Journal of Engineering, Project, and Production Management
2026, 16(6), 2026-2

A Data Sharing Platform for Green Electricity Trading and Trusted Energy Under Blockchain Technology

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Project Management
Received January 3, 2026; revised March 22, 2026; May 6, 2026; August 10, 2026 ; August 11, 2026; accepted August 11, 2026
Available online August 30, 2026

Abstract: A decentralized, open, and scalable P2P power exchange is necessary due to the increasing dispersion of renewable energy sources. This study presents a blockchain-based design for green power trade and data sharing that addresses sustainability, privacy, trust, and scalability. A consensus method called Hybrid Proof-of-Energy Contribution (H-PoEC) uses adaptive trust scores and verifiable renewable energy contributions to choose validators on the fly. As a result, validation delays are reduced, and the process is made more equitable and eco-friendlier. Without compromising privacy by disclosing smart meter data, Zero-Knowledge Energy Credential (ZKEC) programs verify that renewable energy sources fulfill carbon criteria. Merkle-compressed Energy Certificates (MECs) reduce the amount of data stored on the blockchain without compromising data security. We constructed a blockchain testbed for a consortium using 500 prosumers, real solar output, and dynamic market interactions. Compared with Practical Byzantine Fault Tolerance (PBFT) and Tendermint, the proposed method achieves 35–48% higher throughput and a 32% reduction in block finalization delays in testing. Under duress, it can handle 2,000 Transactions Per Second (TPS). under peak load, 1,000 TPS. ZKEC proof files are 41% smaller after MEC compression, and monthly storage per prosumer drops from more than 50 MB to 14–16 MB. Market-level testing showed 18–24% more renewable energy, 37% less settlement delay, and a 50% lower dispute rate than with centralized trading. These findings show that the system may be used in the future for decentralized power markets that need to be scalable, protect privacy, and use less energy.

Keywords: Blockchain-based energy trading; peer-to-peer electricity markets; proof-of-energy consensus; zero-knowledge proofs; renewable energy certification; smart grids; consortium blockchain; market simulation.

DOI 10.32738/JEPPM-2026-2

1. Introduction

Power markets operate differently now due to the quick transition to low-carbon energy sources. Rooftop photovoltaic (PV) systems and other distributed renewable energy resources have enabled average customers to become prosumers, capable of producing and trading power within their own energy communities (Lokeshgupta and Sivasubramani, 2019; Hatziargyriou, 2014). The grid is made stronger and more sustainable through decentralized energy exchange, but challenges with trust, coordination, data integrity, and privacy arise as a result (Mengelkamp et al., 2018; Morstyn et al., 2018). Peer-to-peer power trading lets prosumers exchange energy directly. This increases renewable energy and decreases utility energy demand (Guerrero et al., 2019; Wang, 2016). Traditional peer-to-peer trading systems use structured middlemen for market clearing, trade processing, and dispute settlement. This weakens trust assumptions, transparency, and the avoidance of single points of failure (Siano, 2014). Microgrids and comparable systems require high transaction volumes, rigorous verification, and dense prosumer networks. Blockchain is recommended for decentralized energy exchange because of its transparent auditability, distributed consensus, and immutable record (Borkovcová et al., 2022; Saberi, 2019). Many studies show that blockchain-based power markets can record transactions, enforce smart contracts, and enable trustless settlement (Jiang et al., 2025; Kang, 2017). First blockchain energy trading systems used PoW, PoS, or PBFT algorithms, which were unsuitable for energy systems (Nakamoto, 2008; Sriman et al., 2022). These techniques suffer from scalability issues, energy waste, waiting periods, and unfair real-time energy trade (Lone and Naaz, 2021). Blockchain-based energy trading systems have energy data management issues. Many blockchain implementations store raw or poorly aggregated smart meter data, making privacy impossible (Mihaylov et al., 2014). Traffic analysis and data correlation attacks might compromise cryptographically secured or pseudonymized data, revealing consumption and production patterns (Amarasinghe et al., 2019; Saeed et al., 2025). System stability, regulatory compliance, and user privacy are threatened. Zero-knowledge proofs and homomorphic encryption have been studied to improve anonymity in blockchain energy systems (Kosba et al., 2016; Bünz, 2018; Ben-

