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Scalable Blockchain Consensus for Peer-to-Peer Energy Trading: QBFT vs. Clique

João Pedro Ferreira Catarino

Master Thesis

presented as partial requirement for obtaining the Master Degree in Information Management

NOVA Information Management School
Instituto Superior de Estatística e Gestão de Informação
Universidade Nova de Lisboa

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Scalable Blockchain Consensus for Peer-to-Peer Energy Trading: QBFT vs. Clique

by

João Pedro Ferreira Catarino

Master Thesis presented as partial requirement for obtaining the Master’s degree in Information Management, with a specialization in Information Systems and Technologies Management

Supervised by

Ian Scott

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledged the Rules of Conduct and Code of Honor from the NOVA Information Management School.

João Catarino

Lisbon, July 15, 2024

DEDICATION

This thesis is dedicated to my family, whose boundless love, support, and encouragement have been fundamental in helping me achieve this milestone.

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I would like to express my sincere appreciation to my thesis advisor, Professor Ian Scott, for offering me the chance to undertake this research. Although I started with limited knowledge of energy markets, his consistent guidance and constructive feedback throughout the project were crucial to its success.

ABSTRACT

This thesis explores the scalability of blockchain technology in Peer-to-Peer (P2P) renewable energy trading. As energy systems shift toward decentralized models, blockchain's secure and transparent nature supports direct transactions between producers and consumers. Scalability remains a key challenge as networks must manage increasing transaction volumes. This study evaluates the performance of Quorum Byzantine Fault Tolerance (QBFT) and Clique within Hyperledger Besu using Hyperledger Caliper. Results show QBFT's superior handling of higher transaction loads with lower latency and higher throughput, highlighting its suitability for high-frequency energy trading and blockchain's potential in decentralized energy systems.

KEYWORDS

Blockchain; Consensus Mechanisms; Quorum Byzantine Fault Tolerance (QBFT); Clique; Peer-to-Peer Renewable Energy Trading; Hyperledger Besu; Scalability; Transaction Latency; Throughput; Decentralized Energy Systems

Sustainable Development Goals (SDG):

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LIST OF ABBREVIATIONS AND ACRONYMS

CDA	**C**ontinuous Double Auction
DC	Direct Current
DER	Distributed Energy Resources
PoA	Proof of Authority
PoEG	Proof of Energy Generation
PoET	Proof of Elapsed Time
PoR	Proof-of-Reserve
PoS	Proof of Stake
PoW	Proof of Work
P2P	Peer-to-Peer
QBFT	Quorum Byzantine Fault Tolerance
SoC	System on a Chip
TPS	Transactions per Second

1. INTRODUCTION

The integration of blockchain technology into the energy sector, in this case in the context of Peer-to-Peer (P2P) Renewable Energy Trading, is gaining considerable attention for its potential to revolutionize energy distribution and consumption. The global energy market is experiencing a shift towards more sustainable and decentralized models of energy production and distribution. The traditional centralized energy systems are increasingly being supplemented by decentralized networks, encouraging local energy generation and direct trading between producers and consumers, driven by the need for more resilient, efficient, and environmentally friendly energy systems (Devi et al., 2023; M. Gupta et al., 2023).

P2P renewable energy trading allows individuals to produce, consume, and trade energy directly with one another, bypassing traditional energy suppliers, not only aiming to increase the financial returns for individual energy producers but also seeks to reduce energy costs for consumers, and by enabling direct transactions, P2P energy trading can enhance energy efficiency and grid stability while fostering a more sustainable energy ecosystem (Sahebi et al., 2023; Zhou et al., 2023).

To support this change in the energy sector, appears blockchain technology, known for its decentralized, secure, and transparent nature, is a natural fit for facilitating this type of trading. This technology provides a reliable platform for recording and verifying transactions, ensuring data integrity and security. Smart contracts, a feature of blockchain technology, automate transaction processes, making energy trading more efficient and less reliant on intermediaries, thereby improving the overall solution (Devi et al., 2023; M. Gupta et al., 2023).

Despite the advantages, one of the critical challenges facing blockchain-based P2P energy trading is scalability (Huang et al., 2022). The ability of a blockchain network to handle an increasing volume of transactions without compromising performance is crucial for its practical implementation. This thesis investigates the scalability of two blockchain consensus mechanisms, Quorum Byzantine Fault Tolerance (QBFT) and Clique, within Hyperledger Besu. By conducting empirical benchmarks using Hyperledger Caliper, this study provide insights into the performance and scalability of these mechanisms in a simulated environment.

2. LITERATURE REVIEW

This literature review investigates two areas in sustainable energy. The review begins with an analysis of Peer-to-Peer (P2P) Renewable Energy Trading, focusing on the market dynamics, challenges, and innovations shaping this sector.

Following this, the review explores blockchain technology, discussing fundamental attributes and implications for data security and transaction efficiency.

The concluding section integrates these two areas, examining the application of blockchain within P2P renewable energy trading. This part specifically assesses how blockchain can enhance scalability and efficiency in these systems.

2.1. PEER-TO-PEER RENEWABLE ENERGY TRADING

Peer-to-Peer (P2P) Renewable Energy Trading is a concept where energy, generated from renewable sources, is traded directly between producers and consumers without the need for traditional intermediaries (Sahebi et al., 2023). These systems aim to facilitate energy exchange between energy producers and consumers, ultimately increasing revenue from electricity sales while reducing consumption expenses (Zhou et al., 2023).

Several methodologies have been proposed to optimize bidding quantities and pricing within these systems. These approaches include predictive control models for bid optimization (Yan et al., 2023), robust optimization frameworks to handle uncertainties in renewable energy generation (Xia et al., 2023), and pricing mechanisms integrating preferences, uncertainties, and local pricing dynamics.

Figure 1 - P2P renewable energy trading model with battery storage

To provide a holistic view of the peer-to-peer renewable energy trading landscape, I have examined foundational concepts and methodologies. Now, shifting the focus to market structure, I explore the roles of different stakeholders in shaping energy exchange systems and introduce the decentralization in this field. To support this, appears blockchain, that is a decentralized technology that is increasingly been integrated into peer-to-peer renewable energy transactions since enhance security, reduce costs, and enable efficient energy exchange (Devi et al., 2023; M. Gupta et al., 2023).

2.1.1. Market Structure

In the ecosystem of peer-to-peer renewable energy trading, the market structure plays an important role. This structure typically involves a range of participants, such as consumers, prosumers, and distributed energy resources (DERs), with the occasional inclusion of a system operator. Prosumers, who own DERs like rooftop solar panels, wind turbines, and battery storage systems, stand out in this landscape. Unlike regular consumers, prosumers have the unique capability to both generate and consume energy. This dual role enables them to engage in direct energy trading with one another, bypassing the need for external regulatory oversight (Kirthiga et al., 2013; Morstyn et al., 2019).

To enhance the efficiency and synergy of these assets, the concept of a community manager emerges. This nonprofit virtual entity coordinates the activities of prosumers, acting in a capacity similar to a system operator (Moret & Pinson, 2019). The community manager's role is ensuring that the market operates smoothly, aligning the objectives and actions of the different stakeholders.

A key aspect of managing this system is understanding the operational schedules and flexibility of prosumers. Their energy generation and consumption patterns can significantly vary throughout the day. Addressing this variability, Sahebi et al. (2023) conducted simulations using real-world data factored in time-dependent limitations and incorporated a range of decentralized generation sources and battery storage options within households. Moret & Pinson (2019) further contribute to this discussion by proposing a comprehensive strategy focused on stabilizing energy distribution and mitigating market uncertainties. They suggest the introduction of a community manager to oversee market operations, ensuring fairness and efficiency through the analysis of market mechanisms.

