registration

This stage mostly involves interactions between institutions and Fabric-CA. The Fabric-CA manages the identity certificates of all users in the network, including identity registration as well as issuing, renewing, or revoking digital certificates. Only users who have obtained the certificates can enter the Fabric network. The identity access mechanism is also a feature of the alliance chain. In this study, Fabric-CA needs to issue an identity certificate C_{user} to the application user; complete the initialization process of the CP-ABE algorithm; and generate public parameter PK, master key

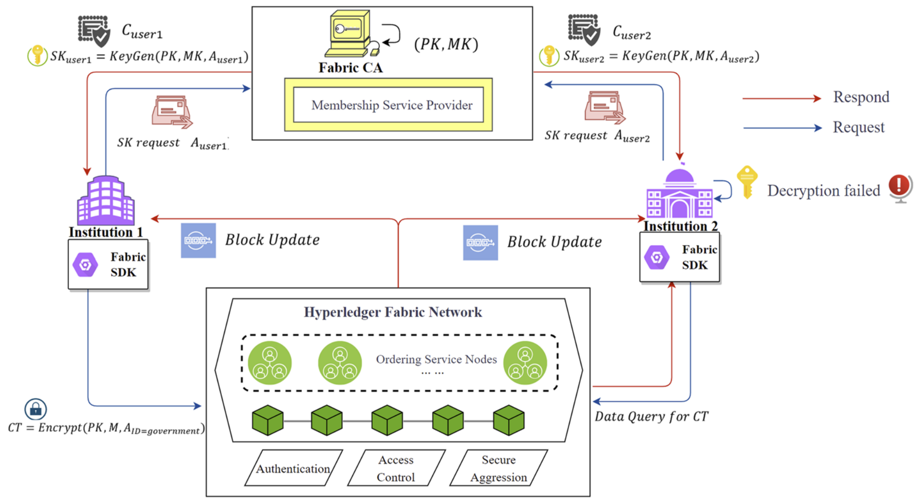


Fig. 2 The process of carbon tracing for supervision in Fabric

Table 2 The description of symbols

Symbols	Detail	Symbols	Detail
C_{user}	User's identity certificate	SK_{user}	Private key of user
MK, PK	the system master key, public key	M, CT	Plaintext to be encrypted, encrypted ciphertext
A_{user}	User attribute set	A_{policy}	Ciphertext access attribute set

MK, and specific user private key SK_{user} according to the identity attribute. Then, SK_{user} and C_{user} will be sent to the user to facilitate subsequent operations.

(2) Data upload

During this stage, Institution 1 interacts mostly with the Fabric network. If Institution 1 wishes to upload data to the Fabric network, it computes a ciphertext using the CP-ABE encrypt algorithm on the necessary data. When encrypting, it needs to point out the attributes of users who can access the plaintext. For example, the access policy $A_{policy} = \left(Org_{ID} = Org_{enterp1}\right) and (USER_{ID} = gover)$ means that only users in the government and the same organization can access the content, and users with other attributes in the network cannot access the data or information. After encryption, ciphertext CT_A will be generated, and then, the firm's blockchain network will initiate a transaction $Tx(CT_A)$ containing ciphertext CT_A. $Tx(CT_A)$ will be uploaded to the blockchain for storage after sorting and verification by relevant nodes.

(3) Data access control

During this stage, Institution 2 interacts mostly with the Fabric network. Institution 2 requests the blockchain network for transaction $Tx(CT_A)$ to obtain the corresponding ciphertext CT_A and further decrypts CT_A using private key SK_{USER2}. A mismatch in the access policy A_{policy} causes the decryption process to fail. However, the government can use SK_{gover} that meets the access policy A_{policy} to derive the plaintext. Based on the CP-ABE scheme, we can accomplish fine-grained access control of blockchain data and protect participants' privacy.

