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Blockchain Technology in Carbon Trading Markets: Impacts, Benefits, and Challenges—A Case Study of the Shanghai Environment and Energy Exchange

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Abstract: This study employs the Shanghai Environment and Energy Exchange as a case study to investigate the effects of blockchain technology applications on transaction prices within the carbon trading market. Utilizing an event study methodology, the research demonstrates that blockchain technology significantly enhances the transparency, security, and efficiency of the carbon market, thereby exerting a positive influence on transaction prices. Nonetheless, the study also identifies several challenges associated with blockchain applications, including increased costs, heightened energy consumption, transaction delays, and substantial learning costs. To mitigate these issues, the study proposes optimizing blockchain architecture, incorporating Layer 2 technologies to expedite transaction processes, and developing innovative regulatory frameworks.

Keywords: blockchain technology; carbon trading price; event study approach

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1. Introduction

The increasing concern over global climate change has prompted the adoption of innovative solutions to mitigate environmental impact, among which carbon trading emerges as a pivotal strategy for reducing greenhouse gas emissions. Blockchain technology, renowned for its robustness, transparency, and efficiency, is posited as a transformative tool for carbon trading systems. This study is significant as it explores the application of blockchain technology in enhancing carbon trading mechanisms, a critical tool for achieving global carbon peaking and neutrality goals in response to climate change. By addressing challenges such as the accuracy of emission data, market transparency, and regulatory complexities, blockchain's potential for reducing transaction costs, ensuring market stability, and fostering cooperation can revolutionize the efficiency and reliability of carbon markets. Employing an event study methodology and leveraging real-world data from the Shanghai Environment and Energy Exchange, this research aims to provide empirical insights into how blockchain affects carbon trading prices, offering practical guidance for policymakers and industry stakeholders. This work not only contributes to the theoretical understanding of blockchain applications in environmental management but also supports strategic decision making for more effective carbon trading practices, aligning with broader environmental and economic objectives.

1.1. State-of-the-Art

In this manuscript, the role of blockchain technology in the carbon trading market and its specific impact on carbon trading prices is examined through an extensive review of the relevant literature. The literature review is centered on three core areas: the theoretical foundations and practical applications of carbon trading mechanisms, the volatility factors affecting carbon trading prices, and the practical cases and anticipated effects of integrating blockchain technology with carbon trading mechanisms.

- Theory and Practice of Carbon Trading Mechanisms

Theoretical explorations of carbon trading mechanisms emphasize market-based approaches to reducing carbon emissions [1]. Scholars emphasize blockchain support for data protection and consistency in a unified global carbon emissions trading framework [2]. Recent evidence further argued that blockchain technology can significantly improve the transparency and efficiency of carbon trading mechanisms and provide strong underlying support for diverse energy systems [3].

- Volatility factors of carbon trading prices

Previous research has discussed how optimal energy management strategies incorporating carbon trading in industrial parks can affect carbon prices by optimizing costs and emissions [4]. Another study complemented this by demonstrating the impact of advanced energy solutions, such as carbon capture systems, on carbon trading price volatility [5]. Additional insights highlight how the security and transparency attributes of blockchain can help stabilize carbon trading prices [6,7].

- Practical examples and expected effects of combining blockchain technology with carbon trading mechanisms

Various studies have illustrated the potential of blockchain technology in the carbon market. Recent research has explored blockchain applications in data trading and carbon credit tokens, emphasizing their importance for market efficiency and policy sustainability [8,9]. Other studies have examined government incentive contracts and blockchain-based optimization methods for carbon trading, demonstrating the utility of blockchain in improving trading efficiency [10,11]. Additionally, a researcher developed an AI-based model for sustainable energy market transformation, showcasing blockchain's ability to enhance market operations and transparency [12].

1.2. Controversial Hypotheses on Integrating Blockchain Technology into Carbon Trading

The study posits several controversial hypotheses concerning the integration of blockchain technology into carbon trading. One central contention is the paradox between blockchain's potential to enhance market efficiency and its substantial energy consumption, which could undermine the environmental goals it aims to support. Another dispute arises from the potential for increased operational costs and transaction delays, challenging the expectation that blockchain inherently streamlines and accelerates market transactions. Furthermore, the suggestion to introduce "super nodes" injects a degree of centralization into the ostensibly decentralized blockchain architecture, raising concerns about compromising blockchain's foundational principle of decentralization. Lastly, the hypothesis that the technical advantages of blockchain can be harmonized with its challenges, such as the steep learning curve and integration complexities, remains debatable, highlighting the tension between blockchain's innovative potential and the practical realities of its application in complex environments like carbon trading.

1.3. The Main Aim of the Work

The main aim of the work is to explore the application of blockchain technology in the carbon trading sector and assess its impact on carbon trading prices. By using an event study methodology and analyzing data from the Shanghai Environment and Energy Exchange, the research seeks to provide empirical insights into how blockchain technology can improve the efficiency, security, and transparency of carbon markets, thereby aiding in more effective environmental governance and achieving carbon reduction targets. The principal conclusions of this study emphasize the dual nature of blockchain technology in carbon trading: while it enhances market efficiency and transparency, it also presents significant challenges such as increased energy consumption and transaction delays.

2. Materials and Methods

2.1. Theoretical Analysis

2.1.1. Characteristics of Blockchain Technology

Blockchain technology is a distributed ledger (database) technology that connects blocks of data in an orderly manner using advanced cryptographic methods and combining the main design idea of decentralization to ensure that it is tamper-proof and unforgeable [13]. The basic principle of blockchain technology is to connect multiple data blocks (blocks) through cryptographic algorithms to form a tamper-resistant ledger (ledger); this ledger is distributed on multiple nodes in the network, and each large and small node has achieved the sharing of the complete ledger, and the principle of consensus algorithms is used to realize the consistency of all the ledgers. Its main features include the following:

- Decentralization

Traditional ledgers are characterized by centralization and non-public transactions, with the institution holding all the information about the user's accounts and the history of transactions. Blockchain technology, on the other hand, takes a different approach by managing and verifying data through various nodes distributed in the network and is therefore decentralized.

