An Incentive-Compatible Blockchain Consensus Mechanism for Construction Carbon Markets Based on Verified Carbon Credit Sales

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Abstract –
Carbon markets offer a promising path to unlock carbon emission reduction (CER) potential in the construction industry; however, the industry often lacks sufficient incentives to adopt CER activities. This study proposes a blockchain-based consensus mechanism, namely Proof-of-Carbon-Sold (PoCS), to incentivize CER of the construction industry in the carbon markets by linking participants' verifiable carbon-credit sold to consensus eligibility and reward earning through Carbon Sold Credits (CSC). Building on PoCS, a CSC burning rule and a Verifiable Random Function (VRF) in the election phase are introduced to improve fairness and unpredictability for fragmented private participants from the construction industry in carbon markets. Hyperledger Fabric experiments show that PoCS enables low-carbon participants to accumulate CSC to enter consensus and earn rewards, thereby encouraging CER activities. Meanwhile, the burning rule and VRF-based election help prevent large enterprises with scale advantages from monopolizing consensus opportunities and reduce the risk of malicious behavior, providing a fairer participation environment for private participants with substantial CER potential in the construction industry. This study contributes to incentivizing low-carbon transitions in the construction industry and improving fairness in carbon-market participation.

Keywords –
Blockchain; Consensus Mechanism; Carbon Market; Construction Industry

1 Introduction

The construction industry has substantial emissions-reduction potential [1], particularly among the numerous private residential buildings [2], where activities such as energy-efficiency retrofits can significantly reduce carbon emissions [3]. However, the construction industry is often considered lacking in decarbonization motivation due to high upfront investment and long payback periods [4], as well as accountability-allocation challenges arising from dispersed emissions and the involvement of multiple stakeholders [5, 6]. These issues are especially pronounced in fragmented private residential buildings [7].

The carbon market has been proposed as an economic instrument to incentivize investment and participation in carbon emission reduction (CER) activities through financial returns [8]. However, the construction industry has not been mandatorily covered by Chinese carbon markets [9], and empirical evidence also suggests that financial incentives are often insufficient to motivate sustained CER activities [10]. Consequently, existing carbon market mechanisms provide limited incentives for decarbonization in the construction industry, calling for additional incentive mechanisms built on top of carbon markets to engage stakeholders in the construction industry, especially the numerous private sectors with huge CER potential [7].

Blockchain has been proposed as an important technology for improving carbon market management [11]. A core component of blockchain is the consensus mechanism, namely a set of rules that participants use to verify a new block [12], which can serve an incentivization function [13]. By transforming the cost of maintaining the network into obtainable rewards, consensus mechanisms enable participants to cooperate and comply with rules even without a central authority [14]. A canonical example is Bitcoin, where consensus nodes (miners) that successfully generate a new block via Proof of Work (PoW) receive economic rewards consisting of a fixed Coinbase subsidy and transaction fees [15]. Therefore, designing blockchain-based consensus mechanism incentives is a promising direction for motivating sustained CER in the construction industry and participation in carbon market trading.

Proof-of-Reputation (PoR) is the most commonly adopted consensus mechanism in blockchain-based energy or carbon trading markets, where blockchain activities are incentivized by rewarding reputation points (RP) [16-18]. However, CER activities in the construction industry, like energy-efficiency retrofits, are fragmented [5, 6], where sustained reductions are often delivered by numerous dispersed private buildings. If consensus elections rely heavily on carbon-market trading history, resource-rich participants with large transaction volumes may dominate consensus, limiting private participants' access to on-chain rewards and weakening incentives for sustained emissions reduction [12]. Therefore, while incentivizing construction stakeholders to engage in CER activities, the consensus design must also account for the fairness problem in existing literature to avoid the "strong-get-stronger" dynamics commonly observed in PoR-like mechanisms, which is still not addressed in existing literature.

