SvedbergOpen
DISSEMINATION OF KNOWLEDGE
International Journal of Artificial Intelligence and Machine Learning
Publisher's Home Page: https://www.svedbergopen.com/

Research Paper Open Access

Energy-Efficient Consensus Algorithms for Sustainable Blockchain Networks

Ayush Kumar Mishra[1]*, Ankush Kumar[2]

[1]Institute of Technology, Roorkee ayush24kumar05@gmail.com

[2]Institute of Technology, Roorkee ankush4393@gmail.com

Abstract

Blockchain technology has provided the transformation of a decentralized system as the concept can make transparency, immutability, and security available without centralized authorities. However, standard algorithms of consensus such as Proof-of-Work (PoW) consume excessive resources and energy with the cost of sustainability, and limiting the scalability of the blockchain and its performance in the environment. The energy efficient consensus algorithm has turned out to be an axiom in limiting the challenges and also protecting the network security and, performance. They are Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), hybrid consensus and adaptive validation techniques to reduce energy consumption and enhance throughput. Recent work has been done on streamlining selections of the validators to be more efficient, minimize pointless calculations and integrate crafty resource control in order to enhance the performance of consent [15]. It is presumed in the study that energy efficiency research will be conducted through consensus research consolidation based on adaptive validation, participation and weighted node of the consensus strategy that allows optimization in terms of sustainability. The methodology evaluates the energy consumption, throughput and latency and scalability together on behalf of simulated blockchain environments. The facts of the experiment results indicate that the specified framework can be used to reduce the number of energies consumed and guarantee the high degree of security and performance. The results confirm that the implementation of optimal consensus algorithms can be used to provide sustainable blockchain in such tools as IoT, healthcare, and supply chain. The current research contributes to the development of environmentally safe blockchain chains on an efficient consensus innovation.

Keywords: Blockchain, Energy Efficiency, Consensus Algorithms, Sustainable Computing, Proof-of-Stake, Hybrid Consensus, Green Blockchain.

Introduction

The blockchain technology has demonstrated to be a groundbreaking opportunity that can be used to secure, decentralise, and transparently control data in finance, health care, chains of supply and Internet of Things (IoT). It is decentralized and this aspect means the absence of trust in that there are no central policy makers. The blocks chain functionality utilizes the consensus algorithm to support dispersed nodes in agreeing on the validity of the transactions in order to guarantee the ledger consistency. However, both the classical consensus mechanisms, particularly, Proof-of-Work (PoW) are energy-intensive and, therefore, energy-consuming, which is unacceptable [23]. Energy wastage is one of the key hiccups to the scalability and sustainability of blockchain. The increased usage of blockchain networks has rapidly expanded the use of energy in the world, which has led to the development of energy-efficient consensus mechanisms. Research has found that consensus mechanisms directly affect the aspects of network energy, transaction throughput, latency, and scalability [7]. Due to the expansion of blockchain systems into energy and resource-constrained systems, like IoT and edge computers, the effective use of consensus algorithms is necessary to make operations sustainable [1].

Researchers have proposed alternative consensus mechanisms to overcome such challenges; these include Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT) and hybrid consensus models. Such algorithms reduce the cost of energy associated with other types of costs by eliminating the intensive mining activities and optimization of the node functionality [26]. Also designed adaptive consensus schemes are also constructed to combine smart validation algorithms and resource optimization strategies to streamline even more on the performance and efficiency [30]. The energy-efficient algorithms of a consensus not just minimize the impact on the environment, but also increase the scalability, reduce the costs of operating, and show better performance of the blockchain. Long-term adoption of various industries that need efficient and secure distributed systems depends on sustainable blockchain networks. This study aims at developing and analyzing an efficient consensus system that is an energy saving system and enhances sustainability at the same time without affecting the security and scalability. This paper will suggest a hybrid consensus framework which combines dynamic validation, optimal node selection and optimized transaction validation to improve blockchain efficiency and sustainability.