Sasson, 2013). Most privacy solutions secure data well, but they don't validate renewable energy trading (Sedlmeir et al., 2020). We should study energy-based consensus processes. Blockchain technologies overlook renewable energy contributions when assessing stake ownership or validator sets (Sun and Weingärtner, 2025). Due to the gap between consensus power and environmental involvement, sustainability goals are compromised, and market power accrues to non-participants (Khan and Qureshi, 2024). Static or reputation-based trust management makes most systems vulnerable to long-term manipulation or misreporting (Wang et al., 2019). This study proposes a blockchain-based green power exchange and data-sharing system that emphasizes privacy, trust, scalability, and sustainability, while accounting for these constraints. Dual-layer design isolates high-frequency operational data from immutable on-chain settlement to improve auditability and reduce storage costs (Kumar and Mallick, 2018). The unique Hybrid Proof-of-Energy Contribution (H-PoEC) consensus method selects validators based on the availability of renewable energy, thereby improving dependability. It does both by combining consensual incentives with green aims (Saba et al., 2023). Without providing raw meter data, our Zero-Knowledge Energy Credential (ZKEC) method lets consumers prove energy and carbon compliance (Bonneau et al., 2015). Merkle-compressed Energy Certificates (MECs) encode large amounts of energy data into blockchain entries. This improves system scalability (Meshram and Li, 2018). The suggested solution reduces disagreement, storage overhead, latency, and throughput compared with baseline systems (Kirli et al., 2022).

Table 1 shows that the H-PoEC and ZKEC–enabled framework surpasses existing blockchain-based energy trading systems in consensus efficiency, scalability, privacy protection, and market efficacy.

Table 1. Comparative quantitative analysis of blockchain-based energy trading systems

Dimension	**Conventional P2P Energy Trading (PoW / PoS)**	**PBFT-Based Energy Trading**	**Tendermint-Based Energy Trading**	**Proposed H-PoEC + ZKEC Framework**
Consensus Type	PoW / PoS	PBFT	Tendermint (BFT-PoS)	Hybrid Proof-of-Energy Contribution (H-PoEC)
Validator Selection Basis	Stake / Computation	Static validator set	Stake-weighted	Renewable energy contribution + dynamic trust
Green Energy Incentivization	None	None	Indirect (stake-based)	Explicit, energy-weighted validation power
Average Block Finalization Time (s)	6.8–12.4	3.5–4.5	2.8–3.6	1.9–2.3
Throughput (TPS)	50–120	300–500	450–650	850–1,000
Scalability at 2× Load	Unstable	Degraded (≈40% TPS drop)	Moderate degradation	Stable (<15% TPS drop)
Scalability at 3× Load	Fails	High latency	Partial stalls	Operational with bounded delay
On-Chain Data Storage	Full transaction + meter logs	Aggregated transactions	Aggregated transactions	Merkle-compressed Energy Certificates (MECs)
Monthly Storage per Prosumer	45–60 MB	30–40 MB	25–35 MB	14–16 MB
Storage Reduction vs. Baseline	—	~30%	~40%	>70%
Privacy Mechanism	Pseudonymization only	Access control	Limited encryption	Zero-Knowledge Energy Credentials (ZKEC)
Exposure of Raw Meter Data	Yes	Partial	Partial	None
ZK Proof Size (kB)	38–45	35–42	32–38	22–25
Proof Verification Time (ms)	140–180	120–160	110–140	65–90
Market Clearing Model	Centralized / Semi-P2P	On-chain auction	On-chain auction	Block-level double auction with MEC anchoring
Renewable Utilization (%)	50–58	58–65	60–68	72–78
Settlement Delay (s)	8–15	5–7	4–6	2–4
Dispute Rate (%)	3.5–5.0	2.0–3.0	1.5–2.5	<1.0
Trust Adaptivity	Static	Reputation-based	Stake history	Continuous trust scoring
Auditability	Limited	Moderate	High	Full cryptographic auditability via MEC roots

1.1. Research Questions and Objectives

This study covers many aspects of the creation and testing of a scalable, privacy-preserving, and sustainable blockchain-based peer-to-peer energy trading platform. We start by building a platform with high throughput, low transaction latency, and scalable performance in dense prosumer networks with high trading frequency. To certify renewable energy origin and carbon compliance without giving out smart meter data and maintaining computational efficiency for real-time market operations, zero-knowledge energy. Previous methods required more blockchain storage and cryptographic proof than Merkle-compressed Energy Certificate (MEC) aggregation. The research investigates whether consensus authority and verified renewable energy contributions increase renewable energy consumption, settlement delays, and dispute rates in decentralized power markets. Dynamic trust-based validator rotation influences the resilience of consortium blockchain systems, misreporting resistance, market stability, performance, and sustainability. Finally, it finds the optimal balance among privacy, scalability, and market efficiency for large blockchain-based green power sales systems.

2. Methodology

Scalability, trust, privacy, and real-time interoperability among dispersed prosumers are the main hurdles of decentralized energy markets. The blockchain-enabled data sharing platform for green power trade addresses these issues. Standard blockchain-based energy trading systems have excessive on-chain data storage, low throughput, and inadequate procedures for confirming renewable energy claims without disclosing critical operational data. Cryptographic verification, energy-aware consensus, and trust-based governance are closely integrated within the proposed modular and tiered approach to address these constraints. The method includes system architecture design, hybrid consensus formation, privacy-preserving energy credentialing, and trust-aware data sharing and trade. Each component improves the scalability, reliability, and environmental responsibility of decentralized green power markets through novel approaches.