Learned auction strategy

The present characteristics of the EU-ETS auction process are single rounds, sealed bids, and uniform prices (Al Sadawi et al. 2021). However, unlike ordinary single commodities, carbon allowances are homogeneous and divisible public goods. They are auctioned in the market many times a year, which can be regarded as a sequential auction (Rao and Li 2013). In addition, the transaction information of each auction is public. The bidding subject in the market can speculate on the auction strategy of the competitor according to the transaction information and formulate the quotation for the next round. Based on the characteristics of homogeneous carbon emission rights, multiple rounds of auctions, and disclosure of transaction information in the blockchain environment, this study considers the learning behavior of bidding subjects. It proposes a carbon auction strategy based on traditional carbon auction methods. After using blockchain technology, the consensus verification mechanism will further promote information dissemination in the market.

The process of carbon auction strategy based on learning behavior is depicted in Fig. 3. First, firms bid according to their bidding strategy. After the auction, they adjust and optimize their bidding strategy by analyzing personal historical bidding results, market public information, the bidding behavior of winning firms, and other information to prepare for the next auction, during which the above process is repeated.

We optimize the auction process by using the PSO algorithm to reflect the learning behavior of bidding firms. However, zero intelligence with constraint (ZI-C) is employed as a bidding strategy without a learning strategy. ZI-C is an auction approach introduced by Gode and Sunder (1993) when simulating the market behavior of bounded rational individuals. This strategy neither considers external market data nor reflects a bidder's preferences. The random value range falls between the minimum price permitted by the

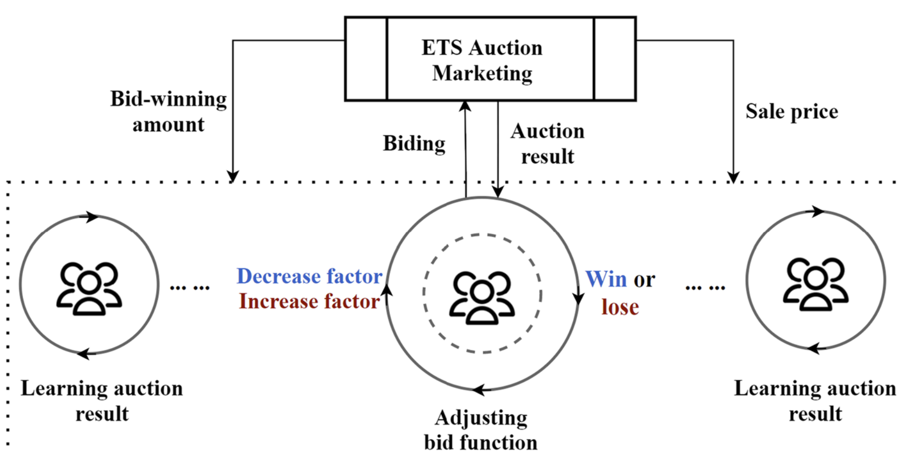


Fig. 3 The learning-based auction process

market and the maximum approved by the decision-maker. The bid price of t auction of bidding firm i is as follows:

$$BP_{i,t} = BP_t + r * (CV_i - BP_t) \tag{1}$$

where $r \sim U[0, 1]$; BP_t is the reserved price of the government at t auction; and CV_i refers to the highest price that firm i can accept or the marginal emission reduction cost of bidding firms.

As the ETS market's previous bidding outcomes are publicly available, the bidders can see the actions of the successful bidders, learn from them based on publicly available market data, and interact with their surroundings. The PSO algorithm presented by Poli et al. (2007) is based on the theory of complex adaptive systems and considers both individual and collective learning. The algorithm is simple to develop and has widespread application in neural network training, function optimization, and other domains.

An update of the PSO algorithm mainly depends on the learning and experience accumulation of particles in inertia, self-cognition, and environmental cognition. Bidding firm i can be regarded as a particle in space, and its position vector $y_i = \{y_i^1, y_i^2, \ldots, y_i^n\}$ represents the position of the particle at inertia t, which is also the bidding price of a firm at n auction round. Velocity vector $e_i = \{e_i^1, e_i^2, \ldots, e_i^n\}$ represents the speed of particle i during t inertias. $p_i^t = \{p_i^1, p_i^2, \ldots, p_i^n\}$ represents the historical optimal position of an individual after t inertias of the particle. $p_i^t = \{p_i^1, p_i^2, \ldots, p_i^n\}$ represents the historical optimal position of an individual after t inertias of the particle. The particle uses its current speed, current position, individual historical optimal position, and group historical optimal position to adjust the next quotation, and its adjustment degree can be expressed as follows:

