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Blockchain System for Transparent Management of Smart Grids: Study and Hybrid Ethereum-Hyperledger Model

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Abstract

The management of smart grids requires enhanced transparency and efficient optimization of energy transactions. While blockchain technology is widely used to ensure traceability and decentralization, existing solutions primarily focus on commercial aspects, often overlooking detailed monitoring of energy flows. This study proposes a hybrid blockchain model combining Ethereum and Hyperledger Fabric to integrate secure transaction execution with real-time energy flow tracking. The adopted approach involves identifying key components of decentralized energy management, conducting a comparative analysis of blockchain architectures, and performing experimental simulations to evaluate their performance in terms of latency, security, and scalability. Specific metrics, such as transaction throughput, block validation time, and energy data granularity, were utilized to assess the efficiency of the proposed model. The results demonstrate that Hyperledger Fabric excels in energy flow monitoring and auditability, whereas Ethereum optimizes transaction execution through its consensus mechanism and broad adoption. The integration of both technologies enables optimal complementarity, ensuring effective interoperability and significantly improving overall system transparency and efficiency. The proposed hybrid model establishes a scalable and resilient architecture that enhances coordination among network participants and optimizes energy governance. It fosters trust among stakeholders by ensuring the integrity and immutability of exchanges while enhancing the management of distributed energy resources. By integrating Ethereum and Hyperledger Fabric, this solution provides an innovative and applicable framework for decentralized energy infrastructures, optimizing transaction management, improving energy flow traceability, and reinforcing the resilience of smart grids against increasing demands for flexibility and sustainability.

Keywords: Blockchain, energy transparency, Ethereum, Hyperledger Fabric, smart grids.

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1. Introduction

Electricity is known as a vector for development, as the majority of equipment used by humans today, and for the production of consumer goods, transportation, and other purposes, fundamentally relies on electricity. The generation, transmission, distribution, and management of electricity are therefore critical for everyone. The sources of energy production are highly variable, ranging from polluting to non-polluting, with today's trend focusing on integrating all sources into the electrical distribution grid. The new trend is to allow both producers and consumers dispersed throughout the grid to participate in the electricity distribution network.

This shift allows consumers to also become producers of electricity (from various non-polluting sources, especially photovoltaic, wind, or biomass), injecting surplus energy back into the grid. Whereas the network used to belong to a single supplier responsible for controlling production and consumers, today's network must manage not only production and consumer needs but also small-scale producers with whom contracts must be established to control both what is injected into the grid and how it is injected, as well as the profitability of this system for each participant in this new distribution-consumption model of electricity.

To better manage the production, distribution, injection points, and billing of activities within this vast electrical grid, we arrive at the concept of the "smart grid." This refers to an electricity distribution network that facilitates the exchange of information between suppliers and consumers in order to adjust the electricity flow in real-time and allow for more efficient management. Smart grids employ IT techniques to optimize energy production, distribution, consumption, and potentially storage, thus enabling better coordination across the entire electrical network, from producers to end-users. It improves overall energy efficiency by minimizing transmission losses and optimizing the efficiency of the production methods used in relation to real-time consumption.

Smart grids are also considered a means of reducing greenhouse gas emissions and combating climate change, making them a key element of the smart city concept. To account for the various points in the grid, both in terms of managing the electricity produced and managing contracts with small suppliers in an extensible and scalable distributed system, it is important to introduce algorithms to monitor and meet the needs of the different actors in the network. This brings us to the concept of blockchain, originally developed as a decentralized system equipped with tools to monitor the status of fixed points in a vast network with distributed and variable data, similar to distributed databases. This structure perfectly aligns with that of a smart grid.

A blockchain is a digital technology for storing and transmitting information without a central authority, initially developed for the Bitcoin system but later expanded to other applications. Technically, it is a distributed database, where the information sent by users and the internal links within the database are verified and then grouped into "blocks" at regular intervals, forming a progressively longer chain. The entire system is secured by cryptography. A blockchain, by extension, is a distributed database that manages a list of records that are theoretically tamper-proof or resistant to modification by storage nodes, making it a secure distributed ledger of all transactions since the launch of the distributed system.

Thus, in a smart grid, the different actors, whether consumers or producers (referred to as prosumers), constitute nodes in the electricity production and distribution chain, with databases of information that vary over time, requiring autonomous monitoring and payments for the electricity injected as needed. Speaking of payments, the payment methods are also varied, ranging from traditional banking currencies to new methods of payment for services and goods, such as cryptocurrencies. Popular standards include Bitcoin, Ethereum, Dogecoin, Solana, XRP Ledger, etc.

A smart grid takes into account the actions of all components and actors, thus forming a peer-to-peer network that optimizes electricity distribution, minimizes losses, and ensures a high-quality and secure supply [1]. In smart grids, all components work together to ensure the efficient operation and management of electrical systems [2], allowing them to play a crucial role in promoting sustainable development and offering solutions to the growing energy challenges faced by urban populations [3]. Smart grids are emerging as the networks of the future. The active involvement of all network members creates a new form of energy community, requiring an energy management method that optimizes exchanges within the community and establishes a framework of trust. This drives the need to develop new roles and market platforms, encouraging active participation from end-users and facilitating their direct interaction. The goal is to maximize demand-side resources, balance supply and demand locally, and offer economic opportunities to users through the sharing and use of clean, locally produced energy [4]. This approach fosters a decentralized management of smart grids.

The decentralized management of an electricity grid enhances the autonomy, independence, and equity of the end-user within the system [5]. As a result, new forms of energy transaction management are being proposed to establish and strengthen this trust between actors. Most of this work focuses primarily on the commercial aspect and how these transactions are managed [4, 6-9]. Trust and strong bonds within an energy community should not only rely on commercial transparency but also on the transparency of the shared and consumed energy. It is therefore crucial to conduct an in-depth study and identify the best management approach to foster a true climate of trust, ensuring the sustainability of this network.

Blockchain plays a crucial role in this decentralized management process and in establishing a climate of trust. Shahinzadeh et al. [10] examine the use of blockchain in energy transactions at the distribution level, highlighting the challenges of energy source transparency and the importance of tracing energy flows. They conclude that tracing is essential to ensure transparency and verify the reliability of energy transactions. The decentralized management aspect has been addressed by Khalid et al. [6]; Li et al. [11] and Yang et al. [12] with the goal of enabling all stakeholders to participate in grid management and access a complete view of all information. All these studies have been conducted with different blockchain platforms. To meet the expectations of a more comprehensive view of both the commercial aspects and energy flow tracking, it is essential to consider a blockchain system capable of addressing these requirements simultaneously.

In this perspective, we highlight the key aspects of a blockchain-based smart grid management model. A blockchain system has been defined to integrate the commercial dimensions as well as energy flow tracking in order to enhance transparency and establish increased trust within the smart grid. The main contributions are summarized as follows:

(1) Identification of key aspects of a blockchain-based smart grid management model.

(2) Definition of criteria for selecting the appropriate blockchain type and system.

(3) Comparative analysis of multiple blockchain systems.

(4) Proposal for a suitable blockchain system for this management model.

(5) Performance validation through practical tests.

The paper is structured as follows: Section II presents a literature review, while Section III explores the different aspects of the blockchain-based smart grid management model. Section IV identifies the most suitable blockchain system for optimal smart grid management. The results and their discussion are presented in Section V, and finally, the conclusion is presented in Section VI.

2. Literature Review

2.1. Blockchain, Operating Principle and Characteristics

The technology known as blockchain was first revealed in 2008 by Satoshi Nakamoto in his article "Bitcoin: A Peer-to-Peer Electronic Cash System," where he describes a peer-to-peer electronic payment method without the participation of a trusted third party. The problem Nakamoto solved with blockchain was that of building trust in a distributed system. More specifically, the problem of creating a distributed storage of time-stamped documents where no part can alter the content of the data or the time-stamps without detection [13]. Several definitions of blockchain are proposed [14-16]. In short, it can be remembered that blockchain is a data transaction storage technology consisting of interlinked blocks, previously validated according to a criterion by the nodes of the network, in an open manner to the general public and in a secure and disintermediated manner.

Its principle of function is represented by Figure 1 in accordance with the description of Bodkhe et al. [16]. Dai et al. [17] identify six key features of blockchain technology. We tried to summarize them and illustrate them in Figure 2.

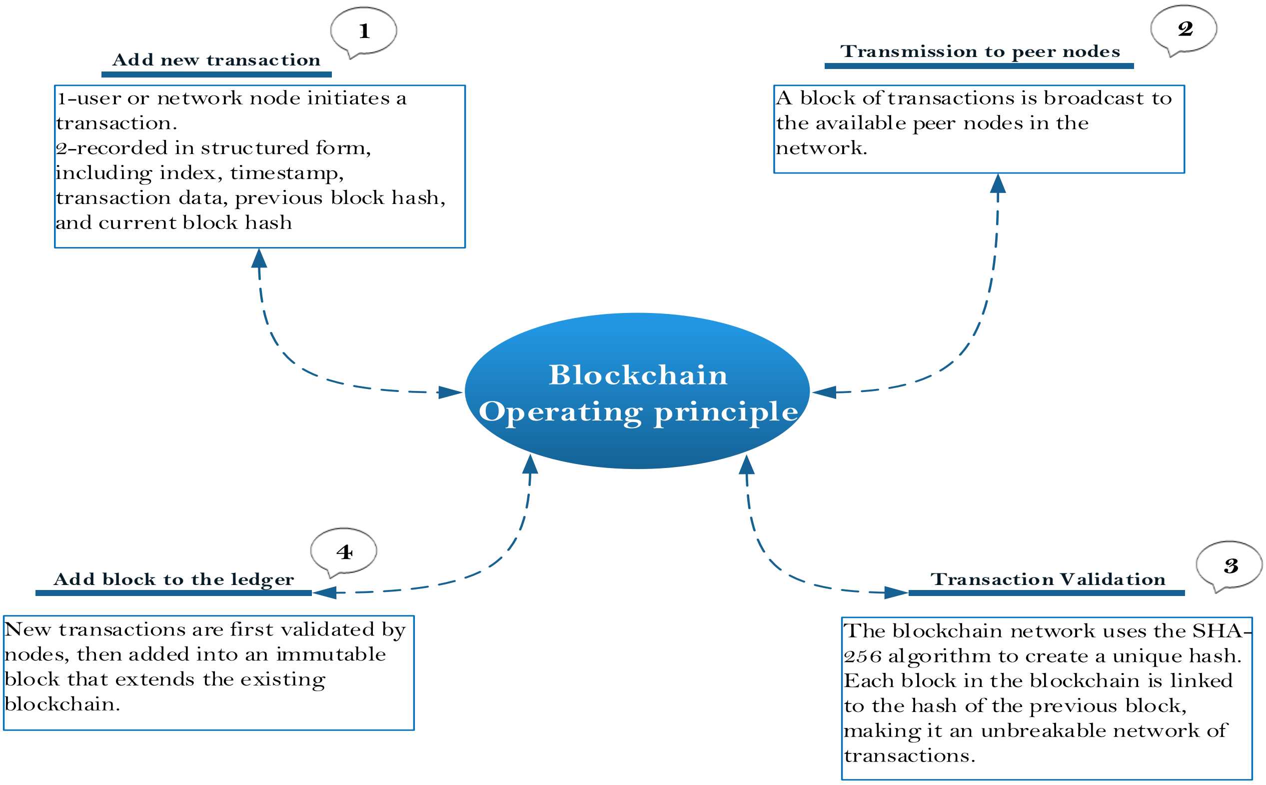

Figure 1.
Principles of blockchain operation.

1

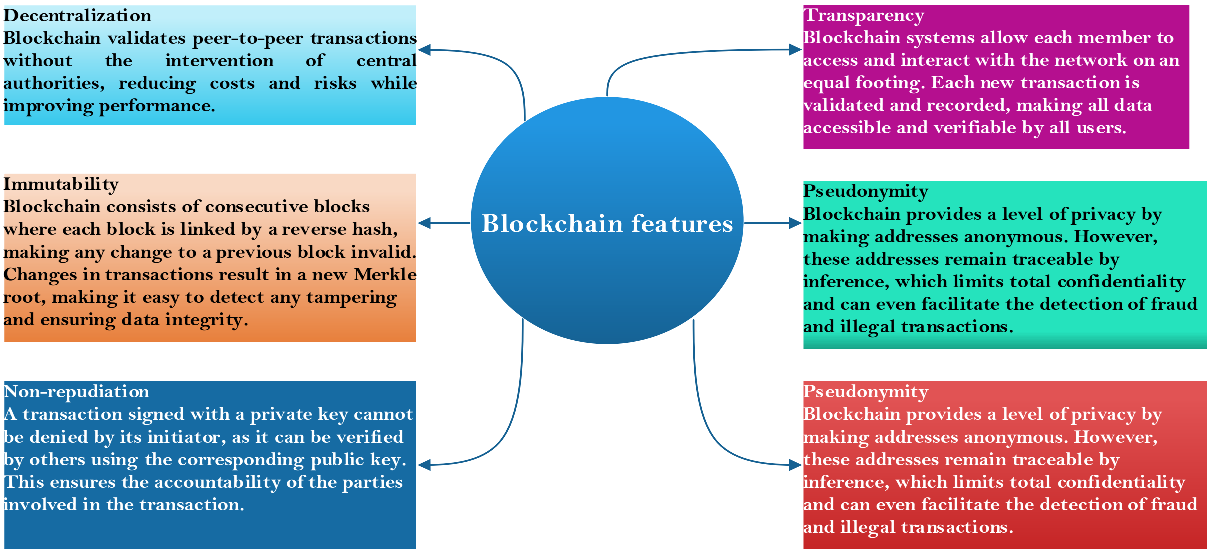

Figure 2.
Characteristics of the blockchain.

2.2. The Different Types of Blockchain

The evolution of blockchain technologies has led to a variety of classifications depending on access and mode of operation within the network. As of 2017, Guegan [18] mainly distinguished two types of blockchain: public and private, each meeting specific needs in terms of transparency, security, and control. In 2018, Chen [19] broadened this distinction to include hybrid blockchain, combining the features of public and private models. As technology has evolved, other classifications have emerged, such as the 2020 classification, which also mentions the consortium model, for secure sharing of resources in the field of embedded computing [20] More recently, in 2021, a more comprehensive classification was proposed, identifying four blockchain types: public, private, consortium and hybrid [21]. This diversity of classifications reflects the flexibility of the blockchain and its various applications, adapted to the specific needs of different sectors and governance models.

The public blockchain is without authorization, it designates a decentralized network in which access and participation are open to all, without the need for approval or prior authorization, thus allowing total transparency of transactions [22]. According to Guegan [18], its governance is based on the "Code is Law" law. In contrast, private blockchain is characterized by a limited and predefined number of participants, which is necessary for the consensus process to take place. This type of blockchain is based on centralized control and is frequently used by some institutions that want to enhance the security of their transactions [18]. On the other hand, the blockchain consortium represents a model where only authorized nodes can participate in the management and maintenance of shared and distributed databases [23]. It is important to note that, like private blockchain, the blockchain consortium benefits from the security and privacy advantages of this type of blockchain [24]. Finally, hybrid blockchain combines the characteristics of public and private blockchains. This model is chosen to take advantage of the transparency offered by the public blockchain while preserving the confidentiality of the data according to the specific needs of the organization. As a result, entities can select the information they want to make public while keeping the information they want to keep private [25].

