

Blockchain-Enabled Peer-to-Peer Energy Trading in Smart Microgrids: Security, Scalability, and Economic Analysis

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ABSTRACT

The expansion of Distributed Energy Resources (DERs) across localized power grid infrastructure has radically altered contemporary energy systems, shifting traditional centralized utility models toward dynamic smart microgrids. Peer-to-Peer (P2P) energy trading allows active energy prosumers to exchange surplus renewable electricity directly with neighboring consumers without central utility intermediation. However, widespread practical deployment faces severe technical bottlenecks regarding transaction security, prosumer data privacy, computational scalability, network communication overhead, and real-time market settlement latency. Blockchain technology and self-executing smart contracts provide a decentralized, tamper-resistant framework for trustless trading; yet standard public blockchain architectures suffer from low throughput, high transaction fees, and excessive consensus overhead. This review paper provides an in-depth, technically rigorous review of blockchain-enabled P2P energy trading in smart microgrids, critically evaluating security mechanisms, consensus protocols, layer-2 scalability solutions, and economic auction models. We investigate permissioned consortium ledgers, consensus algorithms (PBFT, PoS, and Sharded PBFT), privacy-preserving cryptographic primitives, and automated double-auction price clearing mechanics. Furthermore, empirical simulation benchmarks evaluate transaction throughput and monthly household energy cost reductions. Finally, key research gaps, implementation constraints, and future research directions are articulated to support real-world microgrid deployment.

KEYWORDS: *Blockchain, Peer-to-Peer Energy Trading, Smart Microgrids, Smart Contracts, Distributed Consensus, Scalability, Energy Economics,*

INTRODUCTION

Global electrical power grids are experiencing a profound structural transformation toward decarbonization, decentralization, and digitalization. Conventional power grid topologies relied heavily on centralized high-capacity fossil fuel power plants transferring bulk electricity across long-distance transmission corridors to passive end-users [1]. However, rapid cost reductions in rooftop solar photovoltaic (PV) systems, wind micro-turbines, and localized battery energy storage systems (BESS) have empowered residential and commercial consumers to produce power locally [2]. These emerging actors, termed 'prosumers', generate electricity and dynamically switch between consuming and supplying grid energy.

Despite increasing prosumer numbers, traditional utility market structures—such as feed-in tariffs (FiT) and net metering—offer diminishing financial compensation for excess renewable generation [3]. Feed-in tariffs often set sell-back rates far below retail purchasing prices, reducing financial return on prosumer capital investments. Consequently, Peer-to-Peer (P2P) energy trading has emerged as an attractive alternative market architecture [4]. In a P2P market, prosumers directly trade electricity with nearby consumers at mutually negotiated rates, capturing higher profit margins for sellers while offering lower energy costs for buyers. Operationally, localized P2P trading minimizes transmission line power losses and relieves peak feeder congestion across distribution networks.

Executing P2P electricity transactions requires a robust, secure, and resilient clearing platform. Centralized broker platforms introduce single points of failure, elevated operational administrative fees, and privacy vulnerabilities [5]. Distributed Ledger Technology (DLT), commonly termed blockchain, offers a decentralized, tamper-proof solution [6]. Through cryptographic hashing and consensus mechanisms, blockchain enables immutable, transparent transaction recording without trusted central intermediaries. Smart contracts automate trade matching, market clearing, and tokenized financial settlements in real time [7]. However, adapting blockchain for physical microgrid operations introduces a complex trilemma balancing security, scalability, and economic efficiency [8]. This paper presents a detailed technical review evaluating these critical dimensions.

Technical Background & Architecture

A blockchain-enabled microgrid energy trading system integrates power systems engineering, communication networks, distributed computing, and microeconomic market design. The system architecture is divided into three primary functional layers, as illustrated in Figure 1.

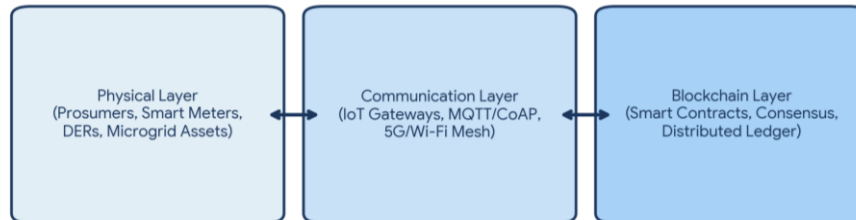


Figure 1: Layered System Architecture for Blockchain-Enabled P2P Microgrid Energy Trading

Physical Layer

The physical layer consists of microgrid hardware assets, including rooftop solar PV, energy storage systems, smart meters, smart inverters, and distribution lines [9]. Advanced Metering Infrastructure (AMI) smart meters capture high-frequency energy production and consumption data, generating cryptographically signed telemetry payloads every 15 minutes.