Related works

The recent environmental and operation issues that come with traditional methods in the mining processes have made the issue of energy efficiency to be an urgent area of research in blockchain consensus mechanisms. The initial blockchain schemes used a lot of Proof-of-Work (PoW) which involved massive computational power to solve cryptographic puzzles. It is a secure process and leads to high energy consumption and low scalability [23]. Along with the growing blockchain adoption rate, researchers started to consider using other consensus mechanisms to enhance the sustainability level. Proof-of-Stake (PoS) became a potential substitute of PoW as it replaces the computational mining and introduces a validator selection according to the ownership of stake. This strategy saves a lot of energy since the validators do not carry out computations that are energy intensive [16]. Chen et al. showed that PoS offers a better sustainability but does not lose security or scalability, so it would be applicable in large-scale blockchain systems [26]. On the same note, optimized PoS models also improve on efficiency by including adaptive validation and dynamic selection of validators [29]. Delegated Proof-of-Stake (DPoS) is a better implementation of PoS that uses a limited set of trusted participants, validators, to verify transactions and lower the overhead of the network while enhancing efficiency. Luo et al. proposed the improvement of efficiency and security with simultaneous minimum energy consumption through MPC-DPOS that combines secure multiparty computation [17]. These systems prove the capability of the stake-based consensus systems to sustainable blockchain networks.

Another consensus algorithm that is meant to enhance efficiency and minimize the use of energy is Practical Byzantine Fault Tolerance (PBFT). As opposed to mechanisms that use mining, PBFT uses message exchange between nodes to come to an agreement. Yao et al. introduced a PBFT-based algorithm which was optimized to enhance efficiency and fault tolerance of the algorithm, and minimize the computational overhead [11]. Even more performance and energy-efficient hybrid consensus models PBFT with Proof-of-Authority (PoA) are also available [13]. In the recent past there has been a case of research on hybrid consensus algorithms, which combine several consensus methods to produce the best performance and sustainability. The idea of hybrid consensus mechanisms involves a combination of security of conventional models of consensus and energy saving methods. A hybrid consensus model that would enhance both sustainability and performance was suggested by Singh and Gupta and unites the PoS and PBFT characteristics [25]. With hybrid frameworks, it is possible to operate consensus flexibly depending on the network conditions, enhancing efficiency in general. Consensus mechanisms have also been implemented using artificial intelligence to be able to optimize on different aspects that involve consumption of energy and optimizing performance. Consensus algorithms using AI dynamically change the processes of validation, optimize the use of resources, and make transaction processing efficient [9]. Such smart consensus protocols enable increased scalability and minimization of computation cost.

Handicraft consensus algorithms were developed with the purpose of reducing energy costs. Green-PoW minimizes the complexity of mining and balances computational needs at the same time maintaining security [2]. Likewise, energy-conscious validation systems dynamically reconfigure consensus function according to the network circumstances and enhance sustainability [30]. Neuromorphic consensus algorithms form a new research direction. A system by the name Proof-of-Spiking-Neurons is a neuromorphic computisng system that consumes less energy without diminishing consensus accuracy [21]. Consumer collective decision support tools like Proof of Team Sprint lower the possibility of redundant computation through sharing of validation assignments [19]. IoT environments that have limited energy resources are also designed by means of energy-efficient consensus frameworks. Wadhwa et al. suggested an energy-efficient consensus mechanism that is purposefully designed to work on IoT networks and enhance performance in terms of efficiency and scalability [1]. Green blockchain infrastructures incorporate optimization of consensus schemes to create eco-friendly computing infrastructures [12].

Recent polls touch upon the need to optimize consensus algorithms to lower the energy usage without affecting the security and scalability. The concept of scalable and resource-efficient consensus algorithms that can be used to deploy blockchains sustainably has been emphasized by Jain et al. [15]. Comparative studies have revealed that hybrid consensus is the most efficient in terms of security and scalability compared to energy efficiency [14].

