Energy-Efficient Blockchain-based Carbon Trading and Credit Framework for Korean ETS

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***Abstract*—The global effort to combat climate change requires effective and transparent mechanisms for carbon trading and crediting. South Korea's Emissions Trading Scheme (K-ETS) has emerged as a key initiative, yet it faces challenges in transparency, energy efficiency, and scalability. This paper proposes an energy-efficient blockchain-based framework (eBCTC) tailored to the K-ETS, addressing critical issues such as double counting, transaction inefficiencies, and regulatory compliance. By leveraging proof of authority and association (PoA^2) consensus mechanisms and smart contract intelligence, the framework ensures secure and low-energy carbon credit transactions. Performance evaluation indicates that the eBCTC achieves significant improvements in energy efficiency while maintaining environmental sustainability better than PoW and PoA across all K-ETS activities.**

***Index Terms*—allowance, blockchain, carbon credit, incentives, IoT, K-ETS, offset, pollution monitoring.**

I. INTRODUCTION

Climate change has become one of the most pressing global challenges of the 21st century, driven largely by the rise of greenhouse gas (GHG) emissions from industrial and human activities [1]. Efficient carbon trading and crediting models, also known as emission trading systems (ETS), are emerging as critical innovations to curb GHG emissions for a sustainable ecosystem [2]. The Korea Emissions Trading Scheme (K-ETS), being one of the most prominent initiatives in East Asia [3], [4] and the world's second-largest ETS by coverage, is confronted with issues such as lack of transparency, inefficiencies, high transaction costs, potential double counting, etc., despite its operation since 2015. These issues introduced risks such as data inconsistency, manipulation, and market imbalance in the K-ETS. Thus, it resulted in K-ETS experiencing low market liquidity driven by supply shortages by sellers [5].

Blockchain technology (BT), with inherent characteristics such as decentralization, transparency, and immutability, presents a transformative opportunity to enhance the efficiency of ETS processes [6], [7]. Several innovative attempts have been made through the introduction of BT to address issues in ETS globally, as summarized in Table I. Authors [8] proposed a dual-BT architecture that relies on a proof-of-stake (PoS) algorithm and machine learning (ML) to achieve the prediction of carbon trading price for an industrial IoT (IIoT) ETS platform. However, the system has scalability issues, as the increase in transaction latency did not meet the larger network capacity requirement.

Similarly, [9] deployed Hyperledger Fabric that used the Delegated Proof of Reputation (DPoR) algorithm to achieve a decentralized ETS framework for fast malicious miner detection. The framework, however, has high computational overhead and is subservient to data manipulation in large-scale deployment. Also, authors [10] proposed a proof-of-authority (PoA) private permissioned BT framework for real-time verification of carbon credit issuance and trading, but the system lacked details of its performance capacity. Then, to achieve data integrity in ETS, [11] deployed a Practical Byzantine Fault Tolerance (PBFT)-driven BT network on the FISCO BCOS platform. This approach, however, has scalability issues and regulatory uncertainties. These approaches in Table I used mainstream BT consensus implementations, which made them energy-intensive and unsuitable for a sustainable carbon trading and credit framework.

TABLE I
SUMMARY OF RELATED WORKS ON BCTC

Ref.	Blockchain Network	Concensus Protocol	Limitations
[8]	Dual-BT (Privacy chain & self-contained chain)	Proof-of-Stake (PoS), cross-chain synchronization	Scalability issue, latency issue; security risks and real-world deployment concerns
[9]	Hyperledger Fabric	Delegated Proof of Reputation (DPoR)	High computational overhead; potential manipulation in large-scale networks.
[1]	Undefined	Undefined	Energy consumption and scalability issues; regulatory uncertainties.
[10]	Private, Permissioned blockchain	Proof-of-Authority (PoA)	No detailed explanation of the blockchain network used.
[11]	FISCO BCOS platform	Practical Byzantine Fault Tolerance (PBFT)	Scalability challenges; regulatory uncertainties
[12]	Ethereum	Undefined	Traceability Issues
Ours	Purechain	Proof of Authority & Association (POA^2)	None