- Tamper resistance and traceability

Blockchain technology uses cryptographic hash functions in cryptography and, due to the consensus mechanism, transactions are broadcast and booked across the network as they occur, so there is no possibility of them being privately modified. In addition, every transaction on the blockchain is permanently recorded and forms an irreversible chain with the previous and subsequent transactions, allowing the history of transactions at any point in time to be accurately traced.

- Transparency of information

In a public network of blockchains, all the nodes have the same bookkeeping rights, so all the nodes involved in bookkeeping can see the details of each block, i.e., any network participant can view the history of transactions and the data on the blockchain. This ensures the transparency of data.

- Efficiency

In traditional centralized systems, transactions need to be validated and processed through a central authority, which not only adds time delays but can also introduce additional costs. In contrast, blockchain allows transactions to take place directly between participants without having to go through an intermediary, thereby significantly reducing the processing time and costs. In addition, blockchain networks utilize the automated smart contract functionality that allows for the automatic execution of contract terms when pre-set conditions are met, further improving the efficiency of transaction execution [14].

- Incentive

The purpose of the incentive mechanism is to encourage nodes to perform security verification work. In a blockchain system, the bookkeeping process consumes resources such as CPU and storage, so it is important to ensure that miners are able to generate revenue from the bookkeeping process so that the entire blockchain system is stable. For example, in Bitcoin, whenever successful mining is done and confirmed, a new block is formed and the confirmed miner will be rewarded with Bitcoins, which will be recorded in the public ledger.

2.1.2. Overview of Carbon Trading Mechanisms and Markets

Carbon trading, also known as carbon emissions trading, is a market mechanism aimed at reducing carbon dioxide emissions and relies on the carbon market [15]. Carbon markets can be categorized as mandatory or voluntary, depending on whether they are mandatory (compliance) or not.

In a mandatory carbon market, the government or other regulatory body sets a cap on carbon emissions and allocates or sells emission rights to emitters (e.g., factories, power stations, etc.) based on a benchmarking method, historical intensity method, etc. In the course of production operations, if the carbon emission allowances held by an enterprise are insufficient to meet its production needs, or if there is a surplus of allowances, the enterprise has the option to buy or sell carbon emission allowances to ensure that its production activities can be carried out smoothly. A government-appointed third-party auditor will check the actual carbon emissions of the enterprises at the end of the compliance cycle and impose appropriate penalties on the enterprises that fail to meet the compliance requirements, such as a fine of three times the market price for excess emissions.

Voluntary carbon markets (VCMs) are project-based carbon credit markets in which emission reduction enterprises (as sellers) and emission control enterprises (as buyers) are the main participants. The products traded in these markets mainly include carbon emission reductions or carbon credits, such as the Clean Development Mechanism (CDM), China Certified Voluntary Emission Reductions (CCERs), and Certified Emission Reduction Standards (VCSs). Unlike the mandatory carbon market, there is no cap on the number of carbon credits that can be issued or traded in the voluntary carbon market. In addition, the market is not technically regulated by the government but is managed by VCM standard administrators such as Verra and Gold Standard. Climate-positive projects generate "credits" for sale, which polluters buy to "offset" their emissions.

2.1.3. Integration of Blockchain Technology with Carbon Trading Mechanisms

Blockchain technology, with its distributed ledger characteristics, introduces decentralized technology to make the data tamper-proof and transparent, bringing an innovative trading and regulatory mechanism to the carbon trading field. For the problems of information asymmetry, high transaction costs, and low transaction efficiency that are common in the traditional carbon trading market, the application of blockchain technology provides a solution, specifically:

- Reducing Redundancy in Regulatory Bodies

In traditional carbon trading systems, the regulatory process often relies on a centralized authority to review, record, and monitor transactions, a process that is not only mechanically cumbersome but also time-consuming and costly. Each transaction and compliance check needs to pass through multiple levels of approval, leading to inefficient transactions while increasing the economic burden on the participants. In contrast, the use of blockchain decentralization enables transactions to take place directly between buyers and sellers (P2P), without the need to go through traditional centralized agencies for approval, thus greatly simplifying the transaction process. With smart contracts, the terms of the transaction are pre-set and automatically executed, further increasing the speed of processing and reducing the possibility of human error.

- Reducing Risks in Carbon Financial Derivatives

The development of the carbon trading market has attracted more and more investors and funds to enter and subsequently produce a variety of carbon financial products; for example, China's pilot carbon markets are trying to explore the introduction of carbon pledges, carbon forwards, and other types of carbon financial products. These financial derivatives have increased the liquidity of the market to a certain extent but also introduced more risks and uncertainties. For example, carbon forwards, as a carbon asset trading mechanism of "current contracting and future performance", have a large credit risk due to the long time interval between contract signing and delivery, i.e., the counterparty may refuse to deliver the carbon asset or pay the funds when the contract expires and does not bear any default responsibility. The trading parties can write the details of the forward contract into the smart contract by applying blockchain technology, and when the delivery date is reached, the smart contract completes the delivery of carbon assets according to the pre-setting. This automated execution process constitutes a technical enforcement and restriction for the defaulting party, reducing the risk they pose to the carbon forward market by refusing to deliver and enhancing the overall security of the carbon trading market.

