ENHANCING SCALABILITY AND SUSTAINABILITY IN ENERGY AND CARBON MARKETS: A QUANTITATIVE ANALYSIS OF THE ALGORAND-BLOCKCHAIN IN P2P TRADING FRAMEWORK

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Abstract

Local energy and carbon markets created on private or legacy blockchains suffer from limited throughput, high costs, and fragmented settlement, hindering the expansion of household-level peer-to-peer (P2P) trade. This study investigates whether a public, high-throughput blockchain can support real-time, cooperative carbon and energy trade at the local level. The "blockchain trilemma," a three-way trade-off among decentralization, security, and transaction throughput, inhibits reliable, affordable trading until transaction volumes reach the scale of hundreds of smart meters. This raises the question of whether an automated auction contract, in conjunction with a Pure Proof-of-Stake public ledger, can eliminate this barrier and enforce carbon allowance compliance. This study integrates real-time carbon validation and physical power transfer into a single Algorand smart contract, unlike previous research that treated energy and carbon-credit trading separately. Using the same feeder model, it compares results against both non-blockchain and traditional blockchain benchmarks. A standardized three (3)-layer architecture comprises the Algorand ledger, prosumer/microgrid transaction logic, and a time-scheduled dual-auction smart contract in PyTEAL. The architecture was simulated in MATLAB R2021a on a modified IEEE 37-bus feeder with five microgrids. The simulation used UK residential demand (EFERGY) and solar/wind generation profiles over a 24-hour, 48-slot period. The proposed framework achieved a daily energy balance of 0.99 kWh, reduced carbon emissions by 1,485.90 g/day, and supported over 1,000 transactions per second with sub-5-second latency and micro-cent costs. It combines Algorand's Pure Proof-of-Stake with a carbon-aware double-auction contract to enhance P2P energy trading.

Keywords: Algorand, blockchain, carbon allowance trading, decentralization, double-auction smart contract, peer-to-peer energy trading, Pure Proof-of-Stake, scalability.

1. Introduction

Power systems worldwide are changing structurally. A distributed landscape of "prosumers," or homes and small companies that both create and use renewable electricity through rooftop solar panels and small wind installations, is increasingly replacing reliance on massive, centralized fossil fuel power plants. In this evolving environment, conventional utility models struggle: long-distance power transmission from centralized plants results in major transmission losses and CO2 emissions, whereas aggregator companies and centralized management structures introduce middleman fees, low transparency, and congestion that render neighborhood-scale, real-time trading costly and slow. (Karumba & Shrivastava, 2021)

The "blockchain trilemma" makes it difficult for older networks to manage high-frequency smart meter data, resulting in sluggish performance, even though distributed ledgers offer a potential foundation for peer-to-peer trading without middlemen, high costs, or poor reliability. (Crosby, Pattanayak, Verma, & Kalyanaraman, 2016).

As more households, small businesses, and community microgrids become prosumers, interest in local energy and carbon allowance markets is rapidly growing. Three interconnected obstacles currently limit the blockchain ecosystem's ability to serve these markets: (1) scalability, since most existing P2P platforms are built on blockchains that support only a few dozen transactions per second; (2) an absence of genuine trust and transparency in private or permissioned ledgers, requiring participants to trust a platform operator; and (3) faulty automated negotiation, since many current systems rely on simple contracts prone to mispriced or dropped bids. This presents the central research issue addressed in this paper: Can a public, high-throughput blockchain combined with a time-scheduled auction contract solve the scalability bottleneck while also enforcing carbon-allowance compliance?

This study offers a real-time P2P trading platform based on the open Algorand blockchain to overcome these drawbacks. Without compromising processing speed, this approach offers minimal costs, nearly instantaneous transaction finality, and robust security guarantees. Algorand achieves high throughput through its Pure Proof-of-Stake (PPoS) consensus mechanism, which randomly and secretly selects a rotating committee of validators from the pool of token holders. This design provides near-instant transaction finality, strong security guarantees, and low fees without sacrificing processing speed. The system matches purchase and sell offers and carries out financial clearance for local microgrids without the need for human middlemen when combined with an automated, time-scheduled double-auction smart contract.