Therefore, it is imperative to prevent the integration of BT into the ETS platform from constituting an extra burden of energy consumption while attempting to guarantee optimal security in ETS. Hence, in designing an innovative

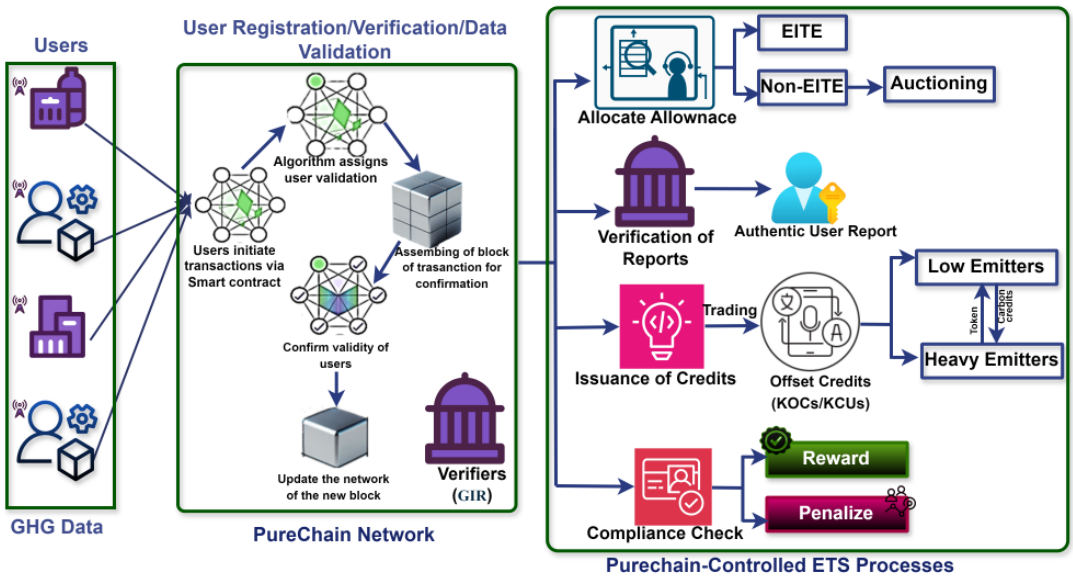


Fig. 1. Proposed eBCTC System Design Framework for K-ETS highlighting the Purechain-controlled processes for optimal security for (a) Allocation of allowances; (b) Verification of industry Emission reports; (c) Issuance and conversion of credits for trading; and (d) Compliance check to determine incentivization.

and sustainable blockchain-driven carbon trading and crediting (BCTC) system, carefully considering the appropriate BT consensus algorithm is necessary to optimize energy efficiency, as BT systems and infrastructure consume energy, ultimately contributing to emissions. This ensures that sustainability and scalability are not sacrificed for optimal security in ETS.

Thus, this study is a novel attempt to develop a holistic energy-conscious blockchain-enabled carbon trading and credit (eBCTC) approach that minimizes the energy consumption characteristics of mainstream BT models, guarantees low transaction costs by enhancing smart contract automation, fosters a transparent incentivization mechanism, and can be seamlessly integrated across platforms for scalable deployment. The eBCTC framework is tailored for the K-ETS, incorporating innovative connected intelligence design principles [13] to ensure regulatory compliance and scalability.

To achieve this, the study made the following specific contributions:

- Developed a decentralized Purechain framework for tamperproof and scalable carbon trading and credit monitoring.
- Designed an energy-conscious smart contract intelligence mechanism to guarantee low transaction costs, mitigate double counting, etc. inherent in mainstream methods.
- Implemented a K-ETS platform to automate emissions tracking, credit issuance, trading, and compliance enforcement.

The rest of the paper is divided into Section II for proposed system design and methodology, Section III for result analysis and discussion, and Section IV concludes the study.

