Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Blockchain Energy Consumption in IoT Environments: A Systematic Literature Review of the Scalability-Energy Tradeoff

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Abstract - **Integrating blockchain technology and Internet of Things (IoT) systems can provide improved security and distributed trust but introduce a fundamental tension between scalability and energy consumption especially since the devices in IoT systems are resource-constrained. In this literature review the author identifies the conflict between the scalability and energy consumption in blockchain integrated Internet of Things contexts. The given systematic literature review synthesizes the results of the researches published between 2015 and 2026 to examine how the scalability-energy tradeoff is defined, quantified, and managed in blockchain-IoT settings. This review compared consensus mechanisms, architectural approaches and emerging solutions within the existing studies. Evidence shows that the selection of consensus mechanism have the primary effect of determining the shape of the tradeoff. Proof of Authority uses 0.5-0.9 J/Tx of energy consumption with a latency of less than 200 milliseconds while hybrid architectures achieve 5,217 TPS but at the cost of complexity. Multi-layer and edge offloading aims to reduce device energy requirements and AI-assisted optimization report reduces energy usage by up to 80% when compared to Proof of Work. Despite the improvements, approximately 42% of the proposed solutions still face challenges when it comes to practical deployments. These findings indicate that the tradeoff is real and significant but can be managed through appropriate consensus mechanism selection, efficient architecture approach, and applying dynamic AI-assisted optimizations.**

Index Terms— **Blockchain, Internet of Things, Energy Consumption, Scalability, Consensus Mechanisms, Literature Review**

I. INTRODUCTION

1.1 Background and Motivation

THE Internet of Things (IoT) has grown at a fast in the past rate. Today, billions of interconnected devices operate in environment such as smart homes, industrial systems, environmental monitoring, and healthcare [1]. These devices produce large volumes of data. When you secure and analyze this data carefully, you can gain insights and improve automation/ Still, most IoT systems rely on centralized designs for security. This setup creates risks such as single points of failure, privacy, and higher exposure to data tampering [2].

Blockchain technology offers a way to address these weaknesses. Its decentralized feature helps strengthen IoT security, supports direct device to device transactions, and builds trust in machine-to-machine communication [3]. The combined use of blockchain and IoT, often called the Blockchain of Things or BIoT, is under study in areas such as smart energy trading, supply chain tracking, autonomous vehicle coordination, and secure data marketplaces [4].

1.1 The Energy Challenge

Despite its advantages, combining blockchain with IoT runs into a major problem such as energy use. Many IoT devices are resource-constrained, these devices usually run on small batteries, have limited processing power, and connect to networks only at times. These limits the potential of blockchain-IoT system with the heavy computation required by traditional blockchain systems [5].

1.2 The Scalability-Energy Connection

A key part of the energy problem involves scalability. Scalability refers to a system’s ability to handle higher

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[1] This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, “This work was supported in part by the U.S. Department of Commerce under Grant BS123456”.

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transaction volumes and support a growing number of devices. This matters for real IoT deployments, which often involve thousands or even millions of connected units [6]. The challenge is that improving scalability usually requires more computation, and more computation means more energy usage on devices that already operate with strict power limits.

This tension between scalability and energy use sits at the core of the blockchain IoT integration problem. To move toward systems that work in real and actual deployments, you need a clear understanding of how large this tradeoff is, how it behaves under different conditions, and what strategies help manage it [7].

1.3 Research Objectives

1.) To investigate how the scalability-energy tradeoff in blockchain IoT environment is defined, measured, and reported in existing studies.
2.) To identify and evaluate the architectural solutions and consensus mechanisms that have been proposed to manage the scalability-energy tradeoff, as well as the strength of empirical support for them.
3.) To evaluate the gap between blockchain IoT solutions implemented in the real world and theoretical models.
4.) To identify future study directions and emerging approaches for enhancing scalability and optimizing energy usage in blockchain IoT systems.

1.4 Research Questions

1.) How is the scalability-energy tradeoff described and quantified in blockchain IoT systems?
2.) What are the consensus mechanisms and architectural approaches have been proposed to help manage this tradeoff, and what is their actual evidence?
3.) What gaps exist between theoretical solutions and practical implementations?
4.) What future research directions show the most potential in helping manage the scalability-energy tradeoff in blockchain IoT systems?