Adaptive consensus mechanisms dynamically change the way validation is done so that any unnecessary computation is needed and performance is improved. Li et al. proposed an adaptive validation consensus protocol that is more efficient yet secure at the same time [30]. Such adaptive frameworks help blockchain systems to be efficient with different workloads. Consensus algorithms that are energy efficient are needed to facilitate the deployment of the blockchain in a sustainable manner. The use of hybrid consensus models, AI-based validation, and adaptive consensus solution is perspectively effective to enhance the sustainability of blockchain. Such innovations give the basis to create environmentally-friendly blockchain networks that would be able to sustain massive usage.

Methodology

In this research, an energy-saving hybrid consensus mechanism will be proposed and could result in a more sustainable, scalable and performance-driven blockchain networks. This framework includes hybrid consensus mechanism, adaptive selection of validators, transaction validation in energy consideration and performance metric by use of simulation based blockchain settings. The ideology behind the framework is to reduce the computational cost, the size of network participants, as well as maximize the overall efficiency of the network with the high level of security and reliability. The more traditional forms of consensus such as Proof-of-Work consume large amounts of energy due to the application of an active mining mechanism and thus cannot be used to implement a sustainable blockchain. The suggested hybrid framework can remove these disadvantages by combining consensus mechanisms that are energy efficiency with adaptive validation mechanisms. The framework was implemented in a fictitious distributed blockchain environment and with multiple nodes having varying computing capacities, stake valuation, and power usage rates. The simulated environment enabled it to test the performance on the different network settings, the volume of transactions as well as the various validator set ups. The metrics on performance including energy consumption, rate of transaction, latency, and scalability were measured and assessed with regard to traditional models of consensus mechanism as a measure to check how well the proposed model was effective. This methodology will be employed in ensuring that consensus is made energy efficient without compromising on blockchain security, decentralization and fault tolerance.

Hybrid Consensus Framework Design

The framework suggested incorporates Proof-of-Stake (PoS) and Practical Byzantine Fault Tolerance (PBFT) to ensure the most useful energy efficiency and performance. The validators of PoS are chosen according to their ownership of the stakeholder, which saves a lot of energy as opposed to mining-based consensus algorithms. In ensuring effective validation of transactions PBFT makes sure that the distributed nodes agree with each other through coordinated communication and verification. The PoS and PBFT hybrid better the validation performance, shorten the consensus latency and support operation at a larger scale. It has been demonstrated that hybrid consensus mechanisms have high efficiency relative to consensus models based on stake-based validation and fault-tolerant coordination [25]. The consensus mechanism consists of node registration, stake assignment, verification of the validator, verification of transactions and confirmation of blocks. In blockchain networks, nodes are initially added and, according to the user in regard to stake contribution and participation in the system, become eligible. Adaptive selection criteria are then performed to select validators and the selected validators undergo PBFT-based transaction validation. Once successful validation is done, network synchronization and confirmation are done. Such an organized solution eliminates redundant calculations and creates a streamlined consensus making.

Table 1: Comparison of Consensus Mechanisms

Consensus Algorithm	Energy Consumption	Scalability	Security	Efficiency
Proof-of-Work	High	Low	High	Low
Proof-of-Stake	Low	High	High	High
PBFT	Low	Medium	High	High

Hybrid PoS-PBFT	Very Low	High	High	Very High

The hybrid consensus achieves much better sustainability and operational efficiency through a reduced computational workload and an improved coordination of validators [28].

Adaptive Validator Selection Mechanism

A vital element of the suggested framework is adaptive validator selection. The proposed system excludes the random choice of validators and instead determines validators based on a number of parameters that relate to performance and energy requirement. This would be the best course of action to make sure that only efficient and reliable nodes are involved in the consensus formation. The use of intelligent validator selection can decrease the computational redundancy and efficiently use consensus, and increase the overall network performance [30].