II. PROPOSED eBCTC METHODOLOGY

A. eBCTC System Design

Fig. 1 highlights the components of the proposed eBCTC for K-ETS. All activities in the K-ETS are controlled by the Purechain architecture to enforce optimal security. The GHG data from the various users (industries) are captured in their emission reports. Upon registering in the Purechain network, each user is validated by the Greenhouse Gas Inventory and Research Center of Korea (GIR) to ascertain if the user is an emissions-intensive and trade-expose (EITE) or non-EITE based on the unique hash value and the allocated allowance, determining the auctioning process. Thereafter, the carbon emission report of each user is verified for authenticity. Users with authentic carbon emission reports are issued credits to allow them to participate in trading activities with either low or high emitters. Finally, each user's emission report is validated for compliance check based on predefined incentivization and penalty parameters. Since all activities are automated via smart contract intelligence in the BT, fraud, mismanagement, double counting, etc., inherent in the existing K-ETS can be addressed.

B. GHG Data Collection and Characterization

The carbon emission and energy consumption data for each user is captured by IoT devices strategically located at their emission sources [14]. Mathematically, the energy consumption per user per specific operation is expressed as in equation (1):

$$\mathtt{User}_e = \mathtt{P}_c \times \mathtt{t} \tag{1}$$

where $\mathtt{P}_c$ = power consumed and $\mathtt{t}$ is time taken.

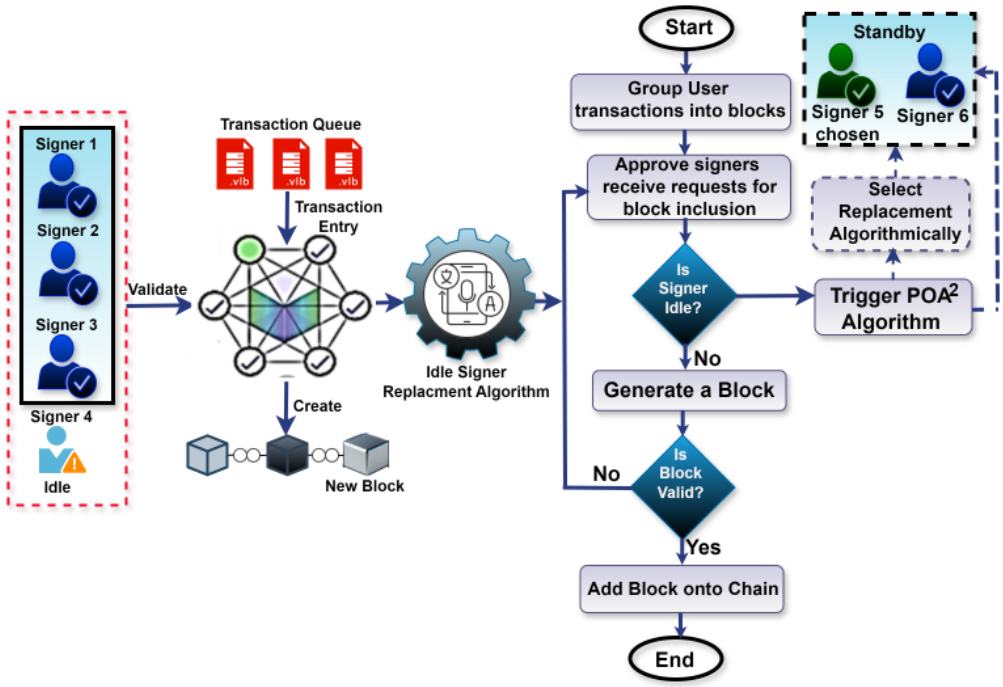


Fig. 2. Flowchart of the Purechain Framework with the proposed POA^2 highlighting steps for Authorizing and Deauthorizing Signers in K-ETS.

Conventionally, GHG emission is measured in metric tons of carbon dioxide equivalent ($\mathtt{tCO_2e}$) and this is used to standardize other GHGs based on their global warming potential (GWP). GWP converts non-CO_2 gases into CO_2 equivalents. GHG Emission is expressed mathematically as:

$$\mathtt{E(tCO_2e)} = \mathtt{A_{Data}} \times \mathtt{E_{Factor}} \tag{2}$$

where $\mathtt{A_{Data}}$=Activity Data and represents the level of activity causing emissions; while $\mathtt{E_{Factor}}$ is the Emission Factor representing the amount of GHG emitted per unit of activity. Thus, the GHG emission level (for instance $\mathtt{CO_2}$) of each user per specific operation is defined in equation (3) as:

$$\mathtt{User}_{\mathtt{E_{factor}}}(\mathtt{CO_2}) = \frac{\mathtt{Mass\ of\ CO_2}}{\mathtt{Volume\ of\ Air}} \tag{3}$$

Other GHG data covered by K-ETS include CH_4, N_2O, HFCs, PFCs, and SF_6. By applying equations (1), (2), and (3), the energy consumed, emission, and emission level of a specific user per operation for all GHG data covered by K-ETS can be derived.

