Blockchain and internet of things synergy: transforming smart grids for the future

Mouad Bensalah[1,2], Abdellatif Hair[1], Reda Rabie[2]
[1]Department of Computer Science, Sultan Moulay Slimane University, Béni Mellal, Morocco
[2]Digitalization Microelectronics Smart Device Center, MAScIR, University Mohamed 6 Polytechnic (UM6P), Ben-Guerir, Morocco

Article Info

Article history:

Received Aug 30, 2024
Revised Apr 3, 2025
Accepted May 24, 2025

Keywords:

Blockchain technology
Decentralized system
Energy security
IoT-based smart grid
Smart meters

ABSTRACT

Conventional smart grid systems face challenges in security, transparency, and efficiency. This study addresses these limitations by integrating blockchain and internet of things (IoT) technologies, presenting proof-of-concept implemented on an Orange Pi 4 single-board computer. The realized prototype demonstrated secure and transparent energy transaction management with consistent throughput between 7.45 and 7.81 transactions per second, and efficient resource utilization across varying transaction volumes. However, scalability challenges, including a linear increase in processing time with larger block sizes, emphasize the need for optimized consensus mechanisms. The findings underscore the feasibility of blockchain-based smart grids in resource-constrained settings, paving the way for advancements in peer-to-peer energy trading, decentralized energy storage, and integration with artificial intelligence for dynamic energy optimization. This work contributes to developing secure, efficient, and sustainable energy systems.

Corresponding Author:

Mouad Bensalah
Department of Computer Science, Sultan Moulay Slimane University
23000 Béni Mellal, Morocco
Email: e.mbensalah@gmail.com

1. INTRODUCTION

In the dynamic arena of smart grid (SG) technology, the pursuit of uninterrupted advancement remains essential. The SG sector is at the forefront of innovation, addressing the increasing demand for efficiency, reliability, and sustainability in society's energy infrastructure [1], [2]. Meeting escalating energy demands while minimizing environmental impact drives the continuous optimization of energy systems [1]. Within this evolving framework, SG systems face challenges such as integrating renewable energy sources, improving grid resilience against natural disasters, and mitigating cyber threats [2], [3]. These challenges highlight the critical need for innovative and adaptive solutions [4].

The rapid progression of technology is poised to transform the SG landscape significantly [5]. Emerging advancements in artificial intelligence, the internet of things (IoT), and blockchain offer unprecedented opportunities to revolutionize energy production, distribution, and consumption. These technologies can enhance efficiency, transparency, and reliability in energy systems, paving the way for a sustainable future [6]. Blockchain technology provides a decentralized and secure framework for addressing SG challenges. Its key applications include reliable data management, peer-to-peer (P2P) energy trading, demand response optimization, and improved grid resilience through immutable records and cryptographic security measures [7], [8]. Several studies have emphasized the role of blockchain in smart grid architectures, highlighting its potential to improve energy trading efficiency, cybersecurity, and grid decentralization [9].

This article explores the integration of blockchain technology into SG systems using a single board computer (SBC) platform. Specifically, Orange Pi 4. This SBC was used as a test bed for developing and testing blockchain-based solutions. Through a detailed examination of blockchain architecture, including consensus algorithms and decentralized ledger protocols, this study provides practical insights into the implementation of blockchain in SG systems. Simulation experiments are conducted to evaluate the performance and resource usage of the Orange Pi 4 platform, shedding light on the scalability and efficiency of the proposed technology.

2. RELATED WORK

Blockchain technology has gained significant attention in smart grid (SG) systems due to its potential to address critical challenges such as decentralization, scalability, security, and efficiency. Cantillo-Luna *et al.* [10] demonstrated the effectiveness of blockchain in managing distributed energy resources, highlighting its ability to improve resource allocation efficiency and reliability. Similarly, Abdella and Shuaib [11] explored P2P energy trading, showcasing blockchain's role in enabling decentralized transactions, reducing operational costs, and enhancing market efficiency. These studies underline blockchain's potential to transform traditional energy infrastructures into decentralized, consumer-oriented systems.

An essential component of blockchain-based SG systems is the consensus mechanism, which ensures scalability and security. Fakhar *et al.* [12] proposed a framework incorporating proof-of-stake and byzantine fault tolerance (BFT) algorithms, tailored specifically for SG applications. Their work emphasized the need for robust consensus models capable of maintaining network integrity while achieving low latency and high throughput. The development of efficient consensus algorithms is crucial for supporting the large-scale adoption of blockchain in SG environments.

