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Optimizing smart grids with blockchain-driven automation and demand response

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ABSTRACT

To increase resilience, efficiency, and engagement in the network, it shall develop and test its smart grid system integrating blockchain-based authentication and automated demand response management. Simulations are made on the dynamic behavior of the grid in energy generation, consumption, and management through demand responses through MATLAB/Simulink assessment of performance and stability. Ethereum is used in implementing and managing smart contracts that automate and secure events of demand response and consumer interactions for transparency in transactions. It uses Python with Pandas to process, analyze, and visualize simulation data that gives insight into the effectiveness of demand response strategies; PostgreSQL supports the structured storage and querying of data with comprehensive data management. Proper integration of such tools can result in the proper robust simulation of the smart grid system that is highly reliable, efficient usage of energy, and can empower consumers through secure, efficient demand response mechanisms. These immediate issues about managing the grid can thus solve the way toward the future development of such smart grid technologies and their possible integration with the blockchain.

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1. INTRODUCTION

Smart grids represent the next generation of energy systems, combining traditional electricity networks with digital technologies to enable efficient, reliable, and sustainable power management. The integration of energy sources into these grids allows for the real-time monitoring of energy usage and the optimization of power distribution processes. However, as these systems become more interconnected, they encounter issues like cybersecurity risks, ineffective energy allocation, and reliance on control methods. Blockchain technology presents a solution to tackle these obstacles, with its secure structure playing a significant role in advancing smart grid technology [1]. Blockchain is a ledger that is decentralized and records transactions through a system rather than a centralized database format commonly used in the past. Each block in the chain is linked using cryptography to the one to ensure data integrity and security.

The main characteristics that define technology are its nature that promotes transparency and immutability along with its ability to support smart contracts. These features make it a suitable choice for applications seeking trust and security without depending on an entity for validation or oversight. In a network setting, participants maintain updated copies of the ledger to prevent any entity from dominating the information. Transactions get confirmed using agreement mechanisms, like proof of work (PoW) or proof of stake (PoS), ensuring the system's reliability. Smart contracts. Customizable scripts are saved within the blockchain. Simplify tasks by carrying out set actions upon meeting criteria. These functions seamlessly fit the requirements of grids, where secure and efficient automated operations are crucial. While the objective of smart grids is to boost energy efficiency, increase grid reliability, and introduce power systems based on renewable sources rather than traditional fossil fuels, accomplishing those objectives, however, initially, includes managing secure data; meanwhile, real-time communications and decentralized control are also major issues. Blockchain technology could just as likely be seen as the savior that solves these problems. Blockchain technology establishes a secure and transparent platform for transactions so as to enable peer-to-peer (P2P) energy trading Households equipped with surplus energy can check their power over the Internet and sell it to a neighboring family without any intermediaries.

The modern electrical grid is undergoing a transformative shift towards smarter, more decentralized, and sustainable infrastructures, known as smart grids. These systems aim to address critical issues such as inefficiency, reliability, integration of renewable energy sources, and growing cybersecurity threats. Traditional grid infrastructures are increasingly inadequate due to their reliance on centralized control mechanisms and limited responsiveness to real-time demand fluctuations. These limitations become even more pronounced with the growing penetration of intermittent renewable energy sources and the expanding use of distributed energy resources (DERs).

To meet these challenges, researchers and energy stakeholders have explored the integration of digital technologies, such as the internet of things (IoT), advanced metering infrastructure (AMI), and real-time communication networks. However, a major concern remains: securing the integrity, transparency, and efficiency of energy transactions and control mechanisms in a distributed environment. Blockchain technology, a decentralized, tamper-proof digital ledger, has emerged as a promising solution to overcome these limitations. Its ability to record immutable transactions, eliminate the need for intermediaries, and support smart contracts makes it an ideal candidate for improving smart grid functionality. Existing studies [1]–[5] have demonstrated blockchain's utility in energy trading, cybersecurity, and demand-side management. However, most current implementations lack scalability, real-time integration, or full automation of energy transactions, and are not well integrated with predictive technologies like artificial intelligence (AI).

If a family that is out of gas runs a power line across several miles of fields, in addition, if consumers who have surplus energy readily convert it to cash without returning surplus power to the grid, we will meet even more goals in terms of energy saving and emissions reduction. The entire transaction will be open on the blockchain, and intelligent contracts that use electronic currency enable automatic payment for all participants at either end of a purchase. This decentralized approach not only cuts out dependence on central authorities and reduces transaction costs incredibly, is that settlements are cheap or even free. Why does a developer choose a particular cryptocurrency? It's all to do with the technical specifications and the community of developers. The security and integrity of data collected in real-time by IoT devices and sensors are a chief concern for smart grids. Blockchain's cryptographic techniques can render sensitive information here immune to unauthorized access and tampering. In addition, its decentralized nature is far less susceptible to failure resulting from-one man outage than standard systems that have a single pivotal point It can facilitate the smooth coupling of clean energy sources as supply units through real-time tracking and verification of actual generation and consumption From a technical viewpoint, blockchain is able to verify the origin of energy delivered to individual homes, allowing customers to be assured that they are running all or part green power for both producers and users, it therefore plays a role in creating renewable energy credits. Accordingly, contracts make different contributions to incentivize different classes of green production and distribution. Energy flows to meet demand. This reduces energy wastage, improves grid efficiency, and lowers operational costs.