On the other hand, carbon credits are issued based on verified emission reductions, avoidances, or removals as expressed in the equation.

$$\mathtt{Carbon_{credit}} = \mathtt{E_{base}} - \mathtt{E_{actual}} \tag{4}$$

where $\mathtt{E_{base}}$ = baseline emissions representing estimated emissions without the project, and $\mathtt{E_{actual}}$ = actual emissions representing emissions after implementing the project.

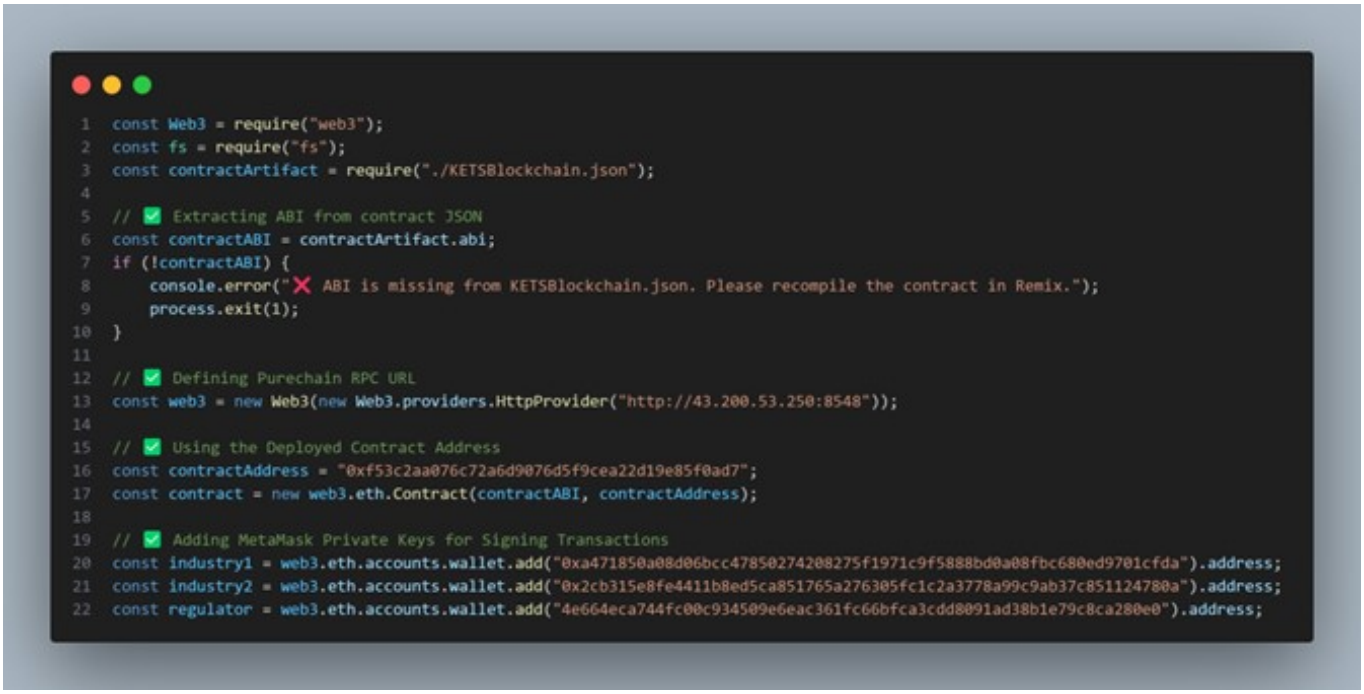
C. Purechain Security Framework

The Purechain security framework uses a consensus proof of authority and association (PoA^2) algorithm. Fundamentally, PoA^2 works based on the PoA principle, which is based on a group of predefined authentic validator nodes to create new nodes by serving as signers. Unlike PoA, the PoA^2 mechanism introduces a standby validator in the network, which monitors and follows other activities of validators in the network, as seen in Fig. 2.