2.3. Application of Blockchain in Decentralized Smart Grid Management

The work of Khalid, et al. [6]; Mihaylov, et al. [26]; Zhang and Wen [27]; Mengelkamp, et al. [28]; Pop, et al. [29]; Li, et al. [11]; Hussain, et al. [30]; Kwak and Lee [31] and Dinesha and Balachandra [32] The latest findings reveal that blockchain research on smart grids has evolved significantly from simple business management to full integration into energy systems between 2014 and 2022. The adoption of technologies like smart contracts (especially via Ethereum) has enabled us to leapfrog the commercial transaction, facilitating supply-demand balancing, sales-condition validation, and real-time regulation, strengthening resilience and reducing reliance on third parties. Since 2019, decentralized inter-micro-grid energy exchange has become a key focus for integrating micro-grids with smart grids, while multi-tier configurations proposed in 2022 place blockchain as a central pillar of distributed energy management. This modular architecture, aiming at sustainability, also responds to optimizing costs and emissions, making energy exchanges more autonomous and efficient.

Thus, the identification and modeling of a blockchain system adapted to smart grids is essential to enable advanced management and decentralized supervision of energy flows. This research highlights the importance of designing a blockchain system that meets the requirements of energy efficiency, security, and sustainability, while facilitating the transparent monitoring of exchanges between participants within an autonomous and resilient environment. It is therefore essential to define an energy transaction system (ETS) integrating all aspects of energy management, the energy market, and the monitoring of energy transfers. This ETS will serve as the basis for proposing a blockchain system model, precisely guiding its modeling to meet the specific energy management needs in smart grids.

2.4. Smart Grids Management: Analysis of Decentralized Approaches

It should also be noted that a lot of work focuses on the management of smart grids using blockchain. In the work presented in Table 1, we examine whether the proposed mechanisms cover both market and energy transfer aspects.

The analysis of the work summarized in Table 1 shows advances in smart grid energy management, but also significant limitations in terms of a holistic approach. Indeed, each project addresses a specific aspect. The system proposed in 2018 by Aggarwal et al. [33] uses blockchain to secure energy transactions, focusing on managing power consumption in smart homes by securely storing data on a cloud server. In 2019, Transactive Energy's approach, Li et al. [11]and Moniruzzaman et al. [34], is based on a decentralized local energy market model, allowing energy exchanges between microgrids, with supervision to ensure grid stability. In 2020, Khalid et al. [6] introduced a three-layer energy trading architecture, using smart contracts for P2P transactions between network participants.

The proposals for Kumari et al. [35] and Immaniar et al. [36] promote the integration of the Ethereum blockchain to manage energy transactions in a decentralized manner, promoting local energy production and energy self-sufficiency. The approach of Li et al. [11] addresses both the energy market and energy transfer areas, but does not clearly demonstrate the monitoring of transaction Indeed, Hyperledger Fabric receives the consumption tokens, which are then converted into Ethereum cryptocurrency, which mainly emphasizes the monetary aspect without sufficiently detailing the tracking of energy flows. Although this work focuses on specific aspects such as data security, P2P transactions or local energy markets, it lacks full integration of all the elements necessary for optimal management of smart grids. In order to ensure real efficiency, the management of smart grids should cover not only the energy market, but also a detailed monitoring of energy transfers between the different actors. This would ensure greater stability and responsiveness in a decentralized energy environment.

3. Key Aspects of the Blockchain-Based Smart Grid Management Model

Based on the principle that the efficient management of smart grids must integrate both aspects of the energy market, in order to ensure transparency and reduce transaction costs while maximizing the satisfaction rate, as well as aspects of energy transactions, to ensure transparency in the monitoring of trade and energy consumption, we propose a model based on a number of identified criteria.

The aspects identified to ensure efficient decentralized management of smart grids are based on a harmonious integration of energy market dynamics and energy transactions, relying on a blockchain infrastructure to ensure transparency, efficiency, and security. They are based on the recommendations of Aderibole et al. [15] and address the issues highlighted by Vangulick et al. [37] and Minlibe and Gnadi [38].

3.1. Key Aspects Identified

3.1.1. Aspects of the Energy Market

This allows for energy market management where prosumers (producer-consumers) can exchange energy in real time. The trading platform is designed to optimize transactions using energy auction mechanisms, supported by smart contracts. The aim is to reduce transaction costs while ensuring a high satisfaction rate by offering transparent and accessible trading opportunities to all participants.

3.1.2. Aspects of Energy Transactions

Blockchain allows real-time tracking of prosumers' energy exchanges and consumption. Each transaction is securely and immutably recorded through intelligent contracts, ensuring transparency and data integrity. The transmission of energy is monitored and optimized to ensure efficient exchanges and management of energy resources, minimizing losses.

3.1.3. Security and Privacy

To protect sensitive data, such as energy consumption information and exchange market financial transactions, advanced security mechanisms are put in place. These mechanisms include encrypting data, managing access permissions, and using private keys to ensure the confidentiality and integrity of information. In this way, blockchain provides a secure framework while preserving the transparency needed to build trust between network participants.

Table 1.
Summary of decentralized approaches to blockchain-based energy management.

Years	Refer nuances	Approaches	Area concerned	Management Level
2018	Chen et al. [39]	The EnergyChain system is offered for energy trading in a network of smart homes. It uses blockchain technology to ensure secure transactions. It includes several phases, including the selection of minor nodes via an algorithm based on the energy capacity of the active nodes. Two types of transactions are available: Store Transactions, to store data such as power consumption on a cloud server, and Access Transactions, to allow a user or service provider to access that data after validation by the blockchain.	Energy consumption	Partial
2019	Aderibole et al. [15]	Propose a transactive energy approach based on a decentralized structure where microgrids exchange energy according to market prices via a P2P system, under the supervision of a system operator guaranteeing the stability of the network. Blockchain secures and automates transactions, ensuring transparency and trust. This model offers flexible management of energy resources and facilitates the integration of distributed renewable energy, promoting a more dynamic and responsive energy environment.	Bitcoin-based energy market	Partial
	Moniruzzaman et al. [34]	The proposed system is based on a Local Energy Market (LEM), which facilitates energy transactions based on the exchange of energy from local renewable sources, such as photovoltaic panels, between prosumers (participants acting both as producers and consumers of energy). The aim is to encourage energy self-sufficiency and to better optimize local resources. This model allows prosumers to sell their surplus energy to the main grid or exchange energy among themselves, depending on local needs.	Ethereum Energy Market	
2020	Khalid et al. [6]	The proposed decentralized architecture is based on the blockchain-based energy trading market and includes three layers: the physical layer (smart homes and related equipment), the virtual layer (transaction management via smart contracts on the blockchain), and the application layer (decentralized user interfaces). The system uses P2P contracts for the exchange of energy between participants and P2G contracts to purchase energy from the main grid as needed, with price adjustments depending on demand periods.	Energy market	Partial
2022	Kumari et al. [35]	They propose a decentralized energy management model in three phases: energy generation (via solar panels), publication of energy data on the blockchain Ethereum, and P2P energy exchanges. This system uses smart contracts to manage transactions and takes into account factors such as distance and amount of energy. A recommendation mechanism encourages the installation of solar panels in under-equipped areas to improve local energy production.	Bitcoin Energy Market	Partial

2023	Immaniar et al. [36]	The proposed system uses the 'Ethereum' blockchain to manage energy transactions in a decentralized manner between producers and users in a P2P network, eliminating intermediaries. This model ensures security, transparency, and integrity of exchanges while optimizing distributed energy management and reducing costs. Tested on university campuses with renewable energy sources, it relies on a cryptographic algorithm to ensure data security and enhance the reliability of smart grids.	Energy market requests to answer Ethereum	Partial
	Chen et al. [39]	The proposed approach integrates blockchain into the packaged-energy (PET) market to foster transparency and decentralization. It allows prosumers to participate in energy exchanges through smart contracts that record auctions and monitor energy flows. Each prosumer uses an agent to interact with the blockchain and manage transactions using a digital wallet (Fabric and Ethereum). A dual blockchain mechanism—Fabric for security and Ethereum for liquidity—is being used, together with smart contracts to manage auctions and power transmission. The infrastructure includes AI modules to optimize prosumer engagement based on their energy strategies.	Energy market and energy transmission	Complete

3.1.4. Scalability and Flexibility

The model must be scalable and adaptable to the growth in the number of prosumers and the diversity of energy sources on the grid. Smart contracts are designed to handle large-scale energy transactions and ensure secure interactions between different blockchains through cross-chain protocols.

3.1.5. Real-Time Monitoring and Analysis

The model needs to incorporate AI-based analytics tools to monitor network performance and prosumer behaviors. These tools allow prosumers to adjust their market participation strategies according to their energy profile, thus optimizing costs and consumption.

3.1.6. Accessibility and Decentralized Governance

The platform is open to all market participants, ensuring fair participation and decentralized governance. Through a blockchain-based consensus mechanism, each participant can play an active role in grid management and energy exchange decisions.

In summary, this decentralized management model of smart grids aims to improve the efficiency of energy exchanges while ensuring transparent, secure, and low-cost management of energy transactions, while allowing each market participant to maximize its satisfaction and have reliable monitoring of its energy consumption and production.
The Figure 3 illustrates a data flow management scenario of the system.

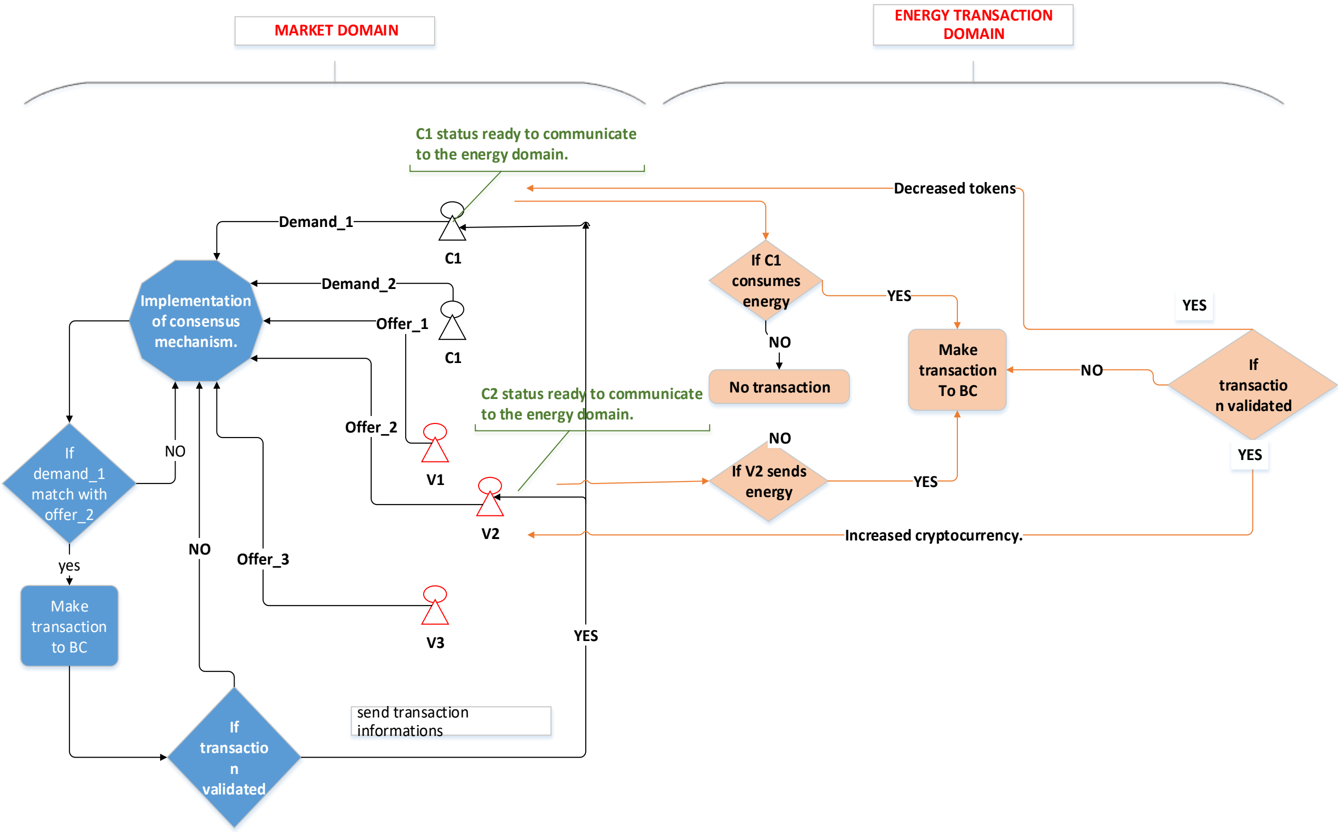

Figure 3.
Transaction flows between the energy market and the monitoring of energy transfers.

An in-depth analysis of the above highlights the key criteria to guide the choice of the type of blockchain system best suited for optimal management. The relevance of this approach is justified by the conclusions of Vangulick et al. [37], which highlight the importance of developing a blockchain specifically tailored to the needs of energy communities in order to effectively support their transactions.

3.2. Type and System Selection Criteria

3.2.1. Criteria for the Choice of Blockchain Type

- Separate transactions into internal and external categories to improve management and transparency.
- Use of cryptocurrencies and tokens for financial management and tracking of energy transfers.
- Enhanced data protection for internal transactions.

3.2.2. Blockchain System Selection Criteria

Table 2.
Summary of criteria and objectives.

Domain		Criteria	Objectives pursued
Management and monitoring of energy transfers	Energy market management	1. Security and confidentiality of transactions	Protect sensitive market data
			Ensure the immutability of financial and auction records
		2. Support for Smart Contracts	Facilitate automation of bids and transactions
			Allow customization of contracts for energy exchanges
		3. Scalability and transactional performance	Supporting a high number of transactions in the market
			Maintain fast transaction times for market efficiency
		4. Cost and efficiency of transactions	Optimize transactional costs to attract participants
			Ensuring energy efficiency of the blockchain used
		5. Accessibility and governance decentralize	Ensure transparent and open governance
			Maintain accessibility that encourages multi-stakeholder participation
		6. Efficiency and low latency in transfers	Reduce delays in tracking transfers
			Optimize tracking costs for greater efficiency

4. Blockchain System for Better Management of Smart Grids

4.1. Blockchain Type

Table 3.
Guidelines for choosing the blockchain type for intelligent networks.

Criteria	Implications	Orientation of the choice
Separation of internal and external transactions	Two blockchains partition internal transactions (private management) and energy market transactions (public management).	Hybrid blockchain
Use of cryptocurrencies and tokens	A cryptocurrency on the public blockchain ensures fast and economical exchanges, while tokens on the private blockchain facilitate the tracking of energy transfers and encourage internal transactions, improving the fluidity of the network.	Public blockchains with cryptocurrency Private blockchain with tokens
Enhanced data protection for internal transactions	Private blockchain for internal transactions enhances the protection of sensitive data, ensures access control in compliance with privacy regulations, and guarantees increased traceability, thus increasing the resilience of the system against intrusions.	Private blockchain for data transfer management

From this Table 3, we conclude that for the management of smart grids, a hybrid model is needed, combining a public blockchain for market transactions and a private blockchain for internal exchanges. Public blockchain needs to be endowed with cryptocurrency to enable fast transactions in the market, while private blockchain, equipped with tokens, will facilitate internal exchanges and energy tracking. This hybrid model thus meets the requirements of the energy market while meeting the internal needs of the community, ensuring a fluid, traceable and secure management.

