
Research article

Operational performance analysis of blockchain-enabled mechanisms for decentralized energy trading in smart grids

Hemant Patel^{1,*}, Aashish Kumar Bohre¹, Souvik Sharma¹, Jalpa Thakkar² and Mohan Lal Kolhe³

¹ Department of Electrical Engineering, NIT Durgapur, Durgapur 713209, West Bengal, India

² Electrical Engineering Department UPL University of Sustainable Technology Ankleshwar, Gujarat, India

³ Faculty of Engineering and Science, University of Agder, 4604 Kristiansand, Norway

* **Correspondence:** Email: hp.23ee1105@phd.nitdgp.ac.in; Tel: +09424382200.

Abstract: With the increasing penetration of distributed energy resources, electric vehicles, and prosumers, the demand for secure, scalable, and low-latency transaction platforms in smart grid-based transactive energy systems has grown substantially. Although blockchain technology offers a promising solution for decentralized energy trading, the choice of consensus mechanism critically determines system performance and practical feasibility. This study evaluates the relative performance of Clique, Istanbul Byzantine Fault Tolerance (IBFT), and proof of work (PoW) consensus algorithms to identify the most suitable approach for transactive energy applications in a smart grid environments. Using a five-node blockchain network, key performance indicators (KPIs)—namely, latency, throughput, and transaction failure rate—are quantified for essential market functions, including bidding, market clearing, payment settlement, and balance queries. The results demonstrate that permissioned consensus mechanisms significantly outperform PoW in term of responsiveness, scalability, and reliability. Among the evaluated approaches, IBFT exhibits the highest throughput and the lowest latency, making it the most suitable choice for real-time and near-real-time energy market operations. Clique delivers satisfactory performance in small-scale deployments but exhibits scalability limitations as transaction volumes increase. In contrast, PoW suffers from excessive latency and high failure rates, rendering it unsuitable for smart grid service operations. Overall, the findings indicate that permissioned blockchain platforms employing IBFT can effectively support efficient, secure, and scalable transactive energy markets for future smart grid infrastructures.

Keywords: smart grid; transactive energy; blockchain; permissioned blockchain; IBFT consensus; Clique consensus; proof of work; distributed energy resources; peer-to-peer energy trading; electric vehicles; market latency; throughput analysis

Nomenclature: BQ: balance query; CPU: Central Processing Unit; DR: demand response; DSO: distribution system operator; IBFT: Istanbul Byzantine Fault Tolerance; IoT: Internet of Things; KPI: key performance indicator; LEM: local energy market; P2P: peer-to-peer; PoW: proof of work; TPS: transactions per second; TSO: transmission system operator; VM: virtual machine; V2G: vehicle-to-grid; PoA: proof of authority; AC: alternating current, DC: direct current

1. Introduction

The blockchain-based energy trading system operates as a decentralized market that does not require users to trust a central governing body for secure transaction validation. Traditional systems encounter operational problems because they rely on centralized points, which create security vulnerabilities, hinder transparency, and lead to prolonged delays in settling transactions. The blockchain technology solves these problems by providing permanent record-keeping and visible information for automated processes that use smart contracts. Transactive energy systems, which use distributed energy resources, electric vehicles, and prosumers, depend on these features to perform secure real-time transactions. To support local energy markets (LEMs), early researchers initially proposed blockchain-based smart grid architectures. In [1], a blockchain-based smart grid system was proposed to facilitate decentralized LEMs. It revolves around the concept of a completely transparent peer-to-peer (P2P) energy trading with automated settlement and improved sustainability as core values. In [2], a detailed exploration of blockchain technology applications in the energy sector was conducted. In [3], an in-depth examination of the architecture and features of blockchain-supported smart contracts was provided. The contract functionalities were first examined from the perspectives of process automation, trust enforcement, and decentralized coordination derived from the application of energy systems. In [4], a consortium blockchain system was proposed to enable P2P localized electricity trading among electric vehicles, thereby ensuring transaction security and reducing reliance on centralized authorities. In [5], an industry-oriented, secure, consortium-based blockchain-based energy trading paradigm was designed, with a focus on privacy protection, transaction integrity, and trusted communication. Authors in [6] established a distributed electricity trading system within active distribution networks by leveraging multi-agent systems and blockchain in tandem, enabling decentralized coordination and highly flexible market participation. In [7], research focused on simultaneous EVCS, soft open points and distributed generation planning under diverse loading scenarios. Another study [8] focused on blockchain applications in Internet of Things (IoT) security and privacy, using a smart home as a case study, where blockchain helped improve data integrity and resistance to single points of failure. This work examined the resilience of a smart grid enhanced by blockchain, which would allow for the secure, fast energy exchange among distributed resources, even at the time of system disturbances, as given in [9]. An all-embracing review of IoT architectures as well as enabling technologies was developed in [10], thus providing a ground-breaking understanding applicable to blockchain-based smart grid and energy trading systems. The study in [11] presents a control strategy for AC and DC microgrids, which indeed serves as a basic control framework for

decentralized energy systems. In [12], a detailed research was presented on the planning of high-power electric vehicle charging stations, examining problems arising from the grid, and proposing a coordinated energy management approach. The research presented in [13] introduced a power-flow analytical, self-adaptive method for managing dynamic distribution network changes in highly distributed generation systems. Based on that, a microgrid mature agent system (MAS) that enables P2P energy trade was realized in [14], and an experiment was conducted using a low-cost computing device to verify the scheme's practicality.

A proof-of-concept implementation of a blockchain-based energy trading platform was described in [15], demonstrating its efficiency in automating transactions and increasing trust among participants. The discussion of P2P energy trading within a local community microgrid was presented in [16], which clearly shows benefits in economic and operational terms compared to centralized market models. A thorough review of current blockchain technologies for energy trading in the energy sector has been conducted in [17], with the analysis primarily focused on system architectures, consensus mechanisms, and the challenges of their deployment. In [18], a comprehensive and informative review of community-based and P2P electricity markets is provided, with market design, regulatory affairs, and operational constraints the main issues under discussion. In the P2P trading system, the framework proposed in [19] used blockchain smart contracts to establish a trustless environment that not only reduced transaction friction but also guaranteed the system's reliability. An in-depth presentation of P2P electricity trading, including concepts, market mechanisms, and optimization strategies, was given in [20]. A real-world case study of a microgrid energy market using blockchain technology and advanced, decentralized, and hierarchical control architectures was presented in [21,22]. The authors of [23] explored a fully decentralized, blockchain-based P2P trading framework for residential energy systems that enables fairness and local community energy independence.