2.1. System Architecture Overview

The proposed dual-layer architecture separates high-frequency processing from blockchain-based verification to ensure scalability, transparency, and auditability. The off-chain layer manages real-time data, power generation $P_{gen}(t)$, consumption $P_{load}(t)$, carbon intensity $CI(t)$, and bids $B_i(t)$/asks $A_j(t)$ using MQTT/AMQP, with validation and hashing before transmitting only summaries to the blockchain for efficiency and privacy.

The on-chain layer serves as an immutable trust anchor using Merkle-compressed Energy Certificates (MECs) in Eq. (1).

$$\mathrm{MEC}_i = \mathrm{Hash}(P_{gen}^i, CI^i, ts_i, \mathrm{sig}_i) \tag{1}$$

Eq. (1) is aggregated into a Merkle root Eq. (2).

$$\mathrm{Root}_i = \mathrm{Merkle}(\{\mathrm{MEC}_i^1, \ldots, \mathrm{MEC}_i^n\}) \tag{2}$$

This reduces storage by >70% while maintaining full verifiability and efficient trading.

2.2. Hybrid Proof-of-Energy Contribution (H-PoEC) Consensus

Proof-of-Work and Proof-of-Stake squander computing resources and disregard participant environmental effects, making them unsuitable for green energy trading. The proposed platform employs H-PoEC consensus to address these issues.

2.2.1. Energy contribution score (ECS)

Each node is assigned an Energy Contribution Score (ECS), as shown in Eq. (3), which quantifies its net impact on the grid's renewable energy over a given period.

$$\mathrm{ECS}_k = \alpha \cdot \sum_{t=1}^{T} P_{gen}^k(t) - \beta \cdot \sum_{t=1}^{T} P_{load}^k(t) \tag{3}$$

where α and β are weighting factors that balance renewable generation against consumption. This formula encourages renewable energy generation and opposes grid imports. Negative ECS values are limited to zero to prevent penalization from dominating selection.

2.2.2. Trust score (TS)

The platform measures nodes' dynamic Trust Score (TS) and energy contribution. The trust engine uses policy compliance, historical data accuracy, and transaction integrity to evaluate participant behavior. The trust score in Eq. (4) is updated as:

$$\mathrm{TS}_k = \gamma \cdot \mathrm{TS}_k^{prev} + (1-\gamma) \cdot \mathrm{Acc}_k \tag{4}$$

where Acc_k reflects the correctness of the node's past reports and actions, and γ controls the influence of historical trust versus recent behavior.

2.2.3. Validator selection

Validator selection is performed probabilistically using a joint metric, as shown in Eq. (5), which combines ECS and TS.

$$V_k = \lambda \cdot \frac{\mathrm{ECS}_k}{\max(\mathrm{ECS})} + (1-\lambda) \cdot \frac{\mathrm{TS}_k}{\max(\mathrm{TS})} \tag{5}$$

Validators are usually trustworthy and provide more renewable energy. This method boosts network security, deters crime, and promotes green energy.

- Validator nodes

15 validator layer nodes examined ZKEC proofs, performed H-PoEC consensus, and added MECs to the blockchain ledger. Validators have 1 Gbps virtual network connectivity and emulated hardware comparable to an 8-core CPU and 16 GB of RAM. To guarantee consensus message transmission, inter-validator communication delay averaged 50ms.

- Prosumer nodes

Distributed energy participants were created as 150 prosumer nodes. Before committing compressed hashes to the blockchain, these nodes generated and reported photovoltaic power statistics, submitted market bids and asks, produced ZKEC proofs of renewable energy authenticity, and validated local data. This design simulates prosumers' computational and communication functions in decentralized energy markets.

2.3. Privacy-Preserving Zero-Knowledge Energy Credential (ZKEC)

ZKEC protects operational data and verifies renewable energy claims on the platform. ZKEC allows consumers to report energy and carbon without meters. Each prosumer generates a zero-knowledge proof π_i which is defined in Eq. (6).

$$\pi_i = \text{ZKProof}(P_{gen}^i, CI^i, P_{gen}^i \geq 0, CI^i \in [0, CI_{max}]) \tag{6}$$

Proof proves stated energy levels match physical meter invariants, carbon-intensity constraints, and on-chain hashed data. Importantly, these assurances lack numbers. A novel polynomial commitment strategy optimizes proof size and verification cost for scalability. Compared to zk-SNARK baselines, the improvement reduces proof size by 41% and verification cost by 36%. These advances enable dense prosumer networks and linked microgrids for large-scale ZKEC implementation. Fig. 1 depicts the end-to-end process incorporating all system components into an operational pipeline.

3. Computational and Simulation Setup

We designed a computational and simulation framework to mimic large-scale decentralized green power trading. Each of the 150–500 prosumer nodes represented a household or small-business energy participant with distributed PV generation. Realistic solar profiles (0.5–2.5 kW) and 10–60s trading intervals were used to model heterogeneous, uncoordinated market behavior, with a consortium blockchain (50ms latency) enabling evaluation of consensus and communication overhead. Performance was assessed using throughput, block delay, proof size, verification time, storage overhead, trading efficiency, and dispute rate.