Additionally, the framework links environmental compliance with physical energy transfer: Just as long as they have enough carbon allowance for that half-hour trading window may prosumers add electricity to the local network.

Specifically, two real-time values are monitored at each interval t: rnet,t, the actual emissions rate linked to the prosumer's net power activity for that block, and rallow,t, the prosumer's allotted carbon-allowance rate. According to these regulations, a prosumer who maintains a low-carbon profile can sell surplus allowance for secondary revenue, while a prosumer whose realised emissions exceed the allowed for that period must immediately buy additional carbon credits from neighbours with lower emissions. Let British pounds be used to represent the monetary reward function (£), be denoted by γ(·). The required mechanism for the marginal compensation to increase as the emissions margin widens; equivalently, to that γ is strictly convex in the allowance variable:

$$\frac{\partial^2 \gamma(r_{allow,t},\ r_{net,t})}{\partial r_{allow,t}^2} > 0 \qquad (1)$$

For the corresponding closed-form reward across a scheduling interval Δt, and financial-rate coefficient α (in £/g), is:

$$\gamma(r_{allow,t}, r_{net,t}) = \begin{cases} \alpha\sqrt{(r_{allow,t}\Delta t)^2 - (r_{net,t}\Delta t)^2}, & r_{net,t} > r_{allow,t} \\ 0, & r_{net,t} \le r_{allow,t} \end{cases} \qquad (2)$$

In order to enhance node-level and system-level scalability for regional energy and carbon markets, this project aims to combine the Algorand blockchain with a time-scheduled smart-contract auction algorithm into a unified trading framework. The specific goals are to: (1) design an integrated P2P trading system that enables energy and carbon credits to be traded concurrently on the Algorand blockchain; (2) deploy an auction-driven, time-scheduled smart contract to coordinate trade matching, settlement, and transactions execution; and (3) evaluate the Algorand-based system's effectiveness against existing centralized, aggregator-based, and blockchain-based P2P trading systems.

2. Literature Review

2.1. Conceptual Review

The confluence of the industrial ledged ledged ledged ledged ledged ledged ledged ledged ledged ledgers. (Muhsen) From a conceptual standpoint, decentralised trading models transfer pricing power and operational control from traditional centralised utility providers to self-enforcing software protocols that operate across individual household nodes. Systems can automate high-frequency auctions while eliminating counterparty risk and pricing manipulation by tokenising carbon credits and physical power blocks (kWh) as native digital assets (Du, Liu, Huang, Jing, Feng, & Yang, 2022).

2.2. Empirical Review

From empirical trials report mixed results. Demir, Ergin, and Sener (2022) built a localised P2P trading platform based on the permissioned Hyperledger Fabric framework, simulated up to 5,000 smart-sensor nodes in an integrating urban configuration; the setup achieved roughly 1,000 TPS with low initial delay, but performance declined and storage costs rose sharply once privacy-safe data shields were enabled, and the study relied on idealised synthetic data rather than real weather variability. For local electricity markets, Wang, Chang, and Zheng (2025) contrasted Proof-of-Stake (PoS) and Practical Byzantine Fault Tolerance (PBFT) consensus; optimised PoS configurations achieved 100–500 TPS with a 91% reduction in energy use in comparison to Proof-of-Work; however, PBFT communication overhead hindered scaling in excess of roughly 100 nodes, and both protocols lost synchronisation during abrupt generation shocks like cloud-driven solar dips. Wang, Chang, and Zheng (2025)

Okafor, Benson, and Appiah (2025) investigated Directed Acyclic Graph (DAG) ledgers, attaining over 1,500 TPS among 500 prosumer streams and a 20% rise in market involvement; however, they revealed ongoing vulnerabilities to spam, reliance on unverified cross-chain bridges, and double-spending. Basic feed-in rates allowed rural microgrid trials to reach a consistent 200 TPS across 500 houses with a 15% reduction in trading costs, but they encountered interoperability and compliance issues (Gilad, Hemo, Micali, Vlachos, & Zeldovich, 2017). The trend toward lightweight, high-throughput designs is supported by more recent research: Nazari and Biswas (2024) show decentralised P2P trading for retail energy markets; Kaif et al. (2025) combine blockchain with cyber-physical smart meters for safe trading within virtual power plants; Alskaif, Crespo-Vazquez, Sekuloski, van Leeuwen, and Catalão (2022) propose completely P2P blockchain trading techniques for domestic systems; and Khorasany, Dorri, Razzaghi, and Jurdak (2021) present a lightweight, geographically aware blockchain architecture for P2P energy trading.

2.3. Research Framework

High-speed public networks like Algorand's PPoS, which offers nearly $0 transaction fees and sub-5-second block finality while avoiding the aforementioned trilemma trade-offs, are encouraged by this body of work (Gilad et al., 2023; Chaudhary & Bhunia, 2024). The proposed framework's underlying theory is based on a three-layer architecture that consists of an Algorand blockchain layer, a prosumer-centric and microgrid-centric trading layer, and a decentralised P2P smart-contract platform layer. In this layer, encrypted sortition (random, secret committee selection) uses staking incentives to solve the traditional "nothing-at-stake" issue, and a time-scheduled double-auction system provides the market clearance logic (Saleh, 2021) as described in Figure 1.

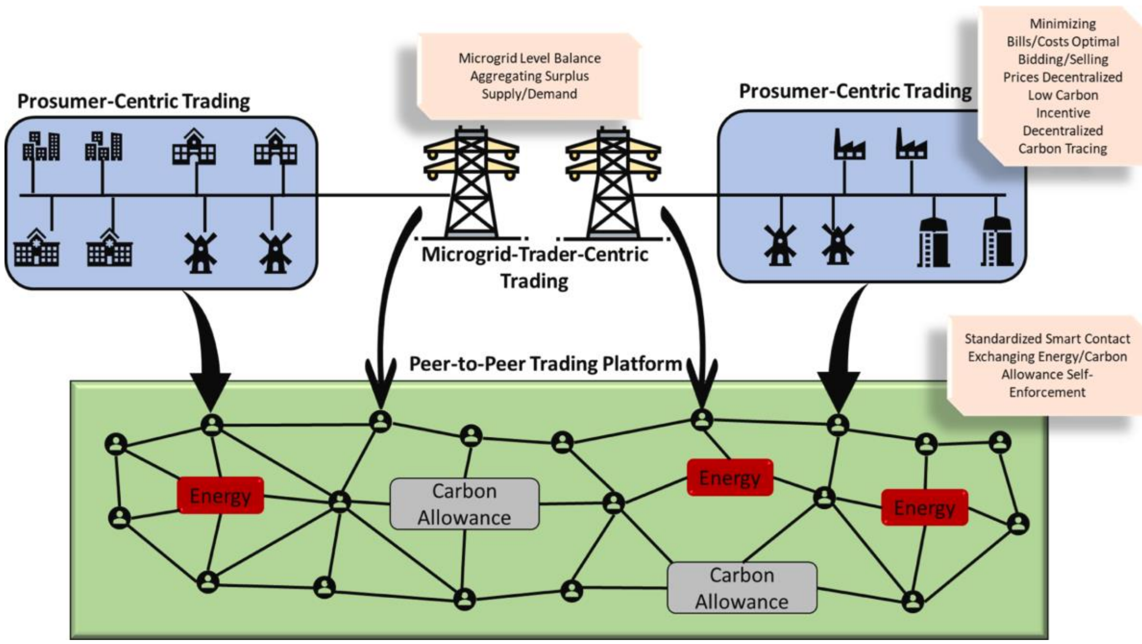

Figure 1. Proposed three-layer framework for peer-to-peer energy and carbon trading.

3. Methodology

3.1. Algorand Blockchain Layer

It secretly and at random chooses a randomised committee for block proposal and validation over PPoS using cryptographic sorting. Algorand Standard Assets (ASAs) are used to tokenise carbon allowances and electricity (kWh), allowing for quick, inexpensive transfers between members.