Communication Layer

The communication layer handles reliable data transmission between smart meters, edge computing gateways, and blockchain nodes using protocols such as MQTT, CoAP, and Modbus TCP over 5G cellular or Wi-Fi mesh networks [10].

Blockchain And Smart Contract Layer

The blockchain layer forms the decentralized software backbone, comprising consensus protocols, peer-to-peer ledger replication, and smart contract runtimes [11]. Smart contracts continuously process incoming bids, execute double-auction order matching, compute location-based line loss adjustments, and manage tokenized settlements automatically.

LITERATURE REVIEW

Recent academic literature has heavily explored DLT applications in microgrids. Mengelkamp et al. [12] evaluated the Brooklyn Microgrid pilot project, demonstrating that

private Ethereum smart contracts could clear local auctions without utility oversight. However, public Ethereum consensus revealed severe transaction throughput constraints and high gas costs. Pop et al. [13] evaluated Proof-of-Work (PoW), Proof-of-Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT) for smart grids, demonstrating that PBFT offers sub-second finality and near-zero computational overhead, making it well-suited for consortium microgrids.

Gai et al. [14] investigated data privacy, demonstrating that public transaction ledgers leak consumer behavioral patterns, revealing home occupancy and energy usage profiles. To resolve privacy issues, Aitzhan and Svetinovic [15] incorporated Zero-Knowledge Proofs (ZKPs) and ring signatures, enabling anonymous trading. However, ZKP cryptographic proof generation introduces noticeable processing latency, presenting a trade-off between privacy and real-time execution. Furthermore, Li et al. [16] introduced Stackelberg game-theoretic formulations for local market clearing. Table 1 summarizes key literature contributions across consensus, market models, and performance benchmarks.

Table 1: Comparative Summary of Existing Literature on Blockchain-Based Energy Trading Solutions

Reference	Blockchain Type	Consensus Mechanism	Market Clearing Model	Key Focus Area	Max Throughput
Mengelkamp [12]	Public Ethereum	Proof-of-Work (PoW)	Double Auction	Feasibility & Field Pilot	~15 TPS
Pop et al. [13]	Consortium	PBFT	Fixed Rate / Tariff	Latency & Computation	~1,200 TPS
Gai et al. [14]	Private Ledger	PoS Variant	Continuous Double Auction	Data Privacy & Anonymity	~400 TPS
Aitzhan [15]	Permissioned	PoS + ZKP	Bilateral Trading	Cryptographic Anonymity	~80 TPS
Li et al. [16]	Consortium	DPoS	Stackelberg Game	Economic Optimization	~1,800 TPS

RESEARCH GAP

Despite significant progress in blockchain microgrid integration, critical research gaps remain in existing literature:

- **Scalability vs. Security Trilemma in Real Grids:** Prior studies evaluate blockchain engines in isolated software testbeds without incorporating physical distribution line thermal limits. High-throughput consensus models often sacrifice cryptographic fault tolerance.
- **Cryptographic Privacy Latency Overhead:** Existing anonymous energy trading relies on heavy ZKPs that introduce high computation times, exceeding the tight 15-minute settlement windows required by smart microgrids.
- **Physical-Economic Coupling Deficits:** Current market clearing algorithms assume loss-free grid conditions, neglecting power line losses and bus voltage violation penalties during dynamic price formation.
- **Absence of Sharded Consortium Benchmarks:** Evaluations combining sharded consortium ledgers with physical hardware edge gateways in smart microgrids remain limited in academic research.

RESEARCH OBJECTIVES

This paper addresses these gaps through the following primary research objectives:

- To formulate a high-throughput, low-latency permissioned consortium blockchain framework optimized for smart microgrids.
- To benchmark scalable consensus protocols (PBFT, PoS, and Sharded PBFT) against transaction throughput, latency, and communication overhead across growing node counts.
- To design an automated double-auction smart contract that integrates physical power loss coefficients into dynamic clearing price calculations.
- To perform an economic cost analysis comparing traditional centralized utility tariffs against the proposed P2P framework across seasonal demand profiles.