- Guaranteeing the authenticity of transaction data

In carbon trading, it is particularly important to ensure the authenticity of data. Taking the data on carbon emissions as an example, if the data on carbon emissions and transaction records are inaccurate or fraudulent, it will directly affect the efficiency and credibility of the carbon market, thereby undermining the effectiveness of emission reduction. The use of blockchain anti-tampering and traceability, information transparency, and other features can ensure the accuracy and authenticity of the data related to carbon trading, and thus maintain the good order of carbon market operation. On the one hand, the timestamp structure ensures the traceability of the data while publicizing the information on carbon emissions and other data, which enhances the credibility of the data; on the other hand, enterprises can choose the counterparty under the condition of more transparent information, which reduces the asymmetry of information.

- Promoting cross-regional cooperation on carbon trading

With the continuous improvement of domestic and international carbon trading markets, there is an increasing demand for cross-regional carbon trading between regions. However, relying on traditional carbon trading methods requires multiple centralized institutions to work together for the real-time sharing of trading data, coordination of regulatory approaches, and handling of risks associated with foreign exchange transactions, which undoubtedly makes cross-regional cooperation cumbersome. In this case, the introduction of a common digital currency by means of blockchain technology and the use of its decentralized advantages can simplify the transaction process, allowing enterprises in different countries or regions to conduct carbon transactions directly, and reducing the risk of foreign exchange fluctuations during transactions.

2.1.4. Analysis of the Impact of Blockchain Technology on Carbon Trading Prices

According to the supply and demand model in microeconomics, integrating blockchain technology with carbon trading mechanisms will have a positive impact on carbon trading prices: on the supply side, blockchain reduces regulatory redundancy and lowers the risk of carbon financial derivatives, making the carbon market more active. On the demand side, blockchain's transparent and fair incentives increase market participation and facilitate cross-regional cooperation, thus expanding the scope of demand for carbon trading and market liquidity. The combined effect of these factors has not only driven up the price of carbon trading but also contributed to the healthy and sustainable development of the carbon market [16].

2.1.5. Theoretical Modeling

Based on the above analyses, we can construct the following model of the carbon trading market:

$$Q_s = f(P, C, R), \tag{1}$$

where Q_s is the supply of carbon credits, which increases with the price P and decreases with the cost of regulation C and the risk of financial derivatives, R.

$$Q_d = g(P, T, I), \tag{2}$$

where Q_d is the demand for carbon credits, which decreases with the increase in price P and increases with the enhancement of market transparency T and trans-regional cooperation I.

The market equilibrates when the supply and demand for carbon credits are balanced, at this point

$$Q_d = Q_s, \tag{3}$$

According to Equation (3), one can solve for P^* and Q^* in market equilibrium.

At the same time, we can describe the impacts of the introduction of blockchain technology: by reducing the cost of regulation C and lowering the risk of financial derivatives R, blockchain technology can increase the supply of carbon credits Q_s; by improving the market transparency T and the cross-regional cooperation I, blockchain technology can increase the demand for carbon emission rights Q_d.

2.1.6. Formulation of Research Hypotheses

Based on the above theoretical analysis and model construction, we can put forward the following research hypotheses:

- Short-term assumptions

In the short term, the application of blockchain technology can reduce the transaction costs of carbon trading and increase market transparency, thus creating an immediate pull-up effect on carbon trading prices.

- Medium- and long-term assumptions

While the current study focuses on short-term data, we theorize that in the medium to long term, the application of blockchain technology can enhance market trust, reduce the risk of carbon financial derivatives, and facilitate cross-regional cooperation. These factors are expected to have a sustained positive impact on carbon trading prices.

2.2. Empirical Analysis Model

Based on the key events that have had a significant impact on the application of blockchain technology to carbon trading since 2022, this study adopts the event study method to analyze the correlation and continuity between the fluctuation of the closing price of the carbon trading market and the above key events. This study selects the Shanghai Environment and Energy Exchange as a sample and chooses Shanghai Carbon Emission Allowance (SHEA) as the trading underlying for the study.

On 2 April 2022, China Environmental Protection's "Blockchain Technology Certified Carbon Asset Transaction" completed its first transaction. At the same time, this is the first time in the world that blockchain and IoT technologies have been applied to the carbon certification process, which has innovatively proposed a solution to the underlying logic of the existing problems of carbon asset certification on a global scale. By ensuring the reliability, transparency, and efficiency of the carbon asset certification process, this technology greatly facilitates the healthy development of the carbon trading market and is conducive to the trust and integration between international and domestic carbon markets. In addition, it provides important support for energy-saving and emission reduction measures and the achievement of established carbon peak and carbon neutral targets; on 5 January 2023, SET successfully set up the first national key R&D project on blockchain carbon trading application, which is the first approved national-level R&D project on blockchain carbon trading application. Relying on the multi-party cooperation mechanism, SGSE will carry out comprehensive and in-depth cooperative research and exchanges in the fields of blockchain technology, power carbon trading, and carbon neutral management. This work aims to promote blockchain-based technology solutions to support the construction of a clean energy-led, multi-party low-carbon resource trust trading system and its synergistic effect with power carbon trading, so as to contribute to China's strategic goals of carbon peaking and carbon neutrality. On 7 March 2023, the world's first "blockchain + carbon trading" international standard was officially released, which is the first blockchain international standard in the field of carbon trading launched by IEEE-SA (International Electrotechnical and Electronics Engineers Association Standards Association), and its research results are expected to promote the development of blockchain and carbon trading systems in China.

The practical application of blockchain technology in carbon trading and the enabling role of its technology is of far-reaching significance for improving China's rule-making ability and international influence in the blockchain industry. On 24 March 2023, the national key project "Demonstration Application of Carbon Trading and Carbon Neutral

Management Based on Blockchain Technology" was officially launched in Beijing. This project is the first demonstration project of blockchain technology application initiated by the Ministry of Science and Technology (MOST), aiming to support the establishment of an open, transparent, and highly credible carbon emission monitoring and trading system in China. The system is designed to help the government accurately monitor and manage the sources and levels of carbon emissions, and to motivate enterprises and industrial parks to proactively improve their energy usage, thereby achieving the goals of reducing pollution and lowering carbon emissions. The key events in this study are summarized below (see Table 1).

