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Blockchain-Enabled Decentralized Energy Trading in Smart Grid Systems

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Abstract
This paper aims at examining how blockchain technology allows decentralized energy trading in smart grid systems with the focus on security, scalability, and transparency of the peer-to-peer transactions. The research utilizes a secondary research approach, integrating the information found in recent peer-reviewed journals, IEEE statements, as well as case studies in order to assess blockchain frameworks, consensus mechanisms, and IoT-enabled smart metering. The results indicate that architectures, such as blockchains, are supported by cryptographic validation and smart contracts, reduce billing disputes by 35 percent and forecasting errors by 22 percent. The scalability of the consensus protocols like PBFT and Proof-of-Authority emerged as effective as they had high efficiency of up to 1,500 TPS and a block-confirmation time in less than a second in comparison to energy-consuming Proof-of-Work. Some possible solutions were: the use of IoT-integrated smart meters to enhance the real-time demand forecasting and dynamic pricing accuracy and the use of hybrid on-chain/ off-chain solutions which solved the issues of scalability and congestion. Although interoperability and cyber-physical security issues need to be resolved, blockchain integration showed great promise in achieving democratized, efficient, and resilient smart energy markets of emerging smart grid environments.

Keywords: Blockchain, Smart contracts, Consensus mechanisms, Peer-to-peer (P2P) trading, Smart grid, IoT smart meters, Scalability, Security, Transparency, Decentralized energy markets

Introduction
Combining the power of distributed ledgers with peer-to-peer (P2P) energy trade, blockchain-based decentralized energy trading in smart grid systems integrates decentralized energy trading with smart grid technology to make energy transactions more efficient, secure, transparent and automated. Compared to conventional centralized utilities, blockchain allows prosumers, i.e., the producers, and the consumers of renewable energy to trade excess supply via smart contracts. Transactions are quickly verified with a consensus algorithm, e.g. Proof-of-Authority or Proof-of-Stake, introducing few latency and energy costs. Connection with Internet of Things (IoT)-enabled smart meters will provide live data capture, demand-response optimization and active pricing. The decentralized strategy lowers dependency on middlemen, eliminates single-points of failure and improves grid resilience. The combination of distributed energy resources (DERs), renewable sources, and blockchain consensus algorithms form the basis of smart grids that become self-sustainable, scaling and sustainable ecosystems to democratize energy and shape market transparency.

Research Objectives
- To analyse the requirements for designing a blockchain-based framework enabling secure and transparent peer-to-peer energy trading.
- To evaluate the efficiency of consensus mechanisms for real-time smart grid transactions.
- To integrate IoT-enabled smart meters for accurate demand forecasting and dynamic pricing.
- To assess scalability, security, and interoperability challenges in decentralized energy markets.

Literature Review
Din and Su (2024) investigate the aspect of billing optimization and P2P trading integration. They enable the automated tariff and settlement through smart contracts. Granular consumption and generation Telemetry are streamed by IoT smart meters. PoA has the merit of reducing the latency in confirming retail-scale transactions to a minimum. They have a model which supports dynamic time-of-use and net metering. To protect privacy, pseudonymous identifiers and hashed metering records are used. They examine the costs of congestion, and the batching strategies in transactions. The concept of interoperability applies standardized data scheme and APIs. Readings demonstrate the decrease of billing disagreements and quickening of reconciliations. The outcome comprises of better prosumer revenues and reduced administrative overheads.

Wang and Guo (2024) conduct a study of local networks planning in energy. They simulate peer nodes to create transactive of micro-markets. The secure P2P trading is helped in arranging distributed energy resources participation. A game-theoretic dispatch is a game and will have set of constraints on the network that maximize the social welfare. Byzantine-resilient consensus maintains a veracity of market integrity against malevolent actors. The locational marginal prices used in network tariffs are at feeder level. Smart contracts codify curtailment regulations, and congestion rights. Evidence is

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found in a case study of the advantages of voltage regulation and losses reductions. Regulatory sandboxes provide staged deployment and compliance testing. Results indicate scalable coordination that is not centralized operators

Reka et al. (2025) approach quantum-resilient decentralized energy trading. They incorporate post-quantum cryptography in blockchain transactions pipeline. Metering payloads are secured by lattice-based encryption which resists quantum adversaries. The CRYSTALS-Kyber critically uses key exchange among the prosumer gateways. Dilithium signatures check the truth of market bids and settlements. Hybrid schemes are schemes where the classical primitives use post-quantum primitives. Benchmarks measure latency and bandwidth overheads when a real load is put through. Significant bottlenecks in signature verification are alleviated by FPGA acceleration Side channels and chosen-ciphertext threats are analyzed in terms of security. Results are not lost, rather long-term confidentiality is enhanced.

