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Blockchain and Sustainability: Applications in Energy Trading and Carbon Footprint Reduction

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ABSTRACT: The integration of blockchain technology into low-carbon supply chains has gained momentum, enabling enhanced transparency and traceability of low-carbon products. This technological shift aims to boost brand awareness and market expansion by allowing consumers to verify the environmental impact of their purchases. However, the substantial operational and construction costs associated with blockchain raise concerns about its impact on the allocation of resources for research and development (R&D) in carbon emission reduction (CER) and overall firm profitability. This study examines the effects of blockchain implementation on CER and profits, focusing on two categories of firms: superior brand firms and inferior brand firms.

Based on our research, we argue that the extent of the positive effect of blockchain on CER and profits is contingent upon: consumer trust in low-carbon preferences; brand awareness; costs associated with building a new system based entirely on blockchain (endogenous factor); challenges arising from conducting R&D and maintaining CER for large firms. Brand companies with higher-level ability can improve the CER level and profits through blockchain when it is easy to R&D or with high distinguishable consumer trust, or hard to R&D but also big scale of low-carbon-preference consumers will follow up your brand strength. In contrast, blockchain technology can help local firms of inferior brand 1) when R&D difficulty is low and consumer trust is high; and 2) when R&D difficulty is high but there exists little public/brand awareness. This work offers strategic advice for companies that are contemplating blockchain implementation in their CER activities and highlights the importance of merging blockchain adoption with firm.

I. INTRODUCTION

Since the reform and opening up, China's economy has experienced rapid development. However, this growth has been accompanied by significant environmental pollution issues, including high energy consumption and severe air pollution. According to greenhouse gas emission data, China has consistently ranked as the world's largest emitter of carbon dioxide for many years. In response, China officially adopted the concept of green development in 2015, making it a crucial component of the national development strategy. To accelerate the transition towards green and low-carbon development and actively combat climate change, China has set ambitious long-term goals: to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. These goals reflect not only the requirements of China's current development stage but also its commitment to international responsibility as a major global player.

Facing increasingly severe resource and environmental challenges, the energy internet—an integration of information technology and energy—offers a promising solution for enhancing the marketization, efficiency, and greenness of energy use. This aligns with the "new progress in the construction of ecological civilization" outlined in China's "14th Five-Year Plan." Concurrently, the rapid development and application of blockchain technology across various sectors have positioned it as a key enabler in constructing the energy internet. Blockchain technology supports the achievement of "carbon peaking and carbon neutrality" goals by breaking away from traditional theoretical frameworks and providing practical, innovative solutions.

Extensive literature review and analysis reveal that the effective development of energy blockchain technology, its integration with dual carbon goals, and the maximization of energy efficiency to reduce carbon emissions are critical research hotspots. However, most current literature focuses on theoretical analysis, with limited integration into practical applications. This paper examines the development status of energy blockchain technology in Anhui Province, China, specifically in the context of achieving carbon neutrality. By analyzing real-world scenarios, this study proposes optimized pathways tailored to local conditions.

Globally, carbon dioxide (CO₂) is recognized as the most significant greenhouse gas contributing to anthropogenic climate change. The international community has developed various mechanisms to regulate carbon emissions, starting with carbon taxes, which have successfully reduced emissions. The cap-and-trade (CAT) system, introduced under the 1990 Clean Air Act in the United States, significantly reduced sulfur dioxide emissions and laid the groundwork for international initiatives like the Kyoto Protocol. Adopted in 1997 and enforced in 2005, the Kyoto Protocol aimed to reduce and regulate greenhouse gas emissions worldwide.

Emission Trading Schemes (ETS), based on the cap-and-trade system, transformed carbon into a tradable commodity, spurring the creation of national compliance carbon markets (CCM). In 2021, these markets represented approximately USD 270 billion in value, with a substantial growth trend continuing into 2022. Additionally, the Kyoto Protocol's flexibility mechanisms, such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) projects, facilitated the emergence of voluntary carbon markets (VCM). Companies engaged in these markets often adhere to Environmental, Social, and Governance (ESG) principles and Corporate Social Responsibility (CSR) to reduce their carbon footprints.