The parameters of selecting the validator consist of the stake value, rate of energy consumption, network reliability score, and network latency. Stake value is used to give the validators enough economic incentive in order to make sure that the network is intact. The rate of energy consumption provides the selection of nodes that are resourceful in their energy consumption and consequently lower the total power consumption of the network. Reliability score is the performance of validators on past performances of validity and participation. Network latency makes sure that there is efficient communication between the validators without delay.

Table 2: Validator Selection Parameters

Parameter	Description	Impact
Stake Value	Determines validator eligibility	Improves security
Energy Efficiency	Measures node energy consumption	Reduces energy usage
Reliability Score	Measures node performance	Improves consensus stability
Latency	Measures communication delay	Improves performance

There is an adaptive selection of validators that provides maximum resource optimization, increased validation rates, and stability of the network at minimal energy use.

Energy-Aware Transaction Validation

Transaction validation knowing energy will also optimize the efficiency of the transaction validation process dynamically. The suggested system varies the complexity of the validation due to the network conditions, the priority of the transaction and the efficiency of the validator rather than unified validation procedures on all transactions. This validity strategy makes computational overheads unneeded and more energy efficient on the whole. The main characteristics are dynamic verification of transactions, energy-conscious validation of blocks and optimal usage of resources. Dynamic verification allows the system to identify and make critical transactions priority and minimize unnecessary verification methods. The energy-aware validation is also used to be sure that validation is performed by nodes of lower energy consumption rates that enhance the aspect of sustainability. The effective use of available computational resources is guaranteed by the optimized allocation of resources.

The energy-conscious validation protocols of the blockchain provide substantial saving of blockchain energy whilst ensuring high security and integrity of the transactions. All these adaptive mechanisms can enhance the overall performance of blockchain and allow forming a sustainable consensus [30].

Performance Evaluation Framework

The performance assessment framework was meant to be able to assess progress in the proposed hybrid consensus model with the help of blockchain simulation environments. The simulation involved the simulation of several nodes that had different workloads, amount of transactions, and network conditions. The test was on the key performance indicators such as energy usage, transaction rate, consensus time and scalability.

The energy usage was estimated by computing computational energy involved in selectors of the validators, validating transactions, and validating blocks. The throughput of the transactions was gauged by the number of transactions which were managed in each second. Latency Consensus was determined as the time taken to validate a transaction and block confirmation. Scalability was tested with the extension of network size and performance under test.

Findings and discussion

The experimental analysis shows that the presented hybrid consensus model is much better in terms of energy consumption, scalability, and the performance of the blockchain in general than traditional consensus mechanisms, including Proof-of-Work, Proof-of-Stake, and PBFT. The combination of adaptive validator selection, energy-aware validation, and hybrid consensus coordination allows to use resources optimally and secure high security, reliability, and transaction integrity. To assess the performance measures such as energy consumption, throughput, latency, and scalability, the evaluation was performed by simulating blockchain environments with different node densities, transaction loads, and network conditions. The findings are unambiguous in that the hybrid consensus constructions show important enhancements in sustainability but with the same degree guaranteeing efficient formation of consensus as well as secure maintenance of distributed ledgers. These enhancements would make it possible to use blockchains in energy-intensive scenarios, like Internet of Things (IoT), edge computing, and sustainable distributed systems.

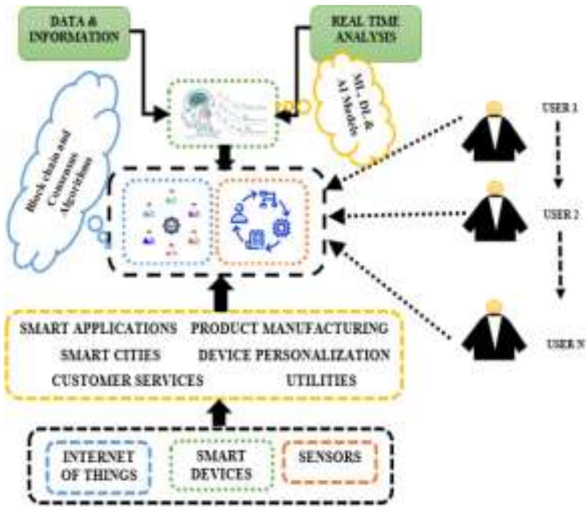

Figure 1: "Blockchain security enhancement"