The authors in [24,25] conducted a comparative study of the proof-of-work (PoW) and Byzantine Fault Tolerant consensus mechanisms and blockchain. The work [26] presented the architectural design of Hyperledger Fabric, emphasizing its suitability for permissioned enterprise and energy applications. The authors of [27,28] presented a next-generation decentralized smart contract platform, which supports programmable blockchain applications and the Ethereum transaction ledger and execution model. In [29,30], the principles and applications of blockchain technology across various industries were discussed, thereby providing a conceptual framework for decentralized energy markets. The study in [31] investigated the role of blockchain in sustainable supply chain management, offering transferable insights and ideas for energy trading ecosystems. The study [32] focused on a decentralized blockchain-based energy trading framework that aims to democratize energy markets. The authors of [33] analyzed how the combination of blockchain and smart contracts can be highly useful for IoT systems, particularly for automation and trust, both of which are highly relevant to smart grids. In [34], a secure demand response (DR) management was proposed through blockchain-based energy trading in smart grid environments. The works [35,36] presented a blockchain-based load-balancing and machine-learning scheme for decentralized hybrid P2P energy markets. In [37], a secure blockchain-powered energy trading tool was conceived over a wireless smart grid network. In [38], a comprehensive survey of P2P distributed energy trading was conducted, summarizing the architectures, challenges, and opportunities for future research. The framework in [39] presented a blockchain-based energy trading model with an incentive system to foster trust and participant engagement. In [40], an Ethereum-based solution for smart-grid energy trading was implemented, which demonstrated strong practical feasibility. The work in [41] proposed a blockchain-based secure

energy trading framework for intelligent transportation systems. The work [42] presented a distributed ledger-based automated marketplace for renewable energy trading in smart grids. In [43], coordinated planning of distributed generation and the use of soft open points to extend distribution system capacity were investigated. A paper on distribution system planning using DG and SOP is presented in [44]. Finally, Reference [45] reviewed the technology and methods for optimizing vehicle-to-grid (V2G), with the main focus on the role of electric vehicle integration in smart grids.

Integrated energy systems, together with decentralized energy management systems, require optimal scheduling methods that enable secure energy trading operations in line with recent technological developments. The study [46] introduced a multi-energy scheduling framework that uses carbon trading as its foundation and employs an optimization technique that employs greedy selection to improve economic performance and operational capacity. The research documented in [47] examined day-ahead energy management solutions for pelagic island microgrid groups and demonstrated how essential accurate energy scheduling becomes when dealing with non-integer-hour power transmission limits. The research in [48] presented a secure, advanced management framework that enables P2P energy trading among multiple microgrid systems operating under unpredictable operational conditions, while delivering improved system dependability, user privacy protection, and transaction security. The study in [49] explored optimal scheduling for renewable power grid and vessel-based hydrogen chain integrated systems, focusing on flexible energy transfer and system-wide coordination. However, these studies do not evaluate the operational performance of blockchain consensus mechanisms, which is essential for real-time energy trading applications.

Researchers have assessed proof of solution (POS) as an optimization-based consensus mechanism for energy trading on blockchain platforms, using solution quality assessment from economic dispatch optimization problems to validate blockchain blocks. Researchers developed a blockchain-based security system for economic dispatch and energy trading that leverages optimization techniques and consensus protocols to enhance performance and security. Research on multi-energy systems and the management of stochastic energy and microgrid P2P trading has shown that platforms need to provide high scalability, fast transaction processing, and secure transaction systems. The developed methods provide specific solutions for particular applications but fail to provide standardized performance assessment across various consensus methods when testing actual smart grid operational scenarios.

Most prior work has mainly addressed aspects of architectural design, security, or economic modeling of transactive energy systems, leaving consensus-level performance evaluation under realistic transactive energy workloads largely unexplored. Furthermore, comparative studies that unambiguously demonstrate how the performance of blockchain consensus mechanisms affects smart grid market operations such as bidding, market clearance, settlement, and balance queries are very few. The current research systematically evaluates and compares permissioned and permissionless blockchain consensus mechanisms from the perspective of transactive energy in the smart grid, thereby aiming to fill this gap.

Research gap and motivation

1. Existing studies focus primarily on conceptual frameworks and lack performance-oriented evaluation.
2. Limited work maps consensus mechanisms to real-time energy market operations.
3. Comparative analysis between permissioned and permissionless systems is insufficient.
4. Scalability and latency under high transaction loads are not adequately addressed.

Moreover, the present work does not adequately study how consensus mechanisms impact core transactive energy processes such as market clearance, bidding, and financial settlement under fluctuating transaction loads, which is critical for real-time monitoring of smart grid requests.

Driven by such discrepancies, the present research conducts a definitive assessment and comparison of permissioned (IBFT and Clique) and permissionless (PoW) blockchain consensus models in the context of transactive energy to determine the architectures that can satisfy the operational requirements of upcoming smart grids with high rigor.

Contribution

This paper mainly contributes to the field of the blockchain-powered energy market through the following points:

1. An investigative framework based on blockchain is proposed for smart grid-enabled transactive energy systems, transparently associating consensus mechanisms with core energy market operations such as bidding, market clearance, payment settlement, and balance queries.
2. First, a comprehensive comparative study is made on permissioned (IBFT and Clique) and permissionless (PoW) consensus mechanisms, focusing mainly on latency, throughput, and transaction failure rate as the performance indicators most closely related to the area of real-time energy trading.
3. The feasibility of the blockchain consensus mechanisms in operation under the condition of gradually mounting transaction loads is explored, thus opening up the scales and short response time requirements of decentralized energy markets and serving as a reference for future work.
4. The study provides solid evidence of the technical excellence of IBFT over other transactive energy applications. Therefore, IBFT could be used in smart grid environments to seamlessly integrate low-latency, high-throughput, and reliable market execution while other features remain unchanged.
5. The results serve as practical guidance for the planning and implementation of blockchain-based transactive energy platforms that are a prerequisite for the integration of distributed energy resources, electric vehicles, and prosumer-driven energy trading.

2. Methodology

2.1. System architecture and test network

Compared with the majority of studies that focus on one market, the P2P energy trading system architecture combines all three real-life market mechanisms—Bilateral Market (BiM), Pool Market (PM), and balancing market (BaM)—for a more realistic energy trading model. The network is divided into two types of nodes: Normal nodes (NNs) that can only read data and send requests, and validator nodes (VNs), such as transmission system operators (TSOs), (distribution system operators (DSOs), market operators, and regulators, which are trusted entities with the right to validate transactions and produce blocks. The framework is governed by five smart contracts: three dedicated contracts for BiM, PM, and BaM, a registry contract for participant identity verification and rule checking, and a payment settlement contract for clearing financial transactions.

In order to compare the performance, two other consensus mechanisms—PoW and Clique—are taken into consideration. PoW uses computational work with probabilistic finality, whereas Clique

allows quicker block proposal, but the finality is delayed due to chain forks. Performance metrics such as read transaction latency, write transaction latency, read throughput, write throughput, scalability, and failure rate are used to evaluate performance. Read transaction latency is the time it takes for query operations to receive a response, and write transaction latency is the delay for confirmed transactions that change the state, such as submitting bids or market clearing. Besides, it considers extra confirmation blocks in PoW and Clique. Throughput metrics show the number of successfully executed operations per second for both reads and writes, and scalability metrics reveal the system's performance as the number of transactions or network size increases. Finally, the failure rate reflects the percentage of transactions that have not been confirmed within a 20-min window, the maximum confirmation time in Ethereum-based networks.

(A) Node role clarification

The blockchain network consists of two types of nodes: VNs and NNs. Validator nodes function as trusted entities, including TSOs, DSOs, and market operators, who validate transactions and create new blocks. NNs function as prosumers and consumers, able to submit transactions and access blockchain information but not participate in consensus activities. The IBFT and Clique consensus mechanisms allow only VNs to take part in consensus voting.