II. RELATED WORK

2.1 Foundational Studies on Blockchain-IoT Integration

A study by [20] Dorri et al. (2019) suggested a blockchain-based innovation named by Lightweight Scalable Blockchain or LSB, designed to function in an IoT system, and in which they utilized a smart house setting where resources-constrained devices are typically located. The design was based on a linear hierarchy with low-capability devices relying on a centralized communicator, while higher-capability devices maintained a public blockchain through an overlay network arranged into clusters. The research indicated a high potential of blockchain to be integrated in the environment of IoT by using the means of lightweight consensus and distributed trust. Nevertheless, scalability remained limited to small-scale implementations.

2.2 Surveys and Reviews on Blockchain-IoT and Scalability

Few recent surveys have brought together current knowledge on blockchain-IoT integration. [1] comprehensively reviewed blockchain integration in smart grids with a special focus on IoT, stated that blockchain's decentralized and immutable features ensures secure and transparent energy transactions, while IoT devices enable real-time data collection and monitoring. Their review identifies challenges including regulatory barriers, high computational costs, and scalability problems, highlighting the need for approaches that will help optimize these problems such as hybrid blockchain models and AI-assisted solutions.

[5] Egunjobi et al. (2024) conducted a systematic review of 156 studies on blockchain for energy applications. Their results showed that there are clear gaps between proposed designs and real world implementations. About 42% of studies that introduced new consensus mechanisms and 46% that proposed new platform that relied on simulations reported difficulties in practical real world implementation. They found that the use of existing standard blockchain platforms and consensus mechanisms helps practicality and scalability, while smooth interoperability with IoT still remains a significant challenge due to costs. The review highlighted that standardization of blockchain methodology, interoperability, performance measurement, and governance still remains an issue that require consolidation into existing common frameworks.

[2] Mamun et al. (2026) provided a comprehensive review of blockchain in communication networks, synthesizing 72 primary sources. Their end-to-end taxonomy linked blockchain mechanisms with specific network functions and highlighted several gaps including scalability under high churn, energy and hardware overhead, interoperability across chains and legacy control planes, and regulatory compliance . The authors recommended research directions such as AI-assisted consensus, cross-chain orchestration for multi-domain network slicing, and stronger privacy maintaining accountability methods.

[8] Shujaa et al. (2025) analyzed 49 recent scientific publications on blockchain-based IoT security. The paper studied how existing solutions address challenges in data integrity, authentication, and access control. The review identifies problems related to scalability, energy efficiency, and privacy, proposing future research directions including context-aware security protocols, adaptive trust models, and privacy-preserving analytics approach. The paper also noted that most of the blockchain-IoT integration efforts remain at

the pilot or prototype stage rather than production or real-world deployments.

2.3 Empirical Studies Quantifying the Tradeoff

A study by [3] Elhajj et al. (2025) proposed an IoT-blockchain framework for smart urban energy management that combines hybrid consensus mechanisms (PoS + PBFT), K-means clustering, and lightweight IoT protocols (MQTT/CoAP) for energy efficiency and scalability. Using real-world datasets (UK-DALE, PECAN Street) to train predictive models and group the energy usage patterns. Their simulation results reported a 15% reduction in energy costs on high consumption clusters, an 80% drop in energy usage compared with Proof of Work systems, and near linear scalability with more than 500 IoT devices. These results shows us an idea that adaptive and intelligent control improves the scalability energy balance.

[9] Delladetsimas et al. (2024) studied blockchain-IoT integration specifically for Marine Internet of Things (MIoT) and Internet of Underwater Things (IoUT). These type of environments usually face limits in bandwidth, energy availability, and secure data handling. Their review found that enhancing performance in resource-limited environments requires careful or strategic selection of computing paradigms such as edge and fog computing, and lightweight nodes to reduce latency and improve data processing. The review discussed few solution paths, such as lightweight consensus mechanisms, use of established platforms like Ethereum and Hyperledger or custom blockchains, and addition of fog or edge layers. It also highlighted the role of IPFS(Interplanetary File System) for storage and AI-based security mechanisms made for specific applications.

One study by [10] Salian et al. (2025) proposed a three-layer blockchain architecture that combines different existing consensus mechanisms (PoW + PBFT + PoA) to cloud, fog, and edge layers to help balance performance and security. Results show throughput reaching 5,217 transactions per second, which is 51% improvement over earlier designs, with energy use of 0.05 kWh per transaction. The architecture also includes ASIC-resistant Proof of Work for cloud level security, dynamic leader election in the PBFT layer to achieve about 150ms fog-layer latency, and a device-reputation-based PoA for edge nodes devices. Results showed 68.2% faster attack detection in smart grid scenarios and a 42.1% reduction in latency for healthcare IoT workloads when compared to standard systems.

2.4 Identified Gaps in Prior Work

Despite these contributions, significant gaps still exist. First is the systematic review by [5] reveals that 42% of new consensus proposals fail to achieve practical deployment, indicating a gap between theory and real word implementation. Second, [8] emphasizes that most Blockchain-IoT integration efforts are pilots or prototypes rather than practical or real-world deployments, which limits trust and validation. Third, the Marine IoT review highlights that interoperability issues, high energy consumption, standardization challenges, and costly transitions from legacy systems remain unresolved. Fourth, the three-layer architecture [10], while showing promising results, still points out the complexity of cross-layer coordination as a key tradeoff.

III. METHODOLOGY

To investigate the scalability-energy tradeoff in blockchain-IoT integration, the researcher conducted a systematic literature review. This literature review type allowed the researcher to synthesize existing literatures and identify research patterns that contribute to the scalability-energy tradeoff.

3,1 Search Strategy

The search strategy employed multiple databases and iterative keyword refinement to ensure comprehensive coverage of relevant literature.

Databases searched:

- IEEE Xplore Digital Library
- Scopus
- Web of Science
- ScienceDirect
- ACM Digital Library
- Springer Nature Link
- Research Square
- ResearchGate

Search terms and combinations:
-("blockchain" OR "IoT" OR "energy consumption")
-("blockchain" OR "Internet of Things" OR "scalability" OR "energy")
-("consensus mechanism" OR "IoT" OR "energy efficiency")
-("lightweight blockchain" OR "resource-constrained" OR "energy")
-("blockchain energy tradeoff" OR "IoT")
Search period: 2015-2026 (capturing most recent research)

3.2 Inclusion Criteria

Inclusion criteria:
-Peer-reviewed literatures or conference proceedings
-Published between 2015-2026
-English language
-Explicit focus on blockchain energy consumption in IoT contexts
-Empirical data or systematic analysis relevant to the scalability-energy tradeoff
Exclusion criteria:
-Non-peer-reviewed content
-Other language outside English
-Studies focused exclusively on non-IoT blockchain applications

-Papers without substantive energy consumption analysis
-Duplicate publications

3.3 Quality Assessment

An evaluation of all papers used was done to guarantee the reliability and validity of the findings. This will be necessary in systematic reviews to determine the possible biases and assess the methodologic rigor of the evidence. The evaluation was designed in such way that it would consider the quality of foundational reviews and aspects with particular relevance to the field of blockchain-IoT research. The assessment considered the following dimensions:

Clarity of Research Objectives: Whether the study clearly states its research questions or objectives and explains their importance.

Appropriateness of Methodology: Whether the chosen method (e.g., simulation, experimental, analytical) is suitable for addressing the research questions and is clearly described to enable reproducibility.

Empirical Accuracy: For empirical studies, this includes the validity of the experimental setup, the representativeness of data sources, the clarity of measurement methods, and the appropriateness of any statistical analyses.

Relevance to the Scalability-Energy Tradeoff: The directness with which the study addresses the relationship between scalability and energy consumption in blockchain-IoT systems.

Contribution to the Field: The originality of the insights, the importance of data provided, or the advancement of theoretical understanding.

3.4 Data Extraction and Analysis

On each of the included literature, the following data was collected during the review: author(s), year of publication, research area, research methodology, main findings on the scalability energy tradeoff, possible solutions, limitations, as well as, available empirical data. An analysis was then done to the extracted information by closely paying attention to the similar findings across the studies, disagreements and patterns that appeared through the analysis.

IV. THE SCALABILITY-ENERGY TRADEOFF

4.1 Introduction to the Tradeoff

The integration of blockchain technology into Internet of Things (IoT) results in a conflict between two essential objectives which is enabling systems and transactions to scale as networks of connected devices expand, ensuring low energy consumption on hardware with limited capabilities. As IoT implementations continue to grow in size and complexity, existing blockchain frameworks must also adapt without using too much computational or power demands on devices that are often limited in battery life and processing power. This section explores how various existing blockchain architectures, consensus mechanisms, and deployment/implementation strategies attempt to address this tradeoff.

Within blockchain-IoT environments, scalability refers to the system's capacity to support increasing transaction volumes, support an expanding number of devices, and maintain good performance levels under the rising demand [5]. In contrast, energy consumption includes the computational workload, communication overhead, and storage requirements necessary to sustain blockchain functionality, factors that have a direct impact on the lifespan of the IoT devices. Efficient resource consumption becomes an important factor because many IoT nodes operate in remote or energy-sensitive environments.

