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Decentralization and Blockchain: Comparative analysis of energy management uses

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Abstract. Rising energy demands, the proliferation of sustainable and renewable energy sources, are calling for a new perspective on conventional energy system management. this paper reports how blockchain technology can, through its decentralized and secure nature, enable transparent, automated and peer-to-peer (P2P) energy transactions. We conduct a comparative evaluation of BC applications in three diverse domains: renewable energy, smart grid and Microgrid, and P2P trading platforms. This article discusses different types of blockchains (public, private, consortium), consensus protocols, and their effect on scalability, security, and economic accessibility. The main takeaway is that public blockchains are very transparent but have scalability issues, whereas private and consortium blockchains are more scalable but less decentralized. The system gets more intelligent and smarter with the integration of AI and IOT. Although regulatory and interoperability challenges are being worked out, blockchain could have a significant impact on the industrial energy grid. the article closes with a discussion about how blockchain as part of a wider digital transformation could lead to ultimately more autonomously run and sustainable energy system.

1 Introduction

With the growth of manufacturing activities and automation processes, the balance between supply and demand is getting more unbalanced, so the energy management optimization becomes a big challenge for industrial network. Poor energy management can result in increased air operating expenses, brownouts within the network, and negative environmental impacts [1]. Faced with such challenges, companies are seeking new technology solutions to maximize the utilization of energy resources to enhance infrastructure flexibility and integrate renewable energy sources. Such technological advances, that is, the Internet of Things (IoT), Artificial Intelligence and blockchain are disrupting the energy sector [2], IoT-based consumption data collection and analysis has contributed to better energy flow monitoring and evaluation. Artificial Intelligence, on the other hand is utilized for advance prediction and automation to further improve energy efficiency and shorter reaction time. blockchain also provides a decentralized approach to energy management with security,

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transparency and the automation of transactions between the variety of players in the grid. Still, conventional energy management remains somewhat centralized with intermediaries controlling production, distribution and pricing, though that is changing. There are a few issues with this model, including lower transaction transparency, transaction costs are high because of intermediaries, and the risk of being hacked is deemed to be increased [3]. Moreover, there is no reliable tracking, which prohibits an appropriate integration of renewable energies.

Blockchain can be an answer to these challenges. At the same time, it ensures the add integrity of the energy transactions and reduces the number of intermediaries by using a secure, distributed ledger. Due to the smart contracts, it can also automate energy trading and schedule the transactions based on supply and demand. This attitude also promotes the more autonomous, more flexible energy systems for businesses to trade their surplus energy directly with each other with no third-party involvement [4]. For example, in [5], pilot projects are employing blockchain to verify the origin of solar or wind power, giving consumers a clearer view of their carbon footprint. What is more, this technology promotes the development of new commercial forms, for example regional energy communities, in which consumers can trade energy among themselves in a collaborative and fair manner. Nevertheless, the energy industry poses challenges to the implementation of blockchain, especially in the realm of an intelligent, decentralized energy management system for industrial environments. However, the penetration of blockchain technology in the energy sector is hindered by several challenges, specially designing an intelligent, decentralized energy management system for industrial environments. Powerful tool, but its use requires modification of existing infrastructures, increased awareness of the technology among the industry and a conducive regulatory framework. But the transparency, security and energy efficiency potential of Blockchain make it a crucial technology in supporting the energy transition and the modernization of industrial networks. Changes in energy demands and sustainability regulations are prompting organizations to reconsider their energy utilization. Together with other innovative technologies such as AI and IoT, blockchain would bring the energy systems to a whole new level of performance [2]. Thus, by investigating these novel methodologies, it is feasible to envisage a scenario of more efficient, more secure, and more environmentally and economically aligned energy management. The reminder of the paper is as follows: Section 2 presents the methodology, detailing the types of blockchain in energy management, including key concepts. Section 3 explores the comparison of Blockchain based solutions, such as renewable energies, smart grids and microgrids and peer-to-peer energy transactions. Also, the discussion of the results, and analyses the security, scalability, economic impact and the implementation complexity of blockchain-based energy management. And Section 4 concludes the paper.