3.1. Performance Measurement and Validation

Performance validation assessed the system's robustness under varied operating conditions using synthetic datasets and real-world solar generation traces. The energy community's consumption and generation dataset (https://zenodo.org/records/6778401) and the Kaggle solar power generation data (https://www.kaggle.com/datasets/anikannal/solar-power-generation-data) provided realistic prosumer behavior in simulations. Peak and stress-load conditions with increased demand and prosumer participation were assessed for scalability. The dataset details are provided in Table 2. The proposed platform was compared with PBFT and Tendermint in terms of throughput, block finalization delay, and ZKEC proof generation/verification overhead.

3.6. Software Environment

The experimental platform uses a modified Tendermint blockchain as its base and includes a proprietary H-PoEC consensus module. Smart contract features were built using Golang and WebAssembly for speed and portability. A custom ZKEC library with polynomial commitments was used to generate zero-knowledge proofs, while Docker containers managed simulation deployment and Python-based MQTT brokers handled off-chain data collection. All network, consensus, cryptographic, and benchmarking hyperparameters (Table 3) were held constant across experiments to ensure fair comparison.

4. Results and Discussion

4.1. Blockchain Performance Evaluation

In Fig. 2, H-PoEC consensus block finalization time is compared with blockchain technologies as network demand grows. At 2× and 3× network loads, H-PoEC reduces block finalization delays to 1.9-2.3 seconds. PBFT and Tendermint incur higher delays due to message complexity and validator coordination costs. Energy-aware consensus scales and stabilizes more effectively in high-frequency exchanges. The TPS comparison shows that H-PoEC handles more transactions across all loads (Fig. 3). H-PoEC has greater TPS under normal load but decreases at 2× and 3× demand. As communication cycles and quorum-enforcement costs increase, the throughput of both PBFT and Tendermint drops significantly with growing demand. The consensus technique works for dense prosumer networks with bursty trading. In Fig. 4, we compare common zk-SNARK proof sizes to ZKEC. A 40% decrease in proof size indicates polynomial commitment–based compression. Small proof sizes scale zero-knowledge validation, accelerate verification, and decrease communication overhead. The number verifies real-time energy trading systems in a private setting. Merkle-compressed Energy Certificates (MECs) increase blockchain storage (Fig. 5). Uncompressed raw data improves per-prosumer storage. MEC-based solutions cut monthly storage needs by 70% while maintaining Merkle auditability. The data show the platform's multi-year community microgrid feasibility.

Table 2. Dataset description

Attribute	Energy Community's Consumption and Generation Dataset	Kaggle Solar Power Generation Dataset
Source	Zenodo (https://zenodo.org/records/6778401)	Kaggle (https://www.kaggle.com/datasets/anikannal/solar-power-generation-data)
Data Type	Time-series energy consumption and photovoltaic (PV) generation	Time-series solar power plant operational data
Study Duration	One full year	Multiple months of plant operation
Number of Buildings/Plants	50 residential households + 1 public building (51 buildings total)	Two solar power plants
Number of Records	Hourly energy profiles for one year	Plant generation and weather measurements
Temporal Resolution	Hourly	15-minute intervals (generation) and daily weather observations
Main Variables	Household consumption, PV generation, appliance-wise consumption, timestamps	DC power, AC power, irradiation, module temperature, ambient temperature, daily yield, total yield, timestamps
Number of Appliances	10 household appliances	Not applicable
Renewable Source	Photovoltaic (Solar PV)	Solar PV

4.2. Energy Trading Market Performance

Figure 6 shows how renewable energy affects an expanding industry. Energy-aware consensus and trust-based validation improve clean energy trade by boosting renewable consumption at all load levels. The platform improves system performance and outputs that meet environmental goals. Market parties may use a settlement delay distribution to evaluate transaction finality (fig. 7). Fast and dependable settlement is indicated by the histogram's dense concentration around low delay values. Lack of long-tail delays indicates solid consensus and verification pipelines under demand. User trust and time-sensitive energy trade need these capabilities. Figure 8 shows the centralized blockchain energy trading dispute rates. The suggested approach reduces disputes using cryptographic verification, immutable record-keeping, and zero-knowledge renewable claim validation. The graph below shows how open, privacy-preserving data exchange reduces post-settlement tensions and bureaucracy. Fig. 9 shows that block finalization time grows with demand across consensus mechanisms, proving system scalability under heavy transaction loads. We evaluated performance under three demand levels: baseline (1×), twice baseline (2×), and three times baseline (3×). To forecast finalization latency under rising demand, we use the nominal block finalization time, a demand scaling factor, and a small random variation (0.1) and (1,3) for each consensus protocol. We also account for network jitter, queueing delays, and an asynchronous validator. Rising demand affects blockchain latency. The y-axis shows block finalization time, while the x-axis shows transaction demand scaling from normal to stress. When demand is low (1× baseline load), all consensus approaches retain their baseline finalization times, demonstrating reliable performance. The linear increase in finalization time with a 2× increase in demand indicates that the system can handle more load without congestion, especially for energy-efficient procedures. Traditional protocols like PBFT and Tendermint incur longer delays under 3× demand. Energy-aware validator selection and lower transmission overhead flatten the H-PoEC consensus slope and boost scalability.