4.2. Choice of System

To solve this problem by taking into account the criteria listed in Table 2, a comparative performance study is carried out, accompanied by a test proper to validate the results.

4.2.1. Benchmark Performance Study

In order to better understand the technological choices to be made in the context of blockchain systems, several performance studies have been carried out, making it possible to compare the different solutions in terms of efficiency, energy consumption, and resource management. This work offers us elements of reflection to guide the choice of the most suitable blockchain system. According to the work of Khosravi and Säämäki [40], Bitcoin and Ethereum are among the most common blockchains, but their energy profiles and environmental impacts differ significantly. This difference is explained by the fact that Bitcoin, based on the Proof of Work mechanism, is characterized by very high energy consumption, resulting in a considerable carbon footprint. On the other hand, although Ethereum is newer and less studied, its energy consumption also remains high. However, this consumption is expected to decrease significantly with the transition from Ethereum to Proof of Stake. In this dynamic of comparison, Jani [41] notes that Bitcoin has introduced blockchain technology for decentralized digital asset management. Ethereum, by extending this technology, has integrated a comprehensive Turing programming language, enabling the creation and execution of smart contracts, opening the way to more complex and customized applications. Ether, Ethereum's native cryptocurrency, is used to pay transaction fees, thereby serving to secure and validate blockchain transactions while incentivizing participation in the network.

In parallel, the work of Dabbagh et al. [42] focus on comparing the performance of Hyperledger Fabric and Ethereum based on four criteria: success rate, average latency, throughput, and resource consumption. Test results from 100 transactions show that Hyperledger Fabric outperforms Ethereum in terms of latency, throughput, and resource management. However, Ethereum has a higher success rate for transfer transactions. Thus, although Hyperledger Fabric stands out as being more successful overall, Ethereum maintains a slight advantage for the transfer success rate.

In the same line, Afif et al. [43] expand the comparison by including several other authorized blockchain platforms, such as Ethereum, Quorum, Corda and Hyperledger Fabric. This study evaluates their throughput and latency under different workloads and network sizes, with tests performed on Microsoft Azure, providing more reliable results than those obtained with a local deployment. Hyperledger Fabric stands out again as the most powerful platform, thanks to its modular consensus. However, the study suggests that a standardized comparison framework would improve the fairness of assessments between different solutions.

Following on from these analyzes, the study of Pongnumkul et al. [44] examines the performance of private blockchain platforms, Ethereum and Hyperledger Fabric, based on variable transaction volumes. Hyperledger Fabric shows improved throughput and latency performance, especially with volumes up to 10,000 transactions. The differences in latency and execution time become more significant as the volume of transactions increases, and the throughput of Hyperledger Fabric grows faster than that of Ethereum. However, Ethereum manages to handle more competing transactions with similar resources. Future research will focus on assessing consensus protocols, analyzing higher transaction volumes, and comparing private to public platforms. The impact of code differences on performance will also be an important focus of study.

After analyzing this benchmark, it emerges that Ethereum is a public blockchain based on a consensus mechanism called Proof of Stake (PoS), offering significant improvements in energy consumption compared to Proof of Work. This transition to PoS not only reduces the carbon footprint but also improves network scalability while maximizing environmental impact. Ethereum has a robust infrastructure for smart contracts, facilitating the development of decentralized applications (dApps), and its comprehensive programming language allows the creation of complex decentralized contracts, making it a preferred choice for projects requiring secure exchanges of digital assets. Although its latency and throughput are lower than those of systems such as Hyperledger Fabric, Ethereum remains a scalable platform for massive transactions thanks to its wide adoption and constantly evolving ecosystem. In contrast, Hyperledger Fabric is a private (permissioned) blockchain optimized for business applications requiring fast and secure transactions. It delivers improved throughput, latency, and resource management performance, making it ideal for high-volume transactional environments where speed and resource efficiency are paramount. Its modular consensus model and fine-grained management of private transactions allow for maximum flexibility, while its strict control of participants guarantees enhanced security, making Hyperledger Fabric a privileged choice for closed networks or industrial and collaborative use cases requiring confidentiality and efficiency.

In summary, the choice of Ethereum and Hyperledger Fabric is based on the complementarity of their respective architectures. Ethereum stands out for its wide adoption and ability to execute smart contracts, facilitating the development of decentralized applications (dApps) on a public blockchain. On the other hand, Hyperledger Fabric stands out for its modular architecture, suitable for private and permissioned networks, where fine management of resources and secure transactions is crucial. These features give both platforms an advantage over other solutions that may have limitations in flexibility, security, or scalability in specific environments.

4.2.2. Implementation of Validation Tests

Practical experimentation is essential to confirm the results obtained in this benchmark.

Test method used:

For our experiment, we used a computer with an Intel Core i7-2670QM (quad-core) processor running at 2.20 GHz. We configured two virtual machines, each with 8 GB of RAM, a 100 GB hard drive, and the Ubuntu 22.04.1 LTS operating system. Ethereum was installed on one of these virtual machines, while Hyperledger Fabric was deployed on the other. To assess the performance of the two blockchain environments, we used the Hyperledger Caliper benchmarking tool version 0.5, which provides a detailed analysis of platform performance metrics in this benchmarking study.

Using the Caliper tool, it is possible to generate and submit controlled workloads to the blockchain platform, allowing for the measurement of various predefined performance metrics. Caliper is deployed across all client machines, ensuring consistent and standardized data collection for benchmarking. We conducted several rounds of experiments by sending batches of 1,000, 2,000, 3,000, 5,000, and 10,000 transactions to each platform. Our experimental performance results were collected through the HTML report generated by Hyperledger Caliper, providing a detailed analysis of the performance outputs for each scenario tested [42].

The metrics measured for the performance evaluation of Ethereum and Hyperledger Fabric are as follows:

- Transaction Success Rate (SUCC): Indicates the proportion of successful transactions, reflecting the reliability of the blockchain. A high rate ensures stable and continuous execution.
- Transaction Failure Rate (FALL): Measures the number of failed transactions, indicating invalid commit situations. A low failure rate is essential for network stability.
- Send Rate (SEND RATE): Indicates how often transactions are sent, measuring the ability of the blockchain to receive requests continuously, which is fundamental for intensive applications.

- Max Latency: Represents the longest delay for a transaction to complete. This measure identifies the worst response time, which is critical for critical environments.
- MIN LATENCY — Specifies the shortest time to complete a transaction, providing insight into the best performance of the network in terms of response time.
- AVG LATENCY: The average time taken to execute a transaction, which is useful for evaluating the overall responsiveness of the network to a sustained load.
- Throughput (THROUGHPUT): Measures the network processing capacity in transactions per second (TPS). This parameter is key to evaluate the efficiency and scalability of blockchain in high usage contexts.

5. Results and Discussion

5.1. Performance Benchmark Results

Table 4 presents the results of the theoretical analysis of the performance of blockchain systems, in accordance with the established criteria. In terms of security and privacy, Ethereum and Hyperledger Fabric offer better data protection than Bitcoin, which is limited to immutability. For smart contracts, Ethereum and Hyperledger Fabric fully support them, while Bitcoin does not support them. Hyperledger Fabric stands out for its scalability and transactional performance, while Ethereum and Bitcoin suffer from varying burdens and limitations due to Proof of Work, respectively. In terms of cost and efficiency, Hyperledger Fabric and Ethereum are more competitive, with Ethereum optimizing costs via the Proof of Stake. Bitcoin remains the most expensive and energy-intensive. As for decentralized governance, Bitcoin and Ethereum are more open, while Hyperledger Fabric limits accessibility due to its private governance. Finally, when it comes to latency, Hyperledger Fabric performs best, with low latency, while Ethereum and Bitcoin suffer more moderate and high performance respectively.