Another innovative development in this domain is the implementation of a continuous double auction (CDA) mechanism, as suggested by (Esmat et al., 2021). In this system, prosumers participate in energy trading through bilateral agreements within a continuously clearing market. This setup facilitates two types of trading: single products (e.g., Prosumer A sells a fixed amount of energy to Prosumer B for a specific duration) and continuous products (e.g., Prosumer A offers a continuous energy supply over a set period, allowing Prosumer B to purchase varying amounts as needed). This mechanism ensures a flexible and steady energy supply, catering to the fluctuating energy needs of participants.

2.1.2. Technical Challenges

In the P2P renewable energy trading landscape, overcoming technical challenges is crucial for operational success.

Dealing with the unpredictability of renewable energy, Yan et al. (2023) put forward an approach blending robust optimization with fuzzy logic. This method improves the accuracy of energy forecasts, leading to a trading environment that's not only more stable but also predictable, almost like having a clearer roadmap in the often-hazy world of energy predictions. On the other side, Sahebi et al. (2023) turn our attention to microgrids, where the synergy of battery storage and smart meters could be a game changer. This approach is like giving the microgrid a brain upgrade – better decision-making, smoother energy flow, and reliability that just wasn't possible before.

Lastly, Ahmed & Khan (2023) suggest something quite intriguing. By integrating a centralized battery and bringing cryptocurrency into the mix, they're essentially setting the stage for a more engaging, rewarding trading experience. The goal is to make the the system not just work better, but also be more appealing and profitable for everyone involved. A win-win for the energy community.

While Yan et al. (2023) and Sahebi et al. (2023) propose innovative solutions for the unpredictability of renewable energy, there is a need for further research to address the scalability of these solutions in larger grid systems.

2.2. BLOCKCHAIN

Blockchain technology is a distributed ledger system that is both permanent and only allows additions. This system securely archives data and validated transactions across a network of peers. Verified transactions are accumulated into blocks, which are then sequentially attached to the blockchain, much like a distributed database. Figure 2 by Wang & Su (2020), shows a visual representation of how blockchain technology functions, starting with data recorded in chronological order. These data entries are connected sequentially into blocks, forming a chain-like structure with two key properties: immutability and unforgeability. Immutability ensures that data, once added, cannot be altered or deleted, preserving data integrity. The unforgeable nature of the chain ensures security and resistance to tampering. This secure and immutable chain of data blocks is maintained across a distributed network, forming what is known as a distributed ledger.

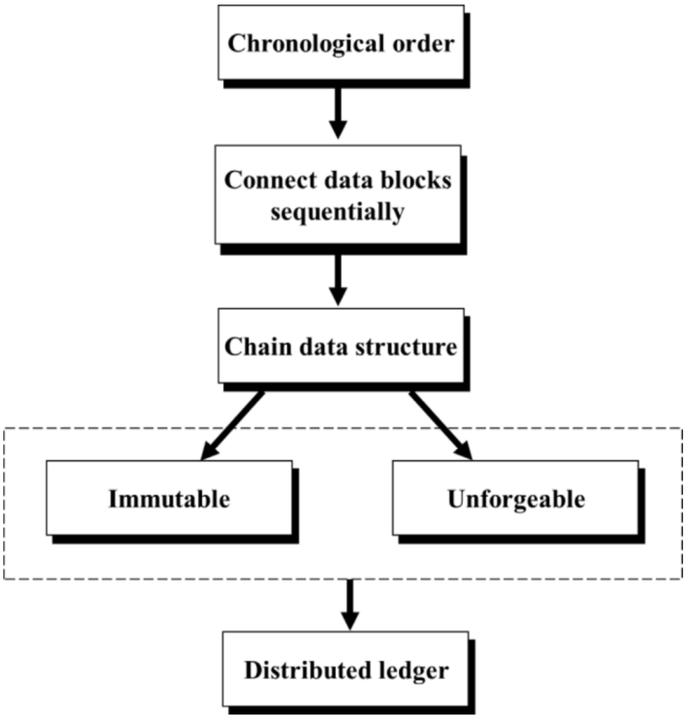

Figure 2 – Narrow data structure of the blockchain (Wang & Su, 2020)

A blockchain is fundamentally a write-only database managed by a distributed network. Primary features include:

- Decentralization Blockchain technology disperses functional operations across an extensive network of computers, eliminating a single point of control or failure and significantly enhancing resilience (Kshetri, 2022).
- Transparency: Each transaction is documented on a publicly accessible ledger, available to all network participants, developing a culture of trust through independent (Devi et al., 2023).
- Immutability Once a transaction is inscribed onto the blockchain, cannot be altered or erased (Kshetri, 2022).
- Security: Advanced cryptographic methods safeguard data, raising the barrier against cyber-attacks. Each block within the blockchain is provided with a unique cryptographic hash, linking it to its predecessor (Oberoi & Raj, 2022).

2.2.1. Data Storage Structure

The data storage structure of a blockchain consists of a linked set of records stored in a decentralized environment (Devi et al., 2023). These records are publicly available but cryptographically secured, making it infeasible to modify the information once recorded (Srivastava & Selvanambi, 2023). A blockchain is generated as a chain of blocks, with each block containing time-stamped digital documents (Malik et al., 2022). The blocks are linked chronologically, with each block comprising a hash of the preceding block, a collection of records, and hashed value records known as a Merkle tree (Khare et al., 2022). The information stored in the blocks varies depending on the blockchain's nature, from transaction details in a bitcoin blockchain to complete health histories in a medical records blockchain (Himanshu, 2022). The blockchain's integrity and strength are preserved through advanced hashing techniques, ensuring its secure distribution.

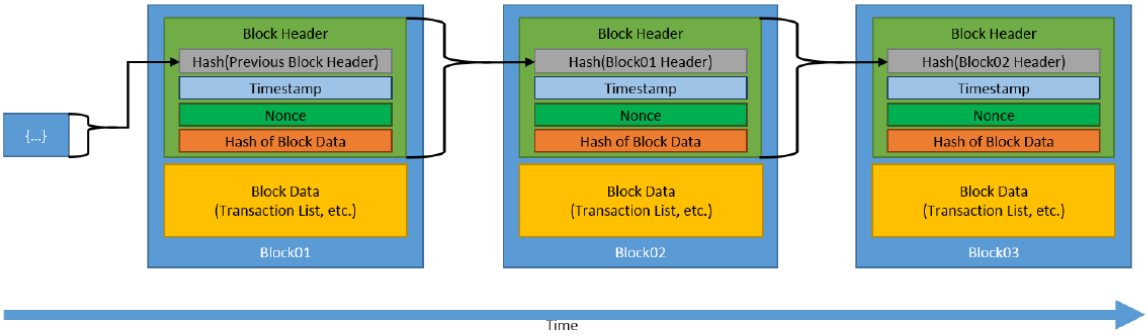

Figure 3 - Chain of Blocks

2.2.2. Categorization

Blockchain networks are categorized into three main types based on their permission models: permissionless, consortium, and permissioned blockchains, each defining specific access levels for adding new blocks (Devi et al., 2023). In a permissionless blockchain, block addition is open to all, much like how the public internet operates with open participation (Aggarwal & Kumar, 2021). Consortium blockchains are also open, but they are limited to a specific group of participants, providing a balance between decentralization and control (Xu et al., 2019). Conversely, a permissioned blockchain limits block addition to certain users, functioning similarly to a controlled corporate intranet. Often used by a consortium of organizations or individuals, permissioned blockchains are important in various contexts. Yaga et al. (2018)

2.2.3. Distributed Ledger

Historically, ledgers recording transactions were physical, penned on paper. They evolved into digital forms, often housed in large databases controlled by a central authority. Recent interest has shifted towards decentralization, enabled by blockchain technology (Reed & Dailey, 2023). Blockchain offers a model where ownership and infrastructure are distributed across an extensive network of computers, driven by concerns over trust, security, and reliability (Barde & Barde, 2023).