2 Methodology

This paper focuses on evaluating performance and discussing the potential benefits and challenges of different blockchain-based energy management systems. A number of factors have been taken into consideration: microgrid blockchain type, consensus process, transaction scalability and latency, effects on renewable energy integration, and security issues of energy trading. The data for this review are drawn from recent articles and experimentations related to the application of blockchain to renewable energies, smart grids and microgrids, and P2P energy trading.

Blockchain is a decentralized ledger technology that stores transactions and other data in a distributed form [6]. It is based on a network of nodes that, following a consensus protocol, validate transactions. Solutions related to energy on blockchain are developed using public, private, and consortium blockchains. Public blockchains achieve full decentralization, processing transactions transparently and immutably. High transaction costs and excessive latency significantly constrain their capabilities to handle applications which require real-time management of flow of energy (e.g. [1]). Private blockchains speed up transactions but are less transparent and their centralized governance can result in a dominant player controlling the network [3]. Consortium blockchains are a hybrid between the two, and add governance to transactional efficiency. They are more difficult to implement as they involve coordination between multiple participants in the energy market, leading to standardization and interoperability issues [2]. A significant barrier for blockchain uptake in energy is its capacity to process millions of transactions per second [1]. Public Blockchains are secure, but they face scalability challenges as the transaction throughputs are limited, and they are prone to congestion and high fee. On the other hand, consortium and private Blockchains permit for low latency, with transactions being validated in a matter of milliseconds, but they are subject to centralized control, which could potentially hinder their adoption. A simulation in a microgrid with 30 EV charging stations presented in, demonstrated that employing a private blockchain with Byzantine Fault Tolerance (PBFT) algorithm reduced latency of transactions to 0.06s, thereby optimizing the responsiveness of EMS [1]. Although significant progress has been achieved, the challenge remains to achieve interoperability with legacy systems, while also allowing for efficient scaling of industrial applications.

The choice of consensus algorithm, which is defined by LIN al. [4] as a mechanism that enables the nodes of blockchain network to agree on the status of transactions without the need for a central authority. It affects the performance and energy consumption of a blockchain system used in energy. For example, Proof-of-Work (PoW), guarantees high security, but its energy cost makes it unsuitable for sustainable energy applications. In opposite, Proof of Stake (PoS) reduces energy consumption and offers faster transaction validation, making it more suitable for P2P energy markets [1]. Other options, such as PBFT and Proof-of-Authority (PoA), are better suited for smart microgrids and industrial networks as shown in **Table 1.** comparison of consensus Algorithms for Energy Management, as they offer fast transaction validation and strong resilience to attacks. However, these algorithms require strict control of the validation nodes, which can limit the decentralization and openness of the network.

Table 1. comparison of consensus Algorithms for Energy Management

Algorithm	Advantages	Disadvantages	Typical Applications	Ref
PoW	High security, decentralization	High energy consumption, low scalability	Public cryptocurrencies	[3]
PoS	Energy-efficient, fast validation	Risk of centralization, depend on the number of tokens held	P2P energy trading	[5],[3]
PBFT	Low latency, high fault tolerance	Limited scalability, potential centralization	Microgrids and consortium blockchain	[5]
PoA	Very efficient, low latency	Centralized validators, requires trust validators	Industrial and private blockchain networks	[7]

Finally, transaction security and data protection are crucial elements in the adoption of blockchain in energy. Thanks to its decentralized and immutable structure, blockchain considerably improves the security of energy exchanges, lowering the risk of fraud and manipulation [3]. However, public blockchain can be exposed to certain attacks, such as the 51% attack, which enables a bad actor to take control of the network if he holds a majority of the computing power [1]. To remedy this problems, private and consortium Blockchain integrate more secure consensus algorithms as PBFT and PoA, who offer increased resistance to attacks and allow faster validation of transactions[2]. In addition, these solutions require rigorous management of validator nodes, which can limit the network's decentralization and resilience. So, while blockchain represents a major advance in cybersecurity for the energy sector, improvements are still needed to ensure a balance between security, performance and accessibility.

