DOI: 10.54254/2755-2721/50/20241687

Leveraging blockchain and graph neural network to enhance carbon emission trading: A decentralized and trustworthy approach

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Abstract. Carbon dioxide emissions are a major cause of climate change and its negative impacts on the environment and human well-being. To address this problem, a blockchain-based decentralized system for carbon emission trading is proposed, allowing anyone to trade carbon allowances as a commodity. The proposed system leverages the advantages of blockchain technology, such as transparency, immutability, and security, to enable efficient and trustworthy transactions among peers without intermediaries. Additionally, the system provides flexibility by enabling customization of permits, represented as Non-Fungible Tokens, thereby enhancing market accessibility and engagement. A graph neural network for identity inference is introduced to infer the attributes of accounts on the blockchain, such as their type and behavior. This can help detect and prevent illegal or malicious activities on the chain, as well as understand and improve user behavior patterns and preferences. The aim is to increase market inclusiveness and diversity, reduce transaction costs and carbon price volatility, and enhance the traceability and verifiability of carbon emissions.

Keywords: Blockchain, Carbon emission trading, GNN

1. Introduction

The challenge of environmental issues, especially climate change, has become urgent as its impacts are increasingly evident and alarming. There is widespread agreement that greenhouse gas emissions need to be significantly reduced to prevent further damage to the planet and its inhabitants. Greenhouse gases, such as carbon dioxide, trap heat in the atmosphere and cause global warming, which leads to various problems such as pollution-related health risks, loss of biodiversity, and depletion of ecosystem resources. Carbon dioxide is particularly problematic because it is the most abundant greenhouse gas and it has a long atmospheric lifetime. Therefore, limiting carbon dioxide emissions is essential to save the environment.

Carbon dioxide emissions are a major contributor to climate change and its adverse impacts on human well-being. The Kyoto Protocol, adopted in 1997 by the Parties of the United Nations Framework Convention on Climate Change, aimed to mitigate this problem by setting legally binding targets for reducing greenhouse gas emissions for developed countries [1]. A key feature of the Kyoto Protocol was the creation of a market-based mechanism for carbon dioxide emissions trading, or “carbon trading”.

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This mechanism allowed carbon dioxide to be traded as a commodity among and between emitters, such as countries, companies, or individuals.

Carbon emission trading is a policy instrument that uses market forces to incentivize the reduction of greenhouse gas emissions, such as carbon dioxide. By assigning a price to carbon dioxide emissions, carbon emission trading creates a financial incentive for emitters to reduce their emissions and sell their surplus allowances to other emitters who need them. Carbon emission trading also encourages the development and adoption of low-carbon technologies and practices, as they become more cost-effective compared to high-carbon alternatives. Carbon emission trading is one of the main mechanisms of the Kyoto Protocol, which allows developed countries to meet their emission reduction targets through domestic or international trading.

Centralized carbon emission trading systems, administered by governments, face several challenges that may hinder their performance and impact. These systems lack personalized price signals that account for the preferences and behaviors of prosumers, who both produce and consume energy and carbon allowances. This may discourage them from engaging in energy trading and reducing their carbon emissions [2]. Moreover, these systems incur high costs in designing, implementing, monitoring, and verifying carbon transactions, which may also increase the chances of fraud and corruption. Furthermore, these systems are susceptible to security breaches and power abuses, which may undermine their reliability and credibility. These challenges indicate that centralized carbon emission trading systems may not be the best option for achieving low-carbon transitions.

This paper proposes a blockchain-based decentralized system for carbon emission trading. Blockchain is a distributed ledger that enables direct and secure transactions between peers without intermediaries. It also provides transparency, immutability, and traceability of the data stored on the chain. Compared to centralized systems, our system offers several benefits, such as (1) Public participation: Our system enables anyone, including individuals, to trade carbon allowances, not just entities like companies, organizations, or governments. This increases the market inclusiveness and diversity and encourages social awareness and acceptance of carbon emission reduction. (2) Trustless efficiency: Using blockchain to enable fast and secure peer-to-peer transactions, our system reduces transaction costs and carbon price volatility. Blockchain also removes the need for trusted third parties or intermediaries that may cause delays or inefficiencies. (3) Transparent accountability: Our system enhances the traceability and verifiability of carbon emissions by using blockchain to store and share the emission data on the chain. Blockchain also helps prosumers establish a good environmentally friendly reputation on the chain, which may motivate them to adopt low-carbon technologies and practices.

We also introduce a graph neural network (GNN) for identity inference to infer the attributes of accounts on the blockchain, such as their type and behavior. Identity inference can help us to detect and prevent illegal or malicious activities on the chain, such as money laundering, fraud, or hacking. Moreover, identity inference can help us to understand the patterns and trends of user behavior on the chain, such as their preferences, interests, or motivations. This can provide valuable insights for designing and improving our decentralized carbon emission trading system.

2. Background and Related Work

2.1. Blockchain and DApps

Blockchain is a distributed ledger technology that enables secure and transparent transactions among multiple parties without relying on a central authority. Blockchain can support various applications, such as cryptocurrencies, smart contracts, supply chain management, and digital identity [3]. Decentralized applications (DApps) are applications that run on blockchain platforms and leverage the benefits of blockchain, such as immutability, trustlessness, and censorship-resistance. DApps typically have a front-end user interface that interacts with a back-end smart contract, which contains the business logic and state of the application. DApps can provide various advantages over traditional applications, such as lower operational costs, higher security, better privacy, and more innovation potential [3].

2.2. Blockchain-based Emission Trading Systems

The initial work in the field of blockchain-based carbon trading systems was conducted by Kawasmi et al. who applied a system-of-systems architecture model for a decentralized carbon emissions trading infrastructure using Bitcoin and Open Transactions [4]. The current works in this field can be broadly categorized into two categories: those that rely on smart IoT and those that rely on a central administrator role.

The first category includes works by Hua et al., Sadawi et al., Sadawi and Ndiaye, and Golding et al., who propose blockchain-based frameworks that potentially rely on IoT smart devices for measuring carbon emissions. These works aim to achieve regional energy balance and carbon emissions reduction by incentivizing low-carbon behaviors and automating the verification, issuance, trading, and redemption of carbon credits. However, they face challenges related to the accuracy and reliability of the data collected by IoT devices.Hua et al. and Zhao et al, who propose blockchain-based peer-to-peer trading frameworks integrating energy and carbon markets [2] [5] [6] [7]. These works aim to achieve regional energy balance and carbon emissions reduction by incentivizing prosumers to adjust their presumption behaviors and rewarding them with a low carbon incentive mechanism.

The second category includes works by Richardson and Xu, and Hu et al., who present models for decentralized carbon emission trading systems based on permissioned blockchain network [8] [9]. These models rely on a central role of administrator for issuing and distributing the permits and utilizes a permissioned blockchain network to facilitate and validate the transactions of carbon permits among various participants. However, it faces issues related to governance and the potential for centralization to limit the benefits of decentralization inherent in blockchain technology.

Despite the promising advancements in the field, all these works recognize some challenges and limitations of their models, such as the need for regulatory compliance, the lack of standardization, the environmental impact of Bitcoin mining, and the necessity of a central administrator for issuing and distributing the permits.

2.3. GNN-based Identity Inference on Blockchain

By applying node2vec, a graph embedding technique, to the Bitcoin blockchain, Michalski et al.achieved a breakthrough in the field, uncovering the characteristics of nodes [9] [10]. Their work exposed the vulnerability of nodes that seek to maintain their anonymity to deanonymization attacks.

Shen et al. proposed a GNN-based method for detecting illicit accounts on blockchain systems [11]. They developed an end-to-end model, I2BGNN, that learns the transaction patterns of subgraphs and classifies them into different categories. However, the subgraph extraction mechanism, which is crucial for the performance of the model, was not adequately described.

Tao et al. introduced a novel approach for inferring the identity of blockchain accounts using GNNs [12]. They designed a new model, I2BGNN, and a new representation learning method, structure-to-vector with random pace (SVRP), which captures both the latent representation and the structural identity of network nodes. The paper demonstrated the effectiveness of the approach in identifying malicious activities, but it did not provide a clear explanation of the subgraph extraction mechanism.

DOI: 10.54254/2755-2721/50/20241687

3. Architecture Design

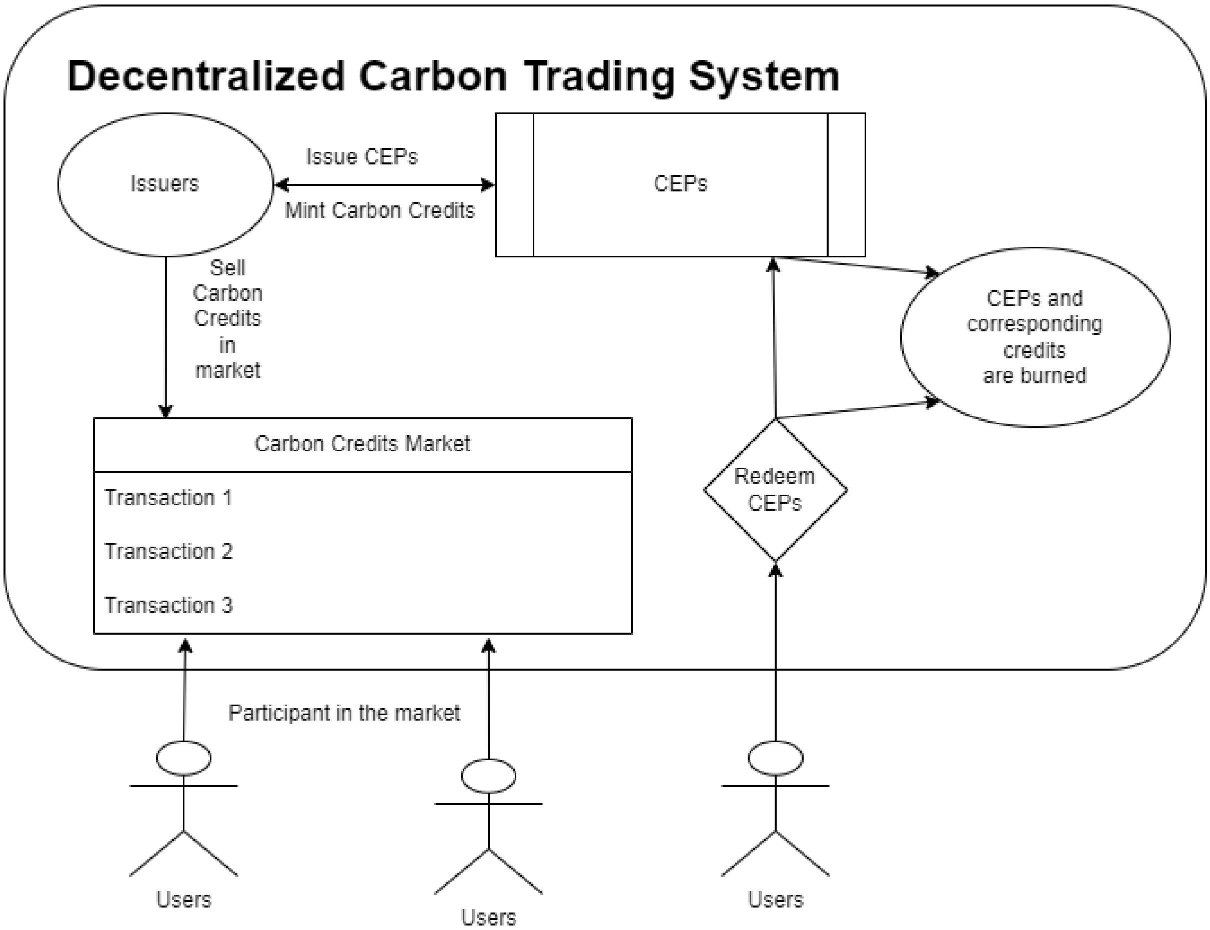

Figure 1. System Architecture

The system, as depicted in Figure 1, is a decentralized platform for carbon emission trading, built on Ethereum and utilizing a combination of ERC20 and ERC721 standards. The ERC721 standard is used to create carbon emission permits (CEPs), which are non-fungible tokens (NFTs) that store metadata such as ID, location, industry, and emission amount in tonnes. The ERC20 standard is used to create carbon credits, which are fungible tokens that can be exchanged on the market. A trusted issuer, such as a government, a regulator, or an environmental organization, can register a CEP with the system by invoking a smart contract that assigns a unique ID to the CEP. The CEP then becomes the property of the system, and the issuer can mint carbon credits equivalent to the emission amount of the CEP. Any market participant, such as an investor, a resident, an environmentalist, or an entity that needs to comply with the emission regulations, can redeem carbon credits for CEPs to use for tax deductions or other purposes. The redeemed carbon credits and CEPs are burned and removed from the system. The system ensures that the total supply of carbon credits and CEPs matches the emission limit.

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3.1. Metadata

Table 1. Metadata Description

Field	Data Type	Data Size	Description
TokenId	unit256	32 bytes	The unique identifier of the permit
Location	string	variable	The location of the permit
Industry	string	variable	The industry sector of the permit
Amount	unit256	32 bytes	The emission amount in tonnes
ValidityUntil	unit256	32 bytes	The expiration date of the permit
Issuer	address	20 bytes	The address of the issuer of the permit
Info	string	variable	Additional information about the permit

The metadata are the attributes that define the CEPs, and they reflect the value of the CEPs.