Signers on the network automatically vote for the transfer of authority. The proposed PoA^2 introduces a redundant signer associated with the network, which monitors and follows up on the signers' activities in the network and, in turn, identifies, removes, and replaces inactive validators. Signers on the network automatically vote for the transfer of authority to a new signer to replace the inactive one. The design emphasizes security and integrity by decoupling network governance from economic incentives and concentrating on trusted, verified entities. The algorithm 1 summarizes the operational flow of the PoA^2 consensus mechanism. With this implementation strategy, the trustworthy identification of eligible nodes is ascertained, the reputation of participating validators is guaranteed, and the activity is continuously monitored to ensure energy efficiency.

D. Experimental & Simulation Setup

The PoA^2 mechanism is implemented using Clique. Conventionally, a clique can accept a single validator, which makes it suitable to serve as the GIR. The protocol uses the Geth method to add and remove signers for authorizing



```
const Web3 = require("web3");
const fs = require("fs");
const contractArtifact = require("./KETSBlockchain.json");

// ✅ Extracting ABI from contract JSON
const contractABI = contractArtifact.abi;
if (!contractABI) {
    console.error("❌ ABI is missing from KETSBlockchain.json. Please recompile the contract in Remix.");
    process.exit(1);
}

// ✅ Defining Purechain RPC URL
const web3 = new Web3(new Web3.providers.HttpProvider("http://43.200.53.250:8548"));

// ✅ Using the Deployed Contract Address
const contractAddress = "0xf53c2aa076c72a6d9076d5f9cea22d19e85f0ad7";
const contract = new web3.eth.Contract(contractABI, contractAddress);

// ✅ Adding MetaMask Private Keys for Signing Transactions
const industry1 = web3.eth.accounts.wallet.add("0xa471850a08d06bcc4785027420827 5f1971c9f5888bd0a08fbc680ed9701cfda").address;
const industry2 = web3.eth.accounts.wallet.add("0x2cb315e8fe4411b8ed5ca851765a276305fc1c2a3778a99c9ab37c851124780a").address;
const regulator = web3.eth.accounts.wallet.add("4e664eca744fc00c934509e6eac361fc66bfca3cdd8091ad38b1e79c8ca280e0").address;
```

Fig. 3. An interface segment highlighting the integration of the PoA^2 simulate.js script with Remix and Metamask

Algorithm 1: Proposed PoA^2 Mechanism Procedure

Data: `Carbon Trading Report(Users)`
Result: `Valid User`

Initialize signers list based on approved GIRs (`clique.getSigners`) ←list
Initialize & Activate `stand − by` mode for secondary signers;
Monitor Users Transaction-id ←t_{id}:
while *True* **do**
  for *each* Transaction *(t_{id}) in list* **do**
    Compute `clique.status()`.t_{id}`Activity`
    Check Signer Status
    if t_{id}`Activity["signer"]` $== 0$ **then**
      Identify redundant node
      Perform Deauthorization ←clique.discard
      Recommend redundant account ←clique.propose
      Algorithmically replace the current block of the supposed signer with the recommended redundant signer
      Grant Signer Authorization
      Trigger block mining operation and timer
    end
  end
end
return `status`

and deauthorizing. Parameters such as storage capacity, computing power, bandwidth, and elapsed block sealing time are considered when selecting secondary sealers. Authorization is granted if it is requested by more than half of the signers. Conversely, de-authorization of a signer is granted if it is requested by half + 1 signers, which removes the block from the list, and all future blocks created are rejected. Clique's adaptability enables customizable block times and facilitates dynamic adjustments to the signer set through voting mechanisms. These capabilities make the system well-suited for resource-constrained environments, delivering an optimal balance of performance, energy efficiency, and security.

The simulation was carried out on a system equipped with an Intel Core i9 3.2 GHz, 32 GB of RAM, and an NVIDIA GeForce RTX 4070 Ti GPU.