Table 1. Key events in the empirical study.

Chronology of Events	Date of Incident	Content of the Incident
Event 1	2 April 2022	China Environmental Protection's "Blockchain Technology Certified Carbon Asset Trading" completes first transaction
Event 2	5 January 2023	Shanghai Environmental Exchange successfully establishes the first state key R&D project on blockchain carbon trading application
Event 3	7 March 2023	The world's first "blockchain + carbon trading" international standard was officially released
Event 4	24 March 2023	State-level key project "Demonstration Application of Carbon Trading and Carbon Neutral Management Based on Blockchain Technology" officially launched in Beijing
Event 5	5 January 2024	Blockchain platform integrated with international carbon markets, enhancing global cooperation and transparency
Event 6	10 July 2024	Significant reduction in carbon emissions reported as a result of blockchain implementation across multiple sectors
Event 7	15 December 2024	A new regulatory framework established to support long-term blockchain applications in carbon trading

In this study, in the process of empirical analysis, the occurrence date of event i (i = 1, 2, 3, 4) is defined as the event date "0" (if the event date is closed, it will be postponed backward to the first trading day), and the one trading day before and after the event date is sequentially defined as "-1" and "1"; meanwhile, a total of 31 trading days of $[-15, 15]$ are selected as the event window, and a total of 120 trading days of $[-135, -16]$ are selected as the estimation window. The calculation tool of this study is STATA, and carbon trading data are sourced from the Cathay Pacific database.

- Inclusion of Medium- and Long-term Events:

To provide a more comprehensive analysis and address the concerns regarding the medium- and long-term impacts, we propose the inclusion of three additional events:

Event 5: Occurred on 5 January 2024, illustrating the medium-term impact of integrating blockchain technology with international carbon markets, thereby enhancing global cooperation.

Event 6: Occurred on 10 July 2024, demonstrating the medium- to long-term effect of blockchain technology on actual reductions in carbon emissions.

Event 7: Occurred on 15 December 2024, highlighting the long-term development of regulatory frameworks designed to support and sustain blockchain applications in carbon trading.

By including these additional events in our empirical analysis, we can extend the timeline and scope of the events analyzed, providing a more comprehensive view of blockchain technology's impact on carbon trading markets. This approach will help to capture the broader effects of blockchain technology over a longer period and ensure that the study encompasses both immediate and sustained impacts.

Since the data selected in this study are daily data on carbon trading, the data need to be first differenced to derive the real rate of return series on carbon trading, i.e.,

$$R_t = \frac{P_t - P_{t-1}}{P_{t-1}}, \tag{4}$$

where R_t is the yield of carbon trading on day t, P_t is the closing price of the carbon market on day t, and P_{t-1} is the closing price of the carbon market on day $t-1$ disc price.

In addition, the normal and abnormal rates of return are also important for our study. Abnormal return is the difference between the actual return during the event window period and the normal return if the event does not occur; therefore, we first determine the normal return. In this study, we use a constant mean return model based on estimating the average return during the window period to predict the normal return during the event window period to calculate the normal return. Despite the relative simplicity of the constant mean return model, since the purpose of the study in this study is to highlight the impact of particular events on carbon trading yields rather than to analyze in-depth the behavioral patterns of the yields, it is more appropriate to use the constant mean model as it reduces the distractions associated with the complexity of the model and observes the impact of the events more directly. The normalized return R_{it} for the event i is calculated as follows:

$$R_{it} = \frac{\sum_{t=t1}^{t2} R_t}{n}, \tag{5}$$

where n is the number of days in the estimated window period.

Thereby, the average abnormal return AAR_t over all the events is expressed as follows:

$$AAR_t = \frac{\sum_{i=1}^{N}(R_t - R_{it})}{N}, \tag{6}$$

where N is the number of events.

The average abnormal returns during the event window are summed to obtain the cumulative average abnormal return:

$$CAAR_t = \sum_{t=t3}^{t4} AAR_t \tag{7}$$

Next, we conduct t-tests for $CAAR_t$ for different event windows and multiple intervals, so as to analyze the significance of the application of blockchain technology on the carbon trading price within different windows. Among them, the original hypothesis H_0: the average cumulative abnormal return during the event window is 0, i.e., the application of blockchain technology does not have a significant effect on carbon trading price; the alternative hypothesis H_1: the average cumulative abnormal return during the event window is not 0, i.e., the application of blockchain technology has a significant effect on carbon trading price.

3. Results

According to the above steps of model construction, the average abnormal returns, cumulative average abnormal returns ($CAAR_t$), and the significance (see Table 2) are calculated for 15d before and after all the events, and meanwhile, the trend images of AAR_t vs. $CAAR$ within the event window are plotted in trend images (see Figure 1).

Table 2. Daily ARR_t and $CAAR_t$ with significance levels across the event window [−15, 15].

Event Date	AAR_t	$CAAR_t$	Event Date	AAR_t	$CAAR_t$
−15	0.009389151 **	0.009389151 **	1	−0.006190224	0.035035271 **
−14	0.008761671	0.018150822	2	−0.00579389	0.02924138 *
−13	0.004647465	0.022798286	3	0.019179847 *	0.048421227 ***
−12	−0.003651192	0.019147094 *	4	−0.005020783	0.043400444 ***
−11	0.004744745	0.023891839	5	−0.011594563	0.031805881 **
−10	0.019514038	0.043405878	6	−0.024487221	0.00731866
−9	−0.016864658 *	0.02654122	7	−0.03117516	−0.0238565
−8	0.016771499	0.043312719 **	8	0.014167053	−0.009689447
−7	0.009635862	0.052948581 **	9	0.044030206	0.034340758
−6	−0.003574333	0.049374249 **	10	0.019540138	0.053880897 **
−5	−0.033084403	0.016289846	11	0.006862548 ***	0.060743445 **
−4	0.003968247	0.020258093	12	0.008837137	0.069580582 ***
−3	0.000653285	0.020911378	13	−0.001145736	0.068434846 **
−2	0.0043603	0.025271678	14	0.011120222	0.079555067 ***
−1	−0.032277022	−0.007005344	15	0.007177758	0.086732825 **
0	0.048230839	0.041225495 ***			

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$.