The design of incentive mechanisms has also been explored to promote participation and ensure stability in decentralized energy markets. Kumari *et al.* [13] introduced a blockchain-driven, real-time incentive approach for energy management systems, focusing on the adaptability of solutions to varying market dynamics. This complements the findings of Junaidi *et al.* [14], who reviewed blockchain's applications in demand response programs, demonstrating its potential to improve market participation and balance supply-demand dynamics effectively. Blockchain-based decentralized management of demand response programs has also been explored, providing enhanced energy trading flexibility and reducing dependency on centralized authorities [15].

The integration of blockchain and internet of things (IoT) technologies has emerged as a transformative approach for enhancing data security, transparency, and system efficiency. Ali *et al.* [16] examined IoT-enabled campus prosumer microgrids, illustrating blockchain's ability to manage secure data exchange and enable efficient energy transactions. Appasani *et al.* [7] emphasized the synergy between blockchain and IoT in creating resilient energy networks capable of real-time monitoring and secure transactions. These studies showcase the significant potential of combining blockchain with IoT to create smarter and more connected energy systems.

Comprehensive reviews have also contributed to understanding the broader applications of blockchain in SGs. Waseem *et al.* [8] analyzed blockchain's architecture, prospects, and challenges, emphasizing its role in decentralized energy trading, data security, and improving grid reliability. Alladi *et al.* [17] provided a detailed exploration of blockchain's various use cases, such as decentralized energy management, data aggregation, and equipment maintenance. These reviews highlight blockchain's versatility in enhancing multiple facets of SG operations.

Emerging research has begun to explore the integration of blockchain with machine learning to address advanced challenges in SG systems. Mololoth *et al.* [18] reviewed the combined application of blockchain and machine learning, identifying their potential to enhance secure communication, distributed energy management, and decentralized energy trading. This intersection of technologies offers promising avenues for creating intelligent, adaptive, and resilient energy infrastructures. This comparison of key studies across thematic areas is summarized in Table 1, which provides an overview of their focus areas and major findings. The table facilitates a comprehensive understanding of state-of-the-art in this field and highlights gaps that future research must address.

3. PROTOTYPE REALISATION

This study utilized an Orange Pi 4 SBC as the central processing unit (CPU) for a blockchain-based SG prototype. The Orange Pi 4's dual-core Cortex-A72 processor, quad-core Cortex-A53 coprocessor, and 4 GB of RAM offered sufficient computational capacity for running blockchain scripts and the Flask web framework. This hardware choice aligns with prior findings by Bensalah and Abdellatif [19], which demonstrated the Orange Pi 4's efficiency in handling SHA-256 computations, critical for blockchain mining. Its cost-effectiveness and processing capabilities make it an ideal candidate for blockchain-based energy applications [20].

To enable real-time data acquisition from smart meters, the RS-485 serial communication standard was employed. Known for its reliability in long-distance data transmission, the RS-485 interface established seamless connectivity between smart meters and the central system. This robust communication protocol ensures secure data exchange, as highlighted by Vionis *et al.* [21]. Figure 1 represents the physical connection between the Orange Pi 4 and smart meters, as well as the data flow for real-time energy monitoring and blockchain-based transaction validation.

Table. 1. Comparative analysis of key studies on blockchain applications in smart grids

Category	Key Studies	Focus Areas	Findings
Decentralized energy management	Cantillo-Luna *et al.* [10], Abdella and Shuaib [11]	Distributed energy management, P2P trading	Improved efficiency, reduced costs, enhanced market reliability
Consensus mechanisms	Fakhar *et al.* [12]	Proof-of-Stake, BFT for decentralized SGs	Addressed scalability and security issues
Incentive mechanisms	Kumari *et al.* [13], Junaidi *et al.* [14], Pop *et al.* [15]	Real-time incentives, demand response management	Enhanced market participation and stability
Blockchain and IoT integration	Ali *et al.* [16], Appasani *et al.* [7]	IoT-enabled microgrids, secure data management	Enhanced transparency, efficiency, and secure transactions
Comprehensive reviews on blockchain in SGs	Waseem *et al.* [8], Alladi *et al.* [17]	Various applications, architecture, challenges	Highlighted use cases, identified prospects and research directions
Blockchain and machine learning	Mololoth *et al.* [18]	Secure communication, distributed energy trading	Demonstrated potential for adaptive and intelligent systems