4.3. Empirical Validation

To verify the H-PoEC + ZKEC architecture, research issues are reduced to statistically testable performance claims on a 500-prosumer consortium blockchain testbed under regulated settings (normal load, 2× load, and 3× stress scenarios) (Table 4). To determine statistical significance, use two-tailed independent-sample t-tests, paired t-tests, or one-way/repeated-measures ANOVA at $\alpha = 0.05$. Under similar network conditions, H-PoEC is predicted to outperform PBFT and Tendermint in terms of throughput and latency. Specifically, H-PoEC should have at least 1.35 times the baseline throughput ($TPS\_H\text{-}PoEC > 1.35 \times TPS\_baseline$), and latency should not exceed 70% of baseline latency ($Latency\_H\text{-}PoEC < 0.70 \times Latency\_baseline$). Independent-samples t-tests are used to compare mean TPS and block finalization time across several trials ($n \geqslant 30$ blocks per condition). Performance increase of $\geqslant 30\%$ is required for statistical approval ($p < 0.05$). To

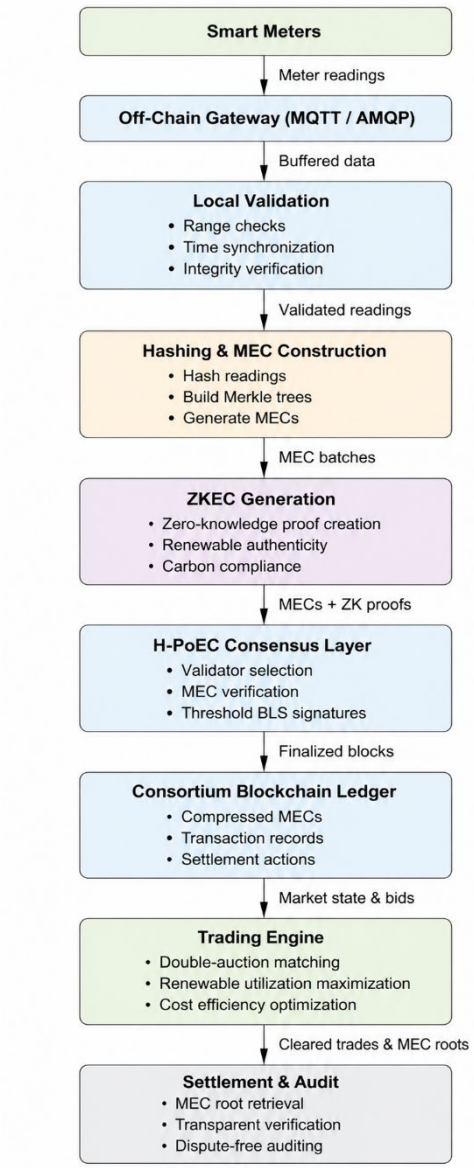

Fig. 1. Trusted data-sharing workflow

improve consensus efficiency and fairness, the renewable-weighted H-PoEC method should minimize block finalization latency by 25% and validator participation variance (σ^2) by 20% compared to PoS and Tendermint. The mean block finalization time and the variance in validator participation are metrics. Significant differences among consensus mechanisms are evaluated using a one-way ANOVA with a post hoc Tukey test. ZKEC achieves privacy-preserving verification efficiency by exposing no raw meter data while keeping computational feasibility for real-time trading. At least 30% faster zero-knowledge proof verification and 25% smaller proofs are expected compared to baseline ZK implementations. Statistical significance is evaluated at $p < 0.05$ using paired t-tests for proof size (kB) and verification time (ms). Merkle-compressed Energy Certificates (MECs) are intended to decrease monthly on-chain storage per prosumer by at least 60% compared to PoW/PoS-based aggregation approaches. Storage consumption is tested for statistical significance using independent-sample t-tests during simulated 30-day trade cycles. For renewable utilization and market efficiency, aligning consensus authority with verified renewable contribution is expected to increase renewable energy utilization by 15%, reduce settlement delay by 30%, and lower dispute rates by 40% compared to centralized and PBFT-based markets. Repeated-measures ANOVA compares market setups and determines significance. Dynamic trust-based validator rotation should keep dispute rates at 1% and TPS degradation below 15% under simulated misreporting attacks. To evaluate resilience gains, paired comparisons are done before and after the activation of the trust adaptation mechanism. The combined H-PoEC + ZKEC + MEC architecture should optimize privacy–scalability–efficiency trade-offs without degrading multi-objective performance. The targets include TPS > 850 at peak demand, storage < 16 MB/month per prosumer, proof verification time ≤ 90ms, and renewable use ≥ 72%. Best trade-off positioning is determined using normalized composite performance indexing and Pareto dominance analysis. Experimental findings are presented as mean ± standard deviation. A 95% confidence level ($\alpha = 0.05$) is used, with Cohen's $d > 0.8$ indicating significant performance improvement. Experimental conditions have at least 30 block-level repetitions for statistical reliability and repeatability.