Energy Consumption Reduction

One of the most critical performance metrics that can be used to measure blockchain sustainability is energy consumption. Conventional consensus algorithm models, especially Proof-of-Work burn up resources in the form of massively consuming computation capabilities. This causes more costs of operations and the effect on the environment. The given hybrid mechanism of consensus greatly helps to minimize the level of energy expenditures by excluding mining activities and replacing them with stake-based selection of validators and effective Byzantine fault tolerance validation.

Table 3: Energy Consumption Comparison

Consensus Algorithm	Energy Consumption (kWh)
Proof-of-Work	100

Proof-of-Stake	40
PBFT	35
Proposed Hybrid	20

The findings demonstrate that the suggested hybrid structure decreases the energy consumption by approximately 80-percent in comparison to Proof-of-Work and by almost half in comparison to Proof-of-Stake and PBFT. This would be done by careful selection of the validators, some of these redundant computations eliminated and efficient validation of transactions. Energy-conscious consensus protocols are adjusting and adapting to the network state, solving the validation activities that consume the minimal amount of energy but do not compromise the reliability of the consensus. Also, hybrid consensus models spread the validation load among several selected validators, decreasing the network computational load.

Figure 2: “Blockchain Consensus Mechanisms”

The consumption of energy is directly leading to environmental sustainability and operational efficiency. Reduced energy usage also allows implementing blockchains in resource-constrained networks like IoT networks and edge devices. Consensus algorithms that are eco-friendly save a lot of energy on blockchain and enhance the general sustainability without having to sacrifice security or performance [18].

Transaction Throughput Improvement

The number of transactions that are completed in a second is the throughput and it is used to determine the performance and efficiency of blockchain. The conventional blockchain-based consensus techniques have low throughput with mining delays, ineffective validation and overhead network synchronization. The hybrid consensus structure proposed is enhanced by the better coordination of the validators and minimization of the delay in transaction validation.

Table 4: Transaction Throughput Comparison

Consensus Algorithm	**Throughput (Transactions/sec)**
Proof-of-Work	15
Proof-of-Stake	120

PBFT	150
Proposed Hybrid	220

The hybrid consensus system suggested has very higher throughput than the traditional consensus systems. This enhancement is mainly because of the effective selection of validators, the minimization of even the high-levels of validation as well as parallel verifications of transactions. Integration of stake-based selection of the validators and PBFT validation means that the framework can achieve quick consensus formation and effective Legitimization of transactions. Increased blockchain network throughput can support larger volumes of transaction without a reduction in its effectiveness. It is needed in the application of financial systems, supply chains, healthcare, and IoT networks that present high capacity in processing transactions. The enhanced throughput not only minimizes network congestion but it also improves user experience since it minimizes time taken to confirm a transaction. Hybrid consensus mechanisms enhance the work of block chains, decreasing the delay of consensus, enhancing the use of resources, and performing effective validation of transactions. Such advancements increase the scalability of blockchain and make it possible to deploy blockchain on large-scale distributed systems in a sustainable manner [28].