We take the view that Hyperledger Fabric is emerging as the most scalable, efficient, and latent platform for environments requiring high privacy and low cost. Ethereum, with its smart contracts and transition to the Proof of Stake consensus mechanism, represents a strong option for decentralized applications, offering robust governance. By contrast, although Bitcoin is widely adopted, its high transaction costs and limited performance impede its use in specific applications. The results of Targets 5 and 6 identify Ethereum as an ideal public blockchain for energy market management, while Hyperledger Fabric, as a low-latency private blockchain, is more suitable for internal transaction management and real-time tracking of energy transfers.

Table 4.
Performance benchmark results.

Objectives pursued	**Validating with Bitcoin**	**Validation with Ethereum**	**Validating with Hyperledger Fabric**
1. Security and confidentiality of transactions	✔ Guaranteed immutability but less protected data [40].	✔ Enhanced security through intelligent contracts [41].	✔ High privacy via private governance [43].
2. Support for Smart Contracts	✗ Not supported.	✔ Fully supported [41].	✔ Adaptable to specific needs [43].
3. Scalability and transactional performance	✗ Limited by Proof of Work [41].	✔ Good performance, but depends on loads [44].	✔ Optimal scalability and performance [44].
4. Cost and efficiency of transactions	✗ High and energy inefficient costs [41].	✔ Transition to Proof of Stake to optimize [41].	✔ Low cost and high efficiency [43]
5. Accessibility and decentralized governance	✔ Decentralized but limited governance [40].	✔ Decentralization assured and increased openness [40].	✗ Private governance limits external accessibility [43].
6. Efficiency and low latency in transfers	High latency ✗ for fast transfers [40].	✔ Moderate performance [44].	✔ Reduced latency, ideal for transfers [44].

5.2. Hyperledger Caliper Report

Table 5.
Results of 2000 transactions sent to Ethereum.

Name	Success	Fall	Sending rate	Max latency	Min latency	Avg latency	Debit
Open	2000	0	50	47,83	4.83	26,33	23
Query	2000	0	100	0.05	0	0	100
Transfer	2000	0	5	7.14	2.05	4.6	5

Table 6.
Results of 2000 transactions sent to Hyperledger Fabric.

Name	Success	Fall	Sending rate	Max latency	Min latency	Avg latency	Debit
Open	1999	1	38.5	2.29	0.21	0.91	36.9
Query	2000	0	100.1	0.04	0.01	0.01	100
Transfer	2000	0	5.1	2.03	0.13	1.07	5

Caliper report

Blockchain: Ethereum
Test performed on: 18-01-2023 at 07:53:13 GMT

Performance Indicators Summary

Description
This is a sample reference for Caliper to test the performance of the Ethereum network with a smart contract having three functions:

- **open:** Allows to open an account by taking an ID and amount as parameters
- **query:** Returns the balance of an account based on its ID
- **transfer:** Transfers an amount from one account to another

Hardware Configuration
A personal laptop with Intel® Core™ i7-2670QM processor, 4 cores at 2.20 GHz, 8 GB RAM, a 50 GB hard disk. Operating System: Ubuntu 22.04.1 LTS.

Performance Benchmarking Tool
Latest version of Hyperledger Caliper 0.5.0, which automatically generates an HTML report after each test series with various performance statistics such as success rate, average latency, throughput, and resource usage.

Name	Success	Fail	Send Rate (TPS)	Max Latency (s)	Min Latency (s)	Avg Latency (s)	Throughput (TPS)
open	2000	0	56.0	47.83	4.83	26.33	23.0
query	2000	0	10.0	0.00	0.00	0.00	100.0
transfer	2000	0	5.0	7.14	2.05	4.60	5.0

Figure 4.
Caliper report of 2000 transactions sent to Ethereum.

5.3. Study of the Latency Times

5.3.1. Ethereum Latency

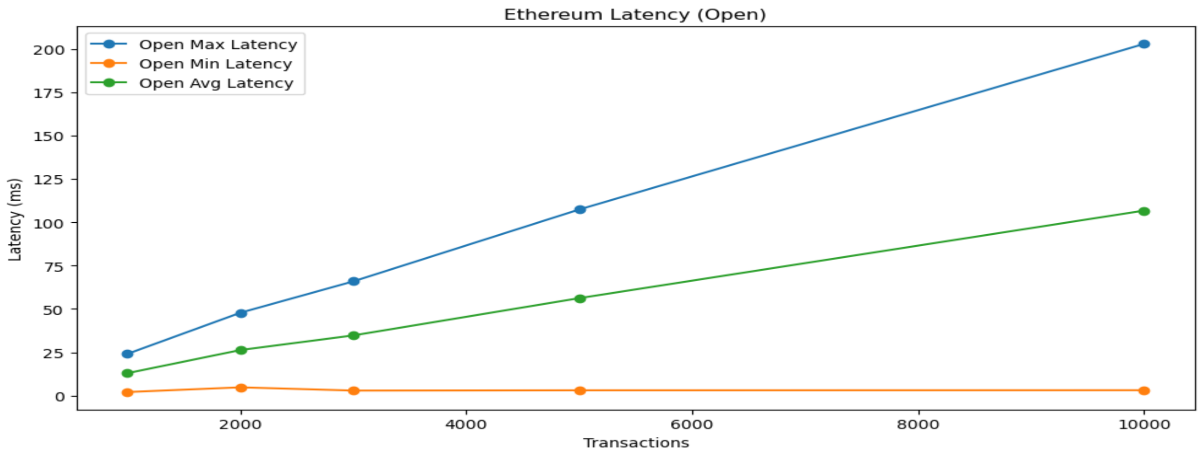

Figure 5.
Ethereum latency.

The analysis in Figure 5 shows that the maximum latency of Ethereum increases as the number of transactions increases, suggesting that the system becomes slower under a large load. However, the minimum latency remains low and stable, indicating that some transactions can still be processed quickly. However, average latency increases with the number of transactions, reflecting an increased delay as network load increases.

5.3.2. Hyperledger Fabric Latency

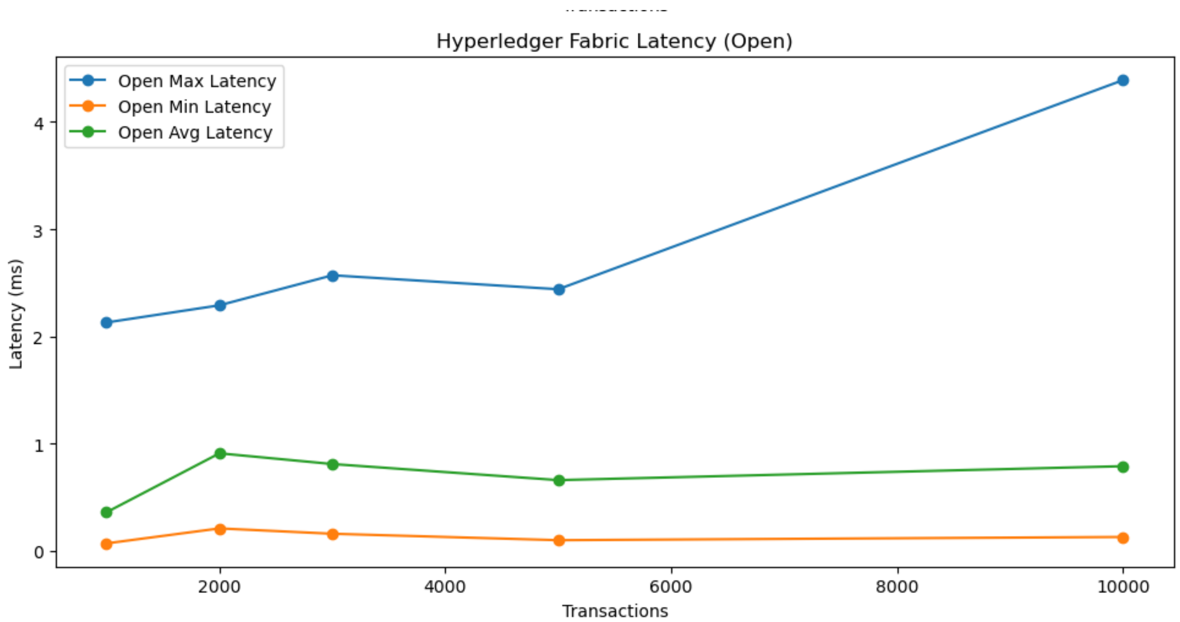

Figure 6.
Hyperledger Fabric latency.