3.2. Trading Framework

By enabling local trading of excess energy and carbon allowance, a prosumer-driven layer lessens reliance on the main grid. Residents become buyers whenever local generation is insufficient; a smart energy controller submits bids and moves flexible loads to periods when renewable power is copious and inexpensive (Khorasany, Mishra, & Ledwich, 2020). A straightforward cost-minimization problem is solved by each purchasing family for each half-hour slot (formulation modified from Morstyn, Farrell, Darby, & McCulloch, 2018):

$$\text{Minimize } C_i = \sum_t [P_{i,t}^{peer} \times b_{energy,t}]$$

according to the requirement that the presented offer stay below the current auction ceiling in order to have a chance of being approved, and that the overall demand for every slot equal the sum of own generation and net acquired power (Green & Miers, 2017):

$$b_{energy,t} < b_{highest,t} \qquad (3)$$

with $b_{highest,t}$ is the highest bid accepted thus far during that half-hour bidding window, constantly updated and available on the public ledger, and $b_{energy,t}$ is the price (£/kWh) the household bids at interval t. The clearing price is just the highest bid that is approved, and all received bids make up the set $B_{energy,t}$:

$$b_{highest,t} = \max\{B_{energy,t}\} \qquad (4)$$

So, to directly reward local clean generation, a family that produces more renewable energy than it uses may instead sell the excess to nearby purchasers at the predetermined clearing price.

3.3. Microgrid-Trader (MT)-Centric Layer

After households finish the prosumer-centric trading round, a Microgrid-Trader (MT) node balances excess supply and demand across neighbouring microgrids using the same optimisation logic utilised at the individual level (Sundararajan, 2017). Each prosumer n in the microgrid's already-optimized generation $g_{i,t}$ and usage $d_{k,t}$ are combined by the MT at interval t:

$$g_{n,t} = \sum_i g_{i,t} \qquad (5)$$

$$d_{n,t} = \sum_k d_{k,t} \qquad (6)$$

The MT then enters the P2P marketplace, where the full auction process is automated by smart contracts (Algorithm 1).

3.4. P2P Platform Layer and Auction Smart Contract

Through a self-enforcing, five-stage smart contract auction—initialization, matching, bidding, withdrawal, and pay-to-seller: prosumers and MTs exchange energy or carbon allowances. These stages are implemented as the functions f_init(·), f_match(·), f_bid(·), withdraw(·), and f_pay(·). Let U and V represent the buyer and seller index sets, respectively.

Algorithm 1. Auction procedure based on time scheduling Smart contract.

1. Function: (initialization) f init (·).
2. Input: id_u, ε, β, m, s_u, $b_{min\ u,t}$, $b_{highest\ u,t}$, τ_u ,
3. Output: O_u
4. Function: (matching) f match (·)
5. While for v ϵ V.
6. Find the optimal offer combination U*v.
7. End while.
8. For function: (bidding) fbid (·).
9. Input: τ_{now}, b*v, m_v, $\pi_{v.}$
10. Require $\tau_{now} \leq \tau$, $m_v = m_u$, $b_{min\ u,t} \leq b_{highest} < b^*v \cdot s_u \leq \pi_{v.}$
11. Submit bids and update the highest bidding price.
12. Halt.
13. Output: $b_{highest\ u,\ t.}$
14. unction: withdrawal f withdraw (·).
15. Input: τ_{now}, b*v, $\pi_{v.}$
16. Require $\tau_{now} > \tau$, v ϵ V, v≠ v*
17. Unsuccessful buyers withdraw their bids to them.
18. End.
19. Output: $\pi'_{v.}$
20. Function: (pay-to-seller) f pay (·).
21. Input: τnow, b*v, $\pi_{u.}$
22. Require $\tau_{now} > \tau$, v = v*.
23. Compensate seller and finalize settlement

3.5. Experimental Setup

A modified IEEE 37-bus distribution feeder split into five microgrids with residential buyers, clean-generation producers, and storage nodes was used to conduct experiments in MATLAB R2021a (Figure 2). The EFERGY domestic-consumption dataset was used to create household demand profiles, whereas actual field data from the United Kingdom throughout a continuous 24-hour period was used to create solar and wind generation profiles. On the Algorand Virtual Machine, PyTEAL smart contracts were used to create the auction and settlement mechanism. The suggested framework was compared to baselines for aggregator-based trading (Nguyen, Tran, & Batten, 2022) and centralised trading (Hua, Jiang, Sun, & Wu, 2020).