$$e_i^{t+1} = w * e_i^t + c1 * r1 * (p_i^t - y_i^t) + c2 * r2 * (p_g^t - y_i^t) \tag{2}$$

where w is the inertia factor, which is the recognition degree of the bidding firm to the current bidding; $c1$ and $c2$ are acceleration factors, representing self-learning ability and social learning ability, respectively; and $r1, r2 \sim U[0, 1]$. The above formula indicates that the quotation adjustment is composed of three parts. The first part of the bidding strategy indicates the degree of recognition of the bidding firm to the last quotation, while the second and third parts reflect the self-learning and social learning of the bidding firm through private and external information, respectively. As a result of learning, the position-adjustment strategy is always evolving.

Case study

Performance evaluation of blockchain network

This study uses Hyperledger Fabric 2.2 to write smart contracts to realize the functions of firm registration, carbon emission right allocation, and capital flow in carbon allowances trading. After the transaction at each stage is successful, the transaction information is stored in the blockchain database through a writing operation. The historical information of ETS can be traced through the reading operation.

As the proposed framework is expected to process a large amount of data stably and simultaneously, the performance of blockchain networks is an important issue and has been evaluated. Generally, permissioned blockchains can achieve higher throughput than public blockchains (e.g., Bitcoin accesses 7 transactions per second (tps) while Ethereum gets around 15 transactions) because of identity control. We use Hyperledger Caliper—an open-source tool developed by Hyperledger Foundation—to test different blockchain networks using predefined cases to evaluate our proposed system. There are three types of organizations in the performance benchmark test, and the performance test results are depicted in Fig. 4.

As depicted in Fig. 4, the throughput decreases and the average latency increases as the test data size increases for reading and writing transactions. For instance, the throughput of reading transactions can reach 225 tps for a 100×100 matrix, whereas it only reaches 55.3 tps for a 300×300 matrix, and the average latency increases from 0.01 to 0.05 s. Compared to the reading operation, the writing operation requires more processes, including producing a new block, broadcasting it to all peers, and updating it on the blockchain, so the writing operation gets lower throughput and higher latency. For example, when the matrix size is 200 dimensions, the reading operation gets 98.5 tps with a 0.03 s average latency, while the writing operation only achieves 6.2 tps with a 0.64 s average latency.

Performance evaluation of CP-ABE

(1) Time cost

This part measures the time cost performance index of the CP-ABE scheme. The CP-ABE scheme includes four basic steps—setup, keygen, encrypt, and decrypt. Among them, the setup phase is executed by Fabric-CA only once, which has no impact on transaction efficiency, so it will not be considered in the evaluation process. In CP-ABE, the number of attributes mainly affects the time cost. In the following content, we test

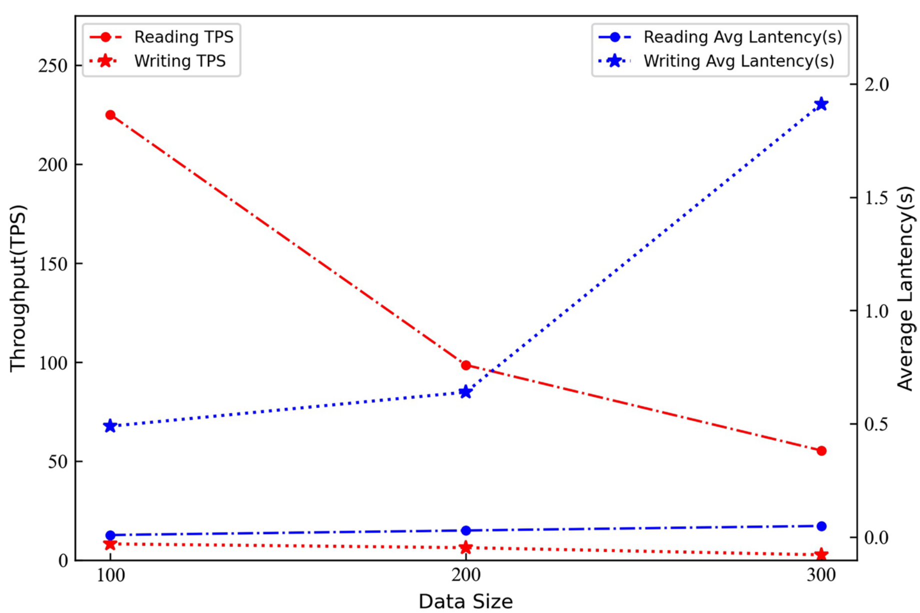
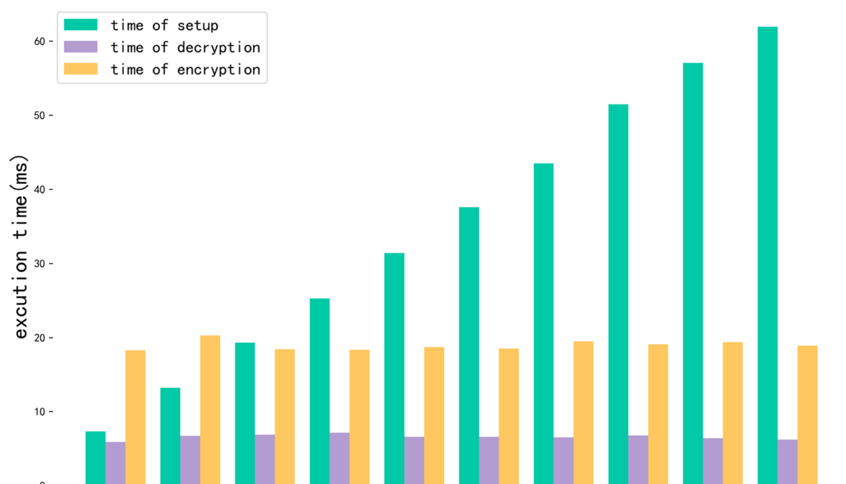


Fig. 4 System performance results

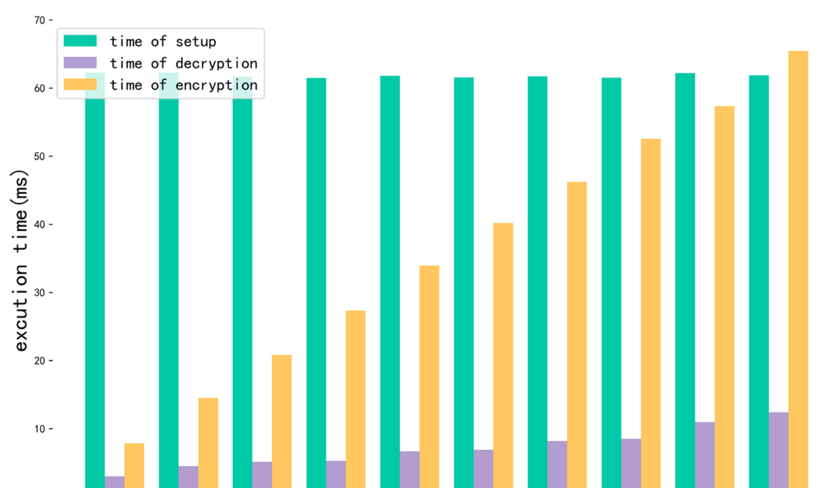
the impact of the size of the user attribute list and access the policy attribute list on time. The result is an average of 50 experimental tests. The system used for the experiment is Ubuntu 16.04, Intel (R) Core (TM) i5-6400 CPU @ 2.70 ghz, 4 GB of ram, which used Python 3 language to run the CP-ABE algorithm.