In a blockchain network, each participant has a copy of the ledger, which enhances security and resilience against data loss (Khan & Anjum, 2023). New nodes obtain a complete ledger from existing nodes upon joining, ensuring continuity and stability (Dong et al., 2022). The network's strength lies in its widespread, diverse node distribution, ensuring resilience against regional disruptions or attacks. Cryptographic techniques like digital signatures and hash functions make the ledger tamper-proof, enhancing its security (Ahmad et al., 2023).

2.2.4. Transactions

Blockchain transactions are the records of exchanges and their associated metadata that are recorded in blocks on a blockchain (S. Gupta & Sadoghi, 2019). Yaga et al. (2018) emphasize that these transactions extend beyond simple monetary exchanges, involving the transfer of digital currencies across the network's users. The complexity of these transactions is particularly evident in business contexts, where they serve not only as financial exchanges but also as records of interactions with both digital and physical assets. Additionally, Yaga et al. (2018) discuss the importance of continually adding new blocks to the blockchain, a process critical for maintaining the system's structural integrity and security. They note that this constant addition of blocks is a key security feature, effectively preventing any attempts to compromise the blockchain by creating an alternate history.

2.2.5. Cryptography

In blockchain technology, cryptography plays a crucial role. Key elements of this cryptographic framework include hash functions, digital signatures, and asymmetric key cryptography (Ahmad et al., 2023). Specifically, a cryptographic hash function takes various inputs (like data, files, transactions, or blocks) and generates a distinct output (D & Baskaran, 2023). This function is designed to be resistant to collisions and functions in a one-way manner, meaning it's virtually impossible to deduce the original input just from the hash output. This characteristic, often referred to as the avalanche effect, guarantees that it's not feasible to use brute force methods to find an input that matches a particular hash (Herlihy, 2019). In many blockchain systems, SHA-256 is the hash function most frequently employed and as Table 1 shows is a good choice since has a high level of safety (Goyal et al., 2023).

Table 1 - Key Features of Common Cryptographic Hash Functions (Goyal et al., 2023)

Encryption algorithm	*Safety*	*Calculation speed*	*Output size (bit)*
MD5	Low (not secure)	High	128
SHA 1	Medium	Medium	160
SHA 256	High	Low	256
SM3	High	Medium	256

2.2.6. Consensus Mechanism

In distributed computing and blockchain technology, the consensus mechanism is a crucial strategy that allows participants to autonomously validate each block and collectively agree on the network's status and the next block to be added. This approach ensures the integrity and consistency of data in high-reliability systems, such as the Bitcoin blockchain (Liang, 2020; Nakamoto, 2008).

In permissionless blockchain models, Proof of Work (PoW) and Proof of Stake (PoS) are the most common consensus mechanisms (Lewis-Pye & Roughgarden, 2023). PoW, used by the Bitcoin blockchain, requires participants to solve complex computational puzzles to publish the next block, serving as proof of effort and enabling efficient block validation (Yaga et al., 2018). In contrast, PoS, adopted by Ethereum 2.0, selects validators based on their cryptocurrency holdings and willingness to "stake" it as collateral (Grandjean et al., 2023).

When conventional methods like PoW or PoS are insufficient, alternative consensus mechanisms are employed. Proof of Authority (PoA) relies on trusted entities to validate transactions, based on their reputation and identity (Nazir et al., 2023). PoA is favored in permissioned blockchains due to the efficiency in achieving fast consensus with minimal computational resources and energy consumption (Nazir et al., 2023; Wankhede & Patel, 2023).

In this thesis will explore the scalability of these two PoA consensus which are Clique and Quorum Byzantine Fault Tolerance (QBFT):

- Clique consensus protocol is used primarily in private Ethereum networks. Clique designates trusted validators to create new blocks, avoiding the energy-intensive process of mining. Validators, chosen based on their reputation, take turns in a round-robin fashion to create blocks. Voting among validators can modify the set of validators, ensuring flexibility and security. However, Clique does not guarantee immediate finality, which can delay block confirmation (ConsenSys, 2021).
- QBFT is also a PoA consensus mechanism designed for high-security enterprise blockchains. QBFT ensures immediate finality by employing a multi-phase process (proposal, pre-vote, pre-commit) that all validators must agree on before adding a block. This mechanism requires at least four validators to be fault-tolerant, making the consensus suitable for high-throughput applications that demand rapid confirmation and high reliability (Tkachuk et al., 2023).

2.2.7. Smart Contract

The rapid advancement of smart contracts represents the evolution in blockchain technology, extending far beyond the original scope of digital currencies (K. & Kesavamoorthy, 2023).

Smart contracts, enabled by blockchain technology, aim to enhance transaction efficiency and trust by automating contract execution upon meeting predefined conditions, eliminating the need for intermediaries (Darusalam et al., 2023). These contracts, inherently programmable and unalterable once recorded on the blockchain, open a myriad of possibilities in various fields. The brisk expansion of smart contracts, with a notable focus on Ethereum-based implementations, has highlighted substantial security concerns as the permanent nature of blockchain transactions, although a fundamental advantage, also brings to light the critical necessity for flawless operation of smart contracts (Fang et al., 2023). This requirement calls for comprehensive security audits and the development of effective risk detection tools. As the field continues to evolve, it emphasizes the need for ongoing research and the establishment of best practices in smart contract development, ensuring their safe and efficient application in decentralized environments.

2.3. BLOCKCHAIN IN PEER-TO-PEER RENEWABLE ENERGY TRADING

In P2P energy trading, blockchain addresses scalability, security, and decentralization challenges with a layered architecture. At the core, a scalable blockchain foundation enables rapid, frequent transactions. Within this ecosystem, two key roles are essential:

- Network Participants: These are the energy traders - prosumers and consumers - who harness blockchain's capabilities for executing renewable energy transactions. Interestingly, some of these participants double as blockchain validator nodes.
- Blockchain Validator nodes: They are the diligent custodians of transaction accuracy, dedicating their computing prowess to maintain the ledger's integrity.

In this network, participants can either supply excess energy to the grid or draw upon it, balancing their energy equations. Prosumers gain incentives to provide renewable energy, compensated via cryptocurrencies or utility tokens. Consumers, on the other hand, access energy at competitive rates, set in a dynamic market influenced by supply, demand, and the inherent volatility of cryptocurrency values. Alternatively, they can use a fixed token that maintains a consistent value rate (Boumaiza & Sanfilippo, 2023).

Some projects offer a glimpse into this intricate system, where energy pricing adapts to market conditions, encouraging the production of renewable energy. In this vibrant marketplace, prosumers and consumers don their hats as independent traders, setting their own prices. Transactions are facilitated on the blockchain, where smart contracts - the digital arbiters - ensure adherence to predefined rules, recording every nuance of energy exchange on a decentralized ledger, thus ushering in an era of transparency and efficiency, far removed from traditional intermediaries (Boumaiza & Sanfilippo, 2023).