Table 1 shows the metadata fields and their descriptions. The tokenId is the unique identifier of the CEP. The location and the industry specify the physical scope of the CEP. The amount indicates the right to emit a certain amount of greenhouse gases in tonnes. One tonne on the CEP corresponds to one carbon credit that can be minted from the CEP. The validityUntil field specifies the temporal scope of the CEP. It is a uint256 value, the same data type as the timestamp in Ethereum, and it represents the number of seconds that have elapsed since January 1, 1970. This makes it easy to verify the validity of the CEP. The issuer field shows the address of the issuer of the CEP. The info field is a string that can contain additional information about the CEP.

3.2. System Users

System Users The system has two types of users: reputable issuers and ordinary users. Reputable issuers are entities that have the authority to issue CEPs. They are registered as the administrators of the smart contract that manages the CEPs. They can register their CEPs on the system by creating ERC721 tokens with the appropriate metadata. The system then assigns an address to each CEP and transfers the ownership to the system. The issuers can then mint carbon credits equivalent to the emission limit of their CEPs and sell them on the market. Ordinary users are individuals or entities that participate in the market. They can be investors, residents, environmentalists, or entities that need to comply with the emission regulations, such as plants and factories. They can buy carbon credits from the market to offset their greenhouse gas emissions, trade them for profit, or contribute to environmental improvement.

3.3. Token supply

The token supply of the system is governed by the market forces of CEPs and carbon credits. The CEP supply is determined by reputable issuers, who have the discretion to issue CEPs with fixed emission limits and expiration dates. The carbon credit supply is dynamic, depending on the minting and burning activities of the issuers and users. The minting of carbon credits increases the supply, while the burning of carbon credits reduces the supply. The smart contracts that manage the CEPs and carbon credits enforce the constraint that the total carbon credit supply cannot exceed the total emission limit of the CEPs. Moreover, the system burns the expired CEPs to preserve the carbon credit supply and deducts the equivalent carbon credits from the issuers. The issuers have the option to renew the expired CEPs or issue new CEPs to compensate for the deduction, or they can accept the deduction as a means to reduce carbon emissions.