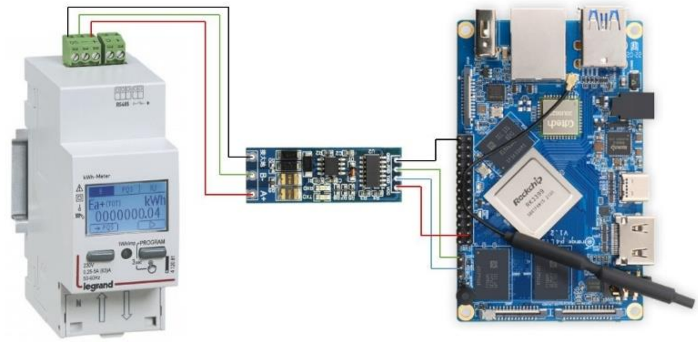

Figure 1. Hardware setup with Orange Pi 4 and RS-485 interface

The blockchain implementation included scripts for creating, validating, and securely storing energy transactions. A consensus algorithm embedded within the blockchain scripts ensured transaction integrity by preventing tampering and maintaining trust in the system. This is consistent with Liu *et al.* [22], who emphasized the importance of blockchain's cryptographic mechanisms and consensus models in maintaining data security in smart grids. The structure of the blockchain system, including key components such as the BlockchainScript, TransactionData, and Transaction classes, is represented in Figure 2, which illustrates their interactions and roles in the system.

To facilitate user interaction, a web-based interface was developed using Flask, a lightweight Python-based framework. The interface allowed real-time monitoring and management of energy transactions, providing users with secure and transparent access to blockchain data. The Flask-based design simplified integration with external systems via RESTful APIs, enabling seamless communication with the blockchain. The sequence of actions in transaction management, from data acquisition to secure storage in the blockchain, demonstrates the system's workflow. This includes data collection, transaction creation, validation, and recording on the blockchain. These processes are visualized in the UML activity diagram in Figure 3, which highlights the integration of hardware and software components for secure energy management.

To evaluate the scalability and efficiency of the proposed prototype, a blockchain simulation was implemented on the Orange Pi 4 using Python. The simulation aimed to generate and validate transactions, mine blocks, and measure computational resource utilization under varying transaction loads. The blockchain model featured a dynamic block size of 20, 50, 100, or 200 transactions per block. Each transaction included randomly assigned sender and recipient identifiers along with an energy transaction value. Transactions were queued for efficient processing, and a new block was mined after every 10 transactions, simulating a decentralized energy trading scenario.

During execution, it was observed that the passive cooling system of the Orange Pi 4 was insufficient for the computational load, leading to thermal constraints. To mitigate overheating and ensure stable performance, an active air-cooling solution was integrated. The simulation script replicated a real-world blockchain environment by dynamically generating transactions, processing them efficiently, and executing mining operations with varying block sizes to emulate different computational workloads. To monitor system performance, CPU and memory utilization were continuously tracked using the psutil library, allowing real-time observation of computational demands during transaction processing and block mining. Additionally, transaction processing time and throughput were recorded to assess system performance under different loads. For comprehensive performance analysis, data visualization techniques using Matplotlib library were applied, enabling the evaluation of performance trends and resource consumption. These visualizations provided insights into the impact of varying transaction volumes and block sizes on processing efficiency.