This study proposes an innovative Proof-of-Carbon-Sold (PoCS) consensus mechanism and introduces optimization mechanisms (burning rules and VRF) to promote CER and carbon market participation in the construction industry. Main contributions are as follows: First, this study proposes the innovative Proof-of-Carbon-Sold (PoCS) consensus mechanism, which links verifiable sold carbon credits to consensus eligibility and rewards via Carbon-Sold Credits (CSC), directly incentivizing sustained carbon emission reduction (CER) activities. Second, to enhance fairness for small-scale participants with fragmented CER potential, PoCS introduces a CSC burning rule and a Verifiable Random Function (VRF). These features increase election unpredictability, prevent consensus monopoly by resource-intensive firms, and mitigate malicious risks. Third, Hyperledger Fabric (HF) experiments validate that PoCS effectively balances CER incentivization and system fairness, offering a feasible low-carbon transition pathway for the construction industry. Fourth, this study provides insights for future research and policymaking on using blockchain consensus to supplement insufficient carbon market revenues, fostering a fairer and more motivating environment for less-advantaged small firms, especially those in the construction industry.

2 Literature Review

In blockchain systems, network members (nodes) use consensus mechanisms to vote on whether to accept or reject a new block [19]. Consensus mechanisms can be broadly categorized into chain-based mechanisms, such as Proof of Work (PoW) [15] and Proof of Stake (PoS) [20], and Byzantine Fault Tolerance (BFT)-based mechanisms, which reach final agreement through message exchanges among nodes [21-23]. BFT-style mechanisms are widely adopted in the literature, including Proof-of-Reputation (PoR) [16], Proof-of-Carbon-Reduction (PoCR) [12], and Algorand [24], etc. Among the various BFT-style consensus mechanisms, PoR consensus mechanisms are widely used in blockchain-based carbon markets. Khaqqi et al. [16] proposed a reputation-based trading system in which access to price offers depends on reputation points. Using priority-based sorting, matching considers both price and reputation to improve fairness. Liang et al. [25] proposed a dual-blockchain structure trading scheme (DBR-ETS) for the secondary carbon credit market, incorporating corporate reputation to encourage companies to actively engage in carbon reduction. Hu et al. [26] developed a blockchain-based distributed carbon emissions trading system (BD-ETS), which uses smart contracts and a reputation-driven Delegated-Proof-of-Reputation (DPoR) consensus mechanism to optimize the efficiency and security of carbon emissions trading. Wang et al. [27] designed a distributed reputation system for a blockchain-based cap-and-trade scheme, using blockchain to manage reputation scores in a decentralized way and support peer-to-peer carbon trading.

However, PoR-based studies often over-relied on nodes' past performance, which favors resource-rich participants and disadvantages new entrants and small-scale sectors [26], thereby undermining fairness and weakening incentives [28]. In the construction industry, participants are predominantly from private buildings [2]. Due to dispersed emissions and the relatively small carbon footprint of individual buildings, these entities often lack the incentive to join the carbon market [5]. Traditional PoR consensus mechanisms inadvertently amplify this disincentive by marginalizing small-scale contributors.

To mitigate such issues, two mechanisms were proposed. The burning rule, which deduct reputation points after consensus participation [29], prevents large participants from monopolizing the consensus process, thereby granting small and medium-sized participants (like single building owners) equitable opportunities to participate and earn rewards. The VRF during the election phase [12], which injects cryptographic randomness into the consensus node selection process, reduce the probability of large participants monopolizing election outcomes and effectively mitigating the risk of malicious collusion.

In summary, while PoR-based mechanisms represent the state-of-the-art for blockchain carbon markets, their inherent design disadvantages industries dominated by small-scale participants, such as the construction sector. Therefore, this study improves upon traditional PoR mechanisms to propose a novel, inclusive consensus mechanism customized specifically for the construction industry's participation in the carbon market.

3 Methodology

In this section, this study first proposes the PoCS consensus mechanism and then introduces methods for evaluating PoCS's performance and fairness.

3.1 Proof-of-Carbon-Sold (PoCS) Consensus Mechanism

Proof-of-Carbon-Sold (PoCS) is an enhanced delegated PBFT-style mechanism inspired by Proof-of-Reputation (PoR). The PoCS consensus procedure consists of 4 stages, as illustrated in Figure 1. Under PoCS, participants sell carbon credits generated from verified CER activities, and the sold amount is converted into carbon-sold credits (CSC).

Before each trading round, PoCS elects the consensus nodes based on carbon-sold credits (CSC) and a Verifiable Random Function (VRF). While participants are initially ranked by their CSC values, relying solely on this ranking could allow resource-intensive nodes to monopolize the consensus process. To address this, a VRF is introduced into the election phase to generate cryptographic randomness. By combining the CSC rankings with the VRF output, the consensus committee for that round is formed, and the leader is selected. This integration significantly increases election unpredictability, prevents persistent dominance by high-CSC nodes, and reduces the risk of malicious behavior. These elected nodes participate in block agreement and receive transaction fees as incentives, thereby encouraging sustained emission-reduction efforts.

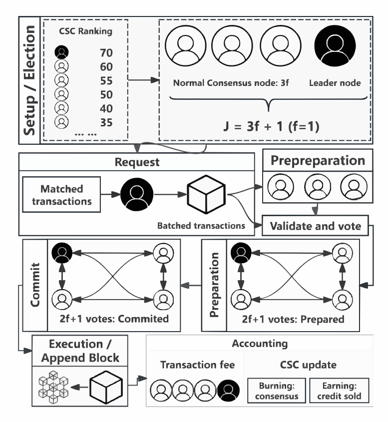

Figure 1. PoCS consensus procedure

In each trading round, buyers and sellers upload their requests to the system; specifically, a seller's request must be accompanied by digital certificates issued by recognized third-party verification agencies and carbon credit registry. This mechanism ensures that the carbon credits entering the system are backed by established off-chain auditing frameworks, thereby providing a reliable trust anchor. To a certain extent, this mitigates the inherent "oracle problem" in carbon accounting: although the blockchain guarantees the immutability and traceability of data once on-chain, it cannot natively verify the physical authenticity of carbon emission reductions at the source. Once these requests pass compliance verification, the leader node invokes the smart contract to match them. The successfully matched transactions are subsequently stored in the transaction pool, awaiting validation and inclusion into the blockchain through the subsequent PoCS consensus procedure.

PoCS begins when finalized carbon market trades are matched into transactions and forwarded to the leader node (Request), which collects these transaction requests and batches them into a new block proposal. The leader node then broadcasts the proposed block to all consensus nodes (Prepreparation). Upon receiving the proposal, consensus nodes validate the block (e.g., correctness and digest consistency) and cast votes (Preparation), which are disseminated among the consensus nodes. Under a PBFT-style setting, the system tolerates up to $f = \frac{J-1}{3}$ Byzantine nodes; once a proposal accumulates at least $2\mathrm{f} + 1$ votes, the protocol proceeds to the Commit phase. In this phase, consensus nodes collect consensus nodes' Preparation votes and, after reaching quorum, broadcast Commit votes. When a node observes at least $2f + 1$ Commit votes for the same digest and sequence number, the block is considered irrevocably committed. After commitment, nodes deterministically execute the committed batch: transactions are applied in order, blocks are cut according to the block formation policy, and the resulting blocks are appended to the ledger.

After a round is finalized, PoCS performs round-level accounting. First, transaction fees are distributed to the consensus nodes to compensate for their participation in ordering and validation. Specifically, the leader receives a fraction ω of the fees, while the remaining portion is shared among the other consensus nodes:

$$R_t = \omega \sum R_{i,t} \tag{1}$$

$$R_{j,t} = \frac{(1-\omega)\sum R_{i,t}}{J-1} \tag{2}$$

Second, PoCS updates each node's CSC using both earning and burning mechanisms. CSC increases when a node completes verified Sell transactions, treating the amount of carbon credit sold as a measurable indicator of emission-reduction achievements. To mitigate the "strong-get-stronger" effect commonly observed in PoR-like mechanisms [12], PoCS introduces a burning rule: nodes that participate in the consensus process lose a fixed amount of CSC after each round. Formally, after round $t - th$ the CSC change for node i is defined as:

$$\Delta CSC_{i,t} = \beta Q_{i,t}^{T} - \theta CSC_{j,t}^{C} \tag{3}$$

Where $\Delta CSC_{i,t}$ determined by the carbon credit selling volume $Q_{i,t}^{T}$, the amount of CSC deduction ($CSC_{j,t}^{C}$) is due to participation in consensus activities. Here, β is the CSC conversion coefficient for the sold amount, and θ depends on the node's role in the round: $\theta = 1$ for a consensus node (not leader), $\theta = 2$ for the leader node, and $\theta = 0$ otherwise. Accordingly, the CSC value for node i is updated as:

$$CSC_{i,t} = CSC_{i,t-1} + \Delta CSC_{i,t} \tag{4}$$

3.2 Evaluation method

To evaluate the proposed PoCS consensus mechanism, experiments were conducted on Hyperledger Fabric version 1.4.4. The experiment is run on a virtual machine equipped with an Intel(R) Xeon(R) Platinum 8370C CPU 2.80GHz (Ubuntu 22.04.5 LTS); notably, while utilizing different hardware would proportionally affect transaction throughput and latency, the core validity and fairness of the PoCS mechanism remain unaffected. The PoCS mechanism was first implemented using GoLang version 18.4, with the core functionalities and configuration structured into four main functional packages, namely cmd, message, node, and server; and seven configuration files, forming the PoCS network. The functionalities of these key files are summarized in Table 1.

Table 1. Main Files and Their Functions in the PoCS Consensus Mechanism

Package	Document	Function
cmd	cmd.go	Initializes PoCS node configuration and generates a shared configuration object for use by other modules.
message	buffer.go	Stores and manages PoCS messages and states across various protocol stages.
	message.go	Defines core structures and methods for PoCS consensus messages.
node	node.go	Specifies the structure and core functionalities of PoCS nodes.
	request.go	Processes client trading requests based on node roles.
	sequence.go	Manages sequence number logic to ensure consistent request ordering across all nodes.
	preprepare.go	Implements the Preprepare phase, including leader node message generation and broadcasting.
	prepare.go	Implements the Prepare phase and part of the Commit phase, including message verification and broadcasting.
	commit.go	Handles receipt and validation of Commit messages, marking messages as executable when conditions are met.
	execute.go	Marks messages as ready for execution, adds them to the execution queue, and notifies execution threads.
	election.go	Defines the rules for PoCS elections and credit changes.
network	docker-compose-base.yaml	Defines and launches service containers in the Hyperledger Fabric network.
	peer-base.yaml	Specifies general configuration for Peer and Orderer nodes, referenced by other Docker Compose files.
	network.yaml	Defines network topology and detailed configuration of components.

The most critical functional file in the PoCS consensus mechanism is "election.go", which defines the PoCS election functions (GetLeader, GetConsensusNodes) and the update logic for the CSC (updateCSC) (Figure 2).

```
Input: CSCTable (map: id ↦ CSC) ; sequence ; lastDigest
       LeaderID ; ConsensusIDs
       MinCSC ; LearderBurn ; ConsensusBurn
       transactions ← GenerateTX(sequence, lastDigest)
Output: Updated CSCTable ; CSCHistory[sequence+1] (snapshot)
for all id ∈ keys(CSCTable) do
  if id = LeaderID then
    if CSCTable[id] > MinCSC + LearderBurn then
      CSCTable[id] ← CSCTable[id]− LearderBurn
    else
      CSCTable[id] ← MinCSC
    end if
  end if
  isConsensus ← false
  for all cid ∈ ConsensusIDs do
    if cid = id then
      isConsensus ← true
    end if
  end for
  if isConsensus = true then
    if CSCTable[id] > MinCSC + ConsensusBurn then
      CSCTable[id] ← CSCTable[id]− ConsensusBurn
    else
      CSCTable[id] ← MinCSC
    end if
  end if
end for
for all tx ∈ transactions do
  if tx.Type = "Sell" then
    inc ← tx.Amount/1000.0
    CSCTable[tx.ID] ← CSCTable[tx.ID]+ inc
  end if
end for
nextSeq ← sequence +1
CSCSnapshot ← copy(CSCTable) // deep copy to avoid later modification
CSCHistory[nextSeq] ← CSCSnapshot
SaveCSCHistoryToFile(CSCHistory)      // optional persistence at the end
return CSCTable, CSCHistory[nextSeq]
```

Figure 2. CSC update algorithm

PoCS was validated in a four-node experimental environment. The initial CSC values of the four nodes are set to 80, 70, 60, and 50, respectively, to simulate participants with different carbon-market entry times. Nodes 0 and 1 are further assigned as buyers, while nodes 2 and 3 are assigned as sellers of carbon assets, thereby representing high-emitting and low-emitting enterprises, respectively, in a carbon market setting.

The experiment is conducted over eight consensus (transactions) rounds. In each round, all nodes elect the consensus nodes (including the leader) based on the ranking in the CSC table. Elected nodes participate in the trading and consensus process, during which the CSCs are dynamically updated. All nodes engage in carbon asset trading every round, resulting in corresponding CSC updating. In this experiment, carbon credits are traded in units of 1,000, and the conversion coefficient is set such that every 1,000 traded credits accumulate 1 CSC. Additionally, a fixed burning rule is applied, where the CSC burned for the leader node is set to 4 CSC per round. These design parameters are empirically determined based on the average transaction volume and specific experimental setup to best reflect the simulated scenario. It should be noted that this study adopts these preliminary yet reasonable settings primarily to validate the feasibility and rationality of the proposed mechanism. In real-world deployments, the exact conversion coefficients, fee distribution, and dynamic burning mechanisms would be established by a regulator or trading institutions, customized for actual market conditions. A comprehensive investigation into these parameter designs is reserved for future research.

To mitigate strategic and malicious behaviors (e.g., collusion and bribery) commonly observed in PoR-based consensus mechanisms, this study further integrates a Verifiable Random Function (VRF) into the PoCS election process [12]. The VRF introduces cryptographic randomness that breaks the deterministic nature of the election, preventing high-reputation nodes from monopolizing block generation rights and thereby significantly increasing the cost of targeted attacks. The VRF-enhanced PoCS election algorithm is detailed in Figure 3. To validate its effectiveness, this study conducted a 200-round ablation study under identical experimental settings to compare the election outcomes of PoCS with and without the VRF integration.

```
Input:  RPTable (map: id ↦ RP) ;  K (committee size, e.g., K = 4) ;
        view ;  lastSeq
Output: Consensus (list of K node identifiers)
ScoreList ← []                                   // list of tuples (id, score)
for all id ∈ keys(RPTable) do
  rp ← RPTable[id]
  seedData ← CONCAT(view, lastSeq, id)
  hash ← SHA256(seedData)
  u ← PRNG(hash) ∈ (0, 1]      // pseudo-random number based on hash
  if u = 0 then
    u ← 10^−10                                   // prevent ln(0)
  end if
  if rp ≤ 0 then
    rp ← 10^−6                  // prevent division by zero or negative
  end if
  score ← ln(u)/rp                               // Efraimidis-Spirakis Key
  ScoreList.append((id, score))
end for
Sort ScoreList by score descending; if tied, sort by id ascending
Consensus ← []
for i ← 0 to K − 1 do
  Consensus.append(ScoreList[i].id)
end for
return Consensus
```

Figure 3. Election with VRF algorithm

The PoCS consensus mechanism and its configuration were embedded into Hyperledger Fabric version 1.4.4 and executed on this server. The operational details of each round, including CSC values and carbon trading activities, were logged for each node, and the CSC changes per node per round were exported for subsequent analysis.

4 Results and Discussion

Figure 4. presents the operational log of Node 1 under the PoCS consensus mechanism on Hyperledger Fabric, highlighting CSC variations and election outcomes for each round.

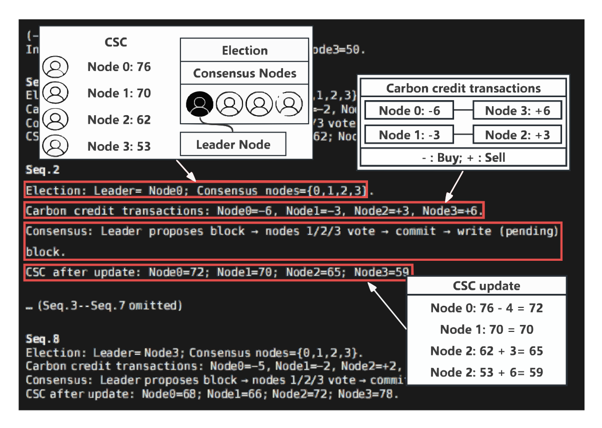

Figure 4. Log output of Node 1

Based on the PoCS execution results, the study compiled the carbon credit transactions for each node in each sequence (Table 2) and the corresponding CSC values (Table 3).

Table 2. Carbon credit transactions per node per sequence

Node /Sequence	0	1	2	3
1	-3	-2	2	3
2	-6	-3	3	6
3	-5	-1	1	5
4	-6	-3	3	6
5	-4	-4	4	4
6	-7	-2	2	7
7	-4	-1	1	4
8	-5	-2	2	5

("-" represents "bought", "+" represents "sold", unit: 1000 credits)

Table 3. CSC values per Node per sequence

Node /Sequence	0	1	2	3
1	80	70	60	50
2	76	70	62	53
3	72	70	65	59
4	68	70	66	64
5	68	66	69	70
6	68	66	73	70
7	68	66	71	77
8	68	66	72	78

The dynamics of CSC values per Node per sequence is visualized in Figure 5.

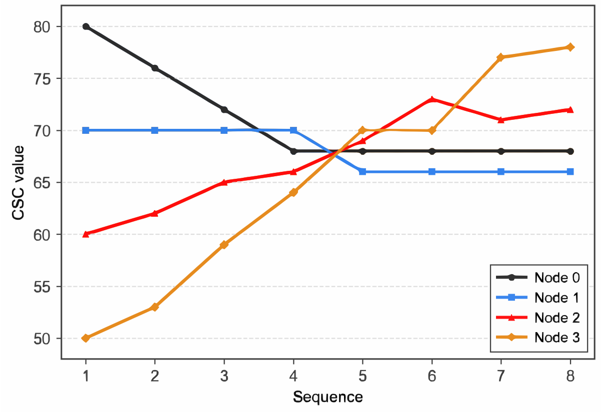

Figure 5. Dynamics of CSC values per Node per sequence

The results indicate that, due to a high initial CSC, Node 0 maintained the highest CSC in the first 3 rounds, even without selling any carbon assets, thus serving as the leader node for rounds 1–3. In the 4th round, Node 1's CSC surpassed Node 0's, resulting in Node 1's election as leader. Although Nodes 2 and 3 started with lower CSCs, their active selling of carbon assets allowed them to accumulate CSC over time. By round 5, Node 3, originally with the lowest initial CSC, had achieved the highest CSC and was elected as the leader. However, since the Leader election reduced CSC, Node 2 became the leader in round 6. In rounds 7 and 8, Node 3 again accumulated significantly higher CSC through carbon asset sales, securing leadership in both rounds.

Based on the observed CSC dynamics, nodes 2 and 3 (the abatement-oriented nodes) earn carbon credit through CER activities and continuously accumulate CSC by selling these credits. As their CSC steadily increases, they eventually gain opportunities to participate in consensus and receive rewards. This result confirms that PoCS provides direct incentives for both CER activities and carbon-credit sales.

Moreover, due to the burning rule, the high-emitting nodes (0 and 1), despite starting with higher initial CSC, experience persistent CSC reductions when they are selected as consensus nodes. Consequently, their CSC rankings gradually decline over time, demonstrating that the burning rule helps enhance fairness by mitigating long-term dominance from a high initial CSC.