3.4. Node classification by GNN

A Graph Neural Network (GNN) based identity inference is deployed for the system to enhance the understanding of the carbon emission trends and the measurement of the system's contribution to carbon emission reduction. Node classification is applied based on the transaction relationship between users, which enables the inference of the identities and behaviors of the market participants, such as emission sources, trading patterns, compliance levels, or environmental preferences. This facilitates the monitoring of the carbon emission trading market, the identification of potential frauds or anomalies, the evaluation of the system's effectiveness, and the provision of feedback and incentives to the market participants. Furthermore, the temporal and spatial information of the CEPs and the carbon credits, such as validity periods, locations, or industries, are leveraged by using a GNN, which captures the dynamic and heterogeneous characteristics of the carbon emission trading market. This assists in forecasting the future trends of carbon emission and carbon price, optimizing the allocation of the CEPs and the carbon credits, and designing better policies and regulations for the system.

3.5. Datasets

Table 2. Characteristics of the Four Datasets Employed in the Study

Name	Detail	Edge	Raw of Features
Cora	Citation Network	5530	2708
Elliptic	Bitcoin Network	234356	203769
Xlabelcloud	Ethereum Network	220439	571533(568999)
CET	Artificial Data	100000	27538

The model under discussion has been subjected to a series of tests on various datasets as shown in Table 2 to evaluate its performance. Initially, the model was applied to the Cora dataset, a well-known benchmark in the field of GNNs. The Cora dataset represents a citation network where nodes correspond to papers and edges represent citations. The task is to predict the category of each paper, making it an exemplary instance of node-level classification in GNNs.

Subsequently, the model was tested on two blockchain network datasets: the Elliptic dataset and the Xlabelcloud dataset. The Elliptic dataset is meticulously designed, with features representing the detailed activities of each user and edges symbolizing transactions between trading pairs. The primary objective of this dataset is to ascertain whether a user's activities are illicit.

The Xlabelcloud dataset, on the other hand, provides information about transactions, trading pairs, and labels. It contains various labels associated with keywords on the accounts, offering a rich source of information for the model to learn from.

Finally, an artificial dataset was created to simulate transactions in the Carbon Emission Trading market. This dataset includes features such as the number of tokens spent, the amount of carbon emission (in tonnes) indicated on the trading permit, the location, and the industry specified on the permit. The trading targets in this market are categorized into several groups:

3.5.1. Government: Government entities might show a trend of trading permits across a wide range of locations and industries. They might also show a pattern of acquiring permits from industries with high carbon emissions and redistributing them to areas with lower emissions. The trading volume could be high at the beginning of a fiscal year and taper off towards the end.

3.5.2. Organizations: These entities might exhibit a trend of selling permits, especially to industries with high carbon emissions. They might also show a pattern of acquiring permits from the government and other organizations. Their trading activity could be consistent throughout the year.

3.5.3. Industrials: Industrial entities might show a high demand for permits, especially during periods of increased production. They might also show a trend of acquiring permits from organizations and the government. Their trading volume could be high during industrial peak seasons.

3.5.4. Investors: Investors might show a trend of balanced buying and selling activities. They might acquire permits when the price is low and sell when the price is high, showing a typical buy-low-sell-high pattern. Their trading volume could fluctuate based on market conditions.

3.5.5. Residents: Residents might show a trend of small but frequent transactions. They might acquire permits from various sources and sell them to a wide range of buyers. Their trading activity could be relatively stable throughout the year.