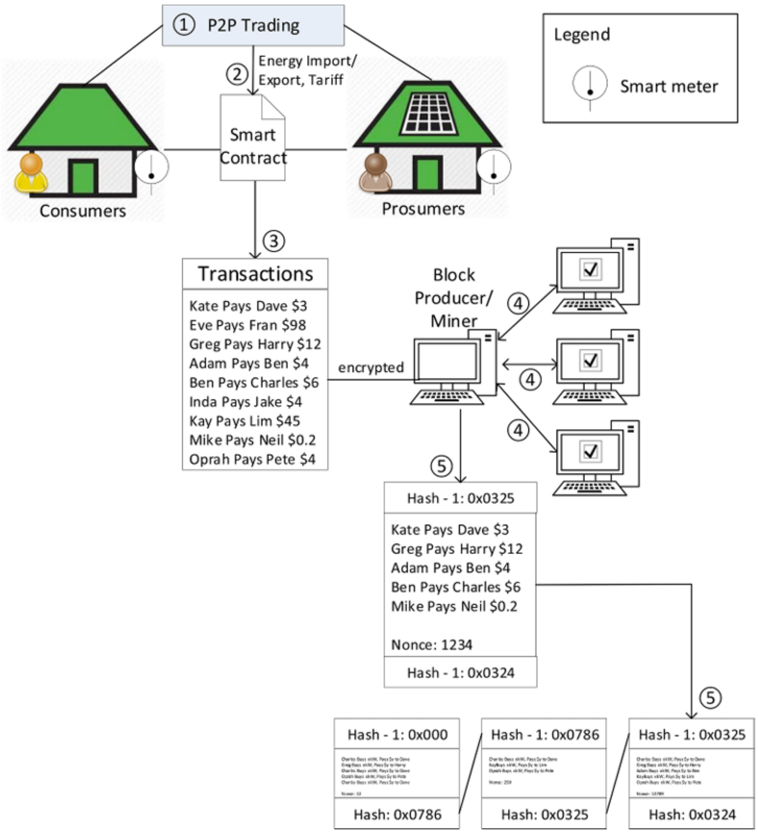

Figure 4 - Overview of blockchain-based P2P trading. (Boumaiza & Sanfilippo, 2023)

As described by Boumaiza & Sanfilippo (2023), Figure 4 shows a P2P renewable energy system blockchain-based flow:

1. Participants engage in a smart contract by depositing a commitment fee and transaction cost into a shared wallet, serving as the contract's holding mechanism. For instance, participants A and B contribute $500 each, representing their investment in the transaction.
2. The transaction, authorized by digital signatures from both parties, is submitted to the blockchain for validation. These signatures, verifiable by public keys, confirm mutual consent for the transaction, with only the participants able to sign using their private keys. The contract can be executed later, with its details recorded on a side chain.
3. The smart contract calculates energy prices, permitting transactions between parties within the limits of their initial commitment.
4. Both parties must mutually agree and sign off on any transactions, with the ability to conduct multiple transactions provided there are sufficient funds in the payment channel.
5. Transactions not on the main blockchain are tracked on a side chain using a proof-of-stake consensus based on the commitment bond. Incentives for maintaining this consensus come from transaction fees, and the side chain's structure expands with increased trading among participants. A fraud-proof mechanism safeguards the

integrity of the chain hierarchy, promoting scalability and minimizing trust dependency through a parent-child chain system.

Numerous real-world projects and academic studies have investigated the application of blockchain technology in P2P energy trading systems. These case studies offer critical insights that help assess the scalability and performance of different consensus mechanisms in my research.

Moniruzzaman et al. (2023) developed a blockchain model for P2P energy trading using the Proof of Energy Generation (PoEG) mechanism on the Avalanche platform. This model ensures accurate energy production validation, facilitating precise transactions and minimizing distribution losses. Their emphasis on validating energy production accurately is crucial for sustaining transaction integrity, particularly in high-frequency trading environments

Choobineh et al. (2023) explored a blockchain-based marketplace for P2P solar energy trading, employing the Proof of Reserve (PoR) consensus mechanism. PoR merges Proof of Stake and Proof of Work to enhance transaction efficiency and equity while reducing energy consumption. This research highlights the potential of hybrid consensus mechanisms to improve transaction efficiency, offering a framework for understanding how different consensus strategies can be optimized

Y. Gupta et al. (2021) introduced HELIUS, a blockchain system tailored to optimize P2P energy exchanges during peak demand periods. HELIUS combines a blockchain ledger with predictive models for energy production and consumption, along with a dynamic energy trading mechanism. This example demonstrates effective management of dynamic, high load trading situations, directly informing my evaluation of transaction latency and throughput.

2.3.1.1. Hyperledger Caliper

Hyperledger Caliper is a benchmarking tool for assessing private or permissioned blockchain systems like Hyperledger Fabric, Besu, Ethereum, and FISCO BCOS. Caliper compares different blockchain architectures under standardized conditions, monitoring key metrics such as transaction speed, delay times, system efficiency, and resource usage (CPU and memory).

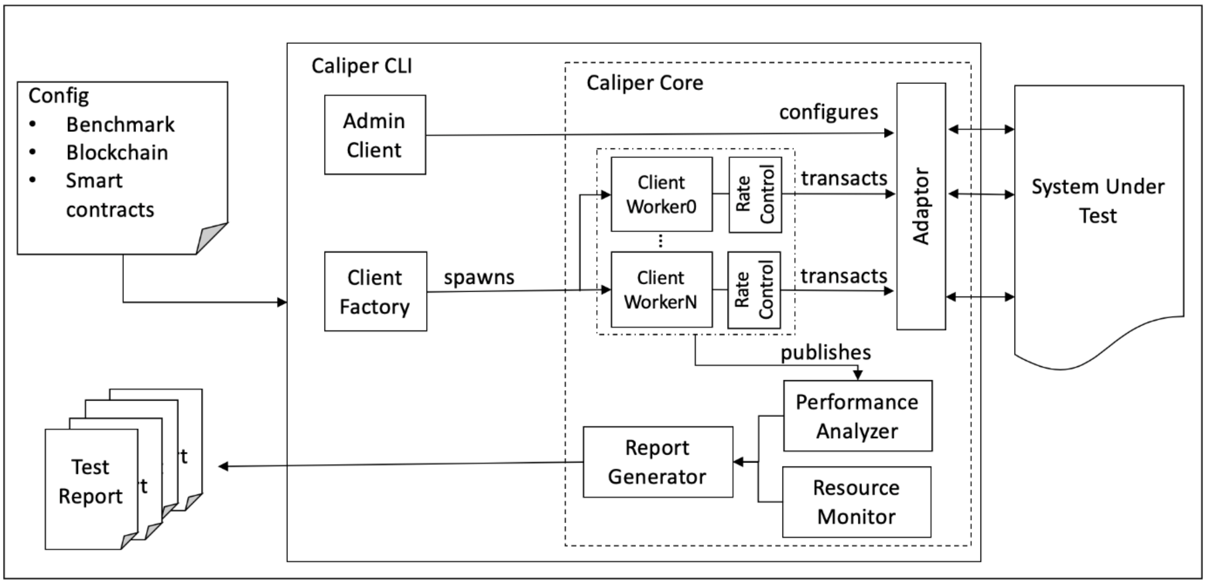

Figure 5 - Hyperledger Capiler Architecture

To illustrate the practical applications of Hyperledger Caliper, several studies have utilized this tool to benchmark different blockchain systems in energy trading scenarios. For instance, Triadi et al. (2023) developed a blockchain system using Hyperledger Fabric 2.0, structuring the network into three entities and testing performance at transaction rates of 50, 100, and 200 transactions per second. By integrating IoT components like a solar panel, the system effectively handled 1000 transactions, demonstrating increased latency at higher transaction rates but stable query latency. This study underscores the importance of assessing how blockchain networks handle varying loads.