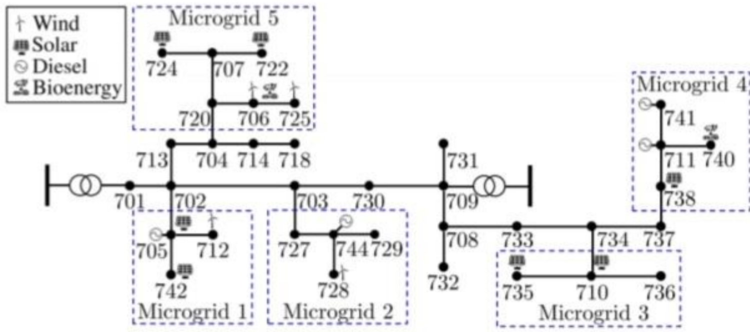

Figure 2. Modified IEEE 37-bus test feeder used for simulation.

4. Result and Discussion

The exact same 37-bus, 5-microgrid topology was used for benchmarking compared to the centralised and aggregator baseline values.

4.1. Local Grid Stabilization

The suggested Algorand-based P2P infrastructure achieved virtually perfect local supply-demand balance, including a net daily surplus margin of only 0.99 kWh across the 24-hour cycle. By comparing them, the aggregator model generated a daily energy scarcity of −4.50 kWh, and the centralized utility architecture crumbled into a much larger shortfall of −46.44 kWh (Figure 3).

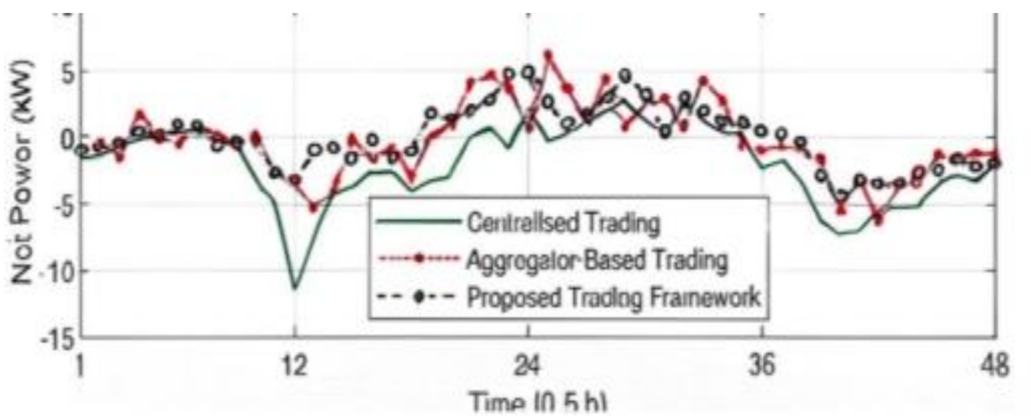

Figure 3. Net local power balance over a 48-slot (24-hour) trading horizon: proposed framework vs. aggregator and centralized baselines.

4.2. Carbon Mitigation

By relating physical power trades to on-chain emissions validation, the framework produced a carbon reduction of 1,485.90 g/day which far exceeding the aggregator threshold (385.91 g/day) and the centralized threshold (168.65 g/day), which was still heavily dependent on fossil-fuel production mixes (Figure 4)

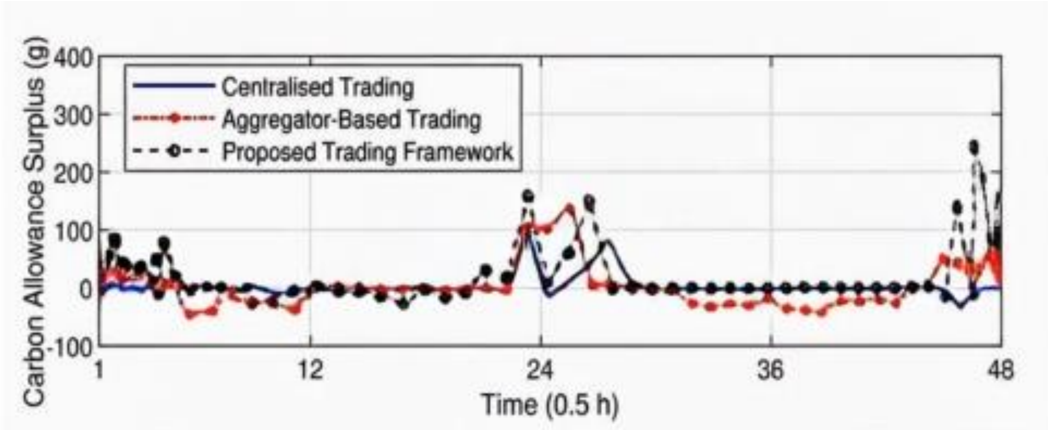

Figure 4. Daily surplus carbon-credit accumulation trends across the three architectures.

4.3. Blockchain Performance

Table 1 summarizes the core blockchain performance parameters recorded for each architecture.

Table 1. Performance comparison across trading architectures.

Evaluation Parameter	Proposed Algorand PPoS	Legacy Private Ethereum	Traditional Centralized Utility
Transaction throughput (TPS)	1,000+	~30	~5
Consensus Latency	4.5s	15 sec-5min	Hours-Days (manual clearing)
Average cost per transaction (€)	~ €0.001	~ €5-50	High

Behavioural monitoring at the microgrid level revealed that during the selected trading block, no residence in Microgrid 5 had a generation excess, but Bus 27 and Bus 06 imported 109 Wh and 319 Wh, respectively. At Bus 724 (113 g), Bus 725 (123 g), and Bus 706 (7 g), three houses provided excess carbon allowance. Similarly, Bus 722 received 419 Wh and 117 g of carbon credits, while Bus 725 received 202 Wh. Matches along the least expensive carbon-allowance path were given priority by the smart contract, and settling was finished atomically in a matter of seconds (Algorand Foundation, 2023). The ideal bidding prices that energy purchasers supplied as auction inputs are shown in Figure 5.

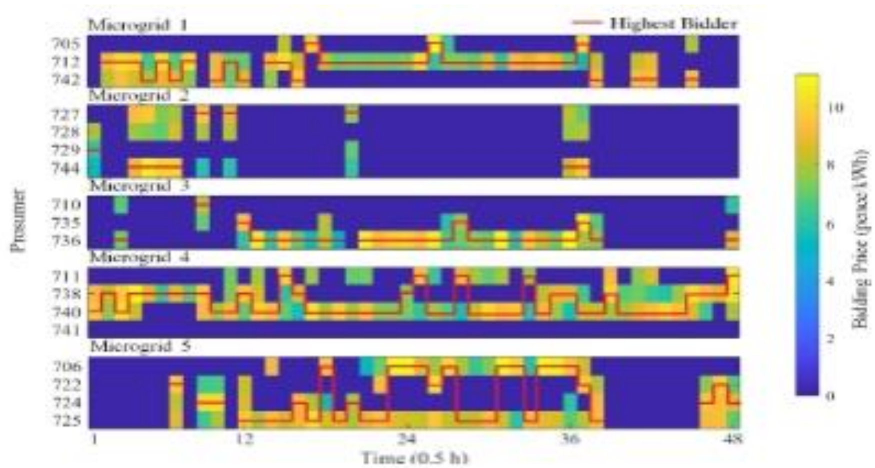

Figure 5. Optimal bidding prices of energy buyers as smart-contract auction input.

4.4.Scalability Comparison

In terms of transactions throughput, settlement latency, and per-transaction energy usage, Algorand's PPoS consensus significantly surpasses traditional private-Ethereum installations (Figure 6).

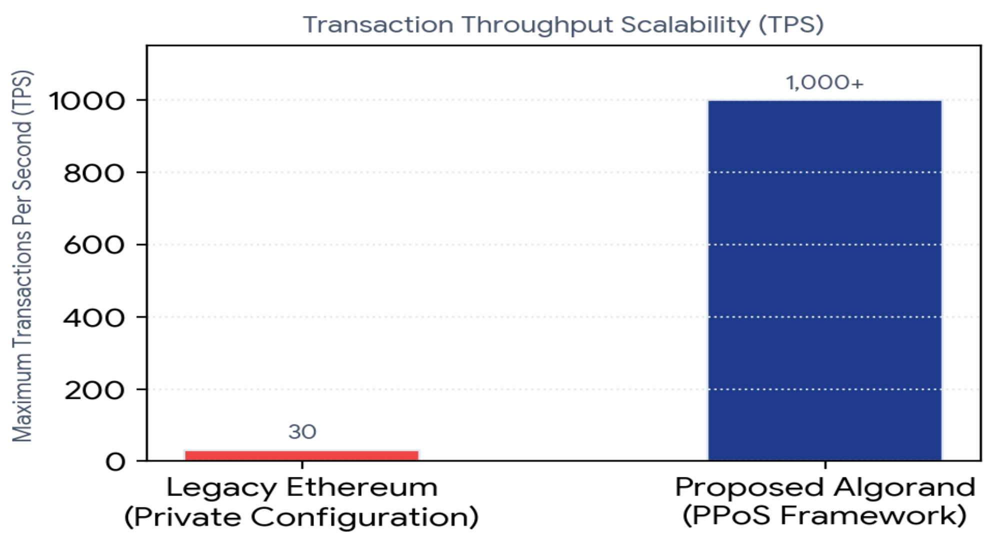

Figure 6. Transactional throughput capacity: Algorand PPoS vs. legacy private Ethereum.

Figure 7 confirms the major share of the proposed framework in comparison to the aggregator and centralised baselines by summarising each architecture's proportionate effect on the overall daily environmental carbon reductions.

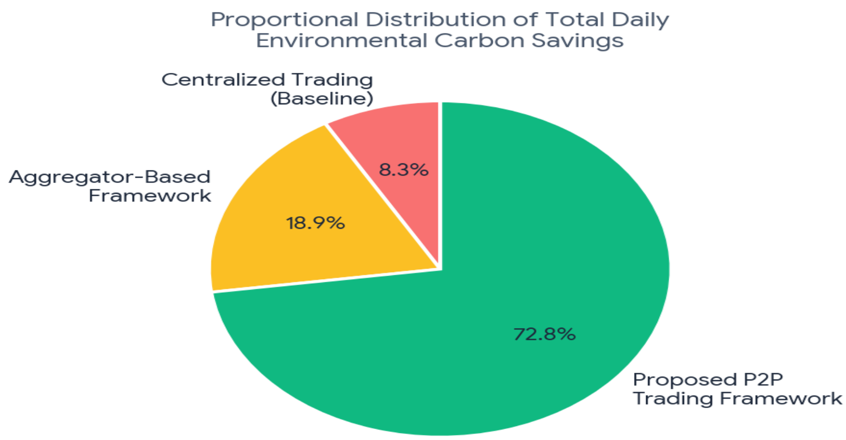

Figure 7. Proportional contribution to total daily environmental carbon savings.

5. Conclusion

This work demonstrates how the scalability issues that have constrained previous P2P energy platforms can be resolved by combining an automated, time-scheduled double-auction smart contract with the high-performance public Algorand blockchain. The architecture overcomes the centralisation vulnerabilities, gas-fee spikes, and processing delays typical of traditional private networks by employing PPoS consensus. Simulations conducted utilising real-world UK power profiles on a 37-bus feeder indicate near-perfect grid stabilisation (0.99 kWh daily residual) while reducing 1,485.90 g of carbon pollution per day, exceeding traditional centralised and aggregator-driven clearing solutions.

There are still a few restrictions. The presented measurements are based on a controlled simulation and do not fully account for the unpredictable nature of real-time physical grid oscillations. The current design also uses a single-chain topology that could encounter storage problems if expanded to national grids containing millions of prosumer nodes; this represents the current simulation and contract design rather than a restriction of the Algorand consensus mechanism itself.

6. Implications/Recommendations

For ordinary homeowners, the framework provides an automated and trustless revenue stream that promotes conservation and low-carbon behaviour; for grid operators, it offers a route to balance microgrids and minimise reliance on fossil-fuel power. In order to formally acknowledge tokenised public-ledger systems for local energy and carbon-allowance trading, energy authorities should think about revising policy guidelines. Future study could include cross-chain atomic asset swaps for interoperability with different networks, and the inclusion of lightweight machine-learning models directly into the smart contracts to dynamically optimise prosumer bidding methods.

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