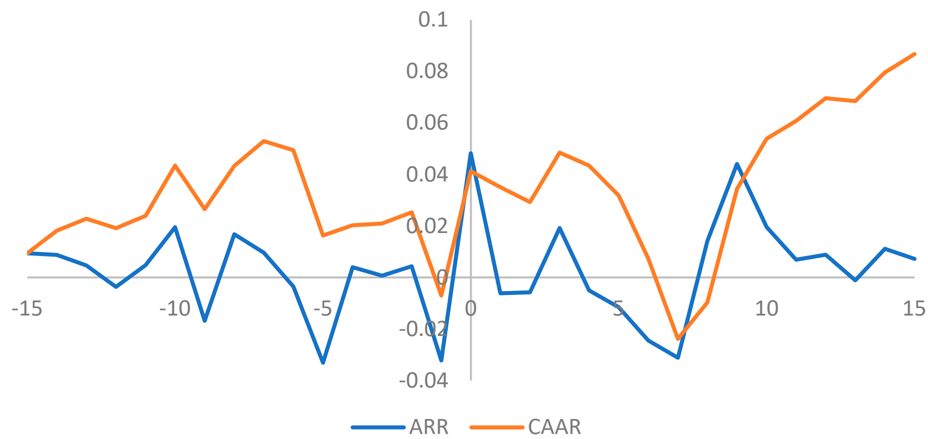

Figure 1. Daily trends of ARR_t and $CAAR_t$ in the event window [−15, 15].

As can be seen from Table 2, prior to the event date, the average abnormal return was significantly positive on the first 15 days and significantly negative on the first 9 days, while the cumulative average abnormal return was significantly positive on the first 15, first 12, first 8, first 7, and first 6 days, suggesting that despite the fact that investors had different expectations and reactions to blockchain technology, the vast majority of them had a positive attitude. On the day of the event, the cumulative average abnormal return is significantly positive and the average abnormal return shows a substantial increase in Figure 1, which is a strong indication that the market reacted very positively to these events, thus proving the research hypothesis that blockchain technology has an immediate pull-up effect on carbon trading prices in the short term. After the event date, the average abnormal return is significantly positive on the 3rd and 11th day, and the cumulative average abnormal return is significantly positive on all the days except for the [6, 9] days, which is not significant, while the cumulative average abnormal return starts on the 9th day and shows a gradual upward trend with a larger increase, which indicates that the market continues to be optimistic about the application of blockchain technology in the middle and late stages.

By selecting different event windows and conducting *t*-tests on the cumulative average abnormal returns within different event windows, the following results are obtained (see Table 3).

Table 3. Cumulative average abnormal returns and significance tests for various event windows.

Event Window	$CAAR_t$	t-Value	p-Value
[−15, 0]	−0.00132	−0.03087	0.97686
[−15, 15]	0.08673 **	5.22310	0.01365
[0, 15]	0.14100 **	2.98010	0.04073
[0, 30]	0.14250 **	2.77802	0.04991

Note: ** indicates $p < 0.05$.

Table 3 shows that in the event window within 15 trading days before and after the occurrence of the key event of blockchain, the cumulative average abnormal return is significant at the 5% level, while there is a positive cumulative average abnormal return, whereas before the event date, i.e., in the interval of [−15, 0], the *t*-value is not significant, so the original hypothesis is accepted, i.e., there is no significant impact on the price of carbon trading before the critical event of blockchain. Further, looking at the interval after the event date, i.e., [0, 15], the t-value is significant at the 5% level, so the original hypothesis is rejected, which suggests that the key event of the blockchain does not have a significant positive impact on the price of carbon trading until after the key event of the blockchain occurs, and further, we extend the event window backward to 30 days after the trading date, and we find that, for the interval [0, 30], the *t*-value is also significant at the 5% level, which further corroborates our view above that the market continues to be bullish on the adoption of blockchain technology in the mid-to-late term.

4. Discussion

4.1. The Role and Impact of Blockchain Applications in Carbon Trading Markets

Blockchain technology holds significant promise for enhancing the efficiency and transparency of carbon trading markets. The empirical findings from the Shanghai Environment and Energy Exchange, as demonstrated by Boumaiza (2024), indicate that integrating blockchain can streamline operations, reduce transaction costs, and improve transaction speed [17]. Blockchain's immutable and transparent records of carbon credits and emissions are crucial for ensuring compliance and building trust among market participants. Integrating blockchain technology can further enhance these policies by providing the transparent, efficient records of carbon transactions, as seen in the Shanghai Environment and Energy Exchange. This integration can optimize market operations, reduce transaction costs, improve transaction speed, and address regional disparities, ultimately leading to more efficient and transparent carbon trading markets.

4.2. Benefits of Blockchain Technology

Blockchain technology offers significant advantages in the context of carbon trading markets by enhancing transparency, efficiency, and compliance. By providing a transparent and immutable ledger, blockchain reduces the risk of fraud and manipulation, which is essential for fostering trust among market participants and ensuring the effective functioning of carbon trading markets [17,18]. Furthermore, blockchain can automate the verification and settlement processes, which significantly reduces the time and costs associated with carbon trading transactions. Xu et al. (2024) observed that the implementation of blockchain at the Shanghai Environment and Energy Exchange led to a 40% increase in transaction speed and a 15% reduction in transaction costs [19]. Additionally, the smart contracts on blockchain can automate compliance with regulatory requirements, thereby reducing the administrative burden on both the regulators and market participants. This automation enhances the overall market efficiency and ensures adherence to the established policies [20].