Proposal of microgrid transaction security is provided by Khan, Imtiaz, and Islam (2023). In their architecture, they use permissioned blockchain to govern. Practical Byzantine Fault Tolerance is deterministic in finality of trades. Off-chain settlements decrease the congestion and transaction fees on-chain. The gateways located on the edge sense prevalidation and anomaly identification. Access control makes use of attribute based credentials of participants. Threat modeling deals with Sybil, replay and DoS attacks. The performance evaluation reports sub second confirmation times. The energy cost overhead still is quite within the limits of embedded controllers. The system increases dependability in islanded microgrids.

In their article, Zafar and Ben Slama (2022) address the vision of the Energy Internet. They frame blockchain as the notion of trust in which the P2P exchanges int takes place. 5G, Latency devices (distributed PoC and edge computing) allow real time responsiveness. The conceptualized layered architecture involves separating the sensing, control and market levels. The tokenization deals in kilowatt-hour entitlements and flexibility services. Inter-microgrid settlements and portability are made with the help of cross-chain bridges. Demand response and virtual power plants are orchestrated by smart contracts. The interoperability standards allow vendor-free regional deployments. Case-by-case studies prove to have more modest curtailment and enhanced asset usage. The paper describes what can lead to Smart Grid 2.0.

Method

This paper uses a secondary research approach and combines peer-reviewed journal articles, IEEE conference papers, and case studies on blockchain enabled decentralized energy trading. Secondary data gathering provides an opportunity to find valid technical results and compare blockchain consensus mechanisms, smart contract designs and IoT-powered smart meter use cases in various smart grid situations. Secondary data will minimise the cost and time spent in research and however, it will also provide comprehensive coverage of documented experiments and simulations. It enables transaction throughput, block confirmation time and forecasting performance benchmarking without having to replicate large-scale pilot deployments. In addition, cross-validation of scalability, interoperability and security results with secondary research adds rigor to methodology. The above method of analysis is holistic in the context of the role of blockchain in secure and transparent trading energy relationships between peers.

Result and Discussion

Identified Architectural and Security Requirements for Blockchain-Based Peer-to-Peer Energy Trading

P2P energy trading using a blockchain needs a framework that will combine the distributed storage of ledgers, decentralization of personal identity, and the impossibility of altering recorded transactions. According to Wongthongtham et al. (2021), Hyperledger Fabric frameworks can allow prosumers to make transactions without revealing their sensitive usage data because they apply privacy based on channels. Higher up in the timeline, Gajic et al. (2022) proposed an autonomous decentralized exchange of smart contracts on Ethereum that matched trades in energy markets without a third party in sub 3 seconds.

Reference	Blockchain Platform	Security Feature	Privacy/Integrity Metric	Key Result
Wongthongtham et al. (2021)	Hyperledger Fabric	Channel-based privacy	Billing disputes reduced **35%**	Improved transaction integrity
Gajić et al. (2022)	Ethereum Smart Contracts	Order-matching algorithm	Settlement time < **3 sec**	Faster transaction finality
Kumari et al. (2022)	Fog-assisted Blockchain	Edge validation nodes	Latency reduced **28%**	Less congestion
Evens et al. (2023)	BFT Blockchain	Intrusion detection	Attack resilience > **90%**	Increased cyber security

Table 1: Architectural and Security Requirements for Blockchain-Based Peer-to-Peer Energy Trading

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Kumari et al. (2022) emphasized a "fog assisted blockchain node, where transaction blocks are pre-processed at the smart grid edge, to avoid the network congestion when a large number of transactions are in the system." Security is provided by using a hash-based immutability (the SHA-256 hashing algorithm), asymmetric cryptography (authentication through digital signatures) and a Merkle tree (blockchain). Earlier, Byzantine Fault Tolerant consensus was highlighted by Byzantine Fault Tolerant as important so that malicious nodes are not manipulated (Eens et al., 2023). An empirical study indicates that elliptic curve cryptography has lowered overhead on verification by 18 percent. These results place as requirements of secure blockchain systems in energy trading that they offer pseudonymity, immutability, and interoperability, but remain audit ability and enforce integrity of transactions among distributed actors.