Building on this, Pradhan & Singh (2021) created a peer-to-peer energy trading framework using Hyperledger Sawtooth and the Proof of Elapsed Time (PoET) consensus mechanism. They implemented a JavaScript-based smart contract to record energy transactions. PoET consensus managed to process 946 out of 1000 transactions, outperforming Proof of Work (PoW) in terms of efficiency. The study focused on performance metrics such as transaction rate, latency, throughput, and CPU usage, all analysed using Hyperledger Caliper, highlighting how different consensus mechanisms impact performance

Jamil et al. (2021), introduced a blockchain platform designed for energy trading within smart grids. Their system featured real-time trading and predictive analytics, utilizing historical data from Jeju, South Korea, to optimize power flow between consumers and prosumers. Performance analysis with Hyperledger Caliper focused on latency, throughput, and resource utilization. This example showcases the practical application of blockchain technology in real-world energy markets and the critical role of performance benchmarking in identifying the most efficient configurations.

2.3.1.2. Real World Projects

2.3.1.2.1. Brooklyn Microgrid

The Brooklyn Microgrid project in New York, by LO3 Energy, merges a physical microgrid with a virtual energy market. This setup provides reliable power during emergencies and facilitates dynamic energy trading between consumers and renewable energy producers using a private blockchain and smart technology. However, the market systems, particularly in allocation and pricing, need more development for optimal performance in the energy sector (Mengelkamp et al., 2018).

2.4. RESEARCH GAP

Blockchain technology has made significant progress in P2P energy trading, but there is still a gap in understanding the scalability of different blockchain consensus mechanisms. This thesis addresses this by analyzing how QBFT and Clique can be effectively scaled within Hyperledger Besu. Understanding the scalability of these mechanisms is crucial for practical implementation, as it impacts the feasibility of blockchain-based P2P energy trading systems in real-world, high-frequency environments. My research will provide insights into the application of blockchain in P2P renewable energy trading, focusing on the importance of scalability for future developments.

3. METHODOLOGY

3.1. INTRODUCTION

This thesis aims to assess the scalability of blockchain consensus algorithms, in this case QBFT and Clique, within Hyperledger Besu's simulated P2P renewable energy trading environment. I follow the approach of (Pradhan & Singh, 2021) but this scalability study focuses on Transaction Throughput and Latency, as the transactions per second (TPS) increase, while keeping the total number of transactions constant. The benchmark was done using Hyperledger Caliper.

Figure 6 – Methodology Flow Diagram

3.1.1. Network Model

1. Node: Co-located nodes participate in the network by transmitting messages and transactions, contributing to consensus building through either Clique or QBFT mechanisms, and maintaining a version of the distributed ledger.

2. Smart Contracts: Rule for the system energy trading, facilitating transactions among prosumers, consumers, and utilities. The validators run these contracts, confirming that all transactions follow the established rules.

3. Transactions and Blocks: Transactions between prosumers and consumers are done according to the smart contract stipulations. Each transaction is securely signed with private keys and subjected to validation under the consensus algorithm in use (either QBFT or Clique).

3.1.2. Participants

1. Prosumers: In this system, prosumers are defined as participants who produce and consume energy, primarily generating power through DERs like solar panels.
2. Consumer: Individuals who purchase energy to meet their demands, participating in the energy market to procure renewable energy from producers directly.

3.1.3. Energy trading smart contract

To establish the market rules, a smart contract was implemented to create the logical framework for this P2P blockchain marketplace. The smart contract accommodates essential interactions between households in energy generation, consumption, and trading.

Table 2 – Energy Smart Contract Overview

Component	Description
Structs	• **EnergyRecord**: Represents energy generation or consumption with fields for the energy amount, timestamp, and household ID. • **EnergyOffer**: Represents an offer to sell energy, detailing the energy amount, price per unit, household ID, and availability status.
Arrays	• **generationRecords**: Stores records of energy generated by households. • **consumptionRecords**: Stores records of energy consumed by households. • **energyOffers**: Stores offers for energy sales made by households.
Functions	• **recordGeneration(_amount, _householdId)**: Logs energy generation with the given amount and household ID. • **recordConsumption(_amount, _householdId)**: Logs energy consumption with the given amount and household ID. • **createEnergyOffer(_amount, _pricePerUnit, _householdId)**: Creates an offer for selling energy, specifying the amount, price per unit, and household ID. • **tradeEnergy(offerId, buyerHouseholdId)**: Executes a trade of energy, marking the offer as sold and logging the consumption for the buyer.
Functionality	• **Recording**: Logs energy generation and consumption with timestamps for accurate tracking. • **Energy Offering**: Allows households to offer surplus energy for sale at specified prices.

	- **Energy Trading**: Facilitates energy trading between households, updating records to reflect transactions.
Logic Flow	- Generation and Consumption: Energy activities (generation and consumption) are logged with timestamps as they occur. - Offer Creation: Households with surplus energy can create offers for sale. - Trading Process: Energy offers can be accepted by other households, transferring energy to the buyer, and marking the offer as completed.

3.2. IMPLEMENTATION

This section describes the deployment of the testing environment.

3.2.1. Deploying Besu network

To deploy Hyperledger Besu on Ubuntu 22.04 using the GoQuorum Developer Quickstart, Docker, Docker Compose, and Node.js were first installed. Every step followed the official documentation available on the Hyperledger Besu website. Two separate machines were deployed to differentiate QBFT and Clique.

Table 3 – Requirements and Specifications of the Private Blockchain

Requirements	Specifications
Operating System	Ubuntu Linux 22.04
Hyperledger Besu	
Docker engine	26.0.0
Docker Composer	2.25.0
Node.js	20.11.1
Metamask	
cURL Tool	7.81.0

3.2.1.1. Configuring the network

The first step was to generate the test blockchain configuration files and choose to deploy Besu. To enable the network to process multiple transactions from a single account, the quorum-test-network's config.toml file was modified by adding tx-pool-limit-by-account-percentage="1".

3.2.2. Deploying energy trading contract on the Private Network

To connect the private Besu network with MetaMask, a network matching the new RPC URL and the Chain ID provided in the genesis file was manually added. The energy-trading smart contract was then established by connecting the Remix IDE and MetaMask.

3.2.3. Hyperledger Caliper

3.2.3.1. Workload Module

A Workload Module was added to mimic the P2P network environment, simulating transactions, and interacting with the smart contract to define market behavior. This script simulates transactions, randomly executing actions like energy generation, consumption, creating offers for selling energy, and trading energy between households (18 prosumers and 2 consumers).

Table 4 – Energy Transaction Workload

Section	**Description**
Overview	• Initialization: Defines two groups of households: prosumers (IDs 1-18) and consumers (IDs 19-20). • WorkloadModuleBase: Extends *WorkloadModuleBase* from Hyperledger Caliper for custom transaction simulations.
Key Methods	• ***constructor()***: Initializes transaction index. • ***initializeWorkloadModule()***: Sets up module with Caliper. • ***_createEnergyOffer()***: Simulates creation of an energy offer. • ***_tradeEnergy()***: Simulates an energy trade. • ***submitTransaction()***: Submits transactions based on random selections.
Transaction Types	• Record Generation: Records energy generation by prosumers. Assumes generation data is collected over time. • Record Consumption: Records energy consumption. • Create Energy Offer: Creates a market offer by prosumers. Assumes energy has been previously generated and is available for sale • Trade Energy: Simulates energy trade.

Logic Flow	***submitTransaction()*** method randomly chooses transactions to simulate the energy trading scenario. The method decides the type of household involved, the amount of energy, and the action type.