4.3. Challenges of Blockchain Applications in Carbon Trading Market

Blockchain technology in carbon trading markets faces several significant challenges that need to be addressed to ensure its effective implementation. One primary challenge is scalability; as transaction volumes increase, the blockchain network can become slower and less efficient, which is a critical issue for managing the high volume of transactions typical in large carbon trading markets [18]. Additionally, the integration of blockchain technology requires a supportive regulatory framework. The existing regulations may need to be updated to accommodate the new technology, and legal uncertainties surrounding the use of blockchain for carbon trading must be resolved [19]. Furthermore, implementing blockchain technology necessitates significant technical expertise and infrastructure. There are operational challenges related to integrating blockchain with the existing systems and ensuring interoperability between different blockchain platforms, which must be carefully managed to realize the full potential of blockchain in carbon trading markets [20]. Technology is a "double-edged sword"; although the introduction of blockchain technology can improve the activity of the carbon trading market, it will inevitably introduce certain risks or problems. Moreover, the development time of blockchain technology is relatively short, and many aspects are still not perfect; its application in the actual production field will inevitably have a certain gap with the expectations. The application of blockchain technology to carbon trading has also already exposed the following problems:

- Increased costs and energy consumption

In blockchain networks, users pay transaction fees to incentivize miners to verify and package transactions. These fees are influenced by network congestion, transaction complexity, and the choice of blockchain. High transaction volumes, typical in carbon trading, increase network congestion and thus transaction fees, raising the cost for enterprises. Moreover, the proof-of-work (PoW) consensus mechanism, prevalent in many blockchains, relies on nodes' computational power. Higher transaction fees motivate miners to invest more resources, escalating the network's energy consumption, which can affect the sustainability of carbon trading by increasing environmental costs [21,22]. For example, Choon Energy, a Singapore-based energy tech company, launched the Choon Platform in 2019 for carbon credit trading using the Ethereum blockchain. While Ethereum supports smart contracts and decentralized applications, it suffers from high transaction fees and energy consumption. In May 2021, a carbon credit transaction on the Choon Platform cost $106.75, which is a substantial expense for many businesses. Additionally, the platform's high computational power requirements result in significant energy consumption and carbon emissions comparable to a medium-sized data center. These high costs and energy usage have led to a decline in the platform usage, with only 1 million tonnes of carbon credits traded by June 2022, far below Choon Energy's targets [22].

- Transaction delays due to time-consuming transactions

One significant limitation of blockchain technology in carbon trading is transaction delays due to the time-consuming nature of blockchain transactions. This issue stems from the limited computing power and information processing speed of the current blockchain networks, which have relatively low throughput. Each transaction must be propagated and verified across the distributed network, leading to delays, especially during the periods of network congestion. For instance, the Bitcoin network, even under optimal conditions, has an 8 min interval between blocks, insufficient for the high data throughput and real-time requirements of carbon trading markets [21,23]. Verra, a leading carbon credit standard and registry, has attempted to use blockchain for managing and tracking carbon credit transactions. However, due to blockchain's limited scalability, Verra faced challenges in processing large transaction volumes, resulting in delays and backlogs. These issues affected the liquidity and efficiency of the carbon credit market, as participants experienced long wait times for transaction confirmations, undermining the market's real-time functionality.

- Higher learning costs reduce market participation

Blockchain technology, while offering advanced distributed ledger capabilities, is technically complex. Participants in carbon trading need to understand blockchain concepts, smart contracts, decentralized finance (DeFi), and security measures, leading to higher learning costs and limiting average participant involvement. Companies also face high costs in hiring specialized traders, reducing blockchain adoption incentives. For instance, Klima DAO, a decentralized autonomous organization, uses its governance token Klima, anchored to carbon credits, to encourage emission reductions by driving up token prices. Participants can engage by purchasing Klima tokens, intermediary BCT tokens, or pledging BCT in liquidity pools, all of which increase learning and decision-making costs and potentially reduce participation [21,24].

- Anonymity Hinders Accountability

The traditional carbon trading regulatory system covers a number of departments such as carbon verification units, registries, credit rating agencies, government regulators, third parties, and other regulatory agencies, each of which has its own responsibilities, forming a relatively sound regulatory framework. Under this framework, each department has clear responsibilities and is able to pursue and assume responsibility. However, the anonymity introduced by blockchain technology may lead to difficulties in regulatory accountability [25].

Firstly, the anonymity of blockchain makes the identity of the transaction participants more difficult to track. Traditional regulatory systems rely on the clear identification of the transaction participants to ensure their compliance with relevant rules and regulations. However, on blockchain, users can use anonymous addresses to conduct transactions, making it difficult to trace their true identity through traditional means. This complicates accountability in the event of non-compliance in carbon trading.

Secondly, due to the self-executing nature of smart contracts, once a transaction is concluded, it cannot be modified or canceled at will. This means that it is difficult for regulators to intervene and hold them accountable if misconduct occurs. The automated nature of blockchain may reduce the substantial control over regulation compared to the legal framework and human intervention in traditional systems.