Furthermore, the VRF is introduced to effectively mitigate the risks of bribery and collusion during the election phase. To quantify this improvement, this study defines the Top-K Monopoly Rate (MR, Equation 5), which measures the degree of class solidification and predictability within the system. This metric addresses a core question: "If a node ranks among the top K in the network solely based on its CSC, is it guaranteed to be elected as a Leader?" High MR (approaching 1.0) indicates a system is highly deterministic; nodes with top

CSC are guaranteed election. This lack of randomness makes the system vulnerable to targeted attacks, as adversaries can easily predict the upcoming committee.

$$MR_K = \frac{1}{R}\sum_{r=1}^{R}\frac{\left|Elected_r \cap TopRP_K^{(r)}\right|}{K} \tag{5}$$

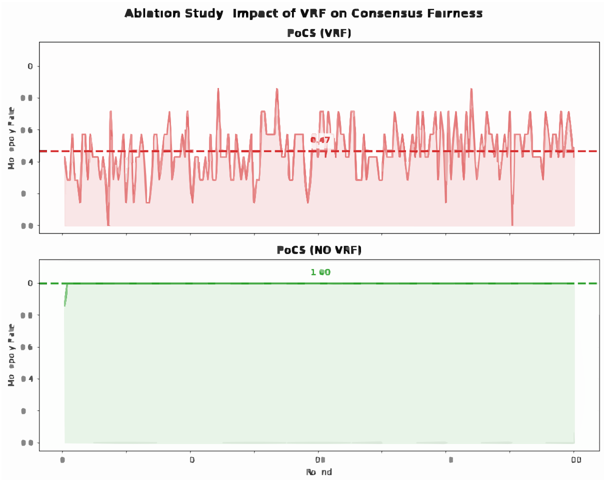

Figure 6. Dynamics of CSC values per Node per sequence

As shown in the experimental results in Figure 6, the PoCS mechanism without VRF exhibits a monopoly rate of 1.00, indicating complete predictability. In contrast, the integration of VRF reduces the average monopoly rate to 0.47. This demonstrates that the VRF successfully breaks the absolute monopoly of high CSC nodes, providing essential stochasticity and security while still maintaining a probabilistic advantage for reputable nodes.

5 Conclusion

This paper proposed a Proof-of-Carbon-Sold (PoCS) consensus mechanism to incentivize sustained CER in the construction industry by directly linking CER and the carbon credit sold amount to consensus eligibility and reward allocation through Carbon-sold Credits (CSC). It further incorporates a burning rule that deducts CSC after each consensus round, along with a Verifiable Random Function (VRF) in the election phase, aiming to increase election unpredictability, reduce the risk of malicious behavior, limit persistent dominance and improve fairness and access for the construction industry's numerous private buildings with huge CER potentials.

A PoCS prototype was implemented and evaluated on HF. Experimental results of an eight-round, four-node setting showed that nodes representing low-carbon participants can accumulate CSC continuously through carbon credits sold, eventually gaining opportunities to join the consensus procedure and receive rewards. This provides practical support that PoCS can create an incentive channel from CER outcomes and market participation to consensus benefits. Meanwhile, nodes representing high-emitting participants (buyers) may initially dominate due to higher initial CSC, but the burning rule gradually reduces their CSC and ranking when they repeatedly serve as leader/committee nodes, while the VRF ensures the node selection process remains unpredictable. Together, these mechanisms effectively limit long-term monopoly, mitigate malicious risks, and improve fairness over time.

Despite these advancements, several limitations of this study should be acknowledged. Future work can further refine the PoCS mechanism by improving scalability. Moreover, the data and parameter settings (e.g., conversion coefficients, burning value) in the current study rely primarily on simulations, lacking real-world Proof of Concept (PoC) within the construction industry. Consequently, determining the optimal values for these system parameters through governance by regulators or industry consortiums, to better balance incentive strength and fairness, thereby reducing long-term dominance while preserving broad participation, remains an important direction for real-world deployments. Finally, should traditional blockchain face future adoption barriers, the system can transition to alternative distributed ledgers or databases, or integrating with technologies like IoT and AI for sustained viability.

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