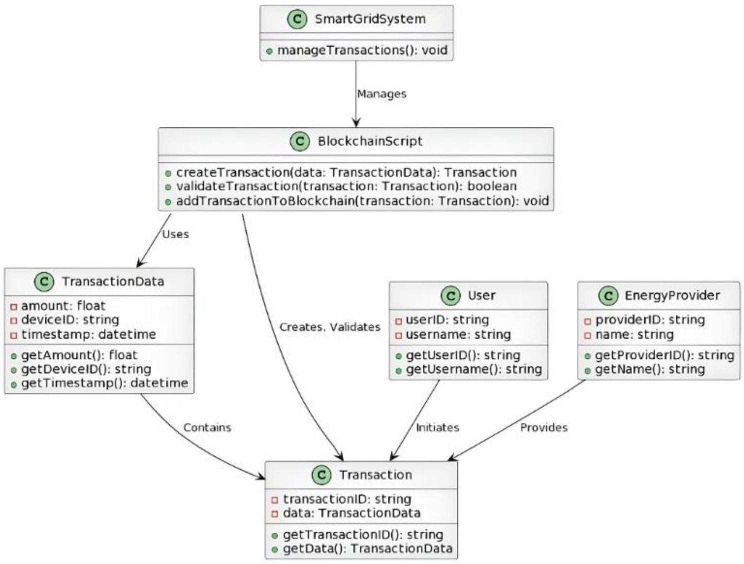

Figure 2. UML class diagram for the blockchain-based energy management system

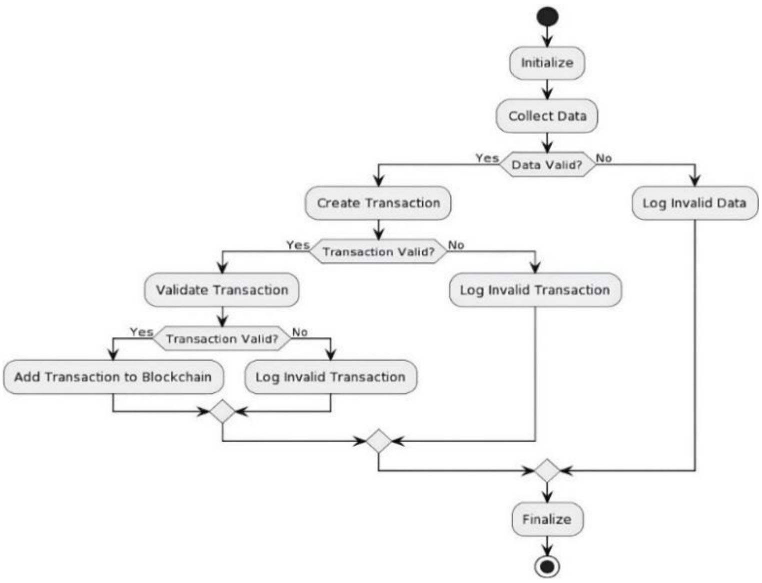

Figure 3. UML activity diagram for blockchain-based transaction processing

The simulation was tested under different transaction loads, with volumes set to 100, 500, 1000, and 2000 transactions to assess scalability. Key performance indicators measured included total execution time, transactions per second (TPS), average transaction processing time, average CPU utilization, and average memory consumption. The evaluation aimed to determine the feasibility of running a blockchain-based energy trading system on lightweight embedded devices and its ability to handle different transaction intensities while maintaining efficient resource utilization.

To provide a clear representation of the physical implementation, an actual image of the simulation setup has been included. Figure 4 illustrates the software simulation environment, which was executed entirely on Orange Pi 4. The blockchain system was tested using generated transaction data to simulate energy exchanges, ensuring a controlled evaluation of its performance under different workload conditions.

Figure 4. Software-based simulation setup executed on the Orange Pi 4

4. RESULT

This study evaluated the performance of a blockchain-based smart grid prototype under varying transaction volumes and block sizes. A Python simulation was used to construct a blockchain system comprising blocks, transactions, and mining capabilities. Transactions were randomly generated to simulate real-world events, and key performance metrics—including transaction processing time, throughput (TPS), CPU utilization, and memory usage—were analyzed for transaction volumes ranging from 100 to 2000. The objective was to assess the system's ability to handle increasing transaction loads efficiently while maintaining stable computational performance.

The results indicate that transaction processing time scales linearly with both transaction volume and block size, demonstrating a predictable increase in processing demands as workload intensity grows. As shown in Figure 5, for 100 transactions with a block size of 20, the total processing time was 13.27 seconds, with a throughput of 7.53 TPS and CPU/memory usage of 6.01% and 23.30%, respectively, as shown in Figure 5(a). When the transaction volume increased to 500 with a block size of 50, processing time rose to 67.08 seconds, with a throughput of 7.45 TPS, and CPU/memory utilization of 14.51% and 24.04%, respectively, as shown in Figure 5(b). For 1,000 transactions, the total time reached 132.29 seconds (throughput: 7.56 TPS, CPU: 14.64%, memory: 24.35%), respectively, as shown in Figure 5(c), while the highest transaction volume of 2,000 transactions resulted in a total time of 256.08 seconds, a throughput of 7.81 TPS, and CPU/memory utilization of 13.71% and 24.63%, respectively, as shown in Figure 5(d). These trends confirm that as block sizes and transaction volumes grow, processing time increases proportionally, highlighting the computational demands of blockchain-based transaction management.

Throughput remained stable across all transaction volumes, ranging between 7.45 and 7.81 TPS, indicating that the system efficiently processes transactions without significant degradation in performance. This stability suggests that the blockchain implementation maintains a consistent transaction validation rate, even as workload intensity increases. However, despite the steady throughput, the moderate increase in CPU utilization reflects the system's response to higher computational workloads. As illustrated in Figure 6, CPU usage ranged from 6.01% at 100 transactions to 14.64% at 1,000 transactions, before slightly decreasing to 13.71% at 2,000 transactions, likely due to variations in workload distribution across processing cycles.

Memory utilization, on the other hand, remained relatively stable, fluctuating between 23.30% and 24.63% across all test scenarios. This consistency suggests that memory demand does not scale as dramatically as CPU usage, indicating that blockchain-related computations are primarily CPU-intensive rather than memory-constrained. These findings confirm that while transaction volume impacts processing time and CPU workload, memory usage remains largely unaffected.