III. RESULT ANALYSIS AND DISCUSSION

After configuring the network, a Solidity-based smart contract was created to simulate critical carbon credit transactions. This contract handled key functions such as industry registration, greenhouse gas (GHG) emissions reporting, carbon credit allocation, trading, borrowing, and auction-based distribution. It was deployed on Purechain PoA^2 using Remix IDE, with transactions signed through MetaMask (see Fig. 3). The generated contract address was then used in the simulation script to enable automated transactions. A JavaScript-based simulation script, simulate.js, was developed using Node.js and Web3.js to assess transaction efficiency. This script automated interactions with the deployed smart contract, executing predefined operations to gather performance metrics. Various optimizations were incorporated, including MetaMask private key integration

to eliminate manual account unlocking and automatic detection of the regulator address, dynamically retrieving it from the contract. To ensure seamless execution, gas limits were increased to 10 million units, preventing transaction failures caused by resource constraints. Fig. 4 is the segment of the K-ETS smart contract intelligence highlighting the automation of all K-ETS activities to enhance security.

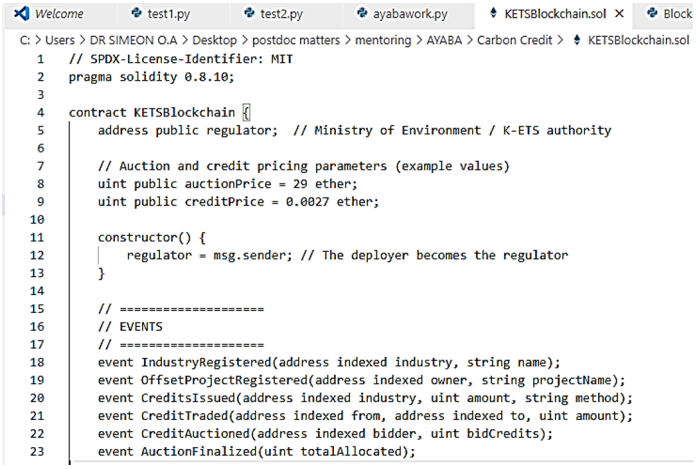


Fig. 4. An interface segment of the K-ETS Smart Contract highlighting the various automated activities for enhanced security intelligence

Table II highlights the comparative analysis of the PoA^2 against other mainstream consensus algorithms in key K-ETS activities to substantiate energy efficiency based on the gas used.

TABLE II
GAS USED BY PoA^2 ALGORITHM FOR K-ETS BLOCKCHAIN INTEGRATION

K-ETS Functions/ Activities ↪	PoW (G_w)	PoA (G_a)	PoA^2 (G_2)	Difference in Gas Used (G_w - G_2)	(G_a - G_2)
Registering Industry	133509	133437	104237	29272	29212
Emissions Update	159498	159486	146286	13212	13200
Free Allocation	54341	54353	49853	4488	4500
Create Auction	93152	93152	86452	6700	6700
Placement of Bid	97086	97086	89286	7800	7800
Finalize Auction	66820	66820	54520	12300	12300
Trading Credits	40435	40423	41535	-1112	-1112

Gas quantifies the computational effort required to execute a specific operation in a BT system such as eBCTC. Hence, low gas usage is an added advantage that automatically translates to network and energy efficiency because smaller gas usage indirectly reduces the energy consumed per transaction, as fewer computational resources are required to process each transaction. Thus, the difference in gas used between the proposed PoA^2 (G_2) and other algorithm in executing each K-ETS activity is equivalent to the energy gained [E] by the PoA^2. Equation (5) is the energy-gained by PoA^2 as against PoW.