An understanding of this tradeoff is vital for practical blockchain-IoT implementations. Applications such as smart grids, supply chain tracking systems, environmental monitoring networks, and marine IoT platforms require

Table 1. Comparative analysis of consensus mechanisms for blockchain-IoT integration.

Consensus Mechanism	**Scalability (TPS, transactions per second)**	**Energy Efficiency**	**Latency**	**IoT Compatibility**	**Limitations**	**Source**
Proof of Work (PoW)	140 TPS	Very Poor (5.2-10.3 J/Tx)	450-780 ms	Unsuitable	High energy consumption	[11]
Proof of Stake (PoS)	210 TPS	Good (0.3-0.7 J/Tx)	150-300 ms	Limited	Computationally intensive	[11]
Proof of Authority (PoA)	190 TPS	Excellent (0.5-0.9 J/Tx)	<200 ms	Good for private networks	Centralized: reliable validators	[11]
Hybrid (PoW+PBFT+PoA)	5,217 TPS	Excellent (0.05 kWh/Tx)	150 ms	Promising	Complexity: cross-layer coordination	[10]
Practical Byzantine Fault Tolerance (PBFT)	Medium(variable)	Moderate	~150ms	Limited in large networks	Communication overhead(n^2)	[13]

Table 2. Comparative analysis of consensus mechanisms of architectural approaches.

Architecture	**Scalability Handling**	**Energy Impact**	**IoT Device Requirements**	**Key Tradeoffs**	
Full On-Device Blockchain	Limited by device capabilities	High on devices	High processing, storage requirements	Simple but impractical	[12]
Edge-Offloading Architecture	Edge nodes handle scaling	Low on devices, moderate on edge	Low	Latency and cost	[9]
Three-Layer Architecture	Cloud+fog+edge	Optimized per layer	Minimal at edge	Complexity; cross-layer coordination	[10]
Lightweight Client	Full nodes hadnle scaling	Very low on devices	Minimal	Trust assumptions	[13]
Ai-Optimized Dynamic	Adaptive based on demand	Optimized dynamically	Variable	Extra AI workload	[3]

enhanced security, transparency, and data integrity offered by blockchain, while depending on the long-term, low-power operation characteristic of IoT systems [7]. Successfully balancing the scalability with energy efficiency will determine the feasibility and sustainability of blockchain-enabled IoT systems in real-world contexts.

4.2 Quantifying the Tradeoff

Recent studies comparing consensus mechanisms in IoT-enabled smart grids provide detailed data on this tradeoff. A comprehensive 2026 study evaluating blockchain performance found that Proof of Authority(PoA) achieves latency under 200 milliseconds with throughput of 190 transactions per second and energy consumption of just 0.5-0.9 Joules per transaction. In the other hand, Proof of Work(PoW) consumed 5.2-10.3 Joules per transaction with latency of 450-780 milliseconds. Proof of Stake(PoS) showed promising energy efficiency (0.3-0.7 J/Tx) and higher throughput (210 Tx/s), but with slightly higher latency (150-300 ms) than PoA [11]. Table 1 presents a detailed comparison of consensus mechanisms relevant to blockchain-IoT integration.

Hardware implementations support these findings. Research in resource constrained marine environments shows that blockchain IoT integration is technically feasible, yet device capacity places firm limits on scalability. When transaction volume increase, processing delays also increase, creating limitations that can make real time IoT applications impractical [9].

Table 1 shows a comparison of consensus mechanisms relevant to blockchain-IoT integration.

4.3 Architectural Approaches to Managing the Tradeoff

Other than consensus mechanism selection, system architecture also plays a crucial role in managing the scalability-energy tradeoff [12]. Several architectural approaches have emerged that attempt to balance these demands through structural design.

4.3.1 Edge and Fog Computing Integration

A common approach which shifts heavy computation away from energy-constrained IoT devices to more capable edge or fog nodes [13]. Reviews about marine-IoT implementation report that edge computing lowers sensor energy consumption while preserving blockchain functions [9]. In this setup, IoT devices handle only the basic tasks such as transaction initiation and cryptographic operation, while edge nodes manage consensus, block validation, and full chain storage.

This design can help manage the scalability-energy tradeoff. Scalability offers the distribution of most of the load to edge infrastructure, rather than end devices, preserving device battery life, but in exchange of requiring an additional cost on supporting infrastructure.