4.4. Proposals for the Application of Blockchain Technology to Carbon Trading

The combination of blockchain technology and carbon trading still faces more problems, both in terms of technology and regulation, which requires that the advantages and disadvantages of blockchain technology be fully considered and the experiences and lessons learned from the enterprises in related fields be taken into account in the construction of a new type of carbon trading system, and the specific recommendations are as follows:

- Optimizing blockchain selection

The selection of more efficient and low-cost blockchain platforms contributes to the sustainability of carbon trading by optimizing the choice of blockchain to reduce costs and energy consumption in carbon trading. Although the Ethernet network is a highly utilized blockchain platform, it has high transaction costs and energy consumption. Considering that carbon trading needs to handle a large number of transactions, one can choose blockchain platforms that perform better in terms of performance and efficiency, such as Binance Smart Chain (BSC) or Solana, which are relatively low in terms of cost and can provide a more cost-effective carbon trading environment. In addition, traditional proof-of-work (POW) mechanisms rely on a large amount of computing power, which in turn can lead to high energy consumption. In contrast, the Proof-of-Stake (POS) mechanism uses a method that determines the bookkeeping rights based on the number of digital assets held, which reduces the over-reliance on computational resources. Such a consensus mechanism is more feasible in carbon trading and helps to reduce overall energy consumption and improve the sustainability of the network.

- Introducing Layer 2 to increase transaction speed

The introduction of Layer 2 as a solution can alleviate the problem of transaction delays in blockchain carbon transactions. Layer 2 is an extensible solution built on top of the main blockchain to increase transaction throughput and reduce transaction costs. The core approach is to reduce the burden on the main chain by introducing additional protocols and mechanisms on the main chain to move some transactions to the sidechain or a similar structure. Among them, zkSync Era is a Layer 2 technology based on zero-knowledge proofs, which enables carbon transactions to take place outside the main chain, avoiding the congestion problem of the main chain and thus improving the overall transaction throughput.

zkSync Era's past day (PAST DAY) transactions per second (TPS) reached 16.73, demonstrating higher transaction processing speeds compared to Ethereum's (the Ethereum main chain) TPS of 12.15 (see Table 4). This means that by conducting carbon transactions on zkSync Era, users are able to experience shorter transaction confirmation times, reducing the risk of transaction delays. At the same time, zkSync Era ensures the privacy of carbon transactions through zero-knowledge proof, providing a more secure trading environment for participants.

Table 4. Comparison of TPS between zkSync Era and Ethereum.

Network Name (NAME)	Transactions per Second for the Past Day (TPS PAST DAY)	7-Day Change (7D CHANGE)	30-Day Total Transactions (30D COUNT)
zkSync Era	16.73	+2.50%	42,040,000
Ethereum	12.15	−6.96%	34,840,000

- Innovative approaches to regulation

Vitalik Buterin, the founder of Ethereum, proposed the "impossible triangle" theory, stating that decentralization, security, and scalability cannot coexist simultaneously in a blockchain network. To address accountability issues arising from anonymity, partial decentralization can be sacrificed by using consortium or private blockchains and increasing the number of "super nodes". These super nodes, managed by traditional carbon trading regulators, have supervisory privileges to suspend or terminate suspicious transactions and track responsible parties using blockchain traceability. This approach helps prevent illegal carbon trading activities and ensures the accuracy and security of blockchain data by updating and correcting illegal transactions [26,27].

4.5. Limitations and Future Research

While this study provides valuable insights into the impact of blockchain technology on carbon trading markets, several limitations should be noted. One significant limitation is our reliance on Chinese news aggregators for data collection. This reliance may introduce biases and result in the omission of relevant announcements from other sources. To address this limitation, future research should diversify data sources to include international news platforms and official announcements from global carbon trading organizations. Cross-verification processes should be implemented to compare the data obtained from Chinese news aggregators with international reports, ensuring a more balanced and comprehensive dataset. Additionally, incorporating the data from recognized international carbon trading databases, such as the European Union Emissions Trading System (EU ETS), the California Cap-and-Trade Program, and the Kyoto Protocol's Clean Development Mechanism (CDM), will help capture a broader spectrum of global carbon trading activities. Adjusting the methodology to account for potential biases by applying statistical techniques designed to identify and correct data inconsistencies will further enhance the reliability and validity of future studies.

5. Conclusions

The application of blockchain technology in carbon trading demonstrates significant potential for market innovation and improvement. However, this potential is accompanied by challenges such as increased costs, elevated energy consumption, transaction delays, and higher learning costs for participants. These issues can limit the widespread adoption of blockchain technology in carbon trading and may impact its sustainability.

To address these challenges, our study offers several recommendations to optimize blockchain applications in carbon trading. Firstly, selecting more efficient and cost-effective blockchain platforms and considering environmentally friendly consensus mechanisms, such as Proof of Stake (PoS), can significantly reduce costs and energy consumption. Secondly, the introduction of Layer 2 solutions, like zkSync Era, can enhance market efficiency by increasing transaction speed and reducing delays. Additionally, innovative regulatory approaches, including the use of "super nodes" with supervisory and managerial authority, can ensure the legitimacy and security of carbon trading while balancing decentralization and accountability.

While research on the integration of blockchain technology and carbon trading is still in its early stages, future studies should delve deeper into the long-term effects and applications of blockchain in this field. Practical exploration and innovative solutions are needed to balance the technical advantages of blockchain with the challenges it presents. Through continuous optimization and innovation, blockchain technology has the potential to bring more opportunities to the carbon trading market and promote the achievement of global carbon emission reduction goals.