3.6. Model Performance

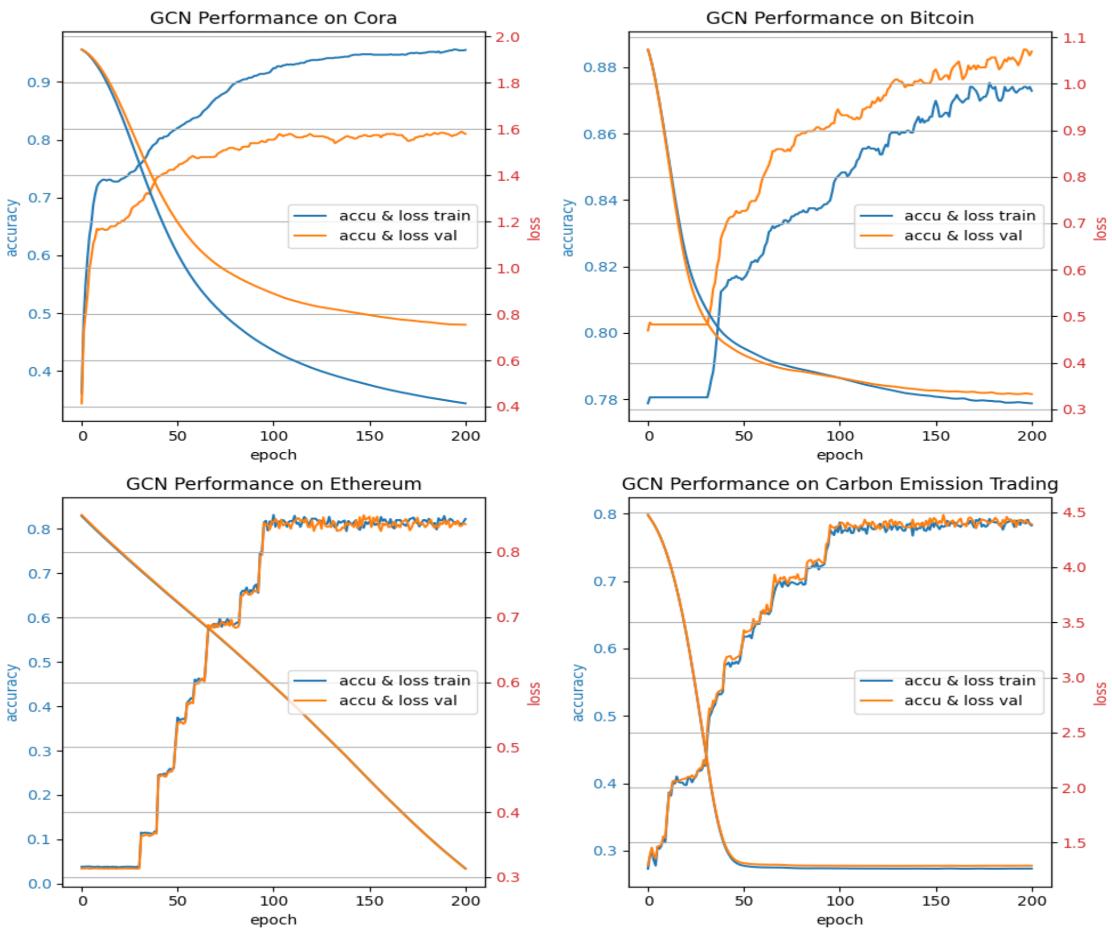

Figure 2. GCN Performance

A Graph Convolutional Network (GCN) model for node classification has been developed and its performance, as shown in Figure 2, on four datasets is robust, as evidenced by the consistent upward trend in training accuracy and downward trajectory in training loss. This indicates effective learning from the data. The model also generalizes well to unseen data, with high validation accuracy and low validation loss throughout the training process, suggesting that it is not overfitting and can make reliable predictions on new data.

In the context of the carbon emission trading system, the primary task is node classification, aiming to categorize users based on their carbon emission patterns. The GCN model's high performance indicates its suitability for this task, providing an overall view of user categories in the trading system, which is crucial for effective carbon emission management. Therefore, the implemented GCN model demonstrates strong performance in both the training and validation phases, making it a reliable tool for node classification in the carbon emission trading system.