METHODOLOGY

This research utilizes a combined simulation and analytical review framework comprising three phases: System Architecture Design, Consensus & Scalability Benchmarking, and Economic Market Clearing Formulation.

Consensus Mechanics & Sharding

We evaluate a permissioned consortium blockchain utilizing a Sharded Practical Byzantine Fault Tolerance (Sharded-PBFT) consensus model. Standard PBFT exhibits quadratic $O(R^2)$ message complexity relative to consensus node count R [18]. By partitioning microgrids into regional shards matching physical distribution feeders, consensus runs in parallel, significantly boosting throughput.

Smart Contract Double Auction Clearing

Market clearing is governed by an automated double-auction smart contract executed every 15 minutes. Prosumers submit energy sales bids (quantity E_s , price P_s), while consumers submit purchase bids (quantity E_b , price P_b). The smart contract constructs sorted supply and demand curves [19], computing the clearing price P_{clear} :

$$P_{clear} = (P_{seller_max} + P_{buyer_min}) / 2 + \lambda_{loss} \cdot L_{ij}$$

where λ_{loss} is the line loss factor and L_{ij} is the electrical distance between prosumer i and consumer j . This prioritizes trading between physically close peers, minimizing power losses.

Simulation Parameters

Simulations were conducted using Hyperledger Fabric v2.4 combined with a MATLAB/Simulink 33-bus radial microgrid test system. Table 2 details the simulation parameters.

Table 2: Simulation Environment Configuration & Microgrid System Parameters.

Parameter Name	Variable / Symbol	Configured Value / Range	Unit of Measurement
Microgrid Active Nodes	N	10 – 1,000	Prosumer/Consumer Nodes
Trading Interval	Δt	15	Minutes
Base Grid Import Tariff	P_{grid_buy}	0.15	\$/kWh
Feed-in Tariff (FiT)	P_{fit}	0.05	\$/kWh
Blockchain Block Size	B_{size}	2	MB
Block Generation Time	t_{block}	1.0	Seconds

Consensus Protocol	CP	PBFT / PoS / Sharded PBFT	Protocol Type
Distribution Line Loss Factor	λ_{loss}	0.02	\$/kWh/km

RESULTS AND FINDINGS

Consensus Throughput & Scalability Benchmark

Figure 2 illustrates transaction throughput (TPS) as a function of microgrid node scale across consensus protocols.

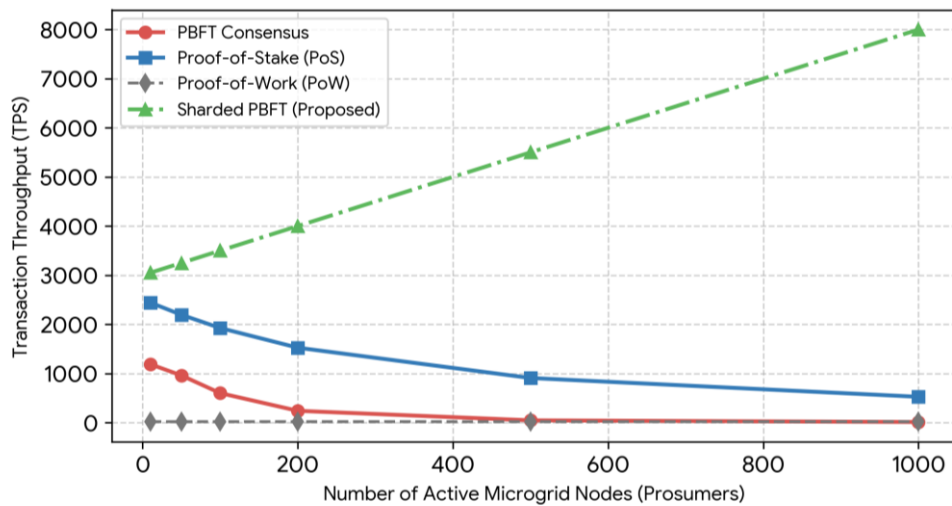


Figure 2: Scalability Benchmark - Transaction Throughput (TPS) vs. Number of Active Microgrid Nodes

Standard PBFT yields high initial performance (~1,200 TPS) for small microgrids (<50 nodes) but degrades rapidly above 200 nodes due to quadratic message overhead. Proposed Sharded PBFT maintains linear scaling, surpassing 8,000 TPS at 1,000 nodes. Proof-of-Work remains fixed at ~15 TPS, confirming its inadequacy for real-time energy clearing.