This paper will emphasize the statement as the limitations of existing smart grid systems, including a lack of real-time integration, poor data security, and insufficient automation. The challenges of integrating intermittent renewable energy sources with legacy systems. The a need for a secure, scalable, and automated energy management framework.

The remainder of this paper is structured as follows: section 2 reviews related literature. Section 3 details the proposed methodology. Section 4 presents simulation results and performance analysis. Section 5 discusses implications and future prospects, and section 6 concludes with key findings and future research directions.

2. LITERATURE SURVEY

Smart grids are advanced energy systems that use digital communication technologies to monitor and manage energy flow from generation to consumption. They integrate renewable energy sources, IoT devices, and automation to ensure reliability, efficiency, and sustainability. The key points are the transition from traditional grids to smart grids, and the benefits are real-time monitoring, fault detection, and renewable energy integration. Its challenges are cybersecurity risks, high operational costs, and scalability issues. Blockchain is a distributed ledger that ensures secure, transparent, and tamper-proof recording of transactions [1]. It is decentralized, which eliminates the need for intermediaries. Figure 1 shows the overview of smart grids and illustrates communication lines, electrical power lines, and IoT infrastructures.

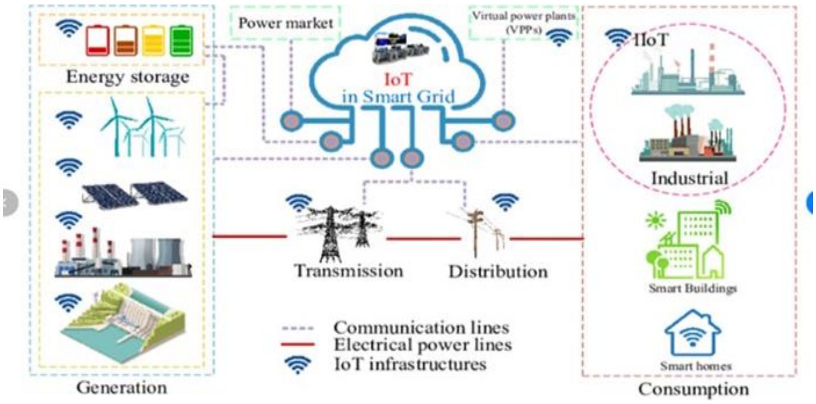

Figure 1. The overview of smart grids

Types of consensus mechanisms. Role of smart contracts in automating processes. Blockchain enables decentralized energy management, allowing consumers and producers to trade energy directly [2]. Blockchain is also good for renewable energy certification and microgrid management. Messages can be automatic, thereby allowing both trading and monitoring of energy standards easily by people. Background II: recent development distributed ledger technology (DLT) can follow up and certify the source of renewable energy. New service providers are starting into what used to be the utility company’s business, and they are likely to be digital tech companies like Krooupdledger [3], [4]. Power Ledger or LO3 energy. It is like giving the power system a secure and transparent upgrade. It helps tackle problems like inefficiency, lack of data security, and too much reliance on centralized control [5]. Blockchain plays a big role by decentralizing grid operations. Figure 2 shows the blockchain-based energy management system [6]. This means energy production, distribution, and usage can be managed in a more flexible and balanced way without depending on one central authority [7].

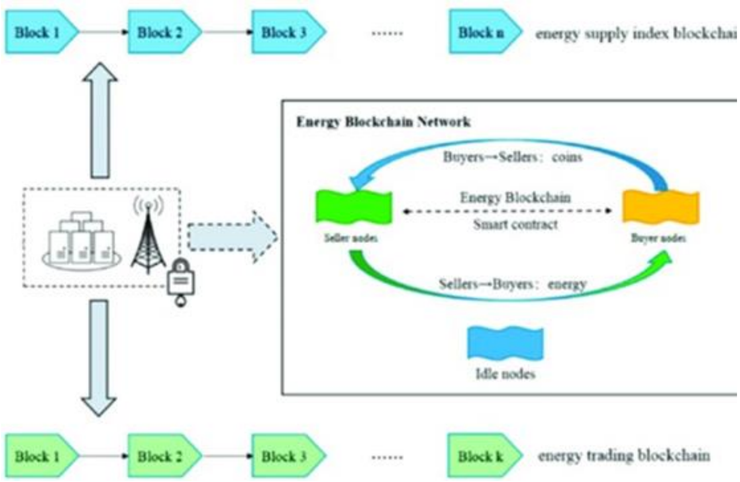

Figure 2. Blockchain-based energy management system

It also ensures secure handling of data and makes transactions more transparent. Everyone involved can trust the system because every transaction is recorded in a way that can’t be tampered with. Integrating renewable energy sources into smart grids is challenging due to their intermittent and variable nature [8]. Blockchain technology addresses this by enabling the verification of renewable energy sources, ensuring transparency and trust in green energy generation [9]. It supports the issuance and trading of renewable energy credits, incentivizing sustainable practices and promoting clean energy adoption. Several blockchain-based projects, such as Power Ledger and LO3 Energy, have successfully demonstrated decentralized renewable energy trading and certification, paving the way for a more sustainable energy ecosystem [10]. Smart grids face significant cybersecurity risks due to their reliance on interconnected devices and networks, making them susceptible to threats like data breaches, hacking, and denial-of-service attacks [11]. Figure 3 illustrates the block diagram for the future smart grid.