3.7. Browser

The browser, designed as a user-friendly interface, provides comprehensive insights into the carbon trading market's activities. It offers a detailed overview of market dynamics through a macroscopic view, illustrating the price of tonnes of carbon emission per token against the block number. This graphical representation allows trend analysis over time. The browser enhances user interaction with functionalities like Search, Filtering, and Sorting, enabling users to locate information, focus on specific data subsets, and organize the data. An exporting function is also available for offline data analysis.

In addition to the market's macroscopic view, the browser provides a Detailed Transaction View for scrutinizing individual transactions, including trading pairs, the number of tokens transacted, and the associated carbon emission. A Predictive Label Explanation feature displays the predicted labels of transaction parties, categorizing them into groups like government, organization, industrial, investor, and resident, with explanations for each label. This comprehensive suite of features makes the browser a robust tool for navigating and understanding the carbon trading market effectively.

4. Discussion

The proposed system design is a decentralized carbon market that uses blockchain technology to enable more transparent, secure, and efficient carbon trading. However, the design also faces some challenges and limitations that need to be addressed.

One of the main challenges is the trade-off between complexity and flexibility. The design uses a combination of ERC20 and ERC721 standards to represent the carbon emission permits (CEPs) and the carbon credits, respectively. This allows the customization of the CEPs with various metadata, such as location, industry, emission amount, validity period, issuer, and additional information. These metadata can create a more diverse and dynamic carbon market, where the CEPs can be differentiated and verified according to different criteria and preferences. However, this also increases the transaction complexity and cost, as it requires two types of tokens and two types of smart contracts. A simpler approach is to use a single ERC1155 standard, which can support both fungible and non-fungible tokens, and to standardize the metadata of the CEPs using JSON or IPFS. This can reduce the transaction complexity and cost and improve the interoperability and scalability of the system.

Another challenge that arises from the design is the dependency on the Ethereum platform, which may affect the performance and cost of carbon trading. The performance is determined by the throughput and the latency of the Ethereum network, which are limited by the consensus protocol and the block size. The cost is determined by the gas price and the gas limit, which are affected by the network congestion and the smart contract complexity. These factors may create bottlenecks and barriers for carbon trading, especially when the demand is high, or the network is congested. A possible way to enhance this aspect is to use a layer 2 solution, such as a sidechain or a state channel, that can reduce the load and the fee of the main chain and increase the speed and efficiency of the carbon trading. This can also improve the user experience and the adoption of the system.

The final challenge that the design has to overcome is the centralized role of the administrator, who is responsible for registering and verifying reputable issuers and their CEPs. This may compromise the security and resilience of the system, as it introduces a single point of failure and trust. A potential solution is to adopt a decentralized governance mechanism, such as a DAO, that can allow the users to vote on the issuers and the CEPs, and to manage the registration and verification process in a distributed manner. This can also increase the accountability and the legitimacy of the issuers and the CEPs, by ensuring that they are aligned with the interests and the values of the community.

5. Conclusion

This paper presents a novel, decentralized approach to carbon emission trading that leverages blockchain technology, reducing costs associated with partner negotiation and enhancing market trust and efficiency. The system design capitalizes on blockchain's inherent benefits, such as transparency and security, and provides a verifiable record of carbon emission permits and credits. It offers flexibility by enabling customization of permits, which are NFTs and promotes market accessibility and engagement. Despite its potential, the design has challenges that need further research. Overall, the system offers a comprehensive solution for carbon emission trading, providing a transparent and efficient platform that could be valuable in global efforts to combat climate change.