The procedure is as follows. First, control the number of attributes in the access policy to 10. Figure 5a depicts how the time cost of CP-ABE changes with the number of



	2	4	6	8	10	12	14	16	18	20
setup	7.313	13.238	19.325	25.286	31.402	37.608	43.51	51.482	57.06	61.938
decryption	5.892	6.721	6.884	7.156	6.584	6.597	6.513	6.769	6.385	6.215
encryption	18.284	20.285	18.427	18.369	18.722	18.531	19.501	19.108	19.387	18.914

(a)



	2	4	6	8	10	12	14	16	18	20
setup	62.248	62.255	61.649	61.491	61.81	61.536	61.718	61.521	62.19	61.872
decryption	2.995	4.502	5.128	5.271	6.666	6.908	8.199	8.535	10.969	12.405
encryption	7.857	14.501	20.811	27.358	33.943	40.191	46.224	52.546	57.344	65.481

(b)

Fig. 5 Time consumption comparison between the number of attributes. **a** Attributes authorities **b** Attributes in the access policy authorized attributes in the three stages of keygen, encrypt, and decrypt. The horizontal axis of the picture is the scale of the authorization attribute list, and the vertical axis is the time consumed. As depicted in the figure, the key generation time ranges from 7.31 ms for two attributes to 61.94 ms for 20 attributes, which increases linearly. The former takes about 19 ms, and the latter takes about six milliseconds. The time of data decryption and encryption remains almost unchanged. This result is consistent with that of Goyal (2006).

The time consumption of keygen, encrypt, and decrypt phases varies with the number of access policy attributes, as depicted in Fig. 5b. On the one hand, when the length of the user attribute list is fixed at 6, the time consumption of keygen has nothing to do with an increase in the number of access policy attributes, indicating that the number of attributes involved in Fig. 5a is the only factor affecting the time consumption of keygen. On the other hand, the encryption time and decryption time are positively correlated with the number of access policy attributes. Among them, when the number of access policy attributes increases from 2 to 20, the encryption time increases from 7.86 to 65.48 ms, and the decryption process takes less time, from 3.00 to 12.41 ms.

After testing the time cost of the three steps of CP-ABE, the results reveal that the operation time of the algorithm is within the acceptable increment. In addition, to change the transaction process of the original Fabric network, this scheme only replaces the plaintext in the blockchain network with the ciphertext encrypted by the CP-ABE algorithm, and this change does not affect the operation efficiency of the Fabric. Therefore, the data supervision and traceability mechanism based on the CP-ABE encryption algorithm implemented in the original Fabric network operation mechanism is feasible.

(2) Safety comparison

In this part, we compare CP-ABE with common symmetric encryption in four aspects—privacy of data, simplicity, the security of key distribution, and revocation. Where "privacy of data" refers to whether the privacy of data is protected; "simplicity" refers to whether the implementation process of the scheme is simple; "the security of key distribution" refers to whether there is a security vulnerability in the key distribution process; and "revocation" refers to whether the authority of an authorized user can be revoked.

As presented in Table 3, compared with similar schemes, this scheme can ensure the privacy and security of data on a firm's chain, simplify the key distribution management process, and support fine-grained data access control. In addition, you can control the ciphertext attribute set *A_policy* to add or revoke users with permission. This can

Table 3 Comparisons between our proposal with symmetric encryption of data governance

Feature	CP-ABE	Symmetric encryption
Privacy of data	✓	✓
Simplicity	✓	✗
The security of key distribution	✓	✗
Revocation	✓	✗

solve the contradiction between firm uplink data privacy protection and government supervision.

Application of learned auction strategy

The findings of ZI-C and PSO auction procedures are presented and compared to investigate the implementation of blockchain technology in ETS. To simplify the model, we use the average auction data on Guangdong Province from 2018 to 2021—one of the earliest pilot projects in China—as the parameter standard for simulation analysis. Parameters such as acceleration factors are divided based on policies and economic development conditions. We assume that the government reserve price is 26 based on the experience of the pilot project in Guangzhou and that each group of symbolization contains 30 bidding firms. The highest valuation of each enterprise for the carbon allowance CV follows the uniform distribution $CV \sim U[30, 45]$, and the annual carbon emission gap Q follows the uniform distribution $Q \sim U[80, 100]$. In addition, we assume that there are 10 rounds every year, and the total amount of each carbon emission rights auction is 2,000. The inertia factor $w = 0.8$, $c1 = 2$, $c2 = 2$, and the initial price of each firm is determined using the ZI-C strategy.