(B) Network size discussion

The experimental setup uses a five-node blockchain network to function as a controlled testing environment, which scientists use to assess how well consensus systems perform. The system provides stable performance assessment through its existing configuration, but actual smart grid systems will require more than one validator node to operate, because multiple DSOs and market operators use their networks for validation. The consensus protocols of IBFT face heightened communication demands when more validators join because the system must transmit $O(n^2)$ messages, which will hinder its ability to scale and create delays.

(C) Hardware/virtual machine (VM) specification

Every blockchain node operates on a virtual machine with standard computational resources as a means of ensuring that experiments are consistent. Each node is provided with 4 vCPUs, 8 GB RAM, and network bandwidth sufficient to support transaction communication. Experiments are run in a controlled, virtualized environment to ensure reproducibility and a fair comparison of different consensus mechanisms. In the experimental design, three of the five nodes are set up as VNs, with the remaining two as NNs. While VNs participate in the consensus process, NNs create and send transactions.

2.2. Transactive energy market operations

The blockchain network facilitates four essential transactive energy activities that are representative of well-functioning smart grid market processes:

- **Bidding:** Prosumers and energy assets offer price-quantity bids to the market.
- **Market clearance:** The presented bids are matched and cleared to establish energy allocation and pricing.
- **Payment settlement:** To settle energy trades among participants, financial transactions are performed.
- **Balance query (BQ):** Contributors check their power and financial balances recorded on the distributed ledger.

These operations are implemented through smart contract functions and executed under varying loads to simulate realistic market participation scenarios for distributed generation, electric vehicles, and flexible loads. The computationally intensive operations in smart contracts, such as bid matching during market clearance, are likely to increase execution time and gas consumption, thereby affecting transaction latency and overall system performance. Moreover, in Ethereum-based systems, the computational cost of executing smart contracts is measured in terms of gas consumption. This means that complex operations, such as bid matching, result in higher gas usage, which might lead to transaction delays.

2.3. Consensus mechanism

Along with standard consensus mechanisms, energy-specific consensus methods have been proposed, such as PoS, in which nodes verify blocks by solving optimization problems, e.g., economic dispatch. Although these methods are a good way to align the goals of the energy system with blockchain consensus, they introduce computational complexity and are not widely adopted operationally. Hence, this work only considers widely used consensus mechanisms like IBFT, Clique, and PoW for performance comparison.

3. Workload modeling and test scenarios

To determine the extent to which the system can grow and still react quickly, transaction workloads were created by incrementally increasing the number of concurrent transactions. Various transaction volumes were used to depict the low, medium, and high levels of market activity. Every trial was conducted for all three different consensus mechanisms with the aim of recording performance characteristics that remain consistent over repeated trials. The scenarios tested mainly involved writing operations (bidding, market clearance, payment settlement) as well as reading operations (balance queries) and hence represent a comprehensive evaluation of consensus performance across different market interactions.

3.1. Performance metrics

The effectiveness of each consensus mechanism is measured through the main indicators that are most relevant to the smart grid, as well as transactive energy applications:

- Latency: The time between when a transaction is initiated and when it is confirmed and finally completed.
- Throughput: The number of transaction requests that can be successfully executed in one second.
- Peak latency and peak throughput: The worst-case performance occurs when the system is at maximum load.
- Transaction failure rate: The fraction of transactions that fail due to timeouts or congestion.

These metrics have been selected to reflect the real-time requirements, scalability considerations, and reliability expectations of decentralized energy markets.

Equations (1)–(3) (transaction latency, average latency, and peak latency): These definitions of latency are typical in blockchain performance benchmarking and consensus evaluation [3,24,25].

Equations (4)–(6) (throughput, average throughput, peak throughput): These throughput metrics

are widely used in blockchain scalability studies and energy trading platforms [3,17,24].

Equation (7) (transaction failure rate): Failure rate metrics are used to gauge the system's reliability under conditions of congestion and stress in blockchain-based energy markets [36,39].

Equation (8) (market operation specific latency): This equation illustrates industry-driven latency across different sectors in the energy market [6,20].

Equation (9) (Consensus Efficiency Index): The combined latency throughput efficiency metric is derived from normalized performance indicators commonly used in consensus mechanism evaluation [25].

Transaction latency is defined as the time elapsed between transaction submission and confirmation on the blockchain ledger.

$$T_{lat} = T_{confirm} - T_{submit} \quad (1)$$

where T_{submit} is the transaction submission time, and $T_{confirm}$ is the transaction confirmation time.

For the average latency over N , the number of successfully processed transactions is given by:

$$T_{lat} = \frac{1}{N} \sum_{i=1}^N T_{lat,i} \quad (2)$$

Peak latency represents the worst-case transaction delay observed during the experiment:

$$T_{lat}^{peak} = \max(T_{lat,1}, T_{lat,2}, \dots, T_{lat,N}) \quad (3)$$

Throughput is defined as the number of successfully confirmed transactions per unit time.

$$Throughput = \frac{N_{success}}{T_{total}} \quad (4)$$

where $N_{success}$ is the number of successful transactions, and T_{total} is the total observation time.

$$\overline{TPS} = \frac{1}{K} \sum_{j=1}^K Throughput_j \quad (5)$$

where K is the number of experimental runs.

Peak throughput represents the maximum observed transaction processing rate:

$$Throughput^{peak} = \max(TPS_1, TPS_2, \dots, TPS_K) \quad (6)$$

The transaction failure rate quantifies the percentage of transactions that fail due to timeout, congestion, or rejection.

$$R_{fail} = \frac{N_{failed}}{N_{total}} \times 100 \quad (7)$$

where N_{failed} is the number of failed transactions, and N_{total} is the total number of submitted transactions.

For a given market operation m (bidding, clearance, settlement, or query):

$$T_{lat}^{(m)} = \frac{1}{N_m} \sum_{i=1}^{N_m} (T_{confirm,i}^{(m)} - T_{submit,i}^{(m)}) \quad (8)$$

To jointly assess latency and throughput performance:

$$\eta_{cons} = \frac{\overline{TPS}}{T_{lat}} \quad (9)$$

A higher value of η_{cons} indicates better suitability for real-time transactive energy applications.

The Consensus Efficiency Index combines latency and throughput, providing a single overall performance metric to assess how well consensus mechanisms perform in real-time scenarios. This index, unlike individual metrics, genuinely reflects the trade-off between transaction speed and processing capacity, making it highly applicable to smart-grid energy-trading systems.

4. Results and discussion

The private PoW network is set up with a block time averaging approximately 12 s and a mining difficulty level kept in check to mimic Ethereum's conditions. This arrangement guarantees a level playing field for comparison, simultaneously showing the real behavior of a PoW network. To comprehensively evaluate the suitability of blockchain consensus mechanisms for transactive energy applications, the analysis is structured into the following cases, each corresponding to a specific market operation and performance objective. Besides, the work is subdivided into separate cases, with each case reflecting a market operation performance objective and assessment of the suitability of blockchain consensus mechanisms for transactive energy.