3 Results and Discussion: Comparative analysis

3.1 Blockchain Applications in Energy Systems

The integration of renewable energy sources into power grids is challenging due to variable production and the requirement of effective decentralized control. For instance, blockchain technology is being considered as a preeminent technology to enhance flexibility of energy transactions, through P2P trading systems and autonomous microgrids [6]. Moreover, with the increasing penetration of blockchain in the industry, the energy transactions can be made more transparent [8], the processes can be automated, and the cost associated with intermediaries can be reduced. Some of these researchers identified major trends in decarbonization such as energy system optimization, green certificates, and decentralized energy markets. These analysts have identified global opportunities in areas including energy system optimization, green certificates and decentralized energy markets. Different techniques and algorithms are being used to integrate blockchain into renewable energy management. The main consensus protocols which is secure and unsuitable for sustainable systems; include PoS, which reduces energy consumption according to the number of tokens held, and PoA, who relies on trusted validators to reduce costs and speed up transactions [9]. A more specific algorithm, such as PoS, has been proposed to directly integrate optimization problems (such as energy allocation and trading) into the consensus mechanism, so that only optimal energy exchange plans are accepted and executed by participants [10].

In addition, renewable energies implementation into smart grids depends on the use of advanced technologies to improve the management of distributed energy resources (DER). These technologies optimize the control of energy flows, ensure the traceability of energy transactions and improve the cybersecurity of distributed energy systems. Among the advanced technologies used to guarantee efficient management of smart grids are Artificial Intelligence. These researchers show that the use of Fuzzy Logic, Knowledge-Based Systems and Artificial Neural Networks can optimize energy distribution and forecast consumption in real time, while the IoT, combined with the architecture of the Internet of Energy, enables continuous data collection and analysis to improve the reliability and stability of microgrids. **Fig. 1** illustrates the integration of renewable energies with blockchain to create a decentralized and automated energy market. Due to smart meters and smart contracts, the management of energy transactions become more secure, transparent and efficient.

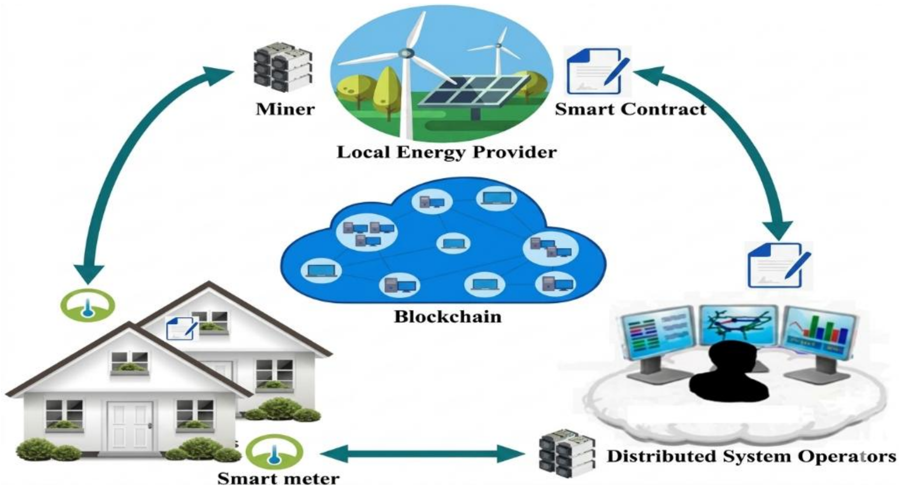

Fig. 1. Integration of Blockchain in Decentralized Renewable Energy Management [4].

Smart microgrids are local systems that combine renewable energies, energy storage and intelligent technologies to optimize energy management. By integrating energy transactions, they significantly reduce intermediary costs. Notably, it offers significant benefits in microgrid management through the automation of transactions between producers and consumers via smart contracts, removing the need for a centralized operator and reducing costs [3]. **Fig. 2** shows an example of a microgrid using blockchain to manage energy flows and automate transactions between different players. In addition, the recording of exchanges on an immutable register improves the transparency and traceability of energy transactions.