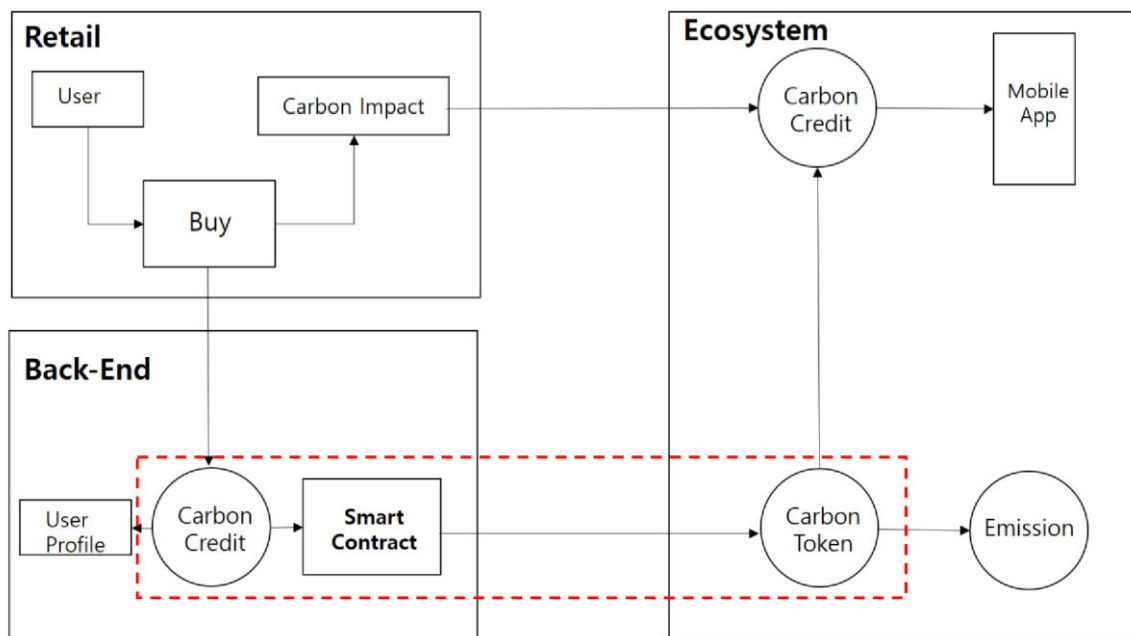


Fig. Smart renewable energy and P2P (Peer-to-Peer) blockchain service.

Blockchain technology, popularized through the rise of cryptocurrencies like Bitcoin, provides a decentralized ledger system that can enhance transparency and trust in carbon markets. This technology offers unique opportunities to improve accountability in carbon trading and support the development of renewable energy micro-grids. However, for blockchain to fully realize its potential in addressing the climate crisis, it should be integrated with macroeconomic policies and regulatory frameworks to finance the substantial transition required.

Overall, the integration of blockchain technology in energy trading and carbon footprint reduction presents a multifaceted approach to addressing climate change. This study aims to bridge the gap between theoretical concepts and practical applications, providing strategic insights for leveraging blockchain to achieve environmental and economic objectives in the context of carbon neutrality.

II. LITERATURE REVIEW

- **Research on blockchain technology applied to low-carbon supply chain**

The integration of blockchain technology with supply chain management (SCM) effectively addresses trust issues by preventing information manipulation, enabling traceability, and enhancing monitoring capabilities for businesses and consumers. Current research on blockchain in low-carbon supply chains focuses primarily on empirical analysis and game theory models.

Empirical studies have shown mixed results regarding blockchain's impact on Corporate Environmental Responsibility (CER). For instance, Tawiah et al. (2022) demonstrated that blockchain significantly improves environmental efficiency in U.S. firms, while Qin et al. (2023) supported blockchain's role in aiding China's carbon neutrality goals. Conversely, Parmentola et al. (2022) reviewed 195 studies and highlighted blockchain's potential negative environmental impacts due to its high energy consumption. Game theory models further explore these dynamics. Jiang and Liu (2022) employed a Stackelberg game model to analyze CER and blockchain investment strategies among supply chain members. Xu and Choi (2021) and Xu et al. (2021) found that blockchain enhances supply chain coordination, leading to better environmental responsibility and increased profitability. Factors such as fairness concerns and consumer green sensitivity also influence blockchain adoption, as noted by Li et al. (2022). Additionally, Biswas et al. (2023) observed that firms are less likely to adopt blockchain when consumer distrust is high due to its environmental impact.

- **Study on the impact of low carbon preference and trust on CER of firms**

Consumer preferences and trust significantly impact CER strategies. He et al. (2020) concluded that online channels are profitable under specific low-carbon sensitivity conditions. Sun et al. (2020) found that consumer low-carbon preferences impact supply chain profits if the lag in CER technology adoption is within a certain range. Xia et al. (2022) examined how market competition and consumer preferences influence firm profits and supply chain decisions. Meng et al. (2021) highlighted that demand for low-carbon products correlates with consumer preferences for both low-carbon and offline channels. Trust plays a crucial role in purchase intentions, as Wasaya et al. (2021) showed that low-carbon trust significantly moderates purchase intentions. Ahmad and Zhang (2020) emphasized the positive influence of low-carbon trust and perceived value. Amin and Tarun (2021) found green trust to be a strong mediator for green purchase intention, whereas Amoako et al. (2020) noted green trust's limited moderation role compared to green values. Game models by Wang and Hou (2020) and Choi et al. (2020) demonstrated that consumer trust affects regulatory needs and blockchain's effectiveness in achieving environmental goals.