3.2.3.2. Benchmarking

The benchmark was conducted with a fixed number of 1000 transactions, while gradually increasing the TPS (Transactions per second) from 50 to 150 to 250 to observe the corresponding changes in latency and throughput. The report generated by Caliper measured three parameters:

Table 5- Scalability Analysis: Benchmarking Energy TransactionWorkload

Transaction Type	**Description**
Open (Household Registration)	Onboarding new households or energy producers/consumers
Query (Energy Offer Management)	Checking the current energy offers available, verifying the energy generation or consumption records of a particular household, or getting the latest prices of energy
Transfer (Energy Trading)	Executing a trade between two parties, transferring ownership of a certain amount of energy from a seller to a buyer and handling the payment

To conduct a scalability analysis, the progression of the average latency and throughput in the three parameters (open, query, and transfer) as the number of TPS increases was compared.

4. RESULTS AND DISCUSSION

This chapter presents the benchmark results of the proposed P2P Energy Trading System, followed by an analysis and discussion.

4.1. BENCHMARK RESULTS

Table 6 summarizes the metrics of the system under different configurations using the QBFT and Clique consensus algorithms.

Table 6 – Comparison of the System Under Test

Name	No. of TXs	Success	Send rate (TPS)	Avg Latency (s)	Throughput (TPS)
QBFT (Open)	1000	1000	50, 150, 250	7.88, 7.99, 8.21	49, 133, 181
Clique (Open)	1000	944	50, 150, 250	13.12, 14.29, 14.51	41, 113, 157
QBFT (Query)	1000	1000	50, 150, 250	5.00, 5.18, 5.21	46, 141, 166
Clique (Query)	1000	1000	50, 150, 250	11.65, 12.08, 12.73	41, 69, 98
QBFT (Transfer)	1000	959	50, 150, 250	5.45, 5.62, 5.90	44, 63, 72
Clique (Transfer)	1000	924	50, 150, 250	13.39, 14.61, 15.49	29, 37, 44

4.1.1. Analysis of Results

4.1.1.1. Household Registration Latency (Open)

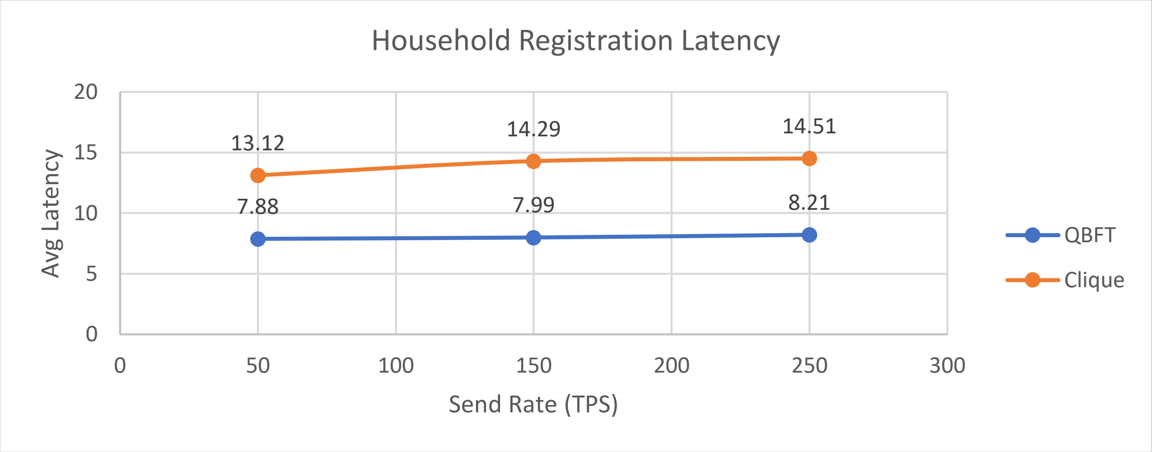

Figure 7 - Household Registration Latency

The results indicated that QBFT's latency showed a minor increase of about 1.40% when TPS rose from 50 to 150, and a slightly larger increase of 2.75% when TPS increased from 150 to 250. Specifically, QBFT's latency moved from 7.88s at 50 TPS to 7.99s at 150 TPS, and then to 8.21s at 250 TPS. Conversely, Clique's latency increased more significantly by approximately 8.92% from 50 to 150 TPS, and by 1.54% from 150 to 250 TPS. Clique's latency values were

13.12s at 50 TPS, 14.29s at 150 TPS, and 14.51s at 250 TPS. These observations suggest that QBFT manages latency better as TPS increases, indicating superior scalability.

4.1.1.2. Energy Offer Management Latency (Query)

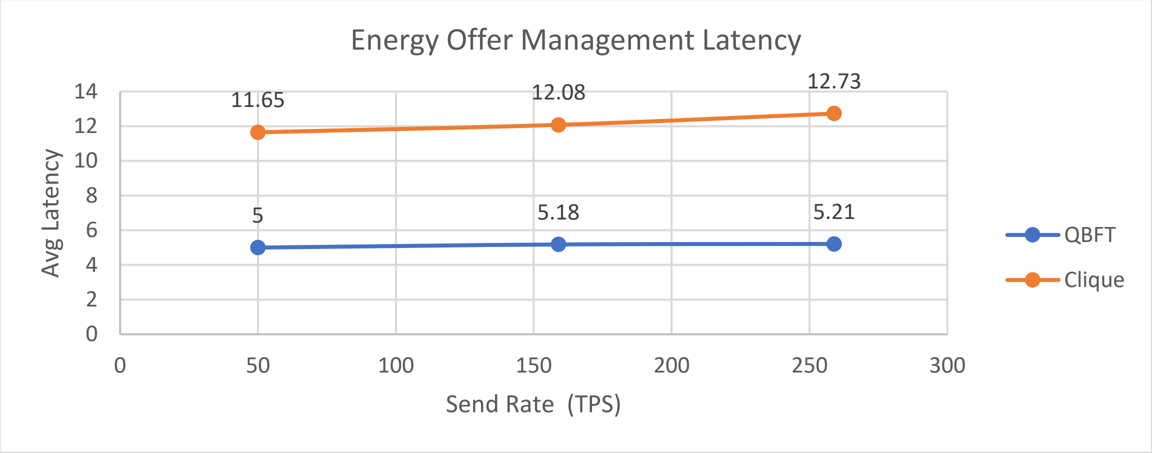

Figure 8 - Energy Offer Management Latency

For the Query workload, QBFT displayed a latency increase of about 3.60% when TPS climbed from 50 to 150, and a marginal increase of 0.58% when TPS went from 150 to 250. Specifically, QBFT's latency shifted from 5.00s at 50 TPS to 5.18s at 150 TPS, and then to 5.21s at 250 TPS. Clique, in contrast, exhibited a latency increase of approximately 3.69% from 50 to 150 TPS, and 5.38% from 150 to 250 TPS. Clique's latency values were 11.65s at 50 TPS, 12.08s at 150 TPS, and 12.73s at 250 TPS. Clique, shows a noticeable latency escalation, particularly between 150 and 250 TPS, suggesting less efficiency in handling higher transaction volumes