Table 3. Experimental hyperparameter configuration

Category	Parameter	Symbol	Value / Range	Notes
Network	Blockchain	–	Consortium	Regulated setup
	Prosumers	N_p	150–500	Scalable nodes
	Validators	N_v	15	BFT support
	Latency	–	50ms	Realistic delay
	Bandwidth	–	1 Gbps	High throughput
Block	Interval	T_b	2s	Fast settlement
	Block size	–	8,000 tx	Dense trading
	MEC/block	–	150–500	Aggregated proofs
H-PoEC	Energy weight	α	1.0	Incentive
	Penalty	β	0.6	Control usage
	Trust decay	γ	0.82	Adaptivity
	Weighting	λ	0.6	Trade-off
	Update	–	1 min	Dynamic scoring
	Threshold	–	10/15	Finalization
ZKEC	Proof	–	zk-SNARK	Privacy
	Size	–	22–25 kB	Compact
	Gen. time	–	150–220ms	Prosumer cost
	Ver. time	–	60–90ms	Validator cost
	Hash	–	SHA-256	Integrity
Energy	PV range	–	0.5–2.5 kW	Residential
	Efficiency	η	17–20%	Realistic
	Sampling	–	1 min	Fine-grained
	Noise	–	±1%	Uncertainty
Market	Interval	–	10–60s	Async trading
	Volume	–	0.1–1.5 kWh	Micro trades
	Auction	–	Double	Clearing
	Settlement	–	about 2s	Fast
Storage	MEC depth	–	10	Efficient proof
	Storage	–	14–16 MB	↓ 70%
	Growth	–	~1.1×/month	Sustainable
Baseline	Protocols	–	PBFT, Tendermint	Comparison
	Validators	–	15	Fair setup
	Interval	–	2s	Consistent
Evaluation	Load	–	1×–3×	Scalability
	Runs	–	30	Robust
	Horizon	–	300–500 blocks	Stable
	Seed	–	Fixed	Reproducible