Overall, the results demonstrate that the system maintains stable transaction processing efficiency across different workload intensities while operating within the resource constraints of the Orange Pi 4. The observed linear processing time increase with transaction volume and block size highlights the computational trade-offs involved in blockchain-based energy transaction management. These insights provide a practical evaluation of the system's performance, reinforcing its feasibility for decentralized energy applications under varying operational loads.

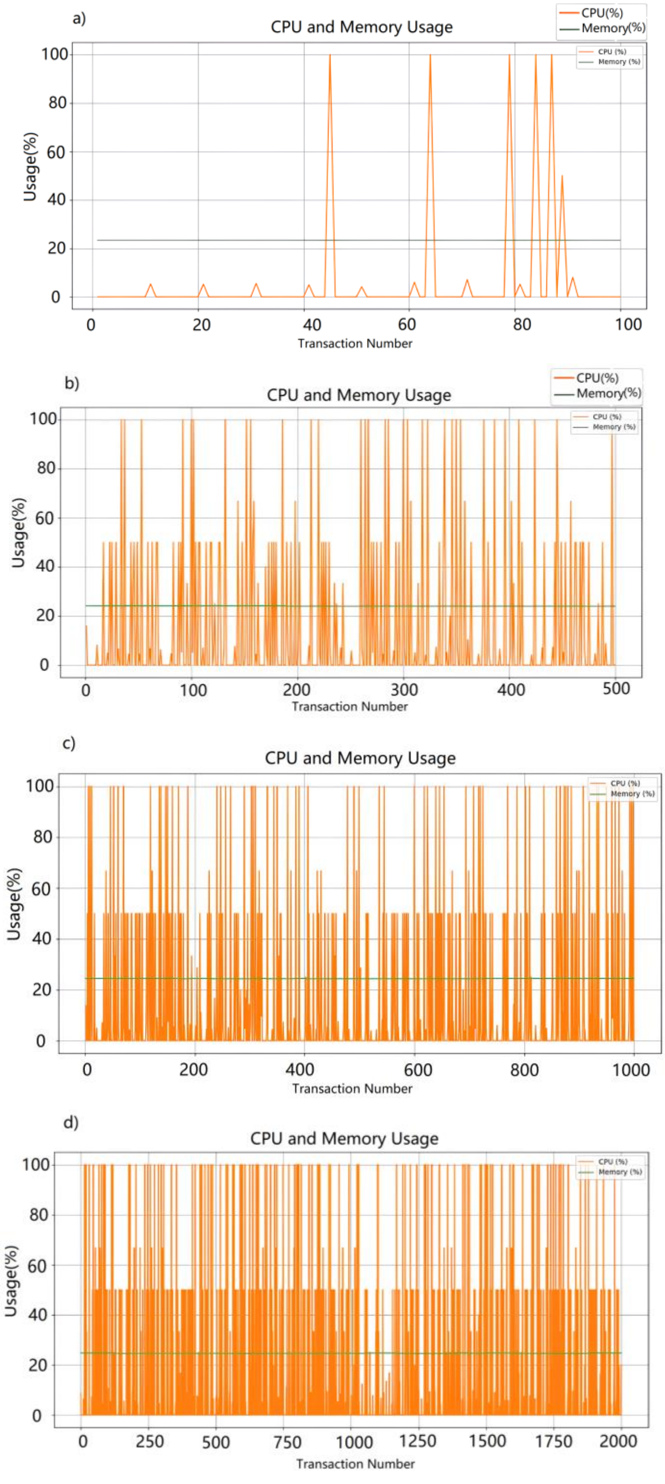

Figure. 5. Combined performance metrics for different transaction volumes and block sizes (a) 100 transactions, (b) 500 transactions, (c) 1000 transactions, and (d) 2000 transactions

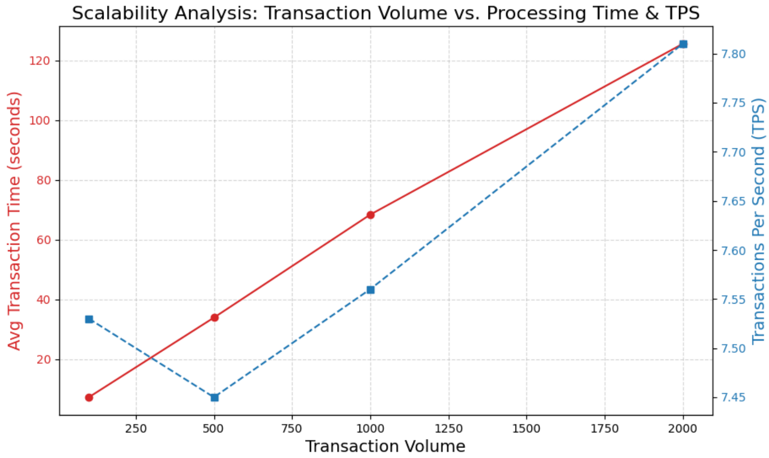

Figure. 6. Scalability analysis of transaction processing time, throughput, and resource utilization