Figure 6 compares the market clearing price using ZI-C auction and PSO bidding strategies over 12 rounds. The median clearing price under the PSO auction strategy decreases slightly over time. In contrast, the clearing price under the ZI-C auction strategy remains relatively stable throughout the auction. To prove the hypothesis statistically, we run a regression and receive significant coefficients (see Table 4), that is, the further the model runs, the lower the final clearing price becomes. There is a significant difference between clearing prices under PSO and ZI-C auction strategies (see Table 5).

Falling prices over the rounds are consistent with the study by Anatolitis and Welisch (2017), who researched renewable energy auctions in Germany using

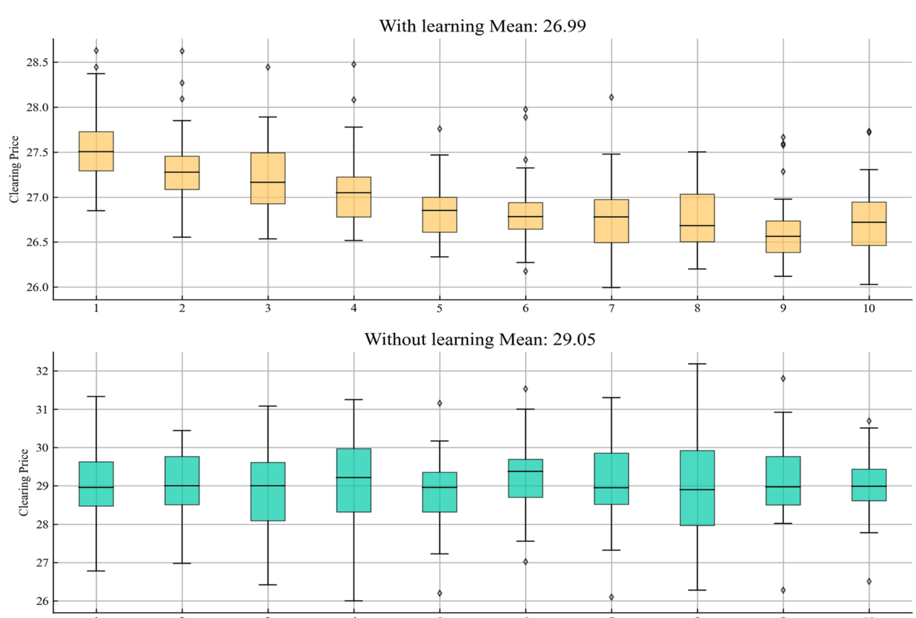


Fig. 6 Market clearing prices for PSO and ZI-C bidding strategy

Table 4 Mann Kendall trend analysis for clearing price

	Trend	h	p	z
PSO	Decreasing	True	0.00047	− 0.31140
ZI-C	No trend	False	0.75550	− 3.49720

Table 5 one-way ANOVA test for market clearing price

	Df	Mean_Sq	F value	Pr (> F)
Auction strategy	1	0.120	843.589	0.000
Residuals	58	0.000	–	–

agent-based modeling, where the agent is assumed to have learning behavior. There are a few differences between their assumptions and our model. For example, they considered three types of agents, namely project developers, citizens' energy companies, and financial investors, all of which have some market share. In our model, the whole market consists of fewer and more polluting firms. This difference does not change the whole market result—similar results are observed in both models. Moreover, we adjusted the submitted bids based on the PSO algorithm while their assumptions did not. As both of us considered the learning behavior of agents, the property that price falls over time applies to both simulations.

However, our result contradicts that of Jeitschko (1998), who paid attention to learning and designed two rounds and three bidders with different value types. He predicted more bidders in the first auction to make a higher winning bid, whereas fewer high-value bidders in the second auction led to less competition and a lower winning price. The first effect is offset by the second effect and thus equal price results in both rounds. There are differences between his assumptions and our model. First, winning bidders can participate in the next round as extra carbon allowances are allowed to be traded in the market, and the number of bidders is stable in our assumption. Second, Jeitschko (1998) concluded that high-value agents would submit higher bids to ensure winning the bid. This effect is similar to that of our case, and we set accelerated factors to adjust the next price according to the latest winning bid. The bigger the gap between the winning and submitted bids, the higher the next price becomes. However, the average final price will decrease. Finally, it seems that the second effect is predominant in our model, leading to a decreasing price. Under blockchain technology, as bidding firms can obtain more comprehensive historical trading records of ETS, after learning and optimizing the bidding, the market clearing price will decrease while the auction profit of each individual will increase relative to random quotations.