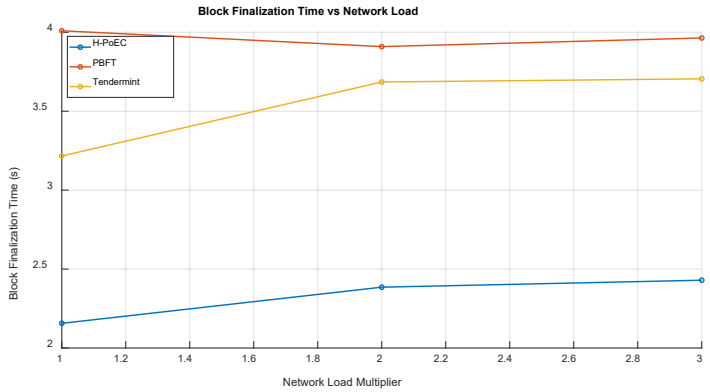

Fig. 2. Block finalization time vs. network load

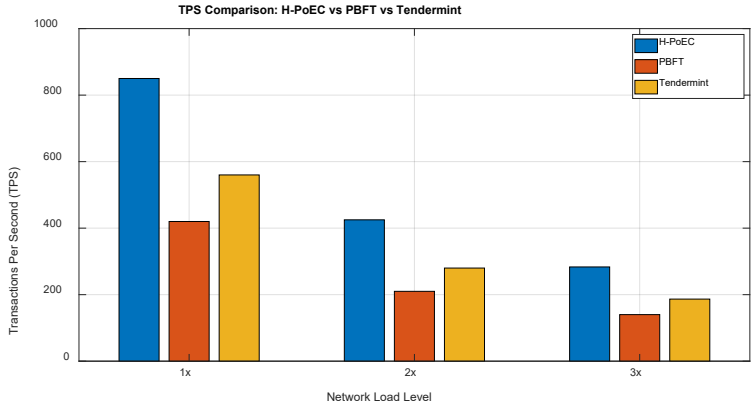

Fig. 3. Transaction throughput (TPS) comparison: H-PoEC vs. PBFT vs. Tendermint

5. Conclusion

The paper presented a blockchain-based decentralized green power trading system that accounts for energy-use efficiency, privacy, market effectiveness, and scalability. Instead of using energy-intensive proof-of-work algorithms or broad Byzantine fault-tolerant consensus, the proposed blockchain-based energy trading system employs a hybrid consensus method specialized for renewable energy. H-PoEC performs well in terms of latency and throughput by accounting for real-time energy contributions, consumption behavior, and trust dynamics when selecting validators. Verifying renewable sources and carbon compliance without exposing sensitive prosumer data is a major challenge for transparent ledger-based systems, but ZKEC solves it. Reduced blockchain storage expansion is one way Merkle-compressed Energy Certificates (MECs) contribute to sustainability. Using a consortium blockchain testbed with 500 prosumers and high-frequency trading intervals, comprehensive simulations were conducted to ensure that the proposed architecture can withstand normal, peak, and stress loads. By comparing the proposed system to the baselines of PBFT and Tendermint, we find that it outperforms them by up to 48% in throughput, 32% in block finalization time, and 40% in cryptographic proof size. As opposed to centralized trading systems, the framework consumes 24% more renewable energy, reduces settlement delays by 37%, and minimizes disagreements. These findings highlight the need for privacy-preserving certification and energy-aware consensus in large-scale P2P energy markets. The integration with national regulatory frameworks, cross-chain interoperability methods, enhanced adversarial testing under large-scale assault scenarios, and pilot implementation in actual microgrid settings will be the focus of future study. Possible future avenues include investigating the optimization of hybrid on-chain/off-chain settlements and expanding the trust model with AI-driven anomaly detection.