$$\mathrm{E}_{\mathrm{PoA}^2} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{G}_{\mathrm{w}_i} - \mathrm{G}_{2_i}) \tag{5}$$

where G_{w_i} and G_{2_i} is gas used by PoW and PoA^2 in executing each function. As seen in Table II, the proposed algorithm achieved an $\mathrm{E}_{\mathrm{PoA}^2}$ value of 29212 and 29272 better than PoW and PoA for registering and authenticating the legitimacy of the users' emission report. Also, PoA^2 achieved an energy gain of 13212 and 13200 for emission update. Overall, PoA^2 achieved high energy gain [E] across all the K-ETS activities better than other mainstream BT algorithms. It achieved an energy gain $\mathrm{E}_{\mathrm{PoA}^2}$ of 4488 and 4500 for free carbon allocation and 1112 for carbon credit trading. Therefore, the net energy gained by deploying PoA^2 to improve the security and sustainability of K-ETS activities is expressed in equation (6):

$$\mathrm{E}_{\mathrm{eBCTC}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{E}_{\mathrm{PoA}^2} + \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{B}_{\mathrm{i}} - \mathrm{C}_{\mathrm{i}}) \tag{6}$$

where = benefits such as transaction fees, block rewards, or utility value) for participants i; while B_{i} = costs (e.g., energy consumption, hardware costs) for participants i.

In evaluating the energy efficiency of the eBCTC system for improving each K-ETS activity, it is given as:

$$\xi_{\mathrm{eBCTC}_{\mathrm{i}}} = \left[\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{G}_2)}{\mathrm{T}_{\mathrm{i}}} \right] \tag{7}$$

where $\xi_{\mathrm{eBCTC}_{\mathrm{i}}}$ = energy consumed/gas used per transaction; $\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{G}_2)$ = total energy expended/gas used; and T_{i} = total number of transactions processed in eBCTC. The results in Table II show that PoA^2 is highly energy-efficient due to the smaller gas usage in executing each K-ETS transaction.

Furthermore, the line graph in Fig. 5 is the transaction cost of PoA^2 and other algorithms in executing the K-ETS activities. The results in Fig. 5 indicate that the proposed algorithm achieved a low transaction cost through enhanced smart contract intelligence.

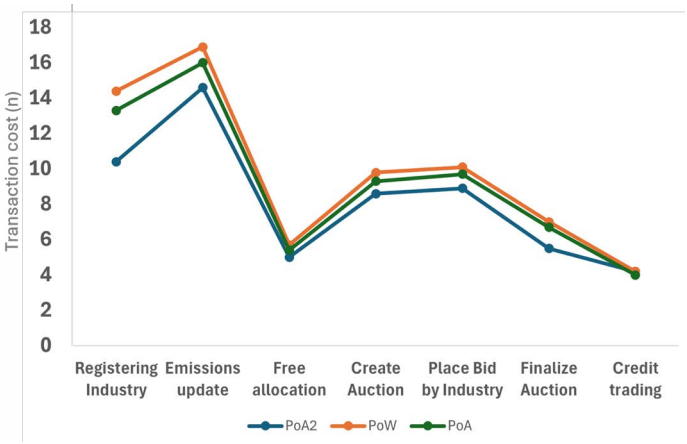


Fig. 5. The transaction costs for the three consensus protocol across all the key functions of the system

Generally, the transaction cost is the product of the gas used and the gas price, that is, $[\mathrm{T}_{\mathrm{c}} = \mathtt{Gas\ Used} \times \mathtt{Gas\ Price}]$. As seen in Fig. 5, PoA^2 achieved a lower transaction cost (T_c) better than PoA and PoW in all K-ETS activities, thus fostering

a transparent incentive mechanism that can be seamlessly integrated across platforms for scalable deployment. Specifically, PoA^2 had the least T_c value for carbon credit trading, free allocation, emission update, etc., making it a better security algorithm than PoW and PoA, respectively. These results validate that the proposed PoA^2 is an improved PoA algorithm with low gas usage capacity to achieve energy efficiency in BT-enabled systems via connected innovation intelligence.

Table III compares the performance of PoA^2 with similar blockchain-based ETS methods.

TABLE III
COMPARATIVE ANALYSIS WITH RELATED WORKS

Ref.	Method	Algorithm	Metrics Performance
[8]	Dual-BT	PoS	***
[10]	Private, Permissioned blockchain	PoA	***
[12]	Ethereum	***	Traceability Issues
Ours	Purechain	PoA^2	Low gas use, price, etc.

***: No information provided

From the analysis of the previous results, the Purechain security framework with the underlying PoA^2 algorithm can guarantee an energy efficient K-ETS with less gas usage, resulting in lower transaction costs, reduced network congestion, improved scalability, a better user experience, and increased incentive innovation to achieve net zero carbon emissions.