4.1.1.3. Energy Trading Latency (Transfer)

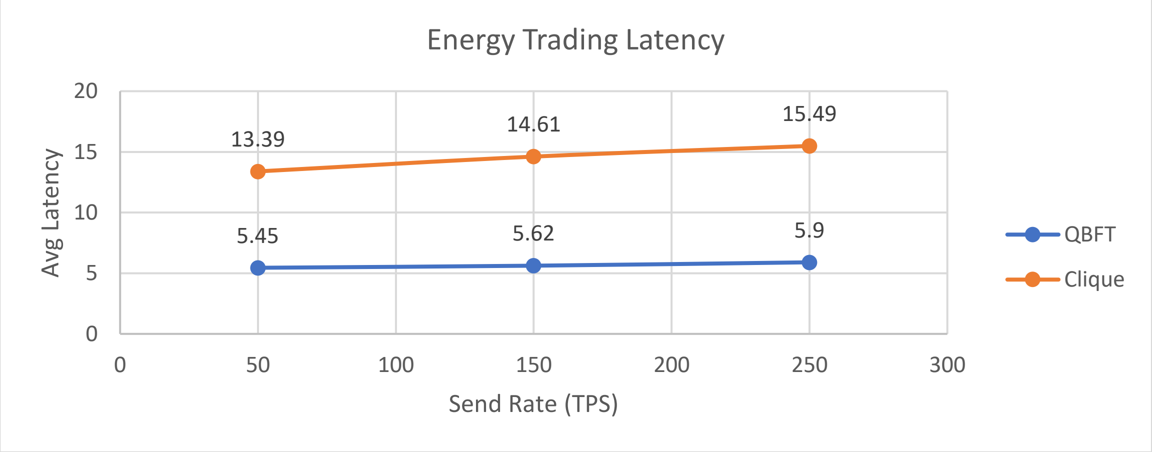

Figure 9 - Energy Trading Latency

In the Transfer scenario, QBFT's latency increased moderately by approximately 3.12% when TPS grew from 50 to 150, and by 4.98% when TPS rose from 150 to 250. QBFT's latency went from 5.45s at 50 TPS to 5.62s at 150 TPS, and then to 5.90s at 250 TPS. Clique's latency increased by about 9.08% from 50 to 150 TPS, and 6.02% from 150 to 250 TPS. Clique's latency values were 13.39s at 50 TPS, 14.61s at 150 TPS, and 15.49s at 250 TPS. The results suggest that while both consensus algorithms see increased latency with higher TPS, QBFT's latency increase is more controlled.

4.1.1.4. Household Registration Throughput (Open)

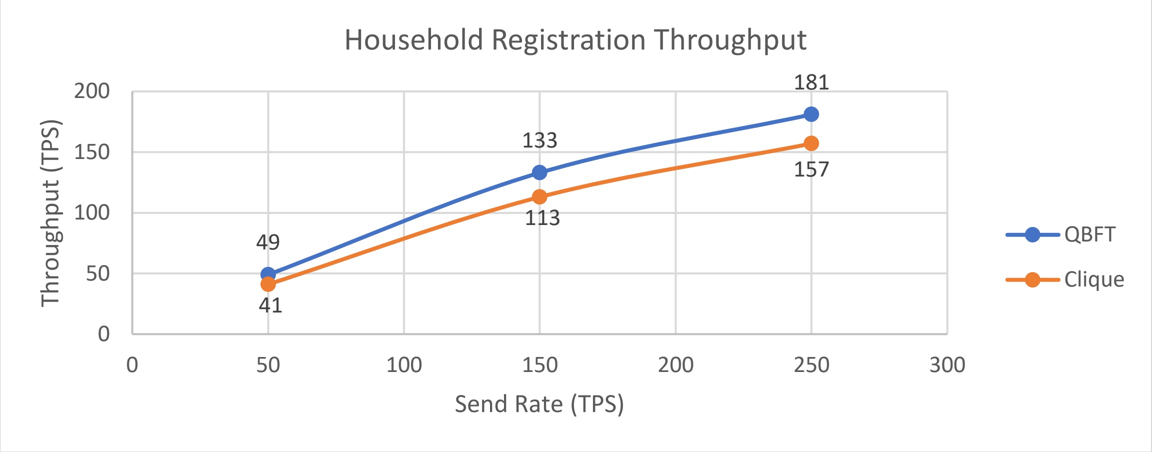

Figure 10 - Household Registration Throughput

QBFT's throughput exhibited a substantial increase of about 166% when TPS rose from 50 to 150, and an additional 36.09% when TPS went from 150 to 250. QBFT's throughput improved from 50 TPS at 50 TPS to 133 TPS at 150 TPS, and then to 181 TPS at 250 TPS. Clique's throughput, on the other hand, increased by approximately 175.61% from 50 to 150 TPS, and by 38.94% from 150 to 250 TPS. Clique's throughput values were 41 TPS at 50 TPS, 113 TPS at 150 TPS, and 157 TPS at 250 TPS. Both consensus algorithms show improved throughput with increasing TPS, but QBFT's performance indicates more consistent scalability, handling higher transaction volumes more effectively.

4.1.1.5. Energy Offer Management Throughput (Query)

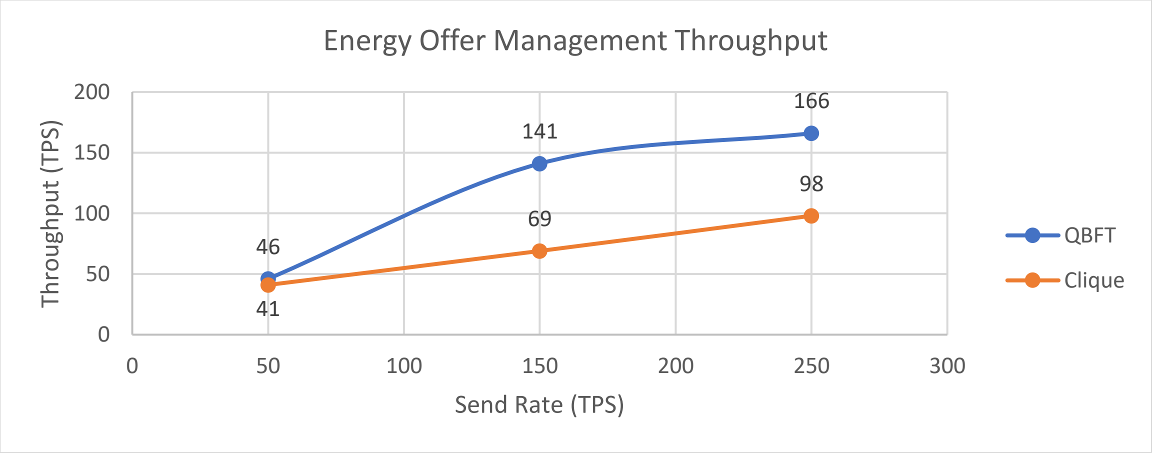

Figure 11 - Energy Offer Management Throughput

QBFT's throughput increased dramatically by about 206.52% when TPS rose from 50 to 150, and by 17.73% when TPS increased from 150 to 250. QBFT's throughput improved from 46 TPS at 50 TPS to 141 TPS at 150 TPS, and then to 166 TPS at 250 TPS. Clique's throughput, increased by approximately 68.29% from 50 to 150 TPS, and by 42.03% from 150 to 250 TPS. Clique's throughput values were 41 TPS at 50 TPS, 69 TPS at 150 TPS, and 98 TPS at 250 TPS. Again, these findings indicate that QBFT significantly outperforms Clique in throughput scalability for Energy Offer Management.