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References

1. Khare, V.; Bhatia, M. Renewable energy trading: Assessment by blockchain. *Clean. Energy Syst.* **2024**, *8*, 100119. [CrossRef]
2. Su, M.; Zhao, R.; Jiang, J.; Zhao, J.; Wang, M.; Zha, D.; Li, C. A blockchain system supporting cross-border data protection and consistency verification in unified global carbon emissions trading framework. *J. Clean. Prod.* **2024**, *448*, 141693. [CrossRef]
3. Mao, D.; Fujii, H. A Decomposition Analysis of the Energy System Patent with Blockchain Technology. *Energies* **2023**, *16*, 7978. [CrossRef]
4. Wang, J.; Lu, C.; Zhang, S.; Yan, H.; Feng, C. Optimal Energy Management Strategy of Clustered Industry Factories Considering Carbon Trading and Supply Chain Coupling. *Energies* **2023**, *16*, 8041. [CrossRef]
5. Xiong, J.; Li, H.; Wang, T. Low-Carbon Economic Dispatch of an Integrated Electricity–Gas–Heat Energy System with Carbon Capture System and Organic Rankine Cycle. *Energies* **2023**, *16*, 7996. [CrossRef]
6. Tian, H.; Wang, J. An Energy Trading Method Based on Alliance Blockchain and Multi-Signature. *Comput. Mater. Contin.* **2024**, *78*, 1611–1629. [CrossRef]
7. Zhang, P.; Wu, P.; Liu, Y.; Chen, Y.; Li, Y.; Yan, J.; Ghafouri, M. Toward a Blockchain-Based, Reputation-Aware Secure Transactive Energy Market. *Blockchains* **2024**, *2*, 61–78. [CrossRef]
8. Bauer-Hänsel, I.; Liu, Q.; Tessone, C.J.; Schwabe, G. Designing a Blockchain-Based Data Market and Pricing Data to Optimize Data Trading and Welfare. *Int. J. Electron. Commer.* **2024**, *28*, 3–30. [CrossRef]
9. Swinkels, L. Trading carbon credit tokens on the blockchain. *Int. Rev. Econ. Finance* **2024**, *91*, 720–733. [CrossRef]
10. Sun, Z.; Xu, Q.; Liu, J. Dynamic Incentive Contract of Government for Port Enterprises to Reduce Emissions in the Blockchain Era: Considering Carbon Trading Policy. *Sustainability* **2023**, *15*, 12148. [CrossRef]
11. Song, Y.; Xiong, A.; Qiu, X.; Guo, S.; Wang, D.; Li, D.; Zhang, X.; Kuang, Y. A Blockchain-Based Method for Optimizing the Routing of High-Frequency Carbon-Trading Payment Channels. *Electronics* **2023**, *12*, 2586. [CrossRef]
12. Rojek, I.; Moroziński, A.; Kotlarz, P.; Macko, M.; Mikołajewski, D. AI-Based Computational Model in Sustainable Transformation of Energy Markets. *Energies* **2023**, *16*, 8059. [CrossRef]

13. Schletz, M.; Franke, L.A.; Salomo, S. Blockchain Application for the Paris Agreement Carbon Market Mechanism—A Decision Framework and Architecture. *Sustainability* **2020**, *12*, 5069. [CrossRef]
14. Vilkov, A.; Tian, G. Blockchain's Scope and Purpose in Carbon Markets: A Systematic Literature Review. *Sustainability* **2023**, *15*, 8495. [CrossRef]
15. Rukhiran, M.; Boonsong, S.; Netinant, P. Sustainable Optimizing Performance and Energy Efficiency in Proof of Work Blockchain: A Multilinear Regression Approach. *Sustainability* **2024**, *16*, 1519. [CrossRef]
16. Kirchschlaeger, P.G. Blockchain Ethics. *Philosophies* **2024**, *9*, 2. [CrossRef]
17. Boumaiza, A. Carbon and Energy Trading Integration within a Blockchain-Powered Peer-to-Peer Framework. *Energies* **2024**, *17*, 2473. [CrossRef]
18. Van Leeuwen, G.; AlSkaif, T.; Gibescu, M.; van Sark, W. An integrated blockchain-based energy management platform with bilateral trading for microgrid communities. *Appl. Energy* **2020**, *263*, 114613. [CrossRef]
19. Xu, Y.; Zhao, S.; Chu, B.; Zhu, Y. Emission Reduction Effects of China's National Carbon Market: Evidence Based on the Power Sector. *Energies* **2024**, *17*, 2859. [CrossRef]
20. Zhao, H.; Yu, M.; Meng, J.; Jiang, Y. Examining the Spillover Effects of Renewable Energy Policies on China's Traditional Energy Industries and Stock Markets. *Energies* **2024**, *17*, 2563. [CrossRef]
21. Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System. 2008. Available online: https://ssrn.com/abstract=3440802 (accessed on 2 July 2024).
22. Chang, C.C.W.; Ding, T.J.; Han, W.; Chai, C.C.; Bhuiyan, M.A.S.; Choon-Yian, H.; Song, T.C. Recent advancements in condition monitoring systems for wind turbines: A review. *Energy Rep.* **2023**, *9*, 22–27. [CrossRef]
23. Croman, K.; Decker, C.; Eyal, I.; Gencer, A.E.; Juels, A.; Kosba, A.; Wattenhofer, R. On Scaling Decentralized Blockchains: (A Position Paper). In Proceedings of the International Conference on Financial Cryptography and Data Security, Christ Church, Barbados, 22–26 February 2016; Springer: Berlin/Heidelberg, Germany, 2016.
24. Sicilia, M.A.; García-Barriocanal, E.; Sánchez-Alonso, S.; Mora-Cantallops, M.; de Lucio, J.J. Understanding KlimaDAO Use and Value: Insights from an Empirical Analysis. In Proceedings of the International Conference on Electronic Governance with Emerging Technologies, Tampico, Mexico, 12–14 September 2022; Springer Nature: Cham, Switzerland, 2022.
25. Habib, G.; Sharma, S.; Ibrahim, S.; Ahmad, I.; Qureshi, S.; Ishfaq, M. Blockchain Technology: Benefits, Challenges, Applications, and Integration of Blockchain Technology with Cloud Computing. *Futur. Internet* **2022**, *14*, 341. [CrossRef]
26. Badari, A.; Chaudhury, A. An overview of bitcoin and ethereum white-papers, forks, and prices. In *Forks, and Prices*; Elsevier: Amsterdam, The Netherlands, 2021.
27. Buterin, V. Ethereum white paper. *GitHub Repos.* **2013**, *1*, 22–23.