In Fig. 7, the boxplots depict the average annual compliance levels (ACLs) and auction efficiencies (AEFs) for both bidding processes. The average yearly compliance level illustrates the extent to which the total amount of carbon emissions collected through auction from bidding firms may close the emission gap.

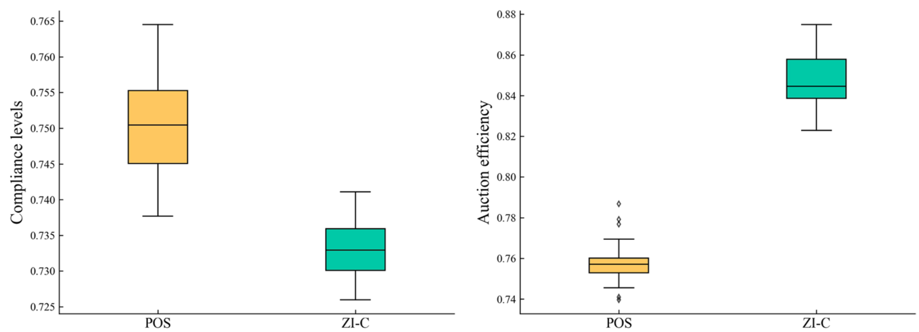


Fig. 7 Comparison of compliance level and auction efficiency

Table 6 One-way ANOVA test for auction efficiency

	Df	Mean_Sq	F value	Pr (> F)
Auction strategy	1	27.141	527.595	0.000
Residuals	58	0.051	–	–

$$ACL = \sum\nolimits_{i=1}^{m} \frac{\sum_{t=1}^{n} q_t}{Q_i} \quad (3)$$

according to Cong and Wei (2012), AEFs are defined as follows:

$$AEF = \frac{gov_i}{gov_i + ep_i} \quad (4)$$

where gov_i refers to the government's earnings from carbon auctions, and ep_i is the total bidders' profit.

With lower clearing prices, the ACL increases significantly, which is a more important signal for the Chinese carbon market. In recent years, carbon and environmental-related instrumental factors in economic policies have gained lots of attention in China (Shahzad 2020). However, how to ensure a degree of performance is still a problem (Yang et al. 2017). Due to the cost reduction, polluting firms can gain more carbon allowance without increasing their budget, leading to a higher performance rate. Moreover, blockchain technology will enhance such an effect because it can build a trust model with a machine guarantee. Regarding AEF, the results under PSO and ZI-C strategies significantly differ after the regression analysis (see Table 6). According to the concept of AEF, the learning algorithm will reduce the market efficiency, and AEF is lower than the market with a random bidding strategy because learning behavior might reduce the bidding price and raise bidders' profit.

Discussion

Faced with the severe problem of climate change, seeking low-carbon development has become inevitable worldwide. The existing literature illustrates those environmental policies, such as carbon trade and carbon tax, have had significant impacts in developed countries (Ghazouani et al. 2020; Shahzad et al. 2020). In recent years, developing countries such as China, India, Thailand, and Vietnam have also introduced similar environmental-related economic policies, following the example of developed countries (Schlegelmilch et al. 2016). Although pilot auction rounds have been executed for several years, China has questionably low levels of ETS projects (Yang et al. 2017). For sustainable environmental development, developing and developed countries should emphasize industry innovation (Bashir et al. 2021), and blockchain technology seems to be a reasonable solution (Zhang et al. 2021).

In this study, we introduce blockchain technology to the ETS process and mainly analyze its impact on the auction phase. Although agent-based algorithms provide a useful tool for modeling complex systems in the real world, excessive reliance on set parameters is a distinct disadvantage. Specifically, human beings have random irrational behavior and unquantifiable psychological features, making the result unreliable. As PSO combines individual and group learning and is more in line with human being decision-making (Zhu 2014), it averts a lack of accuracy and holds under predefined assumptions.