4.3.2 Hierarchy and Multi-Layer Structure

Hierarchical blockchain designs provide ways to improve scalability while keeping energy use under control [8]. A recently proposed three-layer architecture for cloud, fog, and edge integration shows the importance of this approach. The system runs Proof of Work at the cloud layer, Practical Byzantine Fault Tolerance at the fog layer, and a device-reputation-based Proof of Authority at the edge layer. It reaches 5,217 TPS with energy use of 0.05 kWh per transaction. Tests report 68.2 percent% faster attack detection in smart grids and 42.1 percent lower latency in healthcare IoT workloads compared to standard approaches [10].

Table 2 compares architectural approaches to managing the scalability-energy tradeoff.

4.4 *Intelligent Management through AI and Optimization*

Recent studies states that dynamic, intelligent control of the scalability-energy tradeoff outperforms fixed architectural designs [14]. Instead of locking the system into one operating point, adaptive approaches adjust behavior in response to the context or current conditions.

A framework combining hybrid consensus using Proof of Stake and Practical Byzantine Fault Tolerance, K-means clustering for demand response optimization, and lightweight IoT protocols such as MQTT and CoAP. Simulations based on real datasets, including UK DALE and PECAN Street, report a 15% drop in energy costs for high consumption clusters, 80% lower energy use compared with Proof of Work, and near linear scalability beyond 500 IoT devices [3].

Another approach focuses on energy aware consensus. A Deep Neural Network driven authentication scheme selects validators using the remaining battery level and trust scores. Tests on IoT enabled smart grid data show throughput of 372TPS, which is 32%t higher than standard methods, along with 98.69% authentication accuracy, 5.9ms confirmation delay, and an 18% reduction in validator energy consumption [15].

V. FINDINGS

5.1 Empirical Validation of the Tradeoff

The results of this paper provide empirical support for the scalability–energy tradeoff through empirical evidence from several studies. Recent studies show that consensus mechanisms fall at different points along this tradeoff curve. Proof of Authority demonstrates the highest energy efficiency in resource-constrained settings, while hybrid architectures offer higher throughput but with greater architectural complexity [11] [10].

Table 3 shows a comparison of blockchain platforms for IoT integration.

5.2 *Consensus Mechanism Impact*

The results show that core of the tradeoff curve is basically determined by the choice of consensus mechanism. Traditional approaches such as Proof of Work are not suitable for most IoT applications, while Proof of Stake improves efficiency but still have few problems on resource-constrained devices. Emerging hybrid and AI enhanced mechanisms appear promising, although the implementation gap reported in the literature raise concerns [16].

5.3 *Architectural Approach*

The analysis shows that architectural approach also reshape the tradeoff. Integrating edge computing, adopting hierarchical three-layer designs, and applying storage optimization strategies help limit energy use while preserving scalability. Each approach, though, introduces its own set of tradeoffs [9] [13] [10].

5.4 *AI-driven Optimization Potential*

AI-driven optimization emerges as a promising direction. Intelligent adaptive management show promising gains compared with static approaches, including about 15% reduction in energy cost and up to 80% lower energy use. These results suggest the scalability–energy tradeoff is more manageable than earlier work indicated [3] [17] [18].

5.5 *Persistent Gaps*

The findings confirm significant gaps persist, including the absence of standardized measurement metrics, limited understanding of application-specific requirements, lack of longitudinal data, underdeveloped optimization frameworks, and a persistent implementation gap between theoretical proposals and practical deployment [5].

VI. DISCUSSION

6.1 *Implications for Researchers*

For academic researchers, this review identifies several priorities. First, the field need a standardized methods for measuring scalability and energy use in blockchain-IoT systems so studies support meaningful comparison. As reported in [5], a review of 156 papers shows the absence of common benchmarks limits progress, with 42% of new consensus proposals failing to reach implementation or deployment. Second, researchers should also highlight hardware-based validation instead of relying only on simulation, since many theoretical designs do not perform well in constrained environments [5]. Third, there would be a knowledge gap in long term research which would follow the evolution of the tradeoff through prolonged deployments, due to the majority of recent literature concentrating on short time spans of assessment [18] [9]. Fourth, multi objective optimization frameworks that address scalability, energy, latency, security, and cost would better match real system design needs [2] [18].