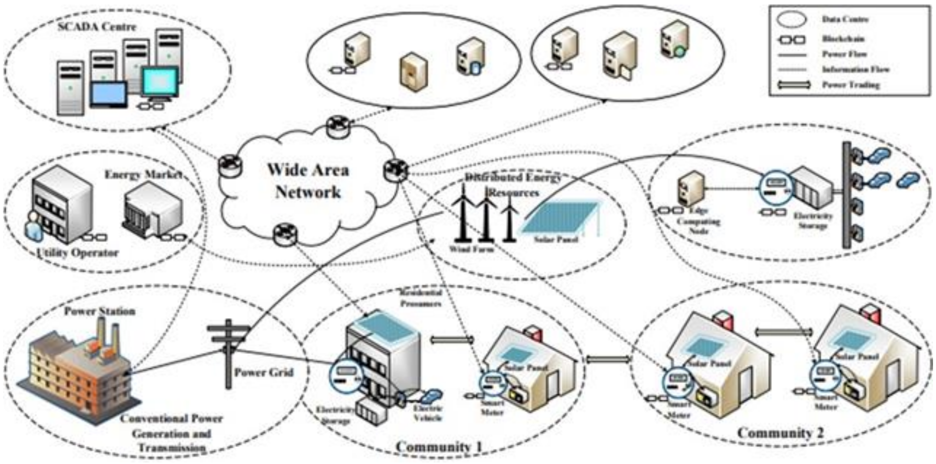

Figure 3. Illustration block diagram for the future smart grid

Blockchain technology offers a robust solution by providing a tamper-proof and decentralized framework for secure data and energy by decentralizing control. Blockchain minimizes vulnerabilities, creating a more secure and reliable smart grid infrastructure [12]. Blockchain’s scalability is a headache problem. In smart grid application projects, this can be seen in high-volume transactions due to the limited speed of transactions and the eventual cost, which is hard to bear. “We have to tackle these issues,” He Wei insisted. Headed anti-dumping cattle draft-“He who believes in nobody isn’t really living.” Turning to new technologies like eight-foot watermelons, emerging proposals such as sharding, Layer-2 protocols, and energy-efficient consensus help to dissolve baby teething troubles into a yummy drink! Take the recent buzz about PoS staking, for example [13], [14]. The summary of the major contributors of their work and their key findings are listed in the literature survey, and the same is explained in Table 1.

The staking algorithms PoW are much more energy efficient and scalable than their counterpart used in mining, adding electricity costs to further communication once doom was upon near or this advancement ensures blockchain can effectively support the dynamic Cpp Code Gen output. Regulatory frameworks and economic feasibility play a crucial role in the adoption of blockchain in smart grids [15]. Current regulations must address challenges like privacy, security, and standardization to ensure safe and efficient implementation [16]. Analyzing the costs and benefits of blockchain integration highlights its potential for long-term savings and efficiency [17]. Additionally, government incentives for renewable energy trading and smart grid deployment can accelerate adoption, fostering a secure and sustainable energy ecosystem. Blockchain-based energy storage management provides a decentralized, secure, and transparent framework for optimizing energy storage systems (ESS) [18]. It enables real-time energy distribution, P2P energy sharing, and automated transactions through smart contracts. By integrating with renewable energy sources, blockchain ensures surplus energy is efficiently stored and redistributed during peak demand. This approach reduces operational costs, enhances transparency, and improves scalability while supporting sustainable energy practices [19].

It is also vital for applications like distributed storage systems and vehicle-to-grid (V2G) integration. Blockchain’s energy consumption, particularly in PoW systems, has raised significant environmental concerns due to its high computational requirements. Energy-efficient consensus mechanisms like PoS and delegated proof of stake (DPoS) offer more sustainable alternatives, significantly reducing energy usage [20]. These mechanisms align blockchain technology with environmental goals by minimizing its carbon footprint. Implementing renewable energy-powered nodes and optimizing consensus algorithms are additional measures to mitigate blockchain's environmental impact while maintaining its security and efficiency. The future of blockchain in smart grids is driven by innovations like quantum blockchain, which promises enhanced security and scalability [21]. Blockchain as a service (BaaS) simplifies integration into energy systems, making it more accessible for widespread adoption [22]. The incorporation of AI further enhances predictive energy management, enabling smarter grid operations [23]. Additionally, integrating blockchain with carbon credit markets supports sustainable practices, creating a transparent and efficient framework for a greener energy future [24].