The main result of this study is that clearing prices fall over the auction rounds, which also directly impacts AEF and ACL. As some assumptions are based on China's pilot and reflect the influence of industry digital innovation, the implication is that supply is greater than demand in the market. We find that companies will strategically bid to ensure their maximum profits when carbon allowance is abundant. For example, companies may submit different prices for multiple projects. Strategic bidding and learning behaviors make the average price of an auction lower than the random price, make the market clearing price lower and close to the government reserve price, reduce the AEF, and make the market performance rate higher.

Our model has some limitations. First, the range of many parameters is formulated according to policies and economic forms, and there is no way to refine them. Second, the extent to which blockchain technology promotes corporate learning behavior cannot be observed. A future study can be extended to carbon quota trading between enterprises, which may impact the auction process. In summary, our study analyzes the pilot carbon auctions in China after applying new technologies through an agent model, which is the first step in scientific research.

Conclusion

Based on Hyperledger Fabric, this study proposes a blockchain-based ETS system. Compared to prior research in this area, the model proposed in this study assures the privacy and security of firm-sensitive data in carbon emission regulation and increases the efficiency of auctions. We combined the CP-ABE algorithm with the Fabric network to provide an effective data access control mechanism, resolving the contradiction between data privacy protection and government oversight and management on the chain without the privacy risk posed by a third trust party. Moreover, a GO-language smart contract is created and deployed on the Fabric network. After testing, the smart contract can realize the flow of funds and carbon allowances and ensure the automatic execution and security of transactions, which increases transactions' digitization degree and processing efficiency.

In addition, the case study reveals the following. (1) The CP-ABE algorithm can perform fine-grained access control and is efficient as demonstrated by the case study. The delay caused by encryption and decryption does not exceed one second. (2) Bidding strategy with learning behavior can reduce the bidding price, increase bidders' profit, and improve the ACL by approximately 2%. (3) The blockchain network has reasonable performance, with average reading operations at 352.5 tps and writing operations at 7.6 tps when the data size is 100.

This study has some limitations as well. First, it only addresses the auction market in the initial allocation of carbon emission rights without analyzing the interaction and linking mechanism between primary and secondary markets; further research can be done in this direction. Second, in the ETS platform proposed in this study, blockchain technology plays the role of information transmission and does not maximize its capacity to construct a trusted system. In the future, carbon money and carbon finance methods can be incorporated into the transaction process to maximize the potential of blockchain technology. Lastly, the format of the displayed information is unclear; a more legible format should be considered in the future.

Abbreviations

ETS	Emission trading scheme
CP-ABE	Ciphertext-policy attributed-based encryption
CCX	Chicago climate exchange
RGGI	Regional greenhouse gas initiative
NSW-GAAS	New South Wales Greenhouse Gas Abatement Scheme
EU ETS	European Union Emission Trading Scheme
PSO	Particle swarm optimization
CFT	Carbon flow tracing
SOC	Service on chain
CDA	Continuous double-auction
P2P	Peer to peer
Org	Organization
ID	Identity document
SDK	Software development kit
ABE	Attribute-based encryption
KP-ABE	Key policy attribute-based encryption
PK	Public key
MK	Master key
SK	Private key
BP	Reserve price of carbon allowance, set by government
A_{user}	User attribute set, obtained at user registration
A_{policy}	Ciphertext access attribute set
C_{user}	User identity certificate
CT	Ciphertext
M	Plaintext
CA	Certification authority
ZI-C	Zero intelligence with constraint
CV	Maximum valuation
Q	Carbon emission gap
ms	Millisecond
ACL	Annual compliance level
AEF	Auction efficiency
tps	Transaction per second

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Author contributions

Y-RW: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review & editing, Software, Supervision. CM: Conceptualization, Writing—review & editing, Visualization, Funding acquisition, Supervision. Y-SR: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review & editing, Visualization, Resources, Supervision, Project administration, Funding acquisition. SWN: Writing—review & editing, Supervision.

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Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

No potential conflict of interest was reported by the author(s).

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