4.1.1.6. Energy Trading Throughput (Transfer)

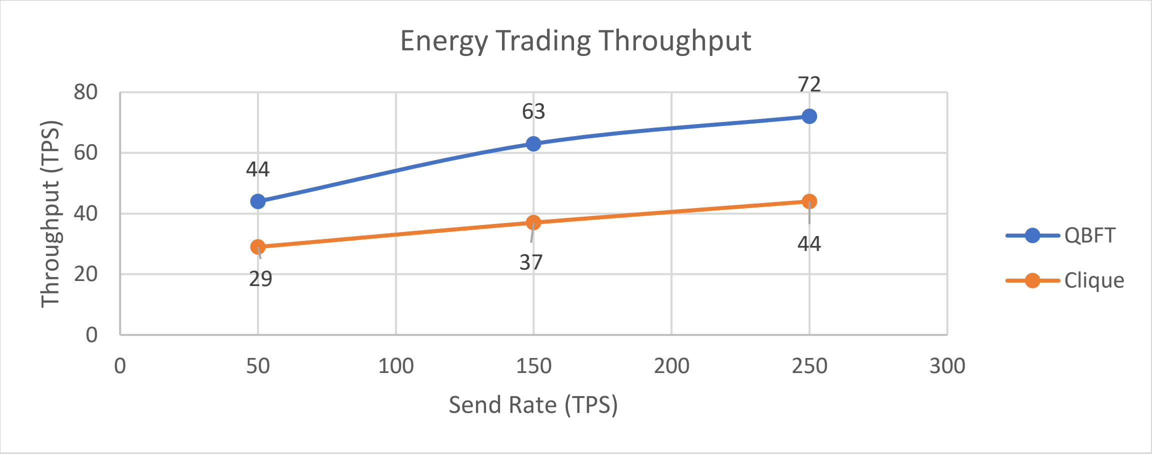

Figure 12 - Energy Trading Throughput

QBFT's throughput increased by approximately 43.18% when TPS rose from 50 to 150, and by 14.29% when TPS went from 150 to 250. QBFT's throughput improved from 44 TPS at 50 TPS to 63 TPS at 150 TPS, and then to 72 TPS at 250 TPS. Clique's throughput, meanwhile, increased by approximately 27.59% from 50 to 150 TPS, and by 18.92% from 150 to 250 TPS. Clique's throughput values were 29 TPS at 50 TPS, 37 TPS at 150 TPS, and 44 TPS at 250 TPS. As in all other scenarios, QBFT offers better scalability, maintaining higher throughput levels as TPS increases, whereas Clique's smaller percentage increases indicate more limited scalability.

4.2. DISCUSSION

The results indicate that QBFT consensus algorithm outperforms Clique in terms of scalability in the proposed P2P Energy Trading System. To understand the reasons behind these performance differences, it is essential to examine the technical details of the consensus mechanisms as reflected in their configuration files and how these settings impact network performance.

A consensus mechanism's configuration file sets critical parameters such as block time, epoch length, and timeout settings. These configurations significantly influence the efficiency and performance of the blockchain network. And by comparing the configuration files for QBFT and Clique, we can identify the key factors contributing to their differing performance:

- In the QBFT configuration file, the block period is set to 2 seconds, and the request timeout is set to 4 seconds, with an epoch length of 30,000 blocks. These settings are designed to optimize the consensus process, allowing for faster and more reliable transaction processing. The shorter block period of 2 seconds means that QBFT can process and confirm transactions much more quickly. Every 2 seconds, a new block can be added to the blockchain, significantly reducing the time users wait for their transactions to be confirmed.
- On the opposite side, Clique configuration file sets the block period to 15 seconds, also with an epoch length of 30,000 blocks. This longer block period inherently slows down transaction processing and consensus. With a 15-second interval between blocks, transactions take longer to be included in a block, leading to higher latency. This slower block generation rate means fewer transactions are processed over the same period compared to QBFT.

The request timeout parameter, unique to QBFT, sets a limit on how long the network waits for consensus messages from other nodes. Setting this to 4 seconds ensures that consensus is reached quickly, even if there are network delays. This contributes to QBFT's lower latency and higher throughput, as it efficiently handles network communication and quickly reaches consensus. It is important to note that the latency in a blockchain network is influenced not only by the request timeout but also by other factors such as network propagation time and processing delays. Therefore, while the request timeout is 4 seconds, the overall transaction latency can be higher due to these additional factors.

In terms of latency, QBFT consistently shows lower latency because its shorter block period and efficient consensus process ensure that transactions are confirmed faster. For instance, during Household Registration (Open), QBFT's latency increase is minimal even as the transaction load increases. Clique, however, experiences higher latency due to its longer block period, causing delays in transaction confirmation, especially under high transaction loads.

Regarding throughput, QBFT achieves higher throughput because it can process more transactions within a given time frame. The rapid block generation every 2 seconds allows the network to handle more transactions, resulting in higher transactions per second. Clique's lower throughput is due to its slower block generation rate, with the 15-second interval limiting the number of transactions included in each block, thereby reducing the overall transaction rate.

The consensus mechanism configurations play a role in determining the performance of a blockchain network. QBFT’s shorter block period and efficient consensus timeout settings enable it to handle higher transaction volumes with lower latency, making it better suited for dynamic, high-frequency applications like P2P energy trading. On the other hand, Clique's longer block period results in higher latency and lower throughput, limiting its scalability under heavy transaction loads. This analysis confirms QBFT's advantages in maintaining efficiency and scalability under high transaction volumes, making it the preferred choice for the requirements of this P2P energy trading system.

5. LIMITATIONS

The benchmark results and analysis offer valuable insights into the scalability and performance of QBFT and Clique consensus algorithms within the P2P energy trading system. However, several limitations should be acknowledged.

First, the benchmarks were conducted using virtual machines. Despite the efforts made to ensure similar specifications, performance variations could still occur due to differences in underlying hardware, network latency, and virtualization overhead. Additionally, the tests were performed at different times, which could affect result consistency due to external factors like network traffic, server load, and background processes on the virtual machines during testing.

Second, the testing environment was simulated and may not perfectly reflect real-world conditions. The network topology, geographic distribution of nodes, and user behavior were simplified. In actual deployments, nodes would be spread across various locations with varying network conditions, potentially affecting consensus mechanism performance differently than observed in this study. In this experiment, nodes were co-located, operating in close physical proximity. In real-world blockchain applications, nodes would be geographically distributed.

Third, this study evaluated the performance of consensus algorithms at specific TPS levels (50, 150, 250). While these levels provide useful insights into scalability, they do not cover the entire spectrum of possible transaction loads.

Finally, the energy trading smart contract and market dynamics were simplified for this study. Real-world energy markets are complex and involve different regulatory, economic, and technical factors not fully captured in this simulation. These simplifications might limit the applicability of the findings to more complex, real-world scenarios.

6. CONCLUSIONS AND FUTURE WORKS

The integration of blockchain technology into the P2P renewable energy trading market presents significant opportunities for enhancing energy distribution, consumption efficiency, and grid stability. This thesis explored the scalability and performance of two blockchain consensus mechanisms, Quorum Byzantine Fault Tolerance (QBFT) and Clique, within Hyperledger Besu, using empirical benchmarks via Hyperledger Caliper.

The results revealed that QBFT outperforms Clique in scalability and overall performance. QBFT demonstrated lower latency and higher throughput across different transaction types, showing minimal increases in latency and significant improvements in throughput as transaction loads increased. This is attributed to QBFT’s shorter block period and efficient consensus process, which allows for faster transaction processing and quicker consensus achievement. Clique revealed higher latency and lower throughput due to its longer block period, which inherently slows down transaction processing and consensus. As transaction loads increased, Clique struggled to maintain performance, highlighting its limitations in handling high transaction volumes.

These findings underscore QBFT's suitability for dynamic, high-frequency applications such as P2P energy trading, where efficient transaction processing and scalability are critical. The robust performance of QBFT in maintaining stability and efficiency under increasing transaction loads positions it as a preferred choice for scalable blockchain-based energy trading systems.

However, the study's limitations, including potential variability in virtual machine performance and the simulated testing environment, should be considered when interpreting the results. Future research should aim to standardize test environments and explore higher transaction per second (TPS) levels to fully understand the scalability potential and limitations of these consensus mechanisms. Another limitation when comparing with real-life applications is that during this experiment, the nodes were co-located, whereas in real-life blockchain applications, the nodes should be distributed.

This work contributes valuable insights into the practical implementation of blockchain in P2P renewable energy trading, highlighting QBFT's superior scalability and performance in a small community setting.

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