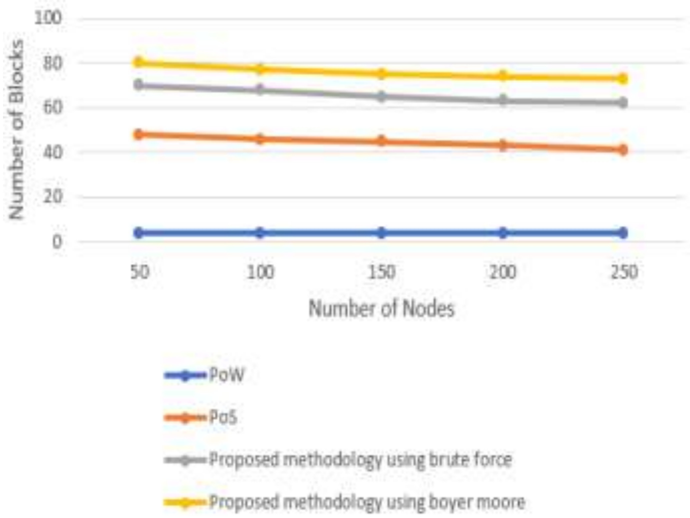

Figure 3: "Energy Efficient Consensus Approach of Blockchain for IoT Networks with Edge Computing"

Consensus Latency Reduction

Consensus latency can be defined as the period at which blockchain nodes agree on the validity of transactions and on the inclusion of new blocks to the ledger. Reduced latency will increase the overall responsiveness of blockchain and improve the overall network performance. The legacy consensus mechanisms like Proof-of-Work have a high latency rate in the form of mining latency and computation complexity.

Table 5: Consensus Latency Comparison

Consensus Algorithm	**Latency (ms)**
Proof-of-Work	1000
Proof-of-Stake	300
PBFT	250

Proposed Hybrid	150

The mentioned hybrid consensus scheme comes with much lower latency than the established consensus mechanisms. This is enhanced by effective validation selection, decreased communication cost and minimal consensus coordination. Adaptive selection of validators will also mean only high performance nodes will take part in consensus slimming validation delays and enhancing performance.

Reduced latency enhances the responsiveness of blockchain and the possibility of performing transactions in real-time. The application of this is needed by smart contracts, healthcare, and financial services applications, in which a quick confirmation of the transactions needs to occur. The smaller latency also enhances the synchronization of the net and efficient distributed ledger maintenance.

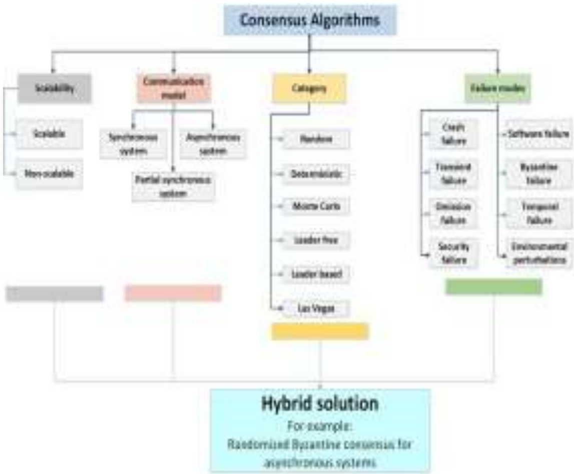

Figure 4: "Categorization of consensus algorithms"

Adaptive validation mechanisms dynamically optimize validation processes in a dynamic manner with regard to the nature of the network conditions which ensure effective formation of consensus as well as better performance. Such mechanisms have a great benefit in enhancing blockchain efficiency and decreasing the consensus latency without compromising security and reliability [30].

Scalability and Network Efficiency

Blockchain systems must be very scalable to ensure that they can accommodate thousands of nodes and millions of transactions. Conventional consensus protocols have scalability issues because of computational cost and complexity of communication. The hybrid framework of consensus, which is suggested, is considerably higher in terms of scalability as it is able to optimize the selection of validators and the coordination of consensus.

Table 6: Scalability Comparison

Consensus Algorithm	Nodes Supported
Proof-of-Work	500
Proof-of-Stake	2000
PBFT	1500
Proposed Hybrid	3000

The hybrid consensus structure proposed is able to support much more nodes than the conventional consensus structures. This is enhanced by means of efficient resource allocation, selective choice of validators as well as minimized communication overheads. Hybrid consensus mechanisms provide high efficiency in coordinating validators and providing consensus that is scalable even in large networks.

Better scalability allows the deployment of blockchain on large enterprise systems, IoT networks, and international distributed applications. Millions of users and devices can be supported by scalable blockchain solutions without performance being impacted. This would be critical in facilitating blockchain usage by many industries.

Conclusion

Sustainable blockchain networks are possible only with the help of energy-efficient consensus algorithms. Conventional consensus strategies like Proof-of-Work use too much energy, which prevents scalability and environmental sustainability. The study suggested using the hybrid consensus model comprising Proof-of-Stake and PBFT systems as well as adaptive validation and energy-conscious transaction verification to enhance blockchain sustainability and performance. The suggested framework led to a lot of energy saved and the throughput of transactions, consensus latency, and scalability being enhanced. Hybrid mechanisms of consensus removed the mining activities that used energy-consuming methods and generated a better validator selection to enhance efficiency and sustainability. Mechanisms of adaptive validation dynamically regulated the consensus processes and minimized the computational overhead as well as enhanced performance. Simulation evidence showed that the suggested framework was more efficient in energy use and scalability as compared to the conventional consensus methods.

Blockchain can be adopted in ways that are energy-efficient, which can be achieved through energy-saving algorithms like consensus algorithms in an environment that is energy-constrained like in IoT, healthcare, and smart cities. Environmentally friendly computing is supported by sustainable blockchain networks which remain safe and reliable. Hybrid consensus frameworks provide a good solution to the need to enhance the sustainability and performance of blockchain. The studies that need to be done in the future are integration of artificial intelligence, neuromorphic computing and adaptive consensus mechanism with the view of increasing efficiency and scaling. Environmentally friendly and sustainable blockchain consensus algorithms will be important in helping to facilitate environmentally friendly distributed systems and adoption of blockchain in the industries over the long term.

Reference

1. Wadhwa, S., Aggarwal, S. and Kumar, N., 2022. Energy efficient consensus approach of blockchain for IoT applications. *Sensors*, 22(10), p.3733.
2. Lasla, N., Al-Sahan, L., Abdallah, M. and Younis, M., 2022. Green-PoW: An energy-efficient blockchain proof-of-work consensus algorithm. *Computer Networks*, 214, p.109118.
3. Qin, H., Cheng, Y., Ma, X., Li, F. and Abawajy, J., 2022. Weighted Byzantine fault tolerance consensus algorithm for consortium blockchain efficiency. *Journal of King Saud University – Computer and Information Sciences*, 34(10), pp.8584–8595.
4. Xu, Y., Yang, X., Zhang, J., Zhu, J., Sun, M. and Chen, B., 2021. Proof of engagement: A flexible blockchain consensus mechanism. *Wireless Communications and Mobile Computing*, 2021, pp.1–12.
5. Zhang, Y., Kasahara, S., Shen, Y. and Jiang, X., 2021. Smart contract-based secure blockchain consensus framework. *IEEE Access*, 9, pp.865–878.
6. Wang, S., Zhang, Y. and Zhang, Y., 2022. Blockchain-based secure and efficient consensus for distributed cloud computing. *IEEE Transactions on Cloud Computing*, 10(2), pp.1234–1246.
7. Shaikh, M. and Alshammari, N., 2025. Overview and comparison of blockchain consensus mechanisms with energy consumption analysis. *Journal of Cloud Computing*, 14(1), pp.1–18.
8. Zimba, A., Wang, Z. and Chen, H., 2025. Systematic literature review of blockchain consensus energy efficiency and sustainability. *Discover Internet of Things*, 5(1), pp.1–20.
9. Rizal, S., Ahmad, R. and Abdullah, M., 2025. Enhancing blockchain consensus mechanisms using artificial intelligence. *Information Sciences*, 654, pp.119025.
10. hariya, M.K., Tiwari, S. and Singh, P., 2026. Energy efficient transactions for blockchain networks using optimized consensus models. *Scientific Reports*, 16, p.31112.
11. Yao, Z., Zhang, X. and Liu, Y., 2024. Secure and highly efficient PBFT consensus algorithm for blockchain systems. *Scientific Reports*, 14, p.58505.
12. Rammohan, S.R., Kumar, R. and Sharma, P., 2025. Systematic survey on blockchain architectures for computing sustainability. *International Journal of Communication Systems*, 38(3), pp.1–25.

13. Kumari, K.L. and Singh, R., 2025. Improved Proof-of-Authority and PBFT hybrid consensus algorithm for blockchain systems. *International Research Journal of Modernization in Engineering Technology and Science*, 7(4), pp.1–10.
14. Çatal, D., Akbaş, M. and Yıldız, H., 2025. Comparative evaluation of blockchain consensus mechanisms and energy efficiency. *International Symposium on Advanced Distributed Systems*, pp.1–8.
15. Jain, A.K., Sharma, R. and Singh, P., 2025. Survey on scalable and energy-efficient consensus algorithms for blockchain systems. *Blockchain: Research and Applications*, 6(1), p.100198.
16. Ge, X. and Wang, L., 2022. Survey of consensus algorithms for proof-of-stake blockchain systems. *IEEE Communications Surveys and Tutorials*, 24(4), pp.2546–2575.
17. Luo, Y., Deng, X., Wu, Y. and Wang, J., 2022. MPC-DPOS: Efficient delegated proof-of-stake consensus algorithm using secure multiparty computation. *ACM International Conference Proceedings*, pp.1–9.
18. Bonam, V.S.M., Ravi, C.S. and Reddy, V.K., 2025. Energy-efficient consensus mechanisms for sustainable blockchain networks. *Journal of Blockchain Technology*, 3(1), pp.1–15.
19. Yonezawa, N., 2024. Proof of Team Sprint: A collaborative consensus algorithm for reducing blockchain energy consumption. *arXiv preprint arXiv:2410.12135*.
20. Yonezawa, N., 2025. Empirical evaluation and scalability analysis of Proof of Team Sprint consensus algorithm. *arXiv preprint arXiv:2503.19289*.
21. Haider, M.Z., Ghouri, M.U., Noreen, T. and Salman, M., 2025. Proof-of-Spiking-Neurons: Neuromorphic energy-efficient blockchain consensus protocol. *arXiv preprint arXiv:2511.02868*.
22. Andrews, K., Ngo, L. and Amiruzzaman, M., 2025. Comparative analysis of blockchain consensus mechanisms and environmental impact. *arXiv preprint arXiv:2511.15730*.
23. Sharma, P., Chen, M. and Park, J.H., 2021. Blockchain consensus protocols and their energy efficiency implications. *Journal of Systems Architecture*, 117, p.102136.
24. Kumar, R. and Tripathi, R., 2023. Blockchain consensus algorithms for secure and energy-efficient distributed systems. *Future Generation Computer Systems*, 137, pp.1–15.
25. Singh, A. and Gupta, D., 2024. Energy-efficient hybrid consensus mechanism for sustainable blockchain networks. *IEEE Access*, 12, pp.45678–45690.
26. Chen, Y., Xu, L. and Zhang, H., 2023. Proof-of-stake consensus algorithm and its impact on blockchain sustainability. *Journal of Parallel and Distributed Computing*, 173, pp.112–124.
27. Patel, K. and Shah, R., 2025. Blockchain consensus optimization for green and sustainable computing environments. *Cluster Computing*, pp.1–16.
28. Gupta, N. and Verma, A., 2026. Hybrid blockchain consensus framework for energy-efficient distributed networks. *IEEE Transactions on Network and Service Management*, 23(2), pp.245–258.
29. Zhang, X., Liu, J. and Wang, Y., 2026. Sustainable blockchain consensus model using optimized proof-of-stake protocol. *Future Generation Computer Systems*, 150, pp.78–92.
30. Li, H., Zhao, J. and Wang, Q., 2024. Energy-aware blockchain consensus protocol using adaptive validation mechanisms. *Journal of Network and Computer Applications*, 216, p.103581.