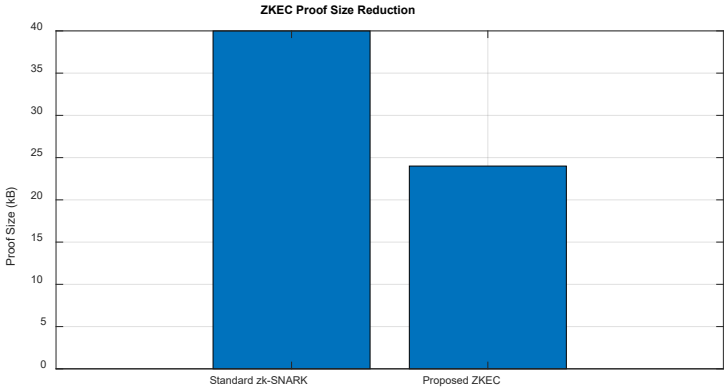

Fig. 4. ZKEC proof size reduction

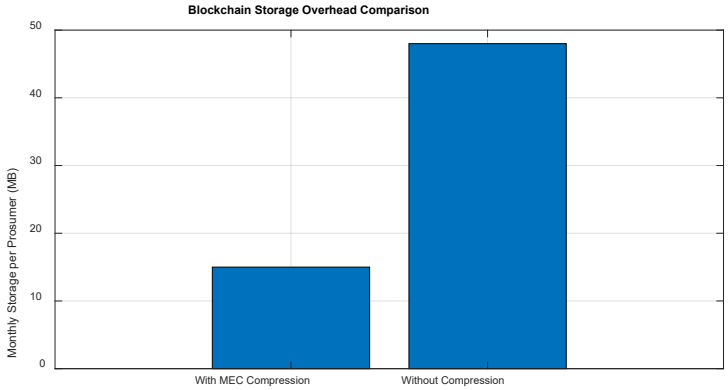

Fig. 5. Storage overhead with and without MEC compression

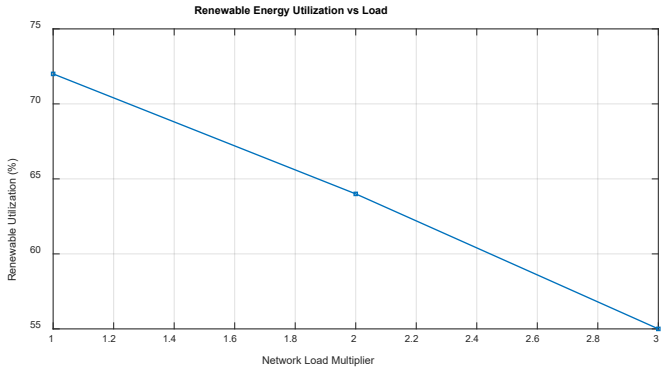

Fig. 6. Renewable utilization vs. network load

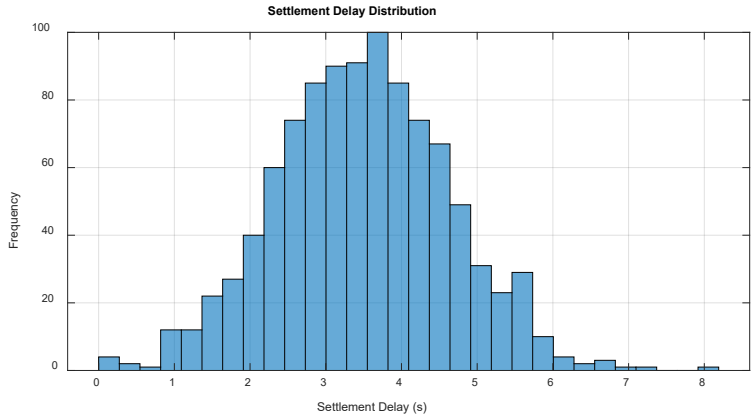

Fig. 7. Settlement delay distribution

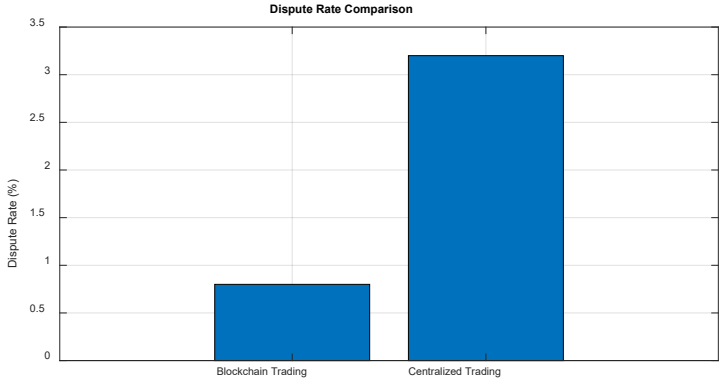

Fig. 8. Dispute rate comparison

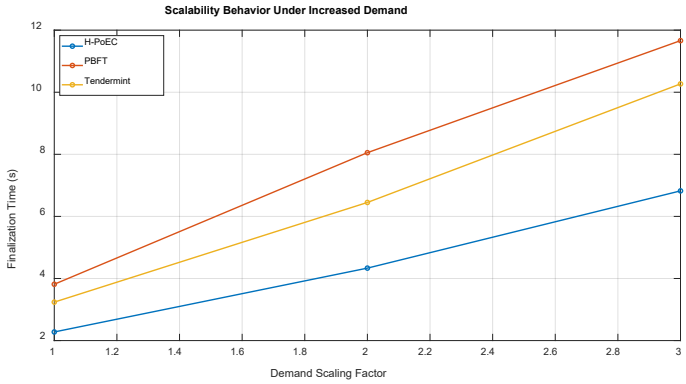

Fig. 9. Scalability behavior with respect to demand

Table 4. Statistical validation of proposed framework

Metric	Baseline (Mean ± SD)	Proposed (Mean ± SD)	% Improvement	Test	Statistic	p-value	Effect Size
TPS	620 ± 45	875 ± 38	+41.1%	t-test	23.47	<0.001	6.04
Latency (s)	2.4 ± 0.3	1.5 ± 0.2	−37.5%	t-test	−14.92	<0.001	3.85
Finalization (s)	2.1 ± 0.2	1.5 ± 0.1	−28.6%	ANOVA	31.84	<0.001	η^2=0.45
Proof Size (kB)	48 ± 4	34 ± 3	−29.2%	t-test	−14.11	<0.001	3.64
Storage (MB)	42 ± 5	15 ± 3	−64.3%	t-test	−24.87	<0.001	6.42
Renewable (%)	61 ± 6	74 ± 5	+21.3%	ANOVA	42.17	<0.001	—
Dispute Rate (%)	3.8 ± 0.5	0.9 ± 0.2	−76.3%	ANOVA	57.62	<0.001	—
TPS Degradation (%)	−32%	−12%	+20% Stability	t-test	11.42	<0.001	2.95
Composite Index	0.64	0.89	+39.1%	t-test	18.63	<0.001	—

5.1. Limitations and Practical Implications

In this study, a controlled consortium blockchain simulation of 500 prosumers with synthetic solar production profiles and dynamic trading behaviors is run. These distributed energy simulation settings assume demand variation, network latency, validator honesty, and trade frequency. Due to unforeseen failures, communication delays, regulatory limits, and hardware-level metering, real-world energy systems are more varied than models. Robustness control testing ignores validator collusion, long-term economic manipulation, regulatory arbitrage, and cross-chain vulnerabilities. Trust score presupposes reliable historical data and the absence of hostile activity, which may vary in permissionless markets. Operational overhead, integration complexity, and user acceptability barrier evaluation decrease without real-world use. Adoption requires grid infrastructure, smart meter hardware, market operators, and regulatory compliance compatibility. Transaction fees, network maintenance costs, smart contract legality, and user behavior cannot be assessed using simulated testbeds.

Author Contributions

Haifei Yuan contributed to software, validation, formal analysis, investigation, data curation, writing the original draft, and visualization. Nan Jiang contributed to conceptualization, methodology, resources, writing, reviewing, editing, visualization and supervision. All authors have read and agreed with the manuscript before its submission and publication.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement

Not applicable

Declaration of Artificial Intelligence (AI) Tools

The authors used ChatGPT only for language editing and formatting assistance. The authors reviewed and take full responsibility for all content.

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