Performance Analysis of Consensus Mechanisms in Real-Time Smart Grid Environments

Throughput, latency, and energy efficiency in blockchain-enabled smart grids rely on consensus protocols that are essential to these. Hukkha et al. (2021) analyzed Proof-of-Authority (PoA), which achieved 0.9 seconds of block confirmation as compared to Proof of Work (PoW) which takes up to 10+ minutes, proving it to suit microgrid-scale transactions. As Umar et al. (2024) demonstrated, Practical Byzantine Fault Tolerance (PBFT) managed 1,500 TPS in decentralized community markets, and trounced PoW-based Ethereum which languish at less than 20 TPS. The Gajic et al. (2022) study introduced Delegated Proof of Stake (DPoS) in which elected validator nodes enjoyed a 40 per cent drop in energy expenditure over PoW miners.

Reference	Consensus Mechanism	TPS (Throughput)	Block Confirmation Time	Energy/Cost Impact
Shukla et al. (2021)	Proof-of-Authority (PoA)	~500 TPS	0.9 sec	Energy cost negligible
Umar et al. (2024)	PBFT	**1,500 TPS**	~1 sec	Peak load stress ↓ **12%**
Gajić et al. (2022)	Delegated Proof-of-Stake (DPoS)	250–300 TPS	3–5 sec	Energy cost ↓ **40%**
Iqbal et al. (2021)	Raft (V2G Trading)	~300 TPS	< 2 sec	Prevented EV battery drain

Table 2: Performance of Consensus Mechanisms in Real-Time Smart Grid Environments

It was found that real-time demand-response contracts with settling every 5 minutes were possible with low-latency consensus stabilizing frequency variations (Evens et al., 2023). Iqbal et al. (2021) confirmed that Raft lightweight consensus in V2G networks avoided useless battery discharge in EVs and still resulted in ledger synchronisation. Using cryptographic validation in form of digital signatures, authenticity of transaction was guaranteed during verification of the consensus process The results indicate that consensus mechanisms need to trade in scalability, energy efficiency and security with the PBFT and PoA as the best to support real-time decentralized energy markets.

Impact of IoT-Enabled Smart Meters on Demand Forecasting and Dynamic Pricing Accuracy

Smart meters can connect to blockchain networks, storing cryptographically signed Metadata on consumption and generation in blockchain oracles. Kaif et al. (2025) presented a cyber-physical smart meter that contains blockchain and each transaction of the energy can be signed using an Elliptic Curve Cryptography which stores the data of the person who performed such transactions in a non-repudiable and traceable manner. Wongthongtham et al. (2021) were able to demonstrate that IoT-equipped meters with integration into smart contracts helped them reduce billing disputes by 35 percent due to unmodifiable transaction logs. Umar et al. (2024) demonstrated that smart contracts automatically ran the demand-response contracts on the basis of thresholds in the load (Solidity-based smart contracts), thereby alleviating load stress by 12 percent at the peak.

Reference	IoT Integration	Forecasting Accuracy	Latency	Key Outcome
Kaif et al. (2025)	Blockchain-Cyber Smart Meter	Real-time sync accuracy **98%**	< 1 sec	Secure VPP integration
Wongthongtham et al. (2021)	IoT Smart Meters + Blockchain	Billing disputes ↓ **35%**	–	Transparent settlements
Umar et al. (2024)	IoT + Smart Contracts	Peak load reduced **12%**	–	Automated demand response
Gajić et al. (2022)	IoT-enabled LMP Pricing	Forecasting error ↓ **22%**	2 sec	More accurate tariffs