IV. CONCLUSION AND FUTURE WORK

This study developed an energy-conscious, blockchain-driven framework for optimal Korean emission trading systems (K-ETS) security. The framework used a proof of authority and association algorithm, PoA^2, to enhance smart contract-connected intelligence, resulting in low transaction costs and gas usage. The results show that the proposed PoA^2 achieved a high energy gain, lower transaction costs, and scalable deployment compared to other mainstream blockchain mechanisms. Thus, PoA^2 enhanced the security of key K-ETS activities without sacrificing scalability and energy usage. Future work will focus on deploying PoA^2 on other ETS platforms and introducing artificial intelligence for optimal intuitive signer selection performance.

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REFERENCES

[1] A. Boumaiza and K. Maher, "Harnessing blockchain and iot for carbon credit exchange to achieve pollution reduction goals," *Energies*, vol. 17, no. 19, p. 4811, 2024.

[2] I. U. Ajakwe, S. O. Ajakwe, J. M. Lee, and D.-S. Kim, "Iot-blockchain frameworks in environmental pollution monitoring and data management," in *2024 15th International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2024, pp. 2147–2151.

[3] J. Lee and J. Yu, "Market analysis during the first year of korea emission trading scheme," *Energies*, vol. 10, no. 12, p. 1974, 2017.

[4] P. Howie, S. Gupta, H. Park, and D. Akmetov, "Evaluating policy success of emissions trading schemes in emerging economies: comparing the experiences of korea and kazakhstan," *Climate policy*, vol. 20, no. 5, pp. 577–592, 2020.

[5] B. Yoon and B. Karali, "Efficiency in the early stages of carbon markets: The case of the korean emissions trading scheme," *Emerging Markets Finance and Trade*, vol. 61, no. 1, pp. 125–141, 2025.

[6] S. O. Ajakwe, I. I. Saviour, V. U. Ihekoronye, O. U. Nwankwo, M. A. Dini, I. U. Uchechi, D.-S. Kim, and J. M. Lee, "Medical iot record security and blockchain: Systematic review of milieu, milestones, and momentum," *Big Data and Cognitive Computing*, vol. 8, no. 9, p. 121, 2024.

[7] S. O. Ajakwe and D.-S. Kim, "Facets of security and safety problems and paradigms for smart aerial mobility and intelligent logistics," *IET Intelligent Transport Systems*, vol. 18, pp. 2827–2855, 2024.

[8] F. Yang, Y. Qiao, J. Bo, L. Ye, and M. Z. Abedin, "Blockchain and digital asset transactions-based carbon emissions trading scheme for industrial internet of things," *IEEE Transactions on Industrial Informatics*, 2024.

[9] Z. Hu, Y. Du, C. Rao, and M. Goh, "Delegated proof of reputation consensus mechanism for blockchain-enabled distributed carbon emission trading system," *IEEE Access*, vol. 8, pp. 214 932–214 944, 2020.

[10] S. Hartmann and S. Thomas, "Applying blockchain to the australian carbon market," *Economic Papers: A journal of applied economics and policy*, vol. 39, no. 2, pp. 133–151, 2020.

[11] D. Effah, B. Chunguang, F. Appiah, B. L. Y. Agbley, and M. Quayson, "Carbon emission monitoring and credit trading: the blockchain and iot approach," in *2021 18th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP)*. IEEE, 2021, pp. 106–109.

[12] A. M. R. da Cruz, F. Santos, P. Mendes, and E. F. Cruz, "Blockchain-based traceability of carbon footprint: A solidity smart contract for ethereum." in *ICEIS (2)*. Prague, Czechia, 2020, pp. 258–268.

[13] S. O. Ajakwe, V. U. Ihekoronye, I. U. Ajakwe, T. Jun, D.-S. Kim, and J. M. Lee, "Connected intelligence for smart water quality monitoring system in iiot," in *2022 13th International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2022, pp. 2386–2391.

[14] A. Boumaiza, "A blockchain-centric p2p trading framework incorporating carbon and energy trades," *Energy Strategy Reviews*, vol. 54, p. 101466, 2024.