A simulation incorporating a Mixed Integer Linear Programme (MILP) optimization algorithm combined with a blockchain showed a 1.68% higher profitability and 2.61% higher consumer satisfaction while reducing environmental impact by 0.97% in a sustainable microgrid [11]. However, the application of blockchain in this field raises several challenges. Compatibility with energy regulations and the need for interoperability with existing EMS are still obstacles to be overcome. In addition, although private and consortium blockchains are better adapted to fast energy transactions, they require standardized protocols and collaboration between several actors to guarantee their widespread adoption. A detailed review of blockchain solutions for smart grids identifies several persistent challenges in the integration of blockchain with microgrids. In the first place, interoperability with existing infrastructures remains limited, as the blockchains used are not always compatible with national energy standards. Secondly, public blockchain ensure complete decentralization, they suffer from high latencies and high transaction costs [1]. On the other hand, private blockchain enable better performance management, but introduces a form of centralization that reduces the transparency of the system. To further clarify, here is a summary of advantages and disadvantages of using blockchain in microgrids presented in **Fig. 3**.

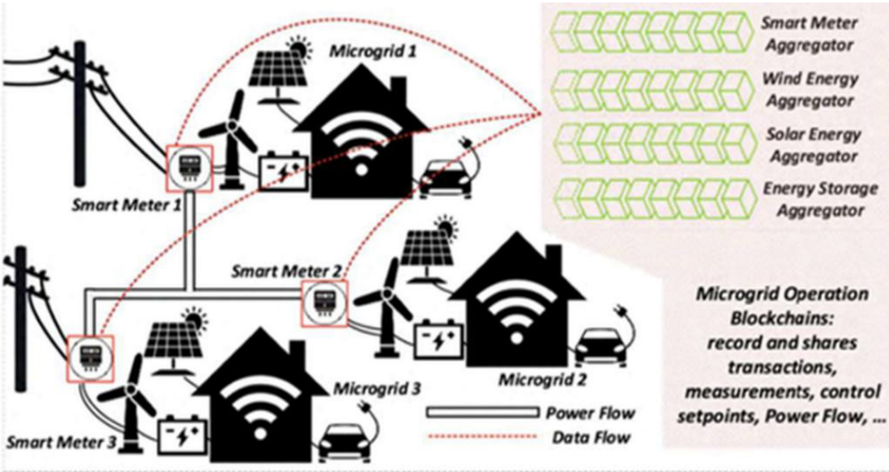

Fig. 2. Integration in smart microgrid for decentralized energy management [4].

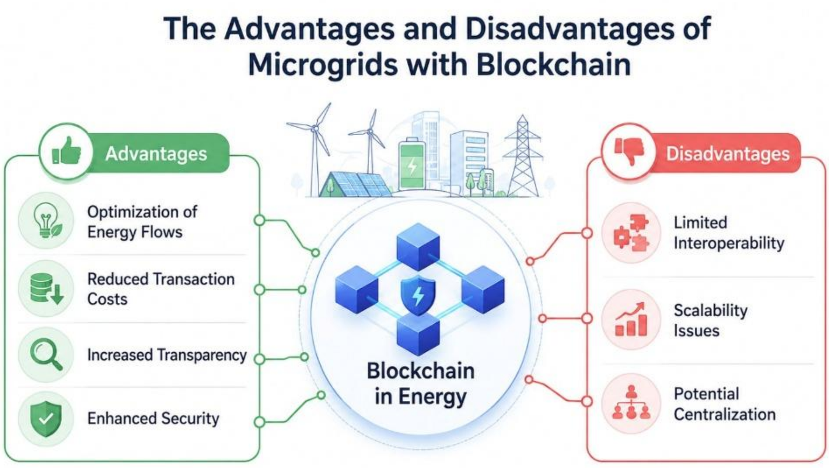

Fig. 3. Opportunities and challenges of implementing blockchain in microgrids.