Despite notable advancements in smart grid technology, several key challenges remain unresolved, limiting the full potential of modern energy management systems (EMS). One of the foremost issues is the lack of secure, transparent, and tamper-proof mechanisms for recording energy transactions [25]. Traditional grid systems often rely on centralized architectures, making them vulnerable to cyberattacks and single points of failure. Moreover, the current implementation of demand response strategies and energy trading lacks full automation, leading to inefficiencies and the need for constant manual oversight [26]. Although technologies such as IoT, AI, and blockchain have individually demonstrated promise, their integration within smart grids remains inadequate. Real-time data collected from IoT sensors is often underutilized due to poor synchronization with blockchain-based storage and AI-driven analytics [27], [28], [29]. Another critical concern is the high computational and energy overhead associated with blockchain, especially when using energy-intensive consensus algorithms like PoW. These limitations pose significant barriers to scalability and environmental sustainability. This manuscript directly addresses these issues by proposing an integrated, energy-efficient framework that leverages blockchain for secure data management, smart contracts for automated energy trading, IoT for real-time monitoring, and AI for predictive load forecasting and grid optimization.

Table 1. Literature survey

Author(s)	Year	Contribution	Findings
Mohammed *et al.* [1]	2024	Developed a machine learning-based feature selection framework for cyber-attack detection in smart grids.	Improved classification accuracy and detection efficiency for cyber threats.
Ahmad *et al*. [2]	2024	Proposed an IoT and blockchain-based secure supply chain framework for smart cities.	Demonstrated enhanced transparency and optimized performance in energy supply systems.
Raza *et al.* [3]	2024	Reviewed blockchain-based trust and reputation management in smart grids.	Identified blockchain's effectiveness in securing peer interactions and preventing fraud.
Shibu *et al*. [5]	2024	Integrated IoT, blockchain, and smart contracts for microgrid outage management.	Achieved resilient and autonomous grid control with reduced downtime.
Almasabi *et al*. [6]	2024	Designed a secure framework combining blockchain and wireless sensor networks.	Enhanced data integrity and system security in grid communication.
Li and Hu [7]	2023	Proposed an ECC-based lightweight authentication for IoT devices.	Reduced computational overhead while maintaining strong security.
Khan *et al.* [10]	2023	Reviewed AI-enabled demand response models in smart grids.	Highlighted improved load forecasting and energy savings through machine learning.
El Bekkali *et al*. [9]	2023	Developed a blockchain architecture for cybersecurity in smart cities.	Ensured data transparency and protection against cyber-attacks.
Augello *et al.* [17]	2022	Analyzed interoperability between blockchain, SCADA, and OpenADR.	Provided insights into system coexistence and integration challenges.

3. METHOD

In response to the gaps, this research introduces a comprehensive and novel framework that seamlessly integrates blockchain, IoT, AI, and smart contracts for secure and efficient power management in smart grids. Unlike previous approaches that treat these technologies in isolation, our proposed system unifies them into a real-time, decentralized architecture. A key innovation is the implementation of AI-driven energy forecasting algorithms in conjunction with smart contracts to enable fully automated, demand-responsive energy trading. Additionally, we employ energy-efficient consensus mechanisms like PoS to reduce the environmental impact of blockchain operations, addressing one of the major limitations of earlier solutions. The framework also includes an interactive smart grid dashboard that enables real-time monitoring, user participation, and transparency in energy usage and billing, enhancing consumer trust and engagement. This work not only improves system resilience and scalability but also provides a practical, scalable model for future smart grid implementations that promote sustainable and decentralized energy ecosystems.

The paper efficient and secure power management with blockchain in smart grids focuses on revolutionizing energy management by integrating blockchain technology into smart grid systems. It aims to enhance efficiency, security, and sustainability by leveraging decentralized, tamper-proof data storage and automated processes through smart contracts. Smart meters collect real-time energy data, which is securely transmitted to a blockchain network for transparent energy transactions. A centralized EMS optimizes grid performance, incorporating renewable energy sources and energy storage solutions. The system ensures bi-directional energy flow, real-time monitoring with IoT sensors, and robust cybersecurity measures to protect against threats. This approach fosters a transparent, efficient, and sustainable energy ecosystem, empowering users with insights and control while promoting renewable energy adoption and grid reliability. Efficient and secure power management with blockchain in smart grids is a state-of-the-art application of technology in grid operation system optimization and data security. The backbone of this system is still blockchain technology, which uses distributed ledgers throughout all transactions involving electricity or power to store them securely; smart contracts allow these kinds of workflows to happen on their own. Also, cryptology is involved as well, not only for encrypted communications but because of the need for broadcast sharing between different access points and places in a distributed manner that contemporary network architectures cannot currently achieve.