6.2 *Implication for Practitioners*

Practitioners working on blockchain-IoT systems can gain a number of insights based on this review. The selection of platforms has to be on actual performance determined in the real world and not on simulations or theoretical assertions. This is demonstrated by the 42% implementation failure rate in [5]. Second, edge computing architectures and hybrid designs provide ways to limit energy impact on end devices while maintaining scalability, while infrastructure costs

Table 3. Comparative analysis of blockchain platforms for IoT integration

Platform	**Consensus Mechanism**	**Transaction per second(Observed)**	**Energy Consumption**	**IoT Focus**	
Ethereum	PoW	45-140	5.2-10.3 J/Tx	No	[11]
Ethereum	PoS	60-210	0.3-0.7 J/Tx	Growing	[11]
Hyperledger	PBFT/variants	200-500	Low	Yes	[13]
Ethereum	PoA	50-190	Low	Yes	[11]
Custom Hybrid	PoW+PBFT+PoA	5,217	0.05 kWh/tx	Research	[10]

require careful evaluation [9] [13] [10]. Third, even on energy efficient platforms there is transaction cost showing real economic constraints and should be factored in deployment planning. Real dataset simulations also demonstrate that AI driven optimization can reduce the energy costs by approximately 15%, but the economic viability remains to be discussed [3]. Fourth, design choices must be based on application-specific needs, because there is no standard or universal solution to the problem of scalability-energy tradeoff [19].

6.3 Barriers to Adoption

Despite the theoretical progress, practical blockchain-IoT deployment still faces hardware limits. The experiments on the hardware indicate that even the capable single board computers experience the loss in the level of performance as the amount of blockchain parameters is increased [7] [9]. In the case of IoT-class devices, the gap between proposed designs and practical implementation remains large.

The economic constraints are also a serious issue. On blockchain platforms, transaction costs increase at an exponential rate as the scale of the IoT data increases. A network of 10,000 devices with an hourly transaction of transactions would have massive accumulating cost [3]. Moreover, even though most of the studies state regulatory uncertainty [1], detailed policy frameworks for blockchain IoT deployment are still limited [5].

VII. CONCLUSION

7.1 Summary of Findings

The paper concludes that the scalability energy tradeoff remains a major challenge in blockchain IoT integration [5] [6]. Evidence shows that consensus mechanisms plays a significant role in reshaping the tradeoff. Proof of Authority delivers strong energy efficiency in resource constrained environments, reported at about 0.5-0.9 J per transaction with latency under 200ms, while hybrid architectures reach higher throughput, up to 5,217 TPS, but at the cost of greater architectural complexity [11] [10].

The study also concludes that architectural strategies, including edge computing and hierarchical designs, help reshape the tradeoff [9] [13]. AI-driven optimization shows meaningful potential for adaptive control, with documented cases reporting around 15% reduction in energy cost [3]. But still, major gaps remain. These include the lack of standardized metrics [5] [8], limited long term evaluation data [7] [9], and a notable recurring implementation gap between theory and practice, where 42% of new consensus proposals fail real world deployment [5].

7.2 Overall Conclusion

The overall conclusion is that the scalability energy tradeoff is real and significant, yet more manageable than early studies suggested when researchers apply context aware strategies instead of searching for universal solutions [2] [19]. Progress depends not on removing the tradeoff, but on building intelligent adaptive systems that can handle it effectively through coordinated use of architectural innovation, AI driven optimization, and application specific design choices [3] [16].

VIII. RECOMMENDATIONS AND FUTURE DIRECTIONS

8.1 Recommendations

Based on the findings and conclusions of this study, several recommendations are proposed to support effective management of the scalability-energy tradeoff in blockchain-IoT integration.

1. Adopt lightweight consensus mechanisms such as Proof of Authority, which consume less energy and are better suited for IoT environments.
2. Implement edge computing architectures to offload heavy computation from resource-constrained devices to more capable infrastructure.
3. Develop standardized measurement frameworks to enable meaningful cross-study comparison and evidence-based platform selection.
4. Prioritize hardware-based validation over simulation-only studies to ensure theoretical advances translate to practical impact.
5. Incorporate AI-driven dynamic optimization to adapt system behavior based on current conditions, demand patterns, and energy availability.

8.2 Future Directions

Future researchers should focus on developing more advanced energy efficient consensus mechanisms that can support large scale IoT deployments without sacrificing sustainability. Studies should also evaluate the integration of blockchain IoT systems with renewable energy sources to reduce environmental impact and support sustainable operation. Finally, there is a strong need for empirical research based on long term real world implementations to evaluate performance, scalability, and energy consumption under practical conditions, which would help reduce the gap between theoretical frameworks and practical solutions.

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