- Case 1: Studies the peak latency and peak throughput of IBFT, Clique, and PoW to compare their operational behavior under maximum transaction load and in the worst case.
- Case 2: Aims to study bidding latency and throughput as the number of transactions gradually increases, to test scalability and the real-time response time for bid submissions.
- Case 3: Examines market-clearance latency to measure the efficiency of decentralized energy markets in bid matching and dispatch finalization.
- Case 4: Aims to examine different payment settlement latencies across varying transaction loads to assess the challenge-resistance and timeliness of financial transactions.
- Case 5: Focuses on analyzing balance query latency and throughput to determine ledger responsiveness and monitor scalability.
- Case 6: Aims to study the transaction failure rate during bidding and balance query operations to measure the reliability of the six consensus mechanisms under stress conditions.

Figure 1 depicts a decentralized and secure system that enables direct energy transactions between participants, thereby maintaining transparency, trust, and operational efficiency in a P2P energy trading architecture. To facilitate LEMs, the architecture brings together prosumers, consumers, utilities, and grid operators in a blockchain-permissioned environment. Each participant is a network node capable of submitting energy bids, offers, and transaction requests. One of the system features is support for various market mechanisms, such as bilateral, pool-based, and balancing markets, that provide trading structures with a high degree of flexibility and are very similar to real-world energy market operations.

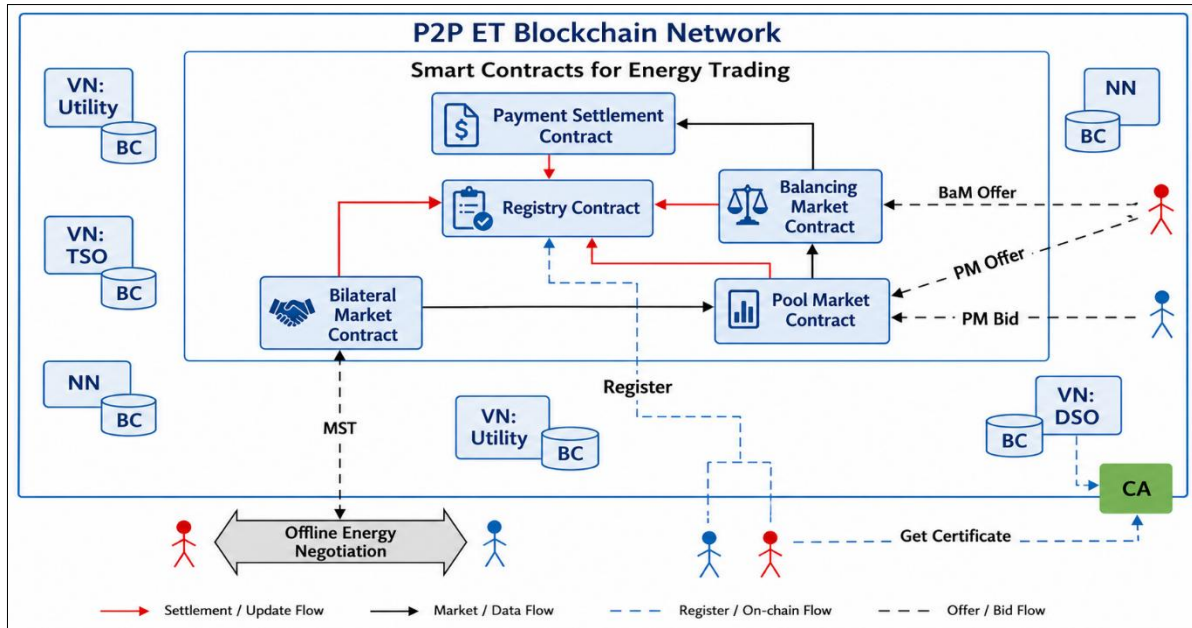


Figure 1. Proposed architecture for P2P energy trading.

Figure 2 compares the peak latency of the Clique, IBFT, and PoW (Case 1) consensus mechanisms with the major market operations of bidding, market clearance, payment settlement, and BQ. The low peak latency is due to the IBFT deterministic Byzantine Fault Tolerant consensus process and the small number of communication rounds with validators. These results demonstrate that IBFT is the most appropriate for time-sensitive transactive energy applications.

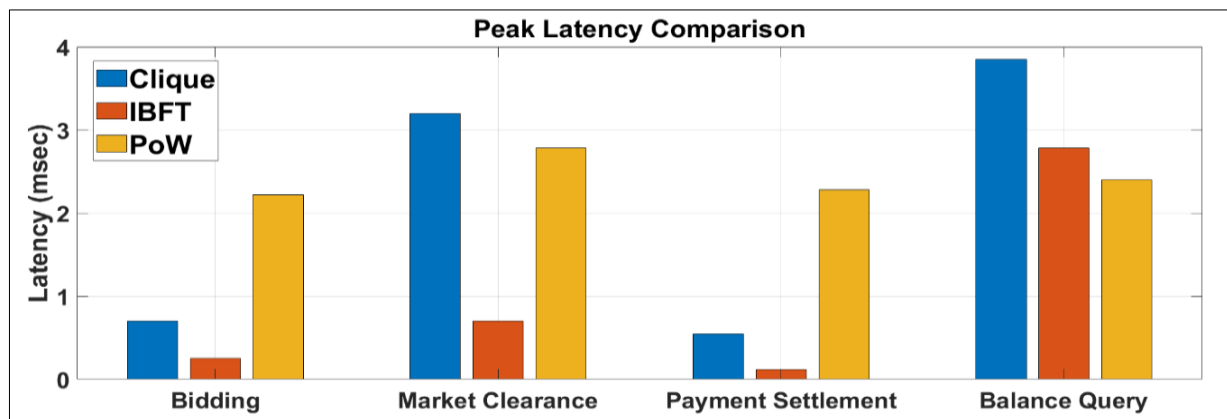


Figure 2. Peak latency comparison.

The peak throughput during bidding and balance query operations for the three mechanisms is shown in Figure 3. In both cases, IBFT achieves the maximum throughput due to parallel message validation and fast block finality. Along with the lightweight authority-based consensus, the Clique authority can maintain a competitive throughput. The block generation delays, as well as the mining difficulty, explain why PoW's performance was notably lower than that of the others. The results

provide strong evidence that permissioned blockchain frameworks are far more efficient than PoW in high-frequency transaction environments such as LEMs. Figure 4 illustrates the change in bidding latency as the number of transactions varies in the 5-node system (Case 2). Even as transaction volume grows, IBFT maintains low latency, enabling high scalability and efficient consensus execution. The increase in latency that Clique experiences beyond moderate transaction loads is quite significant, due to coordination overhead among authority nodes. On the other hand, PoW's latency remains almost the same across the entire transaction range, but it is comparatively high, which is why the delay due to mining-based confirmation is the dominant one, independent of the transaction count.