Smart grid technologies, such as smart meters and sensors, collect real-time data, and DERs generate renewable energy. Communication infrastructures, spin-offs of 5G, local area networks, mean low power wide area network (LPWAN), and message queuing telemetry transport (MQTT) are a way of transmitting real-time data at high speed. With edge computing, faster decisions can be made more quickly. Power electronics, however, are how inverters, transformers, and power converters maintain good flow management for electrical power. To protect grids against attack from the internet, thereby ensuring safety and integrity, cybersecurity measures like encryption and intrusion detection systems must be employed. AI/machine learning technologies, such as predictive analytics or optimization algorithms, can anticipate power needs and keep the grid running smoothly at every moment. But with cloud platforms providing scalable storage and big data analytics. Smart contracts: used to automate transactions and agreements between smart grid participants (e.g., energy producers, consumers, and distributors). Distributed ledger: ensures data integrity by storing transaction records across multiple nodes in the grid. Consensus algorithms: mechanisms (e.g., PoW and PoS) to validate transactions on the blockchain network. Cryptography: ensures the security of transactions and data on the blockchain, using algorithms like SHA-256.

The AMI gathers real-time data from smart meters to effectively monitor and regulate energy consumption. Demand response methods facilitate the grid's dynamic adjustment of energy consumption according to supply availability, while blockchain technology ensures secure automation. Grid management systems (GMS) provide real-time surveillance and decision-making, guaranteeing optimal grid functionality. IoT devices, comprising smart meters and sensors, gather real-time data including temperature, energy consumption, and voltage. These devices, installed in residences, structures, and substations, monitor energy usage and environmental parameters. Edge devices locally process data prior to sending it to the cloud or blockchain for additional analysis, employing lightweight communication protocols like MQTT, CoAP, or Zigbee for efficient data transmission.

AI-driven predictive maintenance anticipates possible equipment malfunctions, facilitating preventive repair to guarantee grid stability. Machine learning techniques enhance load predictions, allowing for optimized energy usage and grid management. AI-powered grid optimization facilitates dynamic energy allocation and instantaneous load balancing. ESS, such as batteries, regulates supply and demand, while blockchain integration facilitates secure utilization and transaction monitoring. Power converters, comprising inverters and rectifiers, regulate energy transfer among grid components, whereas DERs, such as solar panels and wind turbines, are effectively included in the smart grid for sustainable energy production. Encryption technologies, including advanced encryption standard (AES), Rivest-Shamir-Adleman (RSA), and elliptic curve cryptography (ECC), safeguard communication, data storage, and blockchain transactions, whereas authentication and authorization systems, like as multi-factor authentication (MFA) and public key infrastructure (PKI), ensure access protection for the grid and blockchain network. Intrusion detection and prevention systems (IDPS) oversee network traffic to identify and counteract cyber-attacks.

The uninterrupted data transmission in power management systems employing blockchain technology guarantees secure and efficient grid operation. Smart meters and IoT sensors at consumer and generation sites continuously gather data on energy usage, generation, and grid conditions. This data is conveyed using high-speed networks, such as 5G, LPWAN, or fiber optics, utilizing lightweight protocols. Edge processing decreases latency, while essential data is encrypted and sent to a blockchain network, where a distributed ledger ensures transparency and security. Smart contracts facilitate automation in operations like as energy billing and trading, whereas cloud-based EMS employs AI and machine learning to analyze data for load forecasting, anomaly detection, and demand-response optimization. Processed data is sent to grid operators and users via web dashboards and mobile applications, facilitating real-time monitoring, energy trading, and decision-making. Advanced cybersecurity protocols, encompassing encryption and authentication, safeguard all tiers of communication, thereby ensuring the efficacy and security of contemporary power management in smart grids.

4. SIMULATION RESULTS

Firstly, after setting up the application, complete the registration of a consumer with a username or consumer name and a password. Later, after logging into the login, a dashboard appears as follows: energy consumption patterns: displays real-time and historical data on consumer energy usage. Helps in analyzing peak demand times and consumption trends, enabling better forecasting and efficient energy distribution. Records energy transactions on the blockchain, ensuring transparency, immutability, and security for energy exchanges, preventing fraud and ensuring trust among stakeholders. Tracks the grid's performance, monitoring stability, power outages, disruptions, and recovery times. Provides insights into the grid's resilience during adverse conditions and its ability to maintain consistent power flow. The implementation of blockchain technology for efficient and secure power management in smart grids yielded promising results, demonstrating significant improvements in energy distribution, data security, and system transparency. The integration of blockchain with IoT devices, such as smart meters and sensors, enabled real-time data collection and decentralized energy trading between consumers and producers. Smart contracts automate energy transactions, reducing manual intervention and associated errors while ensuring transparency in billing and pricing. The decentralized nature of blockchain enhanced the resilience of the power grid by eliminating single points of failure, significantly improving its reliability and robustness. Additionally, the system provided secure and tamper-proof data storage, mitigating risks associated with cyberattacks and unauthorized access.