Brand awareness also influences CER decisions. Research by Grimmer and Bingham (2013) and Walker and Wan (2012) suggests that strong branding enhances a firm's commitment to environmental sustainability, reducing carbon emissions. Kahraman and Kazançoğlu (2019) found that environmentally responsible brands boost trust and loyalty, increasing purchase intent. Studies on green branding, such as those by Chao and Wang (2019), Kim and Park (2019), and Qiu et al. (2018), indicate that green branding positively impacts CER initiatives by raising consumer awareness and support.

Existing research highlights the critical role of consumer perceptions of brands in strengthening or weakening firms' CER efforts and underscores the potential of blockchain to address historical issues of information asymmetry in supply chains. However, the high costs associated with blockchain and its potential to divert resources from CER R&D present challenges. This study extends current research by using game theory to explore the integration of CER strategies and blockchain investment, considering the impact on profitability and the role of brand awareness, operational costs, R&D difficulties, and consumer preferences and trust. The findings provide valuable insights for practitioners seeking to develop effective low-carbon innovation strategies.

III. PROBLEM DEFINITION

Blockchain, often referred to as a public exchange ledger, operates without a central manager, instead being collectively managed by all participants. This decentralized approach contrasts with the traditional banking system, where banks centrally control trading ledgers, making them vulnerable to hacking. In a blockchain system, each participant has an updated copy of the ledger, enhancing security and reducing hacking risks. With the Paris Agreement in force, carbon emission rights have gained prominence. China has recently implemented an emissions trading system in the power generation sector, and South Korea is considering linking its emission market with China and Japan. Similarly, California and Quebec in Canada have interconnected emissions trading systems, and the European Union operates a unified system. Japan collaborates with 17 developing countries, including Vietnam, on a common offset system, showcasing global efforts to link carbon markets. This global linkage is facilitated by the Paris Agreement, which standardizes emission calculations using tCO₂-eq.

The maximum permissible global greenhouse gas emissions, aimed at limiting global warming to 2°C, can be calculated based on the Paris Agreement. Each country's greenhouse gas reduction targets help define future permissible emission limits. The Paris Agreement's uniform standards for developed and developing countries, along with the allocation of emission rights to countries and businesses, enable global trading of emission rights using a

common unit—carbon dioxide equivalent. The agreement mandates strict prevention of double counting through transparency mechanisms. Blockchain technology, with its decentralized ledger, can enhance transparency and reduce transaction costs in emissions trading.

Recently, the first carbon emission trade using blockchain occurred between a Russian carbon fund and an African carbon emission holding company. Blockchain-based emissions trading was a significant topic at the International Association of Emissions Trading in Barcelona. The advent of a single global emissions trading market and emission currency utilizing blockchain technology could materialize sooner than anticipated. Blockchain is also integral to the fourth industrial revolution in state governance. While the UN and other entities discuss P2P transactions, the proposal here is for blockchain governance, leveraging blockchain's performance and stability through its core algorithms. This approach could revolutionize emissions trading, ensuring transparency, security, and efficiency in line with global environmental goals.

Research Question-

Based on the objectives of this research work, the following research questions (RQ) were formulated:

- RQ1. What are the operation features of blockchain in ETS?
- RQ2. What is the scope of blockchain in carbon offset projects?
- RQ3. How does blockchain address the criteria of quality in carbon offset projects?
- RQ4. What are the obstacles and challenges of blockchain implementation in carbon markets?

IV. RESEARCH METHODOLOGY

The research methodology encompasses an examination of the application of blockchain technology in low-carbon supply chains, with a focus on governance structures and their roles in improving the transparency and efficiency of carbon emission reduction (CER) processes. It integrates various governance frameworks, including blockchain governance, project governance, and fund governance, to provide a comprehensive understanding of the subject.

- **Blockchain Governance Structure**

The blockchain governance aspect entails the utilization of algorithms to verify data accuracy and ensure the integrity of the blockchain system. This involves implementing verification algorithms such as Proof-of-Work (PoW) and Proof-of-Stake (PoS) to secure data verification within the blockchain. Additionally, it includes an analysis of how different blockchains manage their networks through proposals and community forums, assessing their efficiency and security in preventing data manipulation and enhancing traceability in low-carbon supply chains.

- **Project Governance Structure**

Project governance focuses on establishing information communication technology (ICT) and environmental governance systems necessary for implementing carbon emission reduction projects. This involves developing ICT systems to support the governance of carbon reduction projects and creating frameworks to monitor and manage environmental impact, ensuring compliance with carbon reduction targets. Moreover, it employs game theory models to examine how blockchain investments influence CER processes by modeling stakeholder interactions in the supply chain.