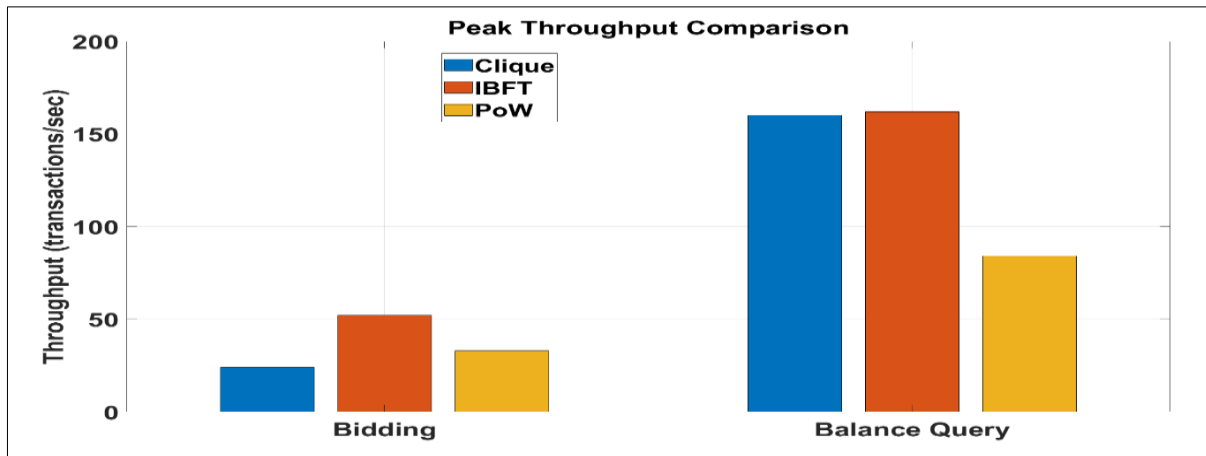


Figure 3. Peak throughput comparison.

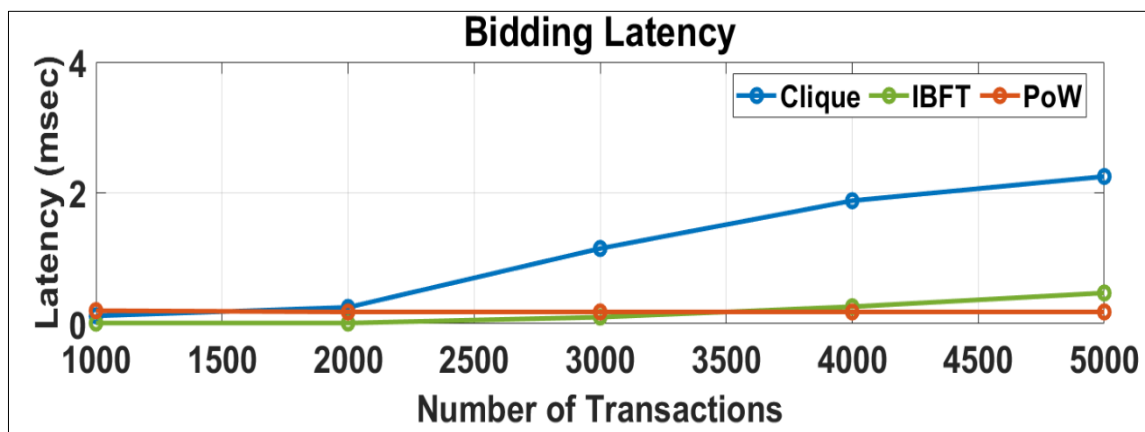


Figure 4. Bidding latency.

Figure 5 compares the bidding throughput of clique, IBFT, and PoW under increasing transaction loads. Closest to the theoretical maximum, IBFT achieves the highest throughput, peaking at medium transaction volumes and then slightly dropping due to validator communication saturation. Clique is pacing reasonably well at low-to-moderate transaction volumes but struggles to increase at higher transaction counts. PoW shows a gradual increase in throughput, but the level is still significantly lower than the permissioned alternatives. These numbers strongly support the use of IBFT for efficient

bidding in scalable transactive energy markets. The minor decrease in IBFT throughput at higher transaction loads can be attributed to increased communication overhead during validators' interactions. To achieve consensus, IBFT requires multiple rounds of message exchange between nodes, leading to $O(n^2)$ message complexity and eventually network saturation under high load.

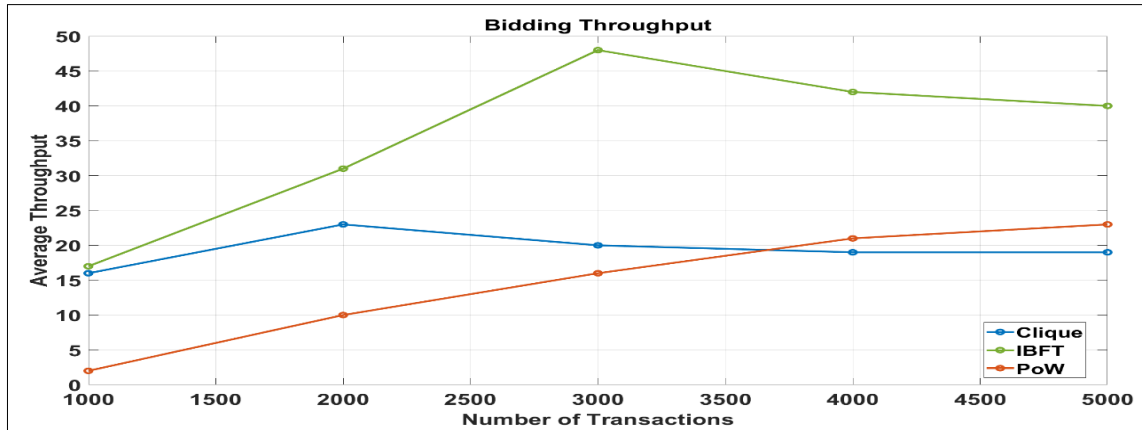


Figure 5. Bidding throughput.

Figure 6 shows market-clearance latency (Case 3) as a function of transaction volume. IBFT outperforms other mechanisms again by keeping latency very low and almost constant, thanks to its immediate block finality. As transaction volume increases, Clique's latency increases, indicating overheads associated with sequential block validation. PoW keeps higher latency levels mostly due to mining delays. This figure demonstrates that IBFT is well-suited for swift market-clearance tasks that require deterministic execution. Figure 7 displays the payment settlement latency (Case 4) for different transaction volumes. Clique sharply increases latency at higher transaction loads, indicating congestion during settlement confirmation. These are the moments that clarify the importance of IBFT in enabling fast, reliable financial settlements in blockchain-enabled energy trading systems. The main cause for the Clique latency increase when transaction volumes go up is its sequential block proposal mechanism. Furthermore, the finality in Clique is probabilistic; temporary forks may require additional confirmations.