5. DISCUSSION

The findings of this study confirm the feasibility of implementing blockchain technology in smart grids using low-cost, resource-constrained hardware such as the Orange Pi 4. The prototype effectively managed high transaction volumes while maintaining stable CPU and memory usage, reinforcing the potential of lightweight single-board computers for decentralized energy applications. These results are consistent with prior research advocating for the deployment of blockchain in the energy sector using cost-efficient hardware solutions [9]. Unlike previous studies that rely on theoretical models or purely simulated environments [8]–[12], this work demonstrates a functional prototype that directly assesses the challenges and trade-offs associated with real-world implementation. By integrating blockchain transactions on a constrained-resource device, this study provides critical insights into the practical scalability and energy consumption of such systems, bridging the gap between conceptual research and tangible deployment.

Despite its demonstrated feasibility, scalability remains a primary concern. The observed linear increase in transaction processing time with transaction volume and block size suggests that as energy systems grow in complexity, traditional blockchain implementations may struggle to maintain efficiency. The findings underscore the importance of optimizing consensus mechanisms to mitigate latency and computational overhead. Existing studies highlight that energy-focused blockchain systems must balance security, decentralization, and performance by adopting efficient consensus mechanisms such as delegated proof-of-stake (DPoS) or hybrid models that integrate off-chain computation for non-critical operations [7], [23]. Implementing such optimizations could significantly enhance transaction throughput while maintaining security and decentralization, making blockchain-based smart grids more adaptable to increasing transaction loads.

Additionally, interoperability between blockchain systems and existing energy infrastructures is a crucial factor in practical deployment. Current smart grid architectures rely on centralized and semi-centralized models for grid management, making integration with decentralized blockchain frameworks a challenging task. Studies such as Musleh *et al.* [23] emphasize the necessity of seamless interoperability to ensure that blockchain can complement, rather than disrupt, existing grid management practices. The ability to communicate with legacy energy management systems, synchronize real-time grid data, and integrate with demand-side management frameworks will determine the success of blockchain-enabled smart grids. Without robust interoperability standards, blockchain solutions risk remaining isolated from larger energy ecosystems, limiting their impact on real-world grid operations.

Beyond these technical considerations, emerging technologies present significant opportunities to enhance the efficiency and intelligence of blockchain-based smart grids. Recent research suggests that integrating artificial intelligence with blockchain could improve grid stability, predictive energy management, and decision-making capabilities [24], [25]. Machine learning algorithms can enhance transaction validation efficiency, detect fraudulent or anomalous transactions in real time, and optimize energy allocation by analyzing historical and real-time consumption patterns. AI-driven consensus mechanisms could also reduce unnecessary computational workloads, enhancing blockchain scalability without compromising security.

Another critical aspect of blockchain-enabled smart grids is their potential to facilitate decentralized energy markets, where prosumers (producers and consumers) can engage in P2P energy trading. Our system leverages blockchain's inherent decentralization, security, and transparency, as demonstrated in the transaction management process. The prototype efficiently records transactions in an immutable ledger, ensuring the integrity and traceability of energy exchanges. Figures 4 and 5 illustrate the system's performance in handling transaction processing and resource utilization, confirming that blockchain-based energy management can operate efficiently even in resource-constrained environments.

The results of this study contribute to the growing body of research on blockchain-enabled smart grids, particularly in resource-constrained environments. While the findings demonstrate the feasibility of implementing blockchain on low-cost hardware, they also highlight critical challenges related to scalability, interoperability, and regulatory adaptation. Future research should focus on optimizing blockchain protocols, refining consensus mechanisms, and integrating complementary technologies such as artificial intelligence and edge computing to enhance real-time decision-making and operational efficiency. Additionally, real-world deployments in diverse smart grid environments are essential to validate the robustness and adaptability of blockchain-based energy management solutions under dynamic and unpredictable conditions.

By addressing these challenges and leveraging emerging technologies, blockchain has the potential to transform energy systems into secure, efficient, and self-optimizing networks. The continued evolution of decentralized energy management models will not only enhance grid reliability and efficiency but also pave the way for more sustainable and resilient energy infrastructures.