P2P energy exchange based on blockchain is a key innovation for energy consumers and producers to transact directly with each other without a centralized intermediary. Differentiating from traditional schemes in which a single entity sells the electricity from production to consumption, this methodology facilitates energy decentralization management, enabling the market to become more flexible, transparent and efficient. Thanks to the blockchain, each transaction is recorded on a nonmodifiable ledger that ensures the traceability and security of the energy transactions. The application of P2P energy transaction based on the blockchain has promising. So, it lets people sell their excess renewable energy and be less dependent on traditional energy providers. Secondly, it improves network robustness, since a distributed system is less vulnerable to global outages or to localized attacks. Finally, exchange security is reinforced, as each transaction is validated by a robust consensus mechanism, guaranteeing total transaction transparency [2]. For example, the integration of PBFT consensus has enabled transactions to be validated quickly and securely, while reducing the energy consumption associated with traditional mechanisms like PoW [4]. In addition, another experiment [12] was performed to set up a decentralized P2P energy market, combining blockchain and a pipelined delegated Byzantine fault tolerance (PDBFT) consensus algorithm to implement a trusted joint energy-and-reserve trading mechanism. In this system, prosumers can sell or buy energy and reserves through secure, automated exchanges on the blockchain, ensuring auditability and tracking of transactions. Numerical results show that, relative to a mechanism considering only energy trading, the proposed joint energy-and-reserve market reduces the total market cost by 16.03%. Furthermore, compared with using the traditional PBFT consensus algorithm, the PDBFT-based blockchain trading algorithm decreases the computational time of market clearing by 45.90%. Nonetheless, there are several challenges and limitations hindering its mass adoption. One of the key obstacles is reliance on national regulations. Indeed, many countries do not permit the resale of energy by individuals, or they regulate decentralized energy trade heavily. Another challenge lies in terms of scalability of blockchain. Public blockchains remain too slow to process large batches of parallel transactions, while private blockchains, although faster, dilute the decentralization of the system [13]. The ability for blockchains to integrate with the traditional energy systems is also a significant barrier. Most conventional power grids were not built to handle distributed transactions at such volume, which complicates efforts to link blockchain with these networks. With the advance of blockchain protocols, greater integration of artificial intelligence for energy efficiency, and regulation evolving in more relaxed venues, P2P energy trading may transform smart grid management.

3.2 Consensus Mechanisms for EMS

Industrial EMS play by rules that are very different from the familiar ones in the public blockchain space. In microgrids and industrial energy systems, transaction validation cannot afford to be delayed by long confirmation wait times since dispatching decisions, distributed coordination, and local balancing schemes are often based on near real-time execution. The communication protocol itself is also inherently different from that of the cryptocurrency related protocols. A lot of industrial EMS solutions are built around consortium or permissioned models in which the members are established entities like utilities, aggregators, managed service providers, or large consumers. In this case, the consensus scheme is the one that enables the blockchain layer to stabilise or to degrade the system performance.

The comparison between PoW, PoS, PBFT, and PoA reveals substantial differences in latency, scalability, decentralization, and behaviour energy efficiency. To provide a clear overview, the main characteristics of the most widely used blockchain consensus mechanisms in the context of industrial EMS and microgrid applications are summarized in **Table 2**. The PoW is generally the least compatible mechanism for industrial EMS deployment because its consensus process depends on computational mining and repeated block confirmations, which significantly increase both validation delay and electricity consumption. Public PoW networks can reach thousands of kWh per thousand validated transactions, creating an energy burden that directly conflicts with the sustainability objectives of smart grids and renewable-based microgrids. Transaction throughput also remains limited, often around a few transactions per second, making PoW unsuitable for intensive energy trading and high-frequency EMS coordination tasks.

Table 2. Comparison of Consensus Mechanisms in Blockchain-Based EMS

Metric / Mechanism	PoW	PoS	PBFT	PoA	Ref

Latency	High latency with multiple block confirmations (typically several seconds to minutes)	Moderate latency (typically 2–3 s depending on validator configuration)	Very low latency with deterministic finality in the millisecond-to-second range	Very low latency in permissioned environments, often comparable to PBFT-based architectures	[14, 15]
Scalability	Limited throughput (≈5–7 TPS) and poor scalability with increasing network size	Moderate scalability; throughput may reach 85–120 TPS but can degrade with large validator sets	Limited scalability due to $O(n^2)$ communication overhead; more suitable for small and medium consortium networks	Good scalability in permissioned networks with a limited number of authorities	[2,4]
Energy Efficiency	Very high energy consumption; public PoW systems can consume several thousand kWh per 1000 transactions	Low energy consumption (around 0.04 kWh/transaction reported in some studies)	Higher energy use than PoS but significantly lower than PoW due to the absence of mining operations	Low energy consumption because validation relies on predefined authorities without mining	[15]
Decentralization	High decentralization through public mining participation, although mining concentration may emerge	Medium-to-high decentralization depending on staking distribution and validator governance	Medium decentralization based on committee-driven validation in permissioned environments	Low decentralization because the validator set is predefined and institutionally controlled	[10]
Suitability for Industrial EMS / Microgrids	Poor suitability due to high latency, high energy demand, and low throughput	More suitable for public green blockchain applications but less adapted to strict industrial real-time constraints	Well suited for industrial microgrids and VPPs due to deterministic finality, Byzantine fault tolerance, and low latency in consortium networks	Suitable for permissioned industrial networks requiring very fast validation and high throughput, at the cost of reduced decentralization	[6]