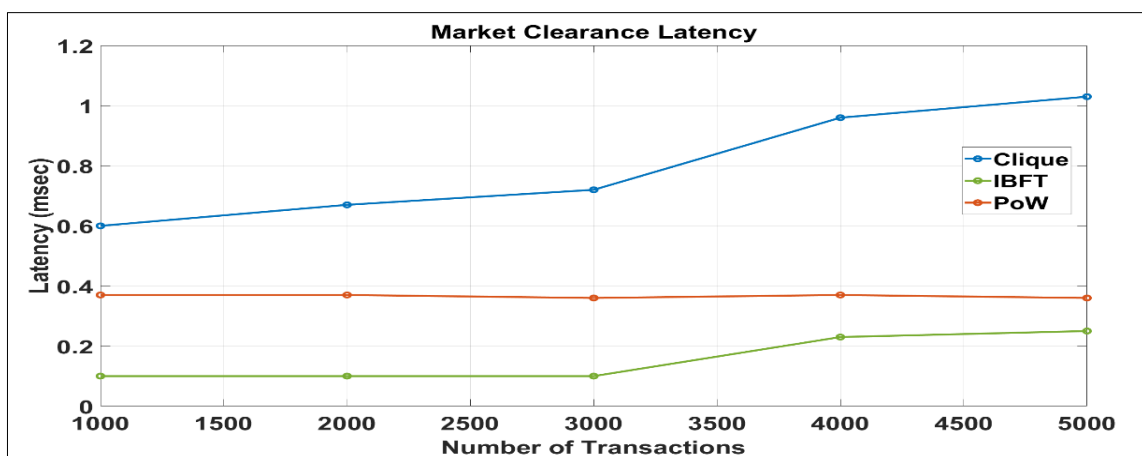


Figure 6. Market clearance latency.

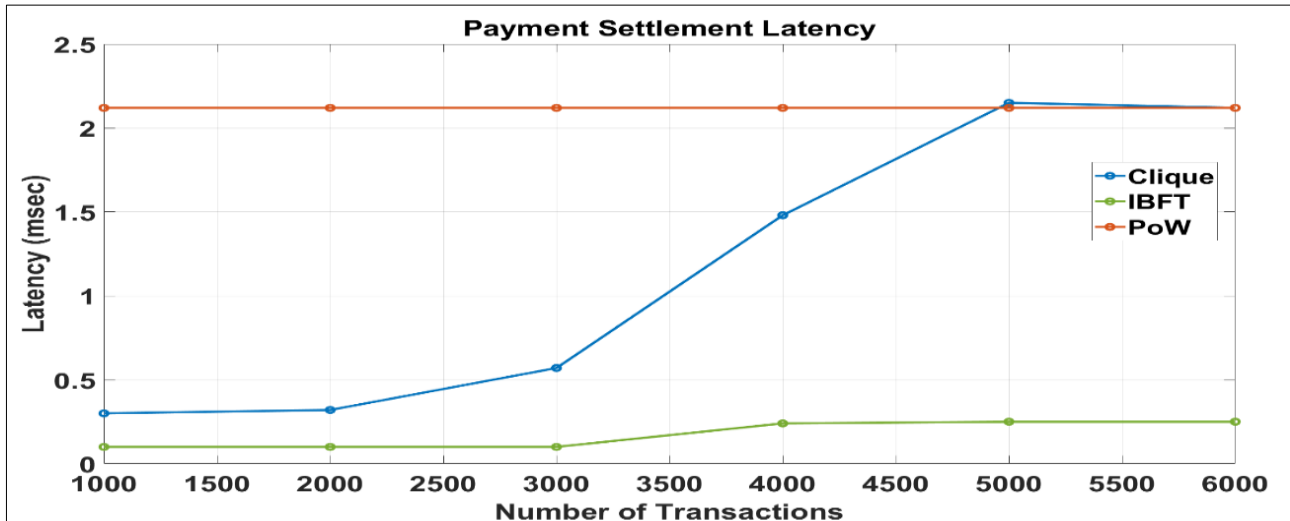


Figure 7. Payment settlement latency.

Figure 8 reveals the balance query latency (Case 5) across different transaction volumes. Clique and PoW show almost constant latency, while IBFT has slightly higher but still negligible latency due to the extra steps of state synchronization among validators. In all, the latency for balance queries is very low across all consensus mechanisms, indicating that read-only operations are efficiently handled regardless of the consensus protocol. Figure 9 compares the BQ throughput between IBFT and PoW. With clean state access and parallel processing, IBFT can ramp up throughput very quickly as transaction volume increases, achieving significantly higher throughput. PoW is hardly able to raise throughput as fast, as it is limited by block access delays and network propagation time. The results demonstrate that IBFT is well-suited for the frequent balance monitoring required in real-time energy market applications.

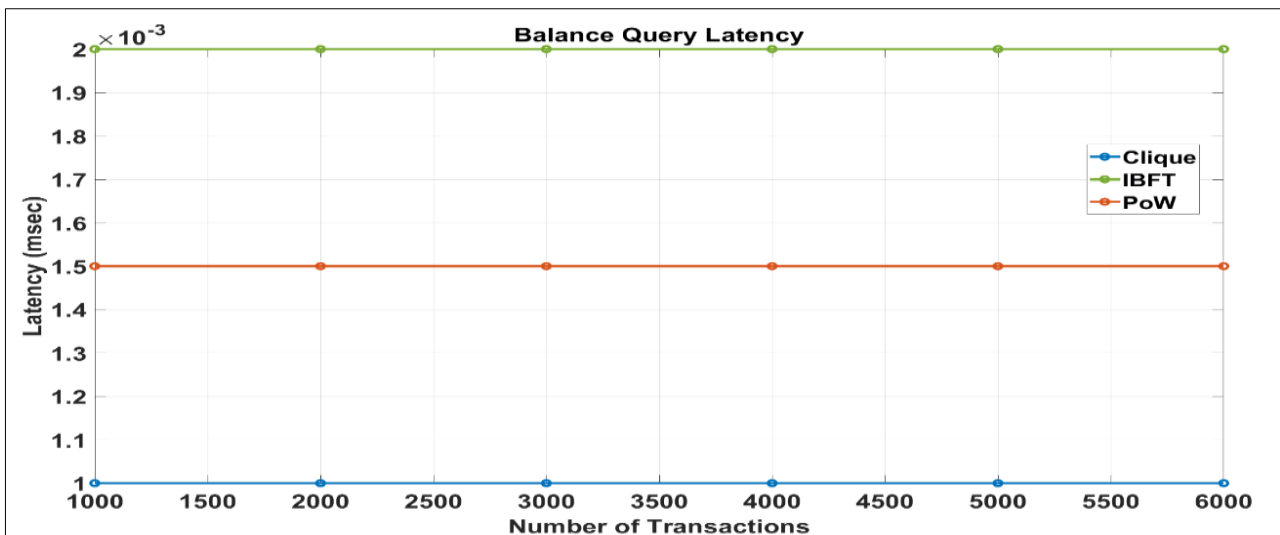


Figure 8. Balance query latency.