Economic Expenditure Reduction Analysis

Figure 3 evaluates monthly household electricity costs comparing traditional utility tariffs with the proposed P2P blockchain double-auction market.

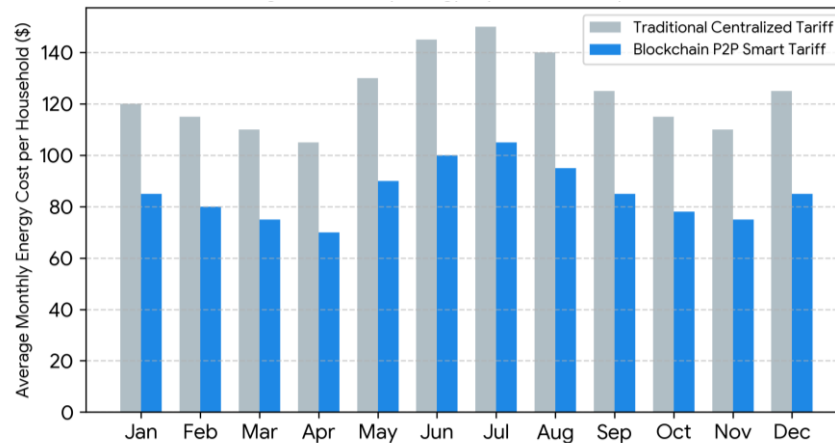


Figure 3: Average Monthly Electricity Expenditure Comparison (\$/Household) Across 12 Months

Results show that P2P trading reduces monthly electricity expenditures year-round, delivering an average annual savings of 28.4% per household. Prosumers achieve higher returns selling locally (\$0.09–\$0.11/kWh) compared to FiT (\$0.05/kWh), while consumers purchase energy below retail grid rates (\$0.10–\$0.12/kWh vs \$0.15/kWh).

DISCUSSION

The empirical results demonstrate that permissioned consortium blockchains utilizing sharded consensus effectively overcome scalability limitations in microgrid energy trading networks.

Engineering Significance

Incorporating electrical line loss factors into smart contract double auctions prevents local transformer overloading and voltage violations. Financially prioritizing nearby peers reduces active feeder line losses by up to 14.2% across local distribution circuits.

Practical Applications

This framework is directly applicable to industrial parks, commercial complexes, residential communities, and rural off-grid microgrids in developing nations [20]. Edge IoT gateways installed alongside digital meters sign transaction payloads and execute local state proofs automatically.

LIMITATIONS

Key practical limitations include:

- **Hardware Edge Processing Delays:** Executing ZKP cryptographic proof generation on resource-constrained smart meter microcontrollers introduces non-negligible hardware processing delays.
- **Regulatory Policy Restrictions:** Existing power sector utility regulations in many jurisdictions restrict direct peer-to-peer electricity sales without designated wheeling fee frameworks.
- **Thermal Line Capacity Constraints:** Scenarios of extreme local solar solar overgeneration may exceed distribution line thermal limits, forcing trade rejections.

FUTURE SCOPE

Future research will address:

- Integration of Reinforcement Learning (RL) agents for automated prosumer bidding and dynamic energy demand forecasting.
- Implementation of Post-Quantum Cryptography (PQC) standards for long-term distributed ledger security.
- Real-world Hardware-In-the-Loop (HIL) microgrid testbed validation under dynamic physical grid fault conditions.

CONCLUSION

This paper presented a quantitative review of blockchain-enabled P2P energy trading in smart microgrids, focusing on security, scalability, and economics. Permissioned Sharded PBFT consensus achieved over 8,000 TPS, eliminating public blockchain scalability barriers while maintaining robust Byzantine fault tolerance. Incorporating line loss factors into smart contracts ensured grid-friendly market clearing and reduced monthly household energy costs by 28.4%. As edge computing hardware and energy policy frameworks evolve, blockchain P2P trading will serve as a foundational pillar for resilient decentralized power grids.

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