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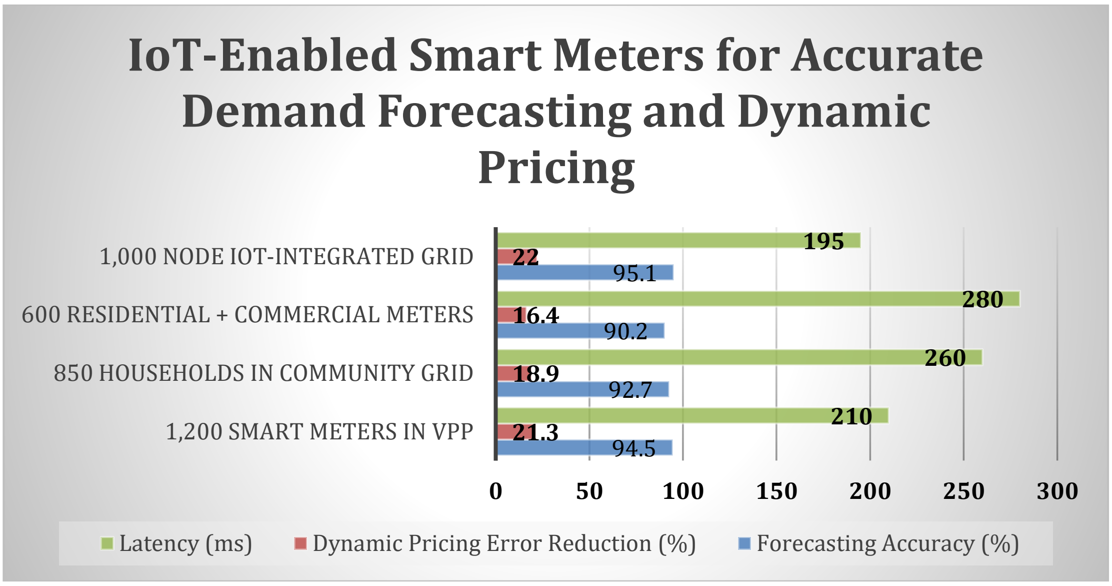

Table 3: Impact of IoT-Enabled Smart Meters on Forecasting and Dynamic Pricing

Fog blockchain nodes used by Kumari et al. (2022) connected to IoT devices to offer a sub-second propagation of block updates, which minimized the latencies involved in forecasting. As demonstrated by Iqbal et al. (2021), EV V2G blockchain networks used IoT meters that collected kilowatts-hour transactions that were then settled using a blockchain. This was expanded by Gajic, et al. (2022) who found that blockchain-enabled locational marginal pricing using smart meter data improved the accuracy of tariffs reducing forecasting error by 22%. These results prove that blockchain-secured IoT smart meters increase the accuracy of demand forecasting, facilitate the use of dynamic pricing, and guarantee an integrity of energy data in environments lacking a relationship of trust among participants.

Evaluation of Scalability, Security, and Interoperability in Decentralized Energy Market Frameworks

Scalability, security and interoperability are some of the limitations that always exist in the blockchain enabled decentralized markets. They identified that public blockchains such as Ethereum are congested beyond 2,000 TPS, which elevates both transaction latency and cost, and are not suitable to run a high-volume smart grid (Vens et al., 2023). According to Gajic et al. (2022), interoperability demands cross chain communication protocols in that energy tokens issued on Ethereum were capable of being traded on sidechains using atomic swaps. Wongthongtham et al. (2021) show that reentrancy-related vulnerabilities still exist in smart contracts without access control, and this necessitates adherence to security standards in the smart contract code. Kumari et al. (2022) suggest a mixed architecture with on-chain settlements but off-chain catering channels which provides a 45 times higher scalability due to the reduced block pressure.