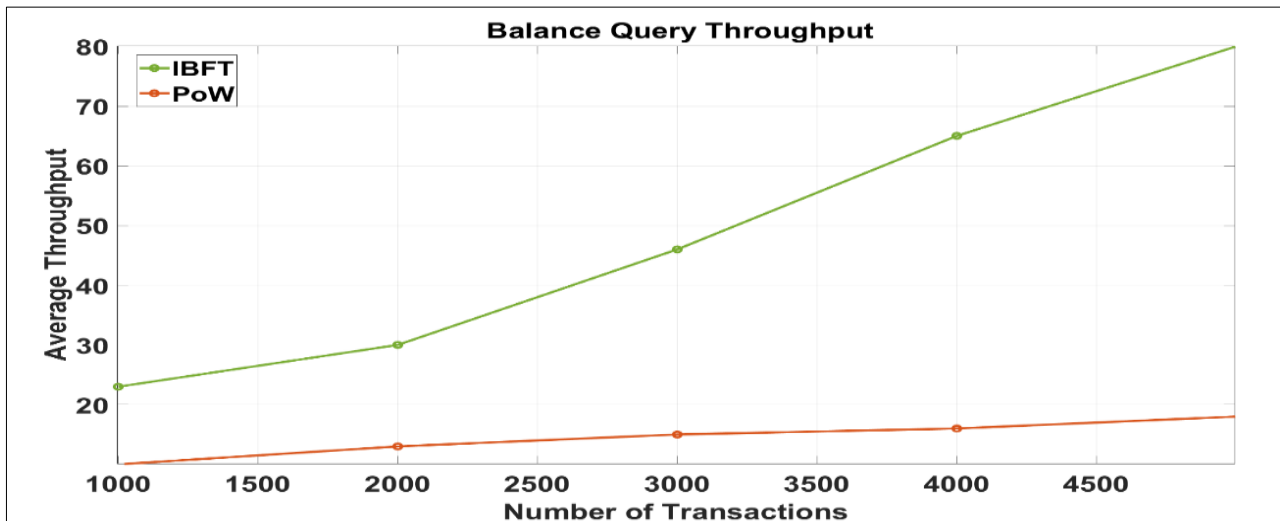


Figure 9. Balance query throughput.

Figure 10 depicts the failure rates of bidding and balance query transactions (Case 6). Across all transaction volumes, Clique records a zero-failure rate, indicative of stable authority-based consensus under controlled conditions. IBFT exhibits a slight increase in failure rate at high transaction loads due to validator timeout restrictions. Differences are stark, as PoW struggles with high failure rates, mainly due to transaction expiration and delayed confirmations.

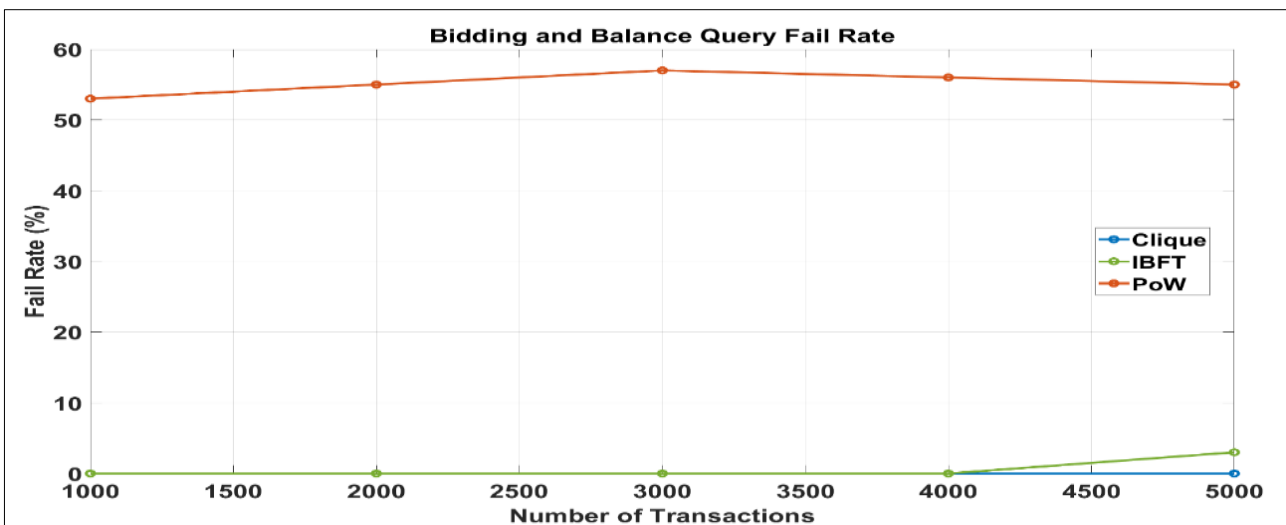


Figure 10. Bidding and balance query fail rate for the 5-node system.

IBFT's rising transaction failure rate under heavy load, as observed in the experiments, is primarily attributable to the consensus protocol's rigid timeout specifications. It may happen that transactions are not included in the confirmation window when the validators' communication delays exceed the predetermined time limits. On the other hand, Clique sidesteps such failures due to its simpler consensus architecture and the absence of stringent timeout requirements, which make it more stable under heavy transaction loads, albeit with lower performance efficiency. The findings provide evidence that

blockchain-based decentralized energy trading systems outperform traditional centralized systems by offering faster transaction finality, greater reliability, and, ultimately, automated execution.

Table 1 summarizes the peak latency and peak throughput observed for IBFT, Clique, and PoW across the major transactive energy operations. IBFT, in general, demonstrates the shortest peak latency of a minute or operations in power bidding, market clearance, and payment settlement, thus making it a highly reliable candidate for time-critical smart grid applications. While Clique has somewhat favorable peak latency, PoW is associated with much longer times of up to an order of magnitude, attributable to mining-based confirmation processes. Regarding peak throughput, IBFT can process more transactions than other consensus methods, especially in bidding and balance query operations, demonstrating IBFT's energy market participatory scalability advantage. Table 2 presents the evolution of bidding latency and throughput with increasing transaction volume. PoW has relatively stable but longer latency and lower throughput, and thus cannot be considered efficient enough for real-time bidding in transactive energy systems.

Table 1. Peak performance.

Metric		IBFT	Clique	PoW
Peak latency	Bidding (ms)	0.25	0.70	2.22
	Market clearance (ms)	0.70	3.20	2.78
	Payment settlement (ms)	0.12	0.55	2.28
	BQ (ms)	2.78	3.85	2.40
Peak throughput	Bidding (transactions per second, TPS)	52	24	33
	BQ (TPS)	162	160	84

Table 2. Bidding performance.

Transactions	IBFT latency (ms)	IBFT TPS	Clique latency (ms)	Clique TPS	PoW latency (ms)	PoW TPS
1000	0.01	17	0.12	16	0.20	2
2000	0.01	31	0.25	23	0.18	10
3000	0.10	48	1.15	20	0.18	16
4000	0.26	42	1.88	19	0.18	21
5000	0.47	40	2.25	19	0.18	23

Table 3 provides a comparison of market clearance and payment settlement latency across various transaction loads. IBFT performs equally well in terms of latency for both operations, enabling fast bid matching and financial settlement execution. Conversely, Clique exhibits a gradual increase in latency with transaction volume, especially during the payment settlement phase under heavy load. Furthermore, PoW increases latency across all cases, making it unsuitable for operational smart grid markets that require deterministic, rapid settlements.

Table 3. Market clearance and payment settlement latency.