- **Fund Governance Structure**

Fund governance pertains to managing financial resources required for carbon emission exchange and future peer-to-peer (P2P) transactions in the carbon emissions market. It involves establishing blockchain-based funding mechanisms to support CER initiatives, exploring the use of blockchain to facilitate transparent and efficient P2P transactions, and evaluating the economic implications of blockchain fund governance on the overall efficiency of the carbon emissions trading system.

- **Hybrid Governance Protocol**

To address the complexities and challenges associated with blockchain governance in CER, a Hybrid Governance Protocol is proposed. This protocol integrates on-chain and off-chain governance systems to create a flexible and adaptive governance framework. It incorporates on-chain governance processes within the blockchain network and incorporates off-chain discussions and community inputs to reflect public opinion and expert advice in on-chain governance. Additionally, it applies governance across multiple blockchain networks to ensure interoperability and coordination in global carbon markets.

Furthermore, the research outlines the architecture for introducing blockchain for Measurement, Reporting, and Verification (MRV) in the GHG reduction process. This involves aligning MRV processes with national Clean Development Mechanism (CDM) guidelines, utilizing blockchain to manage extensive data on greenhouse gas emissions, and incorporating artificial intelligence and deep learning engines to enhance the verification and analysis of GHG reduction data. Through the integration of these governance structures and methodologies, the research aims to demonstrate how blockchain technology can effectively enhance the transparency, security, and efficiency of low-carbon supply chains, thereby contributing to global carbon reduction efforts.

A. Blockchain Integration in Carbon Trading:

The integration of blockchain technology into carbon trading has garnered considerable attention worldwide, marking the emergence of "Blockchain +" as a transformative trend. In China, particularly, the utilization of blockchain in carbon asset management has become a focal point, with the Ministry of Industry and Information Technology actively developing national standards for blockchain technology. This underscores the inevitability of blockchain's integration into the carbon industry.

- **Resemblance Between Carbon Trading and Blockchain Mechanisms**

Remarkably, the carbon trading market shares striking similarities with blockchain mechanisms. While blockchain serves as a decentralized database, carbon trading involves the assessment, storage, trading, and management of carbon emissions, essentially functioning as a data-driven process.

- **Blockchain-based Carbon Trading in Corporate Settings**

In corporate carbon transactions, the application of blockchain involves periodic checks on the company's production and consumption status. The corresponding carbon emissions or reductions are stored in the blockchain database, facilitating autonomous trading or block formation. This approach simplifies the trading process and enables direct carbon emission transactions with other parties.

- **Safety and Reliability of "Blockchain + Carbon Trading"**

A primary advantage of "blockchain + carbon trading" is its safety and reliability. The distributed ledger concept in blockchain ensures that transactions are accurately recorded in a shared ledger, with each record timestamped and cryptographically signed. This guarantees the traceability of transactions, making tampering nearly impossible. By establishing a consensus network, blockchain technology detects discrepancies or fraudulent activities in the carbon trading process, enhancing market transparency and integrity. This mitigates risks such as lost quotas or repeated transactions and promptly detects illegal trading activities or fraud, strengthening the normative operation of the carbon market.

V. CONCLUSION

The integration of blockchain technology into carbon trading represents a significant advancement with far-reaching implications. As "Blockchain +" continues to reshape various industries, its application in carbon asset management emerges as a pivotal development, evident by ongoing efforts to establish national standards in China. This convergence underscores the intrinsic similarities between carbon trading and blockchain mechanisms, highlighting the seamless integration of data-driven processes.

In corporate settings, the implementation of blockchain facilitates streamlined carbon transactions, offering enhanced efficiency and transparency. By leveraging blockchain's decentralized ledger, companies can securely record and track carbon emissions, enabling direct and autonomous trading with counterparties. This not only simplifies the transaction process but also ensures the reliability and integrity of carbon trading activities.

One of the key advantages of "blockchain + carbon trading" lies in its robust safety and reliability features. Through the immutable nature of blockchain ledgers and the establishment of consensus networks, the risk of fraudulent activities or data manipulation is significantly mitigated. This fosters market transparency and accountability, fortifying the normative operation of carbon markets and bolstering investor confidence.

As blockchain technology continues to evolve and gain traction in carbon trading, it holds immense promise for revolutionizing the management and trading of carbon assets on a global scale. By providing a secure, transparent, and efficient platform for carbon transactions, blockchain contributes to the advancement of sustainability initiatives and

the realization of carbon emission reduction goals outlined in international agreements like the Paris Agreement. As such, the integration of blockchain in carbon trading represents a critical step forward in fostering a greener, more sustainable future.

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