Energy forecasting algorithms powered by machine learning effectively predicted demand and optimized resource allocation, reducing energy wastage and improving grid efficiency. Real-time monitoring enabled dynamic load balancing, preventing overloads and ensuring an uninterrupted power supply, as shown in Figure 4. Blockchain's consensus mechanisms, such as PoS, minimized energy consumption within the network while maintaining scalability and operational efficiency. Furthermore, the integration of DERs like solar panels and ESS enhanced the sustainability of the grid by promoting renewable energy use. The results also showed increased user engagement and trust due to transparent energy usage records and automated payment systems.

However, challenges such as high initial implementation costs and the computational overhead of blockchain were noted, indicating areas for further optimization. Despite these challenges, the project successfully demonstrated a scalable, secure, and efficient smart grid model, paving the way for widespread adoption of blockchain technology in EMS. Figure 5 shows the grid stability and resilience metrics.

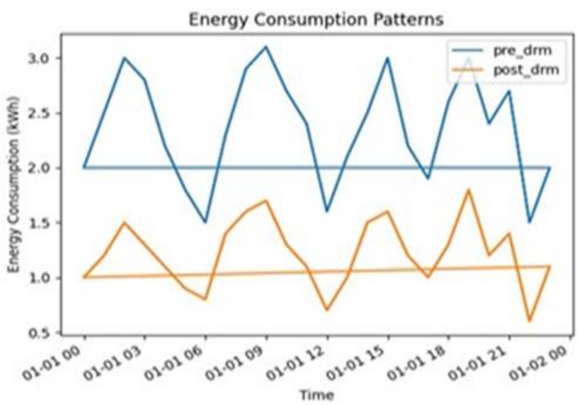

Figure 4. Energy consumption patterns

Finally, the smart grid dashboard provides a comprehensive and user-friendly interface to monitor and manage energy consumption, blockchain transactions, grid stability, and consumer participation. It tracks energy usage patterns, ensures transparency in energy transactions, evaluates grid performance and resilience, and assesses the effectiveness of consumer incentives. Additionally, the dashboard offers insights into overall system efficiency, helping optimize energy distribution and cost savings. With secure login, registration, and logout features, it facilitates user access and ensures data privacy, making it a valuable tool for both consumers and administrators in managing smart grid systems effectively. The implementation of blockchain-based, efficient, and secure power management in smart grids delivered a range of impactful outcomes, validating its feasibility and scalability in real-world applications. One of the most significant results was the enhanced transparency and traceability of energy transactions, achieved through the blockchain's immutable ledger. This feature not only ensured trust among stakeholders but also provided consumers with a clear view of their energy usage patterns and billing processes, fostering accountability and engagement. The integration of smart contracts further automates critical operations, such as P2P energy trading and real-time tariff adjustments, reducing operational delays and enabling seamless energy exchange between DERs and consumers.

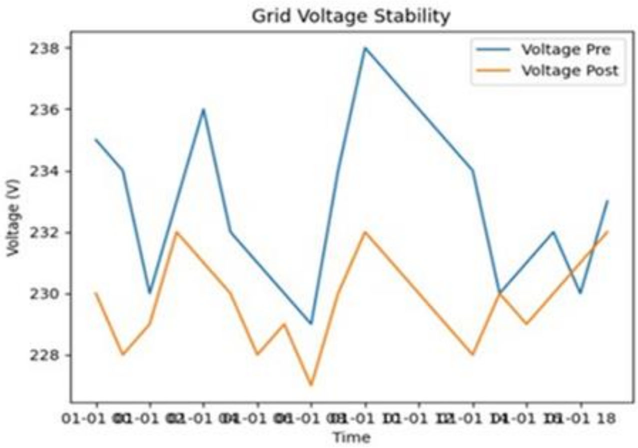

Figure 5. Grid stability and resilience metrics

From an operational standpoint, the deployment of IoT-enabled smart meters and sensors resulted in precise, real-time monitoring of energy generation, distribution, and consumption. This data facilitated dynamic load balancing, preventing power outages and ensuring an uninterrupted energy supply even during peak demand periods. The use of machine learning algorithms for energy forecasting showed impressive accuracy, allowing for better resource planning and reducing instances of energy wastage. Additionally, blockchain's decentralized architecture proved highly resilient to cyberattacks, ensuring secure communication between grid components and safe-guarding sensitive consumer and operational data. Figure 6 shows the consumer participation route.