The analysis in Figure 6 shows that the maximum Hyperledger Fabric latency is much lower than that of Ethereum, with values of 4.39 ms versus 202.79 ms for Ethereum, indicating more efficient management of the transactions under load. Minimum latency is also lower for Hyperledger Fabric. Minimum latency remains low and stable, with Ethereum recording values ranging from 0 to 3.17 ms, while Hyperledger Fabric ranges from 0.07 to 0.13 ms, which is a good indicator of network efficiency in processing simple transactions. Finally, Hyperledger Fabric's average latency, with values ranging from 0.36 to 0.91 ms, is significantly lower than Ethereum's average latency (from 13 to 106.71 ms), indicating better overall performance for transaction processing.

5.3.3. Ethereum vs Hyperledger Average Latency Comparison

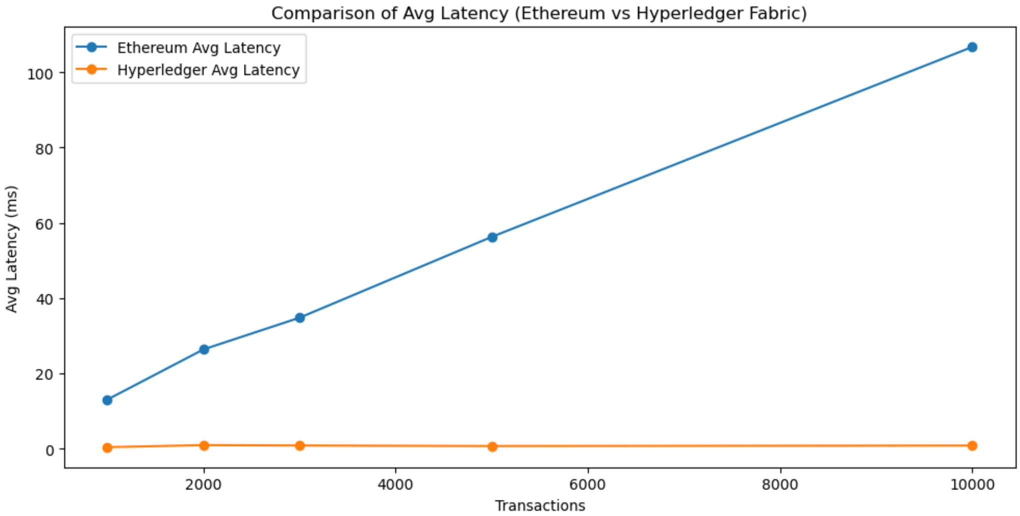

Figure 7.
Ethereum vs Hyperledger average latency comparison.

The analysis in Figure 7 reveals significant differences in latency between Ethereum and Hyperledger Fabric depending on the number of transactions processed. Indeed, for a batch of 1,000 transactions, Hyperledger Fabric has an average latency of 0.36 ms, while Ethereum reaches a latency of 13 ms, demonstrating a notable difference in performance. As the volume of transactions increases, this difference increases: for 10,000 transactions, Ethereum records a latency of 106.71 ms, while Hyperledger Fabric maintains a latency of 0.79 ms.

This observation highlights Hyperledger Fabric's ability to handle large transaction loads with much lower and stable latency, making it a more efficient option for applications requiring fast and secure processing of large-scale transactions.

5.4. Throughput Study

5.4.1. Ethereum Throughput

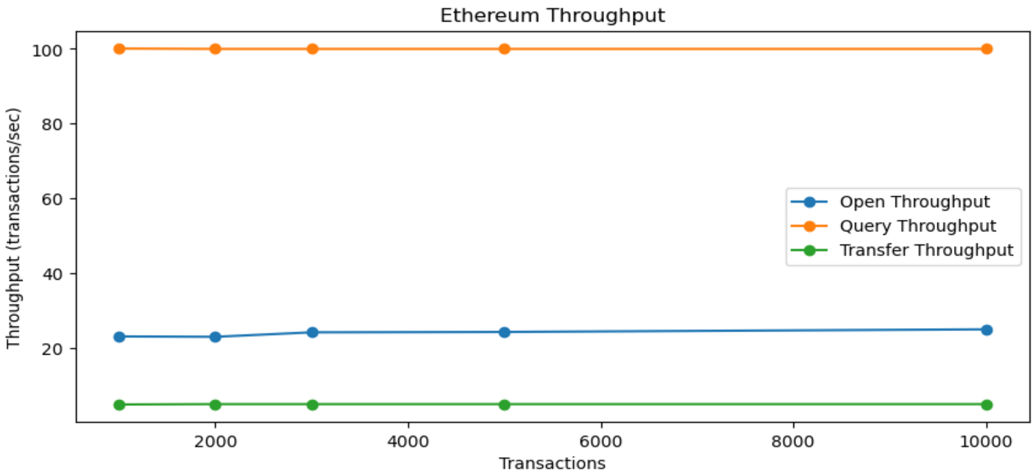

Figure 8.
Ethereum throughput.

The Figure 8 shows the throughput of the various categories of transactions (Open, Query, Transfer) remains stable, fluctuating between 23 and 25 transactions per second. No significant changes are observed as the number of transactions increases, which may indicate that Ethereum is not effectively adapting its processing capacity to accommodate the increased volume of transactions in these tests.

5.4.2. Hyperledger Fabric Throughput

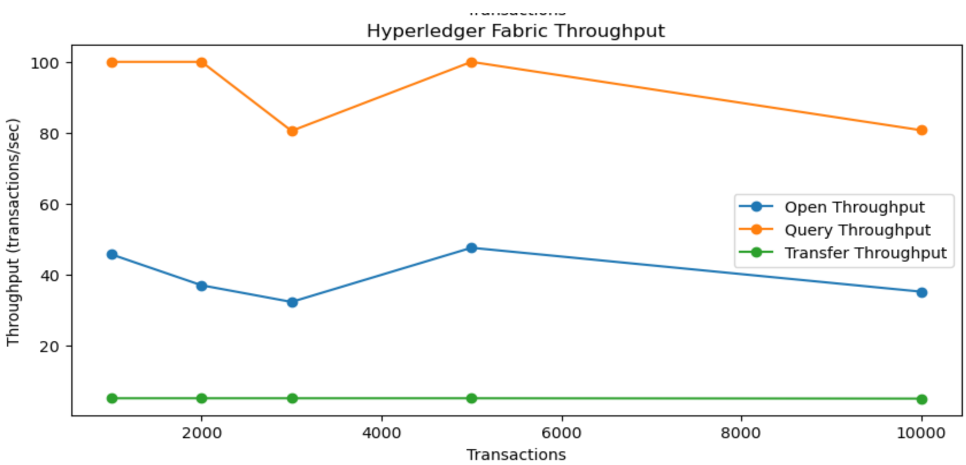

Figure 9.
Hyperledger Fabric throughput.