6. CONCLUSION

This study demonstrated the feasibility of integrating blockchain technology into smart grids using a low-cost, resource-constrained platform. The prototype, implemented on the Orange Pi 4, successfully facilitated secure and transparent energy transactions while maintaining stable resource utilization across varying workloads. Performance evaluations confirmed its efficiency, but scalability challenges persist as transaction processing time increases with block size and volume. Optimizing consensus mechanisms, improving transaction handling, and enhancing interoperability with existing grid infrastructures are critical for broader adoption. Future research should explore artificial intelligence for predictive energy management and edge computing to reduce latency and computational overhead. Addressing these challenges will enable blockchain-based smart grids to become more resilient, efficient, and scalable, contributing to the evolution of decentralized and sustainable energy networks.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mouad Bensalah	✓		✓		✓	✓		✓	✓		✓			
Abdellatif Hair		✓		✓	✓		✓					✓		
Reda Rabie		✓		✓	✓					✓	✓		✓	

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
E : Writing - Review & **E**diting
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

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] M. H. Hashmi, Z. Ullah, R. Asghar, B. Shaker, M. Tariq, and H. Saleem, "An overview of the current challenges and issues in smart grid technologies," in *2023 International Conference on Emerging Power Technologies (ICEPT)*, May 2023, pp. 1–6, doi: 10.1109/icept58859.2023.10152331.

[2] N. Zareen, M. W. Mustafa, A. J. H. Al Gizi, and M. A. Alsaedi, "Worldwide technological revolutions and its challenges under smart grid paradigm: A comprehensive study," *International Journal of Scientific & Engineering Research*, vol. 3, no. 11, pp. 1–114, 2012.

[3] P. Koukaras *et al.*, "Integrating blockchain in smart grids for enhanced demand response: Challenges, strategies, and future directions," *Energies*, vol. 17, no. 5, p. 1007, Feb. 2024, doi: 10.3390/en17051007.

[4] S. Bhattacharya *et al.*, "Incentive mechanisms for smart grid: State of the art, challenges, open issues, future directions," *Big Data and Cognitive Computing*, vol. 6, no. 2, p. 47, Apr. 2022, doi: 10.3390/bdcc6020047.

[5] J. Bhatt, V. Shah, and O. Jani, "An instrumentation engineer's review on smart grid: Critical applications and parameters," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 1217–1239, Dec. 2014, doi: 10.1016/j.rser.2014.07.187.

[6] I. S. Razo-Zapata, A. Shrestha, and E. Proper, "An assessment framework to determine the strategic value of IT architectures in smart grids," in *Proceedings of the 28th Australasian Conference on Information Systems, ACIS 2017*, 2017, pp. 1–11.

[7] B. Appasani *et al.*, "Blockchain-enabled smart grid applications: architecture, challenges, and solutions," *Sustainability*, vol. 14, no. 14, p. 8801, Jul. 2022, doi: 10.3390/su14148801.

[8] M. Waseem, M. Adnan Khan, A. Goudarzi, S. Fahad, I. Sajjad, and P. Siano, "Incorporation of blockchain technology for different smart grid applications: Architecture, prospects, and challenges," *Energies*, vol. 16, no. 2, p. 820, Jan. 2023, doi: 10.3390/en16020820.

[9] M. Andoni *et al.*, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 143–174, Feb. 2019, doi: 10.1016/j.rser.2018.10.014.

[10] S. Cantillo-Luna, R. Moreno-Chuquen, H. R. Chamorro, V. K. Sood, S. Badsha, and C. Konstantinou, "Blockchain for distributed energy resources management and integration," *IEEE Access*, vol. 10, pp. 68598–68617, 2022, doi: 10.1109/access.2022.3184704.

[11] J. Abdella and K. Shuaib, "Peer to peer distributed energy trading in smart grids: A survey," *Energies*, vol. 11, no. 6, p. 1560, Jun. 2018, doi: 10.3390/en11061560.

[12] A. Fakhar, A. M. A. Haidar, M. O. Abdullah, and N. Das, "Smart grid mechanism for green energy management: A comprehensive review," *International Journal of Green Energy*, vol. 20, no. 3, pp. 284–308, Feb. 2022, doi: 10.1080/15435075.2022.2038610.

[13] A. Kumari *et al.*, "Blockchain-driven real-time incentive approach for energy management system," *Mathematics*, vol. 11, no. 4, p. 928, Feb. 2023, doi: 10.3390/math11040928.

[14] N. Junaidi, M. P. Abdullah, B. Alharbi, and M. Shaaban, "Blockchain-based management of demand response in electric energy grids: A systematic review," *Energy Reports*, vol. 9, pp. 5075–5100, Dec. 2023, doi: 10.1016/j.egyr.2023.04.020.