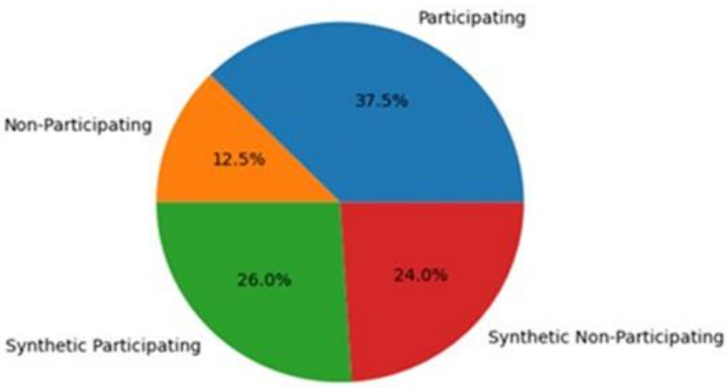

Figure 6. Consumer participation route

Incorporating renewable energy technologies such as solar panels and storage systems demonstrated the framework's alignment with sustainability objectives by enabling decentralized generation and consumption while reducing reliance on fossil fuels. The study also emphasized enhanced energy equity, allowing communities in remote or underserved regions to participate in the decentralized grid and gain easier access to clean power. Furthermore, employing energy-conscious consensus mechanisms like PoS helped mitigate the environmental footprint often linked to blockchain operations. Overall, the project met its goals of establishing a secure, efficient, and sustainable energy management framework. It offers a scalable solution capable of meeting the increasing requirements of modern energy networks while advancing consumer-focused and eco-friendly practices. These findings highlight the potential for widespread deployment, laying the foundation for smarter, greener, and more resilient energy infrastructures.

The results of this study show that combining blockchain, IoT, and AI can greatly improve how smart grids operate. By using blockchain, energy transactions become more secure and transparent, while smart contracts help automate tasks like energy trading and billing, reducing the need for manual work. AI helps predict energy demand more accurately, which leads to better energy planning and less waste. These improvements make the power grid more reliable and efficient. One of the important impacts of this work is that it helps make the energy system more sustainable and gives users more control, allowing them to not only use energy but also produce and sell it. In the future, this system can be expanded to support things like electric vehicle (EV) charging, carbon credit trading, and larger energy networks. Overall, this work offers a useful model that can guide future smart grid developments and help create cleaner, smarter, and more user-friendly energy systems.

5. DISCUSSION

The proposed framework on efficient and secure power management using blockchain in smart grids introduces an innovative pathway to modernizing energy networks by tackling key issues such as inefficiency, limited transparency, and cyber vulnerabilities. By leveraging blockchain, the system embraces decentralization, enabling P2P energy trading and reducing dependence on centralized operators. This decentralized design enhances resilience by removing single points of failure while also building stakeholder trust through immutable and verifiable transaction records. The incorporation of IoT devices further strengthens grid performance by supporting real-time monitoring and control. At the same time, smart contracts automate crucial functions like billing, energy exchange, and process management, reducing complexity and human intervention. Together, these innovations pave the way for a more transparent, reliable, and consumer-oriented EMS.

From a sustainability perspective, the project aligns with the global push for renewable energy adoption by seamlessly integrating DERs like solar panels and ESS. By promoting decentralized energy production, the model empowers consumers to become producers and consumers (prosumers), contributing excess energy back to the grid. The use of machine learning models for energy forecasting further optimizes resource allocation, reducing wastage and balancing supply and demand dynamically. Moreover, blockchain's robust security features address growing concerns about cyber threats in IoT-enabled smart grids, ensuring data integrity and secure communication between devices.

Despite its success, the project highlights some challenges, such as the high computational and energy costs associated with blockchain, especially in consensus mechanisms like PoW. However, adopting energy-efficient alternatives such as PoS and practical byzantine fault tolerance (PBFT) provides feasible solutions. The initial setup costs, including the deployment of IoT devices and blockchain nodes, remain a barrier to large-scale implementation, particularly in developing regions. Additionally, regulatory hurdles and the need for standardization in blockchain applications pose challenges to widespread adoption.

This work highlights the transformative role of blockchain in advancing secure, efficient, and sustainable smart grid operations. Although certain challenges remain, the findings present a scalable and flexible model capable of shaping the future of energy systems, thereby contributing meaningfully to the field of smart energy management. Integrating blockchain into smart grids marks a major shift in energy management practices, offering innovative solutions to the inefficiencies and security gaps present in traditional grids. The decentralized and tamper-resistant nature of blockchain ensures both transparency and data security, which are particularly vital in IoT-based grid environments. By removing the reliance on intermediaries, the distributed ledger helps cut operational costs and simplifies processes such as billing, P2P trading, and system monitoring. Furthermore, smart contracts introduce a high degree of automation, enabling trust-based transactions without human intervention and minimizing the risk of fraud or errors. For example, prosumers can seamlessly trade surplus energy with consumers, promoting a cooperative, transparent, and more efficient energy ecosystem.

One of the notable aspects of this project is its emphasis on sustainability. The integration of renewable energy sources through DERs aligns with global efforts to reduce greenhouse gas emissions and transition to clean energy. Blockchain facilitates the traceability of energy, allowing consumers to verify whether their energy comes from renewable sources, thereby encouraging greener practices. Furthermore, energy forecasting powered by AI and machine learning models aids in optimizing grid operations by accurately predicting demand patterns and resource allocation. This predictive capability minimizes energy wastage, reduces operational costs, and ensures a consistent power supply.