Transactions	Market clearance latency			Payment settlement latency		
	IBFT (ms)	Clique (ms)	PoW (ms)	IBFT (ms)	Clique (ms)	PoW (ms)
1000	0.10	0.60	0.37	0.10	0.30	2.12
2000	0.10	0.67	0.37	0.10	0.32	2.12
3000	0.10	0.72	0.36	0.10	0.57	2.12
4000	0.23	0.96	0.37	0.24	1.48	2.12
5000	0.25	1.03	0.36	0.25	2.15	2.12

Table 4 presents information on BQ throughput and transaction failure rates. First and foremost, IBFT delivers the highest number of balance inquiries per unit time, with almost zero failure rates at low and medium load levels, making it an efficient ledger access and monitoring agent. On the other hand, Clique is characterized by an environment in which the failure rate remains at zero regardless of the number of transactions, a symptom of a stable, authority-centric operation. The main reasons for the high failure rates in PoW are delayed confirmations and congestion. These factors can severely limit already existing market participation in large-scale transactive energy networks.

Table 4. Balance query performance and failure rate.

Transactions	Balance query performance		Failure rate		
	IBFT TPS	PoW TPS	IBFT (%)	Clique (%)	PoW (%)
1000	23	10	0	0	53
2000	30	13	0	0	55
3000	46	15	0	0	57
4000	65	16	0	0	56
5000	80	18	3	0	55

Table 5 illustrates the extent to which IBFT, Clique, and PoW differ in terms of consensus characteristics and operational suitability. IBFT is distinguished by features such as the determinism of the final step, a short delay interval, high throughput, and low energy consumption. All of these factors indicate that IBFT can be a strong candidate for the smart grid sector. Clique compromises performance quality, delivering moderate results. The bright side is the reduced complexity feature, which makes it suitable for small-scale deployments. The biggest downside of PoW is its high energy consumption, which is accompanied by long latency and low scalability, resulting in a significant scarcity of use cases in real-time energy markets. Energy usage in consensus mechanisms is one of the main factors determining the amount of computation they require. PoW, which involves intensive hashing, results in a substantial increase in CPU usage and energy consumption. On the other hand, IBFT and Clique primarily work through message exchanges and authority-based validation, thus leading to much less computational workload. Our experiments showed that PoW had very high CPU usage (approximately 70%–90%), compared with IBFT and Clique (mostly less than 20%), which aligns with the fact that PoW demands more computation and energy. Table 6 lists the notable performance metrics used in this study and their suitability for smart grid applications. Locally significant measures of latency, throughput, and failure rate were selected to represent core operational

characteristics such as responsiveness, scalability, and reliability. From these metrics, one may also derive a thorough comparative study of blockchain consensus protocols operating under energy transaction workload scenarios. Table 7 illustrates the correspondence between blockchain tasks and related smart grid activities. For example, bid, market clearance, payment settlement, and balance inquiry operations correspond to price discovery, dispatch decision-making, financial settlement, and system monitoring. Table 8 presents the different sets of experiments and the transaction loads considered by the research. The study includes scenarios with low, medium, and high transaction volumes, as well as both write-intensive and read-intensive operations. Such a well-rounded assessment framework allows one not only to measure baseline performance but also to test scalability limits, analyze congestion behavior, and reflect the realities of mixed-market conditions—those found in practical transactive energy deployments.

Table 5. Comparison of blockchain consensus mechanisms.

Feature	IBFT	Clique (proof of authority, PoA)	PoW
Blockchain type	Permissioned	Permissioned	Permissionless
Finality	Deterministic	Probabilistic	Probabilistic
Latency	Very low	Moderate	High
Throughput	High	Medium	Low
Energy consumption	Low	Very low	Very high
Scalability	Moderate to high	Moderate	Low
Suitability for smart grid	High	Medium	Low

Table 6. Definition of performance metrics.

Metric	Symbol	Relevance to smart grid
Transaction latency	T_{lat}	Determines market responsiveness
Average latency	$\overline{T_{lat}}$	Indicates real-time capability
Peak latency	T_{lat}^{peak}	Reflects worst-case delay
Throughput	TPS	Measures system scalability
Peak throughput	TPS^{Peak}	Determines maximum market capacity
Failure rate	R_{fail}	Indicates reliability
Confirmation time	$T_{confirm}$	Ensures settlement trust
Peak failure rate	R_{fail}^{peak}	Reliability under stress

Table 7. Mapping of blockchain operations to smart grid functions.

Blockchain operation	Smart grid function	Description
Bidding	Price quantity submission	Prosumers submit energy bids
Market clearance	Dispatch decision	Matching of bids and offers
Payment settlement	Financial settlement	Energy trade settlement
BQ	Market monitoring	Query of energy and credit balances
Smart contract execution	Market automation	Rule-based transaction enforcement
Ledger update	System transparency	Immutable transaction record

Table 8. Experimental scenarios and transaction load.

Scenario	Transaction type	Transaction volume	Objective
Scenario 1	Bidding	Low	Baseline latency analysis
Scenario 2	Bidding	Medium	Scalability assessment
Scenario 3	Bidding	High	Congestion behaviors
Scenario 4	Market clearance	Medium	Clearance efficiency
Scenario 5	Payment settlement	High	Settlement robustness
Scenario 6	BQ	Low	Read-operation latency
Scenario 7	BQ	High	Monitoring scalability
Scenario 8	Mixed workload	Variable	Realistic market emulation

5. Conclusions

This research evaluated the performance of blockchain-based clique, IBFT, and PoW consensus mechanisms in a smart grid-enabled transactive energy system. The test environment consisted of a 5-node network. Test metrics focused on latency, throughput, and transaction reliability, capturing the frontline operational efficiency of core market functions, including bidding, market clearance, payment settlement, and balance queries. The evidence indicates that permissioned blockchain platforms offer a blockchain architecture superior to PoW across all measurable operational aspects relevant to smart grid technology. IBFT presented the lowest latency and the highest throughput, while also demonstrating high transaction reliability, making it an ideal fabric for real-time and near-real-time transactive energy markets. Furthermore, by providing deterministic finality and resilience against Byzantine faults, it enables quick market clearing and, at the same time, secure financial settlement, which is of utmost importance for ensuring grid stability and participants' trust. Regarding Clique, its performance was average and stable, making it feasible for use in small-scale microgrids or pilot projects with low transaction volume.

The results of this study indicate that IBFT-based permissioned blockchain infrastructures possess the characteristics of an efficient, scalable foundation for the realization of decentralized energy trading, P2P electricity markets, and grid-interactive services in smart grids. Allowing such infrastructures to quickly support market operations and settlement can be the vehicle that leads to the next stage, where the use of distributed generation, DR, and the integration of electric vehicles becomes the norm rather than the exception. The findings of this study provide a design for blockchain and the selection of consensus mechanisms to be employed in future transactive energy systems to accomplish the transition toward secure, efficient, and decentralized smart grid infrastructures. Future work will focus on evaluating consensus performance in larger blockchain networks with more VNs and on exploring energy-aware consensus mechanisms, such as PoS, to improve energy-optimized trading.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

Mohan Lal Kolhe served as a Guest Editor for AIMS Energy and was not involved in the editorial review process or in the decision to publish this manuscript. All authors confirm that there are no competing interests.

Author contributions

Methodology, original draft preparation, software development, and validation were performed by Aashish Kumar Bohre, Hemant Patel, and Souvik Sharma. Review and editing were carried out by Jalpa Thakkar and Mohan Lal Kolhe. All authors have read and agreed to the published version of the manuscript.

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