[15] C. Pop, T. Cioara, M. Antal, I. Anghel, I. Salomie, and M. Bertoncini, "Blockchain-based decentralized management of demand response programs in smart energy grids," *Sensors*, vol. 18, no. 1, p. 162, Jan. 2018, doi: 10.3390/s18010162.

[16] A. Ali, H. A. Muqeet, T. Khan, A. Hussain, M. Waseem, and K. A. K. Niazi, "IoT-enabled campus prosumer microgrid energy management, architecture, storage technologies, and simulation tools: A comprehensive study," *Energies*, vol. 16, no. 4, p. 1863, Feb. 2023, doi: 10.3390/en16041863.

[17] T. Alladi, V. Chamola, J. J. P. C. Rodrigues, and S. A. Kozlov, "Blockchain in smart grids: a review on different use cases," *Sensors*, vol. 19, no. 22, p. 4862, Nov. 2019, doi: 10.3390/s19224862.

[18] V. K. Mololoth, S. Saguna, and C. Åhlund, "Blockchain and machine learning for future smart grids: A review," *Energies*, vol. 16, no. 1, p. 528, Jan. 2023, doi: 10.3390/en16010528.

[19] B. Mouad and H. Abdellatif, "Performance evaluation of Orange Pi 4 in SHA256 computation for blockchain mining," in *2023 10th International Conference on Future Internet of Things and Cloud (FiCloud)*, Aug. 2023, pp. 236–241, doi: 10.1109/ficloud58648.2023.00042.

[20] orangepi, "Orange pi website," *orangepi.org*, 2020. http://www.orangepi.org/index.html (accessed Apr. 20, 2024).

[21] P. Vionis and T. Kotsilieris, "The potential of blockchain technology and smart contracts in the energy sector: A review," *Applied Sciences*, vol. 14, no. 1, p. 253, Dec. 2023, doi: 10.3390/app14010253.

[22] C. Liu, X. Zhang, K. K. Chai, J. Loo, and Y. Chen, "A survey on blockchain-enabled smart grids: Advances, applications and challenges," *IET Smart Cities*, vol. 3, no. 2, pp. 56–78, May 2021, doi: 10.1049/smc2.12010.

[23] A. S. Musleh, G. Yao, and S. M. Muyeen, "Blockchain applications in smart grid–review and frameworks," *IEEE Access*, vol. 7, pp. 86746–86757, 2019, doi: 10.1109/access.2019.2920682.

[24] A. Ayub Khan, A. Ali Laghari, M. Rashid, H. Li, A. Rehman Javed, and T. Reddy Gadekallu, "Artificial intelligence and blockchain technology for secure smart grid and power distribution Automation: A State-of-the-Art Review," *Sustainable Energy Technologies and Assessments*, vol. 57, p. 103282, Jun. 2023, doi: 10.1016/j.seta.2023.103282.

[25] Y. Methkal Abd Algani, V. Sreenivasa Rao, and R. Saravanakumar, "AI-powered secure decentralized energy transactions in smart grids: Enhancing security and efficiency," in *2024 IEEE 3rd International Conference on Electrical Power and Energy Systems (ICEPES)*, Jun. 2024, pp. 1–5, doi: 10.1109/icepes60647.2024.10653598.

BIOGRAPHIES OF AUTHORS

Mouad Bensalah currently pursuing a Ph.D. in computer science at Sultan Moulay Slimane University, Morocco, Mouad is dedicated to advancing the field of "Enhancing smart grid efficiency through the integration of IoT, blockchain, and deep learning technologies." He holds a master's degree in engineering with a dual diploma in "Control in smart grids and distributed generation" from UPV, Spain, as well as a diploma in engineering from ESTIA, France. His educational journey has traversed diverse disciplines, including mechatronics, embedded systems, and electrical energy, underscoring his comprehensive understanding of multidisciplinary aspects in the realm of technology and energy management. He can be contacted at email: e.mbensalah@gmail.com and mouad.bensalah@um6p.ma.

Abdellatif Hair currently works as a full professor with the Department of Computer Science, Sultan Moulay Slimane University, Beni Mellal, Morocco, and is a member of the LAMSC Laboratory. His research interests include object-oriented analysis/design, security of mobile agents, wireless sensor networks (WSN), data warehousing, and machine learning (ML). He can be contacted at email: abd_hair@usms.ma.

Reda Rabie is a researcher at the Université Sidi Mohamed Ben Abdellah in Fez, Morocco, specializing in chemometrics and intelligent laboratory systems. His work spans various applications of machine learning and spectroscopy, including the assessment of olive oil quality, soil nutrient measurement, and the analysis of agricultural and environmental samples. He can be contacted at email: reda.rabie@um6p.ma and reda.rabie@usmba.ac.ma.