Future research in carbon emission trading could focus on developing a cryptographic consensus mechanism for tasks like issuing and managing certifications and using Cluster GCNs for a better understanding of the relationship network in the trading system. Advanced GNN methods could be applied for link prediction to identify the main consumers of carbon emission certifications, aiding in effective policy design. The integration of blockchain and machine learning technologies can provide a transparent and efficient platform for carbon emission trading, with potential applications in other areas of environmental regulation.

References

[1] United Nations Framework Convention on Climate Change. 1997. Kyoto Protocol. https://unfccc.int/resource/docs/convkp/kpeng.pdf
[2] Weiqi Hua, Jing Jiang, Hongjian Sun, and Jianzhong Wu. 2020. A blockchain based peer-to-peer trading framework integrating energy and carbon markets. Applied Energy 279 (2020), 115539. https://doi.org/10.1016/j.apenergy.2020.115539
[3] Peilin Zheng, Zigui Jiang, Jiajing Wu, and Zibin Zheng. 2023. Blockchain-Based Decentralized Application: A Survey. IEEE Open Journal of the Computer Society 4 (2023), 121–133. https://doi.org/10.1109/OJCS.2023.3251854
[4] Enas Al Kawasmi, Edin Arnautovic, and Davor Svetinovic. 2014. Bitcoin-based decentralized carbon emissions trading infrastructure model. Systems Engineering 18, 2 (2014), 1098–1241.
[5] Alia Al Sadawi, Batool Madani, Sara Saboor, Malick Ndiaye, and Ghassan Abu-Lebdeh. 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technological Forecasting and Social Change 173 (2021), 121124. https://doi.org/10.1016/j.techfore.2021.121124
[6] Oscar Golding, Guangsheng Yu, Qinghua Lu, and Xiwei Xu. 2022.Carboncoin: Blockchain Tokenization of Carbon Emissions with ESG-based Reputation. In 2022 IEEE International Conference on Blockchain and Cryptocurrency (ICBC). 1–5. https://doi.org/10.1109/ICBC54727.2022.9805516
[7] Alia Al Sadawi, Batool Madani, Sara Saboor, Malick Ndiaye, and Ghassan Abu-Lebdeh. 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technological Forecasting and Social Change 173 (2021), 121124. https://doi.org/10.1016/j.techfore.2021.121124
[8] Zhuo Hu, Yuhao Du, Congjun Rao, and Mark Goh. 2020. Delegated Proof of Reputation Consensus Mechanism for Blockchain-Enabled Distributed Carbon Emission Trading System. IEEE Access 8 (2020), 214932–214944. https://doi.org/10.1109/ACCESS.2020.3041689

DOI: 10.54254/2755-2721/50/20241687

[9] Andreas Richardson and Jiahua Xu. 2020. Carbon Trading with Blockchain. In Mathematical Research for Blockchain Economy, Panos Pardalos, Ilias Kotsireas, Yike Guo, and William Knottenbelt (Eds.). Springer International Publishing, Cham, 105–124.

[10] Radosław Michalski, Daria Dziubałtowska, and Piotr Macek. 2020. Revealing the Character of Nodes in a Blockchain With Supervised Learning. IEEE Access 8 (2020), 109639–109647. https://doi.org/10.1109/ACCESS.2020.3001676

[11] Jie Shen, Jiajun Zhou, Yunyi Xie, Shanqing Yu, and Qi Xuan. 2021. Identity Inference on Blockchain Using Graph Neural Network. In Blockchain and Trustworthy Systems, Hong-Ning Dai, Xuanzhe Liu, Daniel Xiapu Luo, Jiang Xiao, and Xiangping Chen (Eds.). Springer Singapore, Singapore, 3–17.

[12] Bishenghui Tao, Hong-Ning Dai, Haoran Xie, and Fu Lee Wang. 2023.Structural Identity Representation Learning for Blockchain-Enabled Metaverse Based on Complex Network Analysis. IEEE Transactions on Computational Social Systems 10, 5 (2023), 2214–2225. https://doi.org/10.1109/TCSS.2022.3233059