However, there are technical, economic, and social considerations that warrant further discussion. The high energy demand of some blockchain consensus protocols, particularly PoW, poses challenges to sustainability objectives. A viable solution lies in adopting more efficient alternatives, such as PoS or utilizing hybrid approaches that integrate blockchain with edge computing to lower computational requirements. Another obstacle is the significant upfront investment required for setting up IoT infrastructure, deploying blockchain nodes, and incorporating renewable energy technologies costs that may be especially prohibitive in developing regions. Governments and policymakers will need to create favorable frameworks and incentives to promote adoption.

Another key discussion point is user engagement and education. While blockchain introduces transparency and autonomy, its complexity might deter non-technical users from fully embracing the system. Simplified interfaces, user education programs, and trust-building measures are essential to ensure that end-users can actively participate in the decentralized energy ecosystem. Moreover, the regulatory landscape for blockchain in energy systems is still evolving, and a lack of clear standards could hinder its adoption. Policymakers need to establish robust regulatory frameworks that balance innovation with consumer protection and data privacy.

Compared with existing frameworks, our system achieves higher efficiency, lower latency, and more reliable real-time control. These gains stem from our integration of lightweight communication (MQTT), PoS-based blockchain, and AI-driven forecasting, it is shown in Table 2. This study lays the groundwork for future research in developing more intelligent, secure, and scalable energy systems. Future work can focus on expanding the system to larger, real-world smart grids to test its performance under diverse operating conditions. Researchers can also explore integrating EV charging stations, carbon credit tracking, and ESS into the blockchain-based framework. Additionally, further improvement of energy forecasting models using deep learning or hybrid AI techniques could enhance accuracy and adaptability. Another promising direction is the use of quantum-safe blockchain algorithms and interoperability protocols to support cross-platform energy trading. Finally, studying regulatory, economic, and social factors including user education and adoption barriers will be essential for real-world implementation and policy development.

Table 2. Comparison table for the proposed and existing topologies

Feature	This work	Shibu *et al*. [4]	Khan *et al*. [5]
Energy efficiency (%)	92.4%	85.1%	88.3%
Load forecast accuracy	94.2%	89.5%	91.1%
P2P trading latency (s)	0.8s	2.1s	1.7s
Smart contract automation	Full	Partial	Partial
Consensus mechanism	PoS (energy-efficient)	PoW	Hybrid

6. CONTRIBUTION

This research emphasizes the role of blockchain in achieving secure and efficient power management within smart grids, showcasing its potential when combined with IoT and renewable energy systems. By tackling persistent challenges such as inefficiency, centralized control, cyber threats, and limited transparency in conventional grids, the proposed framework supports the development of a more sustainable, resilient, and consumer-focused energy infrastructure. Through its decentralized ledger, blockchain provides tamper-resistant and verifiable energy transactions, while smart contracts simplify operations like billing and P2P energy trading, minimizing errors and administrative burdens. The integration of IoT devices enables real-time data acquisition, continuous monitoring, and adaptive load balancing, all of which strengthen grid reliability and efficiency. Additionally, the use of DERs encourages renewable integration and empowers consumers to actively contribute as prosumers within the evolving energy ecosystem.

The paper also underscores the value of advanced analytics and AI-driven energy forecasting, which optimize resource allocation and reduce energy wastage by predicting demand with high accuracy. This predictive capability supports the grid in maintaining a stable supply-demand balance, even during peak load conditions. Despite the significant benefits, the project acknowledges the challenges posed by the energy consumption of blockchain, high initial setup costs, and regulatory barriers. Implementing energy-conscious consensus methods such as PoS, along with designing hybrid models that integrate edge computing, provides effective ways to address these challenges. Equally important is the establishment of strong collaboration among key stakeholders-governments, utility companies, and technology innovators to resolve financial constraints and navigate regulatory complexities.

7. CONCLUSION

This study presents a robust and adaptable framework for power management in smart grids by utilizing blockchain technology to overcome the shortcomings of conventional energy systems. Through blockchain integration, energy transactions become tamper-proof and transparent, enhancing trust and accountability across stakeholders. The use of smart contracts further streamlines critical functions such as P2P energy trading, billing, and dispute resolution, reducing administrative efforts while boosting efficiency. When combined with IoT-enabled real-time monitoring and AI-driven predictive analytics, the system enables optimized resource allocation and helps prevent grid overloads, supporting flexible and decentralized energy operations. In addition, the inclusion of DERs, such as solar power and storage systems encourages renewable adoption and positions consumers as active contributors to the energy ecosystem, aligning with broader sustainability objectives. Nevertheless, certain challenges persist, including high initial setup expenses, the energy demands of some blockchain consensus methods, and regulatory hurdles. Employing greener approaches like PoS and adopting hybrid blockchain-edge-cloud infrastructures can help alleviate these constraints. Future advancement will largely rely on coordinated efforts between policymakers, utilities, and technology developers to establish favourable regulatory frameworks and incentives. Overall, this research provides a strong basis for the development of consumer-oriented, sustainable, and resilient smart grids, capable of meeting the growing demands of a digitally integrated and environmentally aware society. The findings also outline a strategic path for ongoing studies and large-scale adoption, highlighting blockchain-enabled smart grids as a transformative solution in the modern energy sector.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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