PoS partially mitigates these limitations by eliminating intensive mining operations and replacing them with validator selection mechanisms based on token ownership or staking strategies. The reduction in computational demand improves energy efficiency considerably, while validation latency becomes lower than PoW [14]. Yet the mechanism still exhibits several operational limitations in industrial contexts. Validator concentration may progressively reduce decentralization, especially when a limited number of stakeholders accumulate large token shares. In addition, the probabilistic nature of validation introduces delays that may remain problematic for strict real-time coordination tasks in industrial microgrids, where energy scheduling and balancing decisions evolve continuously under fluctuating operating conditions [15].

A different operational profile emerges with PBFT and PoA. Both mechanisms were designed for environments in which participating nodes are identifiable and partially trusted, a configuration that closely resembles industrial consortium networks. PBFT achieves deterministic finality through Byzantine fault-tolerant message exchange, allowing transactions to be validated within milliseconds or seconds without requiring energy-intensive mining. This characteristic becomes particularly relevant in industrial microgrids, virtual power plants, and IIoT-based energy systems, where dispatching commands, storage coordination, and local energy trading require immediate consistency between distributed nodes. Several studies consistently show that PBFT-based architectures maintain lower latency and stronger transactional coherence than public blockchain approaches when the network size remains controlled.

The principal limitation of PBFT appears during network expansion. Communication overhead increases rapidly because each validator exchanges synchronization messages with the entire committee, producing an $O(n^2)$ communication structure [13]. In large-scale public systems this behavior becomes restrictive. Industrial EMS environments, however, rarely operate with thousands of validators. Most deployments involve a relatively small consortium of trusted entities, making PBFT technically feasible despite its scalability limitations. This explains why several recent studies propose optimized variants such as hierarchical PBFT, CE-PBFT, H-PBFT, or S-PBFT to reduce communication overhead while improving throughput and latency in blockchain-enabled microgrids and distributed energy trading systems. PoA follows a more centralized validation logic. Consensus authority is delegated to a predefined set of validators, generally controlled by industrial operators, aggregators, or consortium members. The mechanism minimizes computational overhead and produces extremely fast transaction confirmation, often comparable to PBFT under controlled conditions [10]. Such behavior explains why PoA is increasingly considered in industrial blockchain infrastructures requiring high throughput and operational simplicity. The trade-off nevertheless remains explicit. Scalability and execution speed improve, but decentralization decreases because the validator set remains institutionally governed and relatively small.

The comparison suggests that consensus selection in industrial EMS cannot rely exclusively on decentralization metrics commonly associated with cryptocurrency systems. Operational stability, deterministic validation, communication efficiency, and infrastructure governance become more critical than fully open participation. Within this context, PBFT appears particularly suitable for industrial microgrids requiring BFT, deterministic finality, and secure real-time coordination inside a limited consortium network. PoA becomes attractive when the priority shifts toward scalability, simplified governance, and ultra-fast execution under institutional trust assumptions. Current research trends reinforce this direction. Several recent works investigate hybrid consensus architectures combining PBFT, PoS, hierarchical validation, or reputation-based mechanisms to balance efficiency, fault tolerance, and decentralization in distributed energy systems.

3.3 Comparison of Blockchain Approaches to Energy Management

The proliferation of decentralized energy systems is leading to an increasing need for coordination mechanisms capable of operating in a "supervision-lite" environment to facilitate secure energy trade1 without a full centralization of supervision. In fact, the problem becomes even worse when renewable sources, storage units and prosumers coexist on the same platform under dynamic pricing in real microgrid applications as the transaction validation speed directly impacts the stability of local energy management. Consequently, blockchain technologies attracted increasing attention, not because they secure transactions via distributed consensus, but because they change how energy is traded, validated and monetized in decentralized infrastructures.