Hyperledger Fabric's throughput varies more by transaction category, but overall remains higher than Ethereum's throughput. For example, for open transactions, throughput tends to be lower at high volumes. However, for the 'Query' and 'Transfer' categories, it remains stable or increases, which suggests more efficient load management. On average, Hyperledger Fabric's throughput ranges from 32.2 to 47.5 transactions per second, surpassing Ethereum's throughput of 23 to 25 transactions per second.

5.4.3. Ethereum vs Hyperledger Throughput Comparison

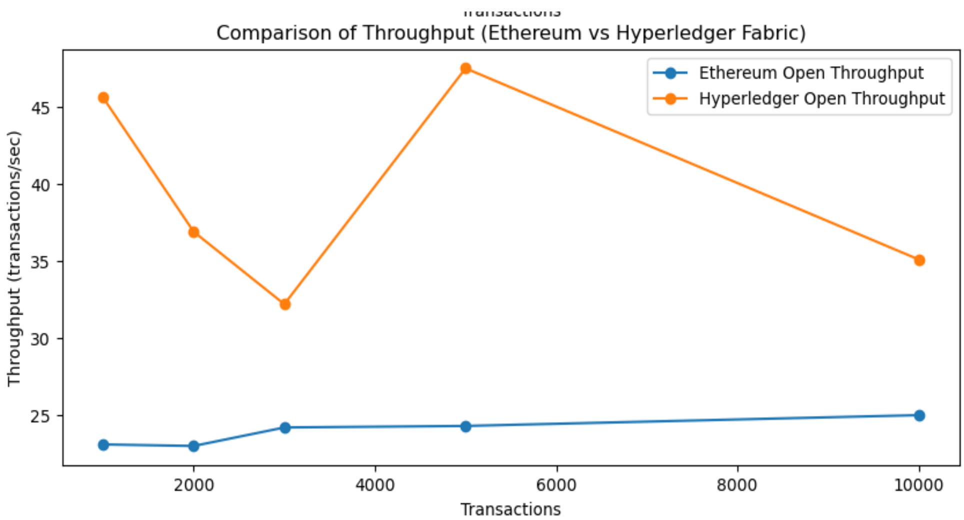

Figure 10.
Ethereum vs Hyperledger flow comparison.

Hyperledger Fabric shows higher throughput, especially for "Open" transactions, processing up to 45.6 transactions per second compared to 23.1 for Ethereum. This difference highlights the ability of Hyperledger Fabric to handle more transactions per second under a similar load, surpassing Ethereum.

Table 7.
Comparison of latency and throughput performance between Ethereum and Hyperledger Fabric.

Platform	Max Latency Mean	Max Latency Std. Dev.	Avg Latency Mean	Avg Latency Std Dev	Throughput Mean	Throughput Std Dev
Ethereum	89,602	62,801	47,408	32,811	23.92	0,763
Hyperledger Fabric	2,764	0,826	0,706	0.19	39.46	6.01

Analyzing latency and throughput statistics for Ethereum and Hyperledger Fabric reveals significant differences in performance and efficiency. A detailed interpretation of these results is presented in Table 8.

Table 8.
Analyze latency and throughput performance between Ethereum and Hyperledger Fabric.

Metrics	Platforms	Parameters	Analysis
Maximum Latency	Ethereum	Max Mean=89.60 ms Max Std Dev=62.80 ms	Ethereum has a relatively high latency with high variability (high standard deviation). This means that while some transactions are processed quickly, others may experience much longer delays, which can affect network responsiveness in critical use cases.
	Hyperledger Fabric	Max Mean=: 2.76 ms Max Std Dev= 0.83 ms	Hyperledger Fabric, on the other hand, has a much lower maximum latency and a much lower standard deviation, indicating greater predictability and stability in response time, which is suitable for environments requiring fast and stable execution of transactions.
Average Latency	Ethereum	Avg Latency (Mean) = 47.41 ms Avg Latency (Std Dev) = 32.81 ms	The average latency for Ethereum is higher than that of Hyperledger Fabric, reflecting slower performance in transaction processing. Furthermore, the high standard deviation indicates that performance can vary considerably, which can be a limiting factor in applications requiring consistently low latency.
	Hyperledger Fabric	Avg Latency (Mean) = 0.71 ms Avg Latency (Std Dev) = 0.19 ms	Hyperledger Fabric has a much lower average latency, with a standard deviation that is also low, making it very efficient for application scenarios where fast responsiveness is essential, such as in industrial environments or private networks where consistent performance is imperative.
Throughput (Mean and Std Dev)	Ethereum	Throughput (Mean) = 23.92 TPS Throughput (Std Dev) = 0.76 TPS	Ethereum, despite its higher latency, manages to process a reasonable average throughput of 23.92 transactions per second (TPS), with a small variation. This can be an advantage in public networks where a high volume of transactions is required, but where latency is not as critical a factor.
	Hyperledger Fabric	Throughput (Mean) = 39.46 TPS Throughput (Std Dev) = 6.01 TPS	Hyperledger Fabric outperforms Ethereum in terms of throughput with 39.46 TPS, which is an indicator of its ability to process a higher volume of transactions in a short time. However, the relatively higher standard deviation suggests that, while it may handle more transactions on average, there may be more variability in throughput, especially at higher transaction scales.

In summary, while Ethereum is designed for complex decentralized applications and intelligent contract execution, it has relatively high latencies, both maximum and average, which can pose challenges in environments requiring rapid transaction validation, such as real-time energy transfer tracking systems. However, Ethereum maintains a competitive throughput and, thanks to its wide adoption, remains a preferred solution for applications requiring a high capacity for digital asset exchange, making it better suited to managing a large-scale energy market. In contrast, Hyperledger Fabric delivers more stable performance with low latency and high throughput, especially in private networks and industrial applications. Thanks to its low standard deviation and reduced latencies, it enables fast, secure, and predictable transaction management. These features make Hyperledger Fabric an ideal solution for systems where responsiveness and safety are paramount, as is the case for setting up a system to track energy transfers, requiring real-time data processing in a controlled environment.

6. Conclusion

This study highlights the crucial role of blockchain technology in enabling decentralized and transparent management of smart grids. By identifying key selection criteria for an optimal blockchain architecture, we established a rigorous framework for evaluating its suitability in energy transactions and real-time monitoring. A comprehensive benchmarking analysis, incorporating performance metrics and constraint parameters, enabled us to assess the efficiency of existing blockchain systems. Through experimental deployments and performance testing on Ethereum and Hyperledger Fabric using the Hyperledger Caliper tool, we demonstrated the feasibility and benefits of a hybrid blockchain approach.

The results confirm that no single blockchain system can fully address all the requirements of smart grid management. Instead, a hybrid architecture emerges as the most effective solution. Ethereum, with its robust smart contract capabilities and transition to Proof of Stake, is well-suited for handling decentralized energy markets despite its higher latency. Conversely, Hyperledger Fabric proves to be an optimal choice for tracking energy flows and managing transactions efficiently due to its low latency, high scalability, and enhanced security features. Its ability to support permissioned networks makes it ideal for industrial applications where performance and data privacy are critical.

By leveraging the complementary strengths of Ethereum and Hyperledger Fabric, this hybrid model provides a scalable, secure, and transparent infrastructure for smart grids. It enables real-time energy tracking, secure financial transactions, and efficient coordination among network participants. This approach lays the foundation for future advancements in decentralized energy management, facilitating greater integration of renewable energy sources, improved demand-side management, and increased resilience against energy disruptions. Ultimately, this research contributes to the development of a more sustainable and intelligent energy ecosystem, aligning with the global transition towards decentralized and efficient energy networks.

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