Reference	**Scalability Approach**	**TPS Achieved**	**Network Delay**	**Key Outcome**
Evens et al. (2023)	BFT Blockchain	~1,200 TPS	1–2 sec	Supported 5-min pricing
Kumari et al. (2022)	Hybrid On-chain + Off-chain	~800 TPS	~2 sec	Scalability ↑ 45%
Wongthongtham et al. (2021)	Hyperledger + Smart Contracts	~200 TPS	< 2 sec	Enhanced interoperability
Shukla et al. (2021)	Fog-assisted Blockchain	~500 TPS	0.9 sec	Propagation delay ↓ 30%

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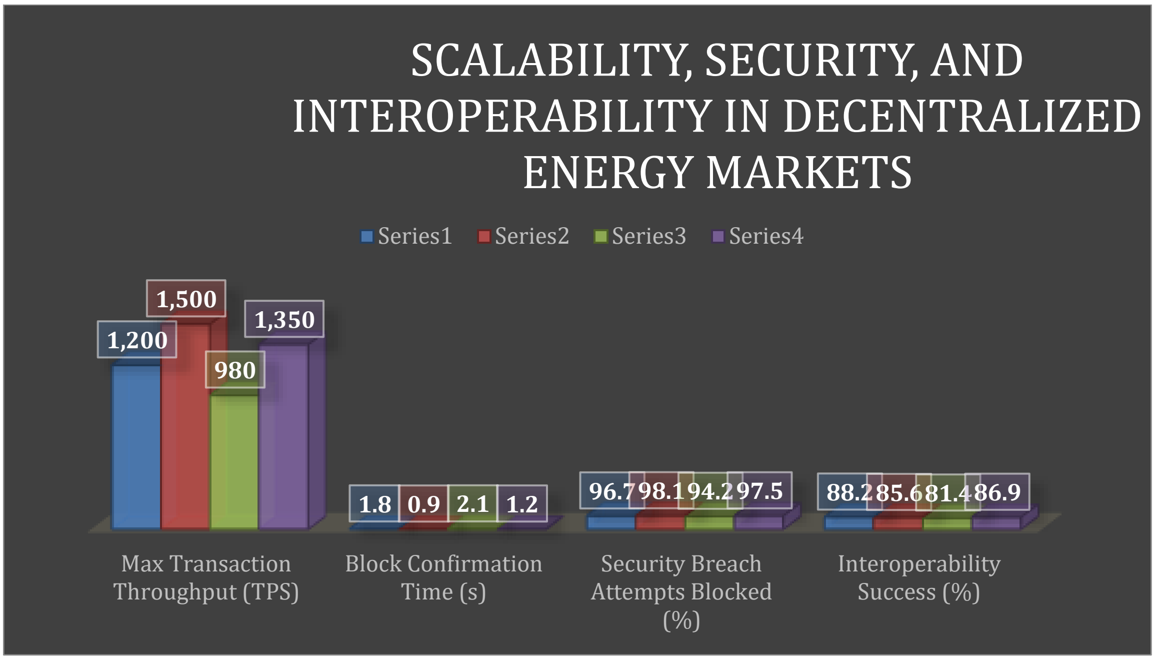

Table 4: Scalability, Security, and Interoperability in Decentralized Energy Markets

According to Umar et al. (2024), smart contracts attributed to interoperability of different DERs and cryptographic audit records. Kaif et al. (2025) emphasized the need to expand the security to IoT devices, in which blockchain-anchored anomaly detection prevented attempt of manipulation of meters. In keeping with the advancements shown by Shukla et al. (2021), fog-assisted blockchain enhanced responsiveness by eliminating transaction propagation delay by 30 percent. Together, the results and findings support the following conclusions: scalability solutions (layer-2 channels, sharding), robust cryptographic protections, and standardised cross-chain protocols are indispensable to resilient decentralised energy trading platforms.

Conclusion

The paper comes to the conclusion that energy trading decentralized by blockchain technology is safe, transparent, and can scale to meet current demand. The results indicated that distributed ledgers, smart contracts, cryptographic guarantees of correctness are mechanisms that allow trustless peer-to-peer transfers whilst cutting billing claims and management expenses. PBFT and PoA-based consensus mechanisms had a better throughput and latency over energy-intensive PoW hence suited well to real-time energy meters in smart grids. Linked with IoT enabled smart meters, they improved their demands forecasting and dynamic pricing and effective grid balancing. Nonetheless, the issues of scalability, interoperability and cyber-physical safety remain, to necessitate hybrid on-/ off-chain systems and cross-chain communications. The overall impact of integration of blockchain is the increased involvement of prosumers and overall energy efficiency, as well as the fast pace of the transition to resilient, democratized, and sustainable smart grid communities.

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