Nonetheless, various blockchain realization does not portray the same performance behaviour when apply to the power system. Consensus protocols that possess a good decentralization quality tend to fail in terms of communication overhead and transaction latency, especially when the number of nodes involved grows. Lightweight schemes alleviate this burden, but often at the expense of some degree of decentralization. This trade-off is particularly evident in industrial microgrids, where decisions on energy scheduling need close to real time validation in the face of severe operating conditions. These distinctions are analysed in **Table 3** by contrasting the use of blockchain in microgrids, smart grids, P2P energy trading tools, and renewable energy integration applications. Insights from recent research indicate that blockchain can enhance transaction traceability, strengthen cybersecurity, enable the direct exchange of energy among prosumers, and reduce reliance on centralized intermediaries. At the same time the constraints on use are still very great. Regulatory risk, integration with existing very reliable grid infrastructure, and scaling issues with consensus protocols are hampering mass adoption, particularly for systems that require continuous, high frequency transaction processing.

Table 3. Comparison of Blockchain Applications in EMS

Elements	Microgrids & Smart Grids	Trading P2P	Integration of renewable energies
Security	The use of private and consortium blockchains enhances security against cyber-attacks and guarantees the authenticity of transactions[6].	The traceability and immutability of transactions provide increased protection against fraud and data tampering in P2P markets [14] .	Blockchain supports certification of the origin of renewable energy and prevents falsification of green/renewable energy certificates [6].
Scalability	Public blockchains suffer from high latency and low transaction throughput, while private/consortium solutions offer better performance but at the expense of transparency and openness[13] .	P2P transactions require fast and efficient consensus mechanisms (PBFT, PoA, PoS variants) to ensure sufficient scalability, which can sometimes reduce the	Large-scale integration of renewable energies requires blockchain systems capable of handling high transaction volumes while

		level of decentralization[14].	supporting efficient coordination and energy allocation [7] .
Economic impact	Blockchain-based smart grids and microgrids can reduce operating costs by removing intermediaries and optimizing local energy exchanges [2].	P2P trading platforms enable prosumers to sell surplus energy, potentially improving their economic returns and creating new local market opportunities[14] .	Tokenization and trading of renewable energy/green certificates improve integration of renewables and create additional revenue streams linked to clean energy production [8] .
Implementation complexity	Deployment requires adaptation of existing infrastructures and interoperability with traditional energy systems and control architectures[8].	Adoption is highly dependent on local regulations and legislative frameworks governing energy trading and data governance, which can hamper widespread deployment [2] .	Integration across different networks requires common standards and protocols to ensure compatibility between legacy grids, renewable assets, and blockchain-based platforms[14].

4 Conclusion

In this paper, we present a comparative analysis of blockchain-based energy management approaches in renewable energy systems, smart grid and microgrid, as well as P2P energy trading platforms. The results imply that blockchain might have a disruptive impact on the energy sector by increasing transparency, security and automatization of energy transactions, particularly when integrated with enabler technologies such as Artificial Intelligence and IoT. Public Blockchains provide unprecedented transparency, but public blockchains also face challenges related to high latency and complexity, making them unsuitable for the real-time energy systems. In contrast, private and consortium blockchains offer lower latency and higher performance at the expenses of decentralization. The consensus protocol selection is still critical, and the recent such as PoS, PBFT and PoA can achieve a good balance between the efficiency, security and energy consumption of the system. Despite the promise, challenges remain for broad practical application, such as regulatory issues, need to interoperate with legacy energy infrastructure, and to develop uniform protocols across distributive networks. Yet sustained advances in blockchain infrastructure and in enabling policy environments may accelerate its adoption in modern energy sectors. In general, blockchain technology is a promising enabler for decentralized, secure, and smart energy management. Its application would enable the creation of a more adaptable, sustainable and self-reliant energy network, thereby advancing the world's shift to more environmentally friendly and intelligent energy systems.

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