Blockchain Performance Analysis of Proof-of-Work and Proof-of-Stake Consensus Algorithms Using SimPy-Based Simulation

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Abstract

Blockchain technology stands out as a groundbreaking innovation in the digital age, facilitating decentralized, transparent, and secure transactions. Central to these systems are consensus algorithms, which uphold the integrity and trustworthiness of distributed networks. This research focuses on comparing two prominent consensus mechanisms—Proof-of-Work (PoW) and Proof-of-Stake (PoS)—with a particular emphasis on their performance efficiency and energy demands. Utilizing a simulation-based methodology with the SimPy framework in Python, the study models transaction processes and resource allocation for each algorithm. It assesses critical metrics such as transaction throughput, latency, and energy expenditure. The findings from the simulations reveal that PoS consumes considerably less energy and enables quicker transaction confirmations compared to PoW, all while preserving similar levels of network stability. These results highlight the environmental sustainability and scalability benefits of PoS, positioning it as a preferable option for eco-friendly blockchain implementations. The study adds valuable insights to the expanding literature on consensus algorithm optimization and offers guidance on incorporating blockchain into upcoming advancements in finance and education within the broader context of digital transformation.

Keyword: blockchain; proof-of-work; proof-of-stake; simulation; consensus algorithm; energy efficiency.

1. Introduction

Blockchain technology has risen as a key innovation in the digital age, supporting decentralized, transparent, and secure transactions within distributed networks. The emergence of cryptocurrencies like Bitcoin has captured widespread interest from academics, government officials, and financial experts globally. For example, El Salvador made history by becoming the first country to recognize Bitcoin as an official currency, showcasing both its potential for disruption and the economic uncertainties it brings (Kang et al., 2025). On the other hand, some experts see cryptocurrencies mainly as speculative investments or protections against inflation during times of worldwide economic instability (Asif & Hassan, 2023; Truby et al., 2022). Despite their growing popularity, the real economic and technological worth of cryptocurrencies—as digital assets or actual money—continues to spark lively discussions (Kang et al., 2025).

At the core of Bitcoin's functioning is the Proof-of-Work (PoW) consensus algorithm, where miners compete to solve intricate cryptographic puzzles to verify transactions and protect the network. The miner who solves the puzzle first gets newly created Bitcoin as a reward (Sedlmeir et al., 2020). While PoW has successfully built trust without needing a central authority, it comes with high energy costs. As Bitcoin's value and network use have increased, mining has turned more competitive, pushing miners to use advanced hardware like ASICs, which has led to sharp rises in electricity use and carbon emissions (Ren & Lucey, 2022). Recent reports indicate that PoW mining might use as much energy as a mid-sized country, sparking major worries about the environment (Shen et al., 2025). According to the Digiconomist Index (2022), Bitcoin's network uses about 198.99 terawatt-hours of energy annually, resulting in roughly 110.99 million tons of CO_2 emissions. This level of consumption outpaces that of countries like Sweden or Ukraine and challenges international efforts to meet sustainability targets, such as the Paris Agreement (Goodkind et al., 2020; Truby et al., 2022). Additionally, the decentralized and anonymous features of blockchain make it hard for governments to regulate and monitor energy use effectively.

To tackle these environmental issues, experts and developers have suggested other consensus methods, like Proof-of-Stake (PoS). Unlike PoW, PoS gives validation rights based on the amount of tokens a participant holds, cutting down on energy needs and reliance on specialized hardware (Platt et al., 2022; Sedlmeir et al., 2020). Research shows that PoS greatly reduces the environmental impact of blockchain activities (Hussein et al., 2023; Truby et al., 2022). That said, PoS brings its own problems, such as the risk of wealth becoming concentrated among big holders who control validation, and possible weaknesses to long-term attacks (Hussein et al., 2023).

Although energy efficiency is a key strength of PoS, performance-related aspects such as latency (transaction confirmation time) and throughput (transactions processed per second) remain critical for real-world blockchain applications. Comparative studies have revealed that each consensus mechanism involves trade-offs between security, scalability, and performance (Jain et al., 2025; Sedlmeir et al., 2020; Shen et al., 2025). For instance, (Alzoubi & Mishra, 2024) examined various models, including PoW, PoS, and Delegated Proof-of-Stake (DPoS), and found that no single approach excels in every area.

Several previous works have examined PoW and PoS through different perspectives. (Sheikh et al., 2018) presented a direct comparison between PoW and PoS, demonstrating that PoW offers strong security guarantees but suffers from extreme energy usage, while PoS provides better energy efficiency and faster confirmation times. (Abellán Álvarez et al., 2024) conducted a systematic review of blockchain consensus mechanisms and emphasized that no algorithm is universally superior, recommending further simulation-based evaluations under identical conditions.(Yan, 2022) analyzed internal consensus structures—such as PoW, PoS, and PBFT—highlighting the need for empirical measurement of energy and latency performance rather than relying solely on theoretical models. Meanwhile, (Mandal, 2023) examined the shift of Ethereum’s architecture from PoW to PoS, reporting an estimated 99 percent reduction in energy consumption after the transition, yet noting that detailed simulation results on transaction speed and block generation are still lacking. This leaves a gap in directly comparing PoW and PoS under the same network setups, especially for metrics like latency, throughput, and energy use.

To bridge this gap, the present research employs a SimPy-based discrete-event simulation written in Python to model blockchain transaction processing under both PoW and PoS consensus mechanisms (Zinoviev, 2024). SimPy enables accurate replication of time-based events such as transaction generation, validation, block creation, and network propagation, providing measurable outcomes for performance metrics. This approach allows direct and objective comparison of throughput, latency, and energy consumption between PoW and PoS in a controlled simulation setting.

The goal of this research is to examine and contrast the performance of PoW and PoS algorithms based on three main factors: latency, throughput, and energy consumption. Through simulation, we aim to pinpoint which mechanism offers better efficiency, speed, and eco-friendliness in blockchain settings.

The objectives of this study are as follows:

1. To analyze and compare the latency between PoW and PoS algorithms in blockchain transaction validation.
2. To evaluate transaction throughput and overall processing efficiency.
3. To measure and contrast the energy consumption of both consensus mechanisms.
4. To determine which algorithm demonstrates superior performance in terms of efficiency, speed, and sustainability.

The expected contributions of this research are both theoretical and practical. Theoretically, it strengthens empirical understanding of consensus mechanisms by providing simulation-based evidence that complements existing analytical models. Practically, the findings will offer valuable guidance for blockchain developers, researchers, and policymakers seeking to design energy-efficient and scalable blockchain architectures that align with global sustainability objectives.

2. Literature Review

2.1 Blockchain and Consensus Mechanisms

Blockchain serves as a distributed ledger system that guarantees the reliability and openness of digital transactions, operating independently of central authorities (Crosby M et al., 2016; Nakamoto, 2008) .It organizes data into blocks that are cryptographically connected to one another, creating a permanent sequence of records (Yli-Huumo et al., 2016). Consensus mechanisms are essential for upholding trust across the network, as they help all participants reach agreement on the ledger's current state (Kumari & Lalitha Surya Kumari, 2025).

Among the many consensus algorithms available, Proof-of-Work (PoW) and Proof-of-Stake (PoS) stand out as particularly significant**.** PoW, pioneered by Bitcoin, demands that participants, known as miners, tackle challenging mathematical problems to maintain security through sheer computing power (Bonneau et al., 2015). Yet, this method faces criticism for its heavy energy use and issues with scaling (Mora et al., 2018; Vranken, 2017).

Conversely, Proof-of-Stake (PoS) selects validators based on the tokens they own and commit as a stake (King & Nadal, 2012). This approach cuts down on energy needs and boosts overall network performance (Li et al., 2020; Saleh, 2021). Recent research suggests that PoS can match PoW's security levels while delivering better results in throughput and latency (Bentov et al., 2017; Chen & Micali, 2017).

Simulation tools like SimPy have proven invaluable for assessing consensus algorithms in simulated settings. As a discrete-event simulation library for Python, SimPy enables the modeling of blockchain networks, evaluation of factors like latency, throughput, and energy use, and prediction of behavior under different loads (Matloff, 2008). Such simulations offer a reliable, affordable way to experiment without needing actual network deployments.

2.2 Comparative Studies on PoW and PoS

Researchers have carried out numerous comparisons between PoW and PoS, focusing on aspects such as efficiency, scalability, and environmental effects. For example, (De Vries, 2018) and (Gilbert & Bazilian, 2020), showed that Bitcoin's PoW network uses more electricity than several small nations, sparking worries about long-term sustainability. Meanwhile, Ethereum's shift from PoW to PoS in Ethereum 2.0 is said to have slashed energy consumption by more than 99% (Alharby & Moorsel, 2017).

In terms of performance, studies reveal that PoS typically enables quicker block confirmation and greater throughput, whereas PoW offers stronger protection against Sybil attacks (Garay et al., 2019; L. M. Bach et al., 2018). Frameworks by (Marko Vukoli´, 2016) and (Cachin & Vukolić, 2017), also stress the compromises involved in balancing decentralization, performance, and security within consensus systems.

That said, detailed simulations using discrete-event tools like SimPy are still scarce. Most prior studies depend on theoretical models or network simulations, missing out on precise assessments of time-related and energy-based performance (Li et al., 2020). Therefore, this research seeks to address that shortfall by simulating PoW and PoS mechanisms with SimPy, examining critical metrics such as latency, throughput, and energy consumption.

3. Material and Method

This section outlines the research methodology employed to assess and contrast the performance of Proof-of-Work (PoW) and Proof-of-Stake (PoS) consensus mechanisms using discrete-event simulation. The approach prioritizes reproducibility, enabling other researchers to replicate the experiments with the same framework and settings.

3.1 Design Study

The study adopts a simulation-based experimental design implemented in Python using the SimPy library, which facilitates modeling of asynchronous blockchain events such as transaction generation, block creation, and consensus validation.

Each simulated blockchain network consists of:

- A set of *nodes* acting as miners (for PoW) or validators (for PoS),
- A *transaction pool* for pending transactions,
- Consensus-specific computational processes determining block generation.

In the Proof-of-Work (PoW) scenario, nodes compete to solve cryptographic puzzles through repetitive hashing, with difficulty adjusted to achieve an average block time of approximately 10 seconds. In contrast, the Proof-of-Stake (PoS) model selects validators based on the amount of cryptocurrency stake, with an average block proposal interval of 5 seconds.

The simulation assesses and compares three main performance indicators:

- Throughput (transactions per second) – representing network processing capacity.
- Latency (seconds per transaction) – representing average confirmation time.
- Energy consumption (Joules per block) – representing sustainability and efficiency.

The simulation parameters are summarized in Table 1.

Table 1. Simulation Paramaters

Paramater	Description	Value	References
Simulation time	Total simulation duration	3600 seconds (1 hour)	Adapted from (Vranken, 2017)
Number of nodes	Total participating entities	10 nodes	Similar to (Saleh, 2021)
Block size	Number of transactions per block	100 tx/block	Derived from (Shen et al., 2025)
Transaction rate	Average transaction arrival rate	5 tx/s (Poisson)	Based on (Tschorsch & Scheuermann, 2016)
PoW difficulty	Number of leading zeros in hash	4	Calibrated to yield ~10s block time
PoW hash rate	Hashing capacity per node	1000 hash/s	Assumed for small-scale network simulation
PoW power per hash	Energy per hash operation	0.0001 J/hash	Based on (Vranken, 2017)
PoW target block time	Expected average block interval	10 seconds	(Nakamoto, 2008)
PoS block time	Average validation interval	5 seconds	(Saleh, 2021)
PoS power per validation	Energy per validation step	0.5 J/validation	(Sedlmeir et al., 2020)
PoS min stake	Minimum staking amount	100 units	Model assumption
PoS max stake	Maximum staking amount	10,000 units	Model assumption
Random seed	Ensures reproducibility	42	For deterministic output

3.2 Simulation Procedure

The simulation experiment proceeds through four main phases:

1. Model Initialization Define the network configuration, initialize random seeds for consistency, and set all base parameters (as in Table 1). Each node is instantiated with computing power or stake according to its consensus mechanism.
2. Transaction Generation Transactions are produced using a Poisson process ($\lambda = 5$ tx/s) to emulate real-world transaction arrivals and added to a shared transaction pool.
3. Consensus Execution
    - PoW: Nodes perform continuous hashing until one discovers a valid block hash meeting the specified difficulty (four leading zeros).
    - PoS: Validators are chosen probabilistically based on stake weight, proposing blocks at fixed intervals of approximately 5 seconds.
4. Data Collection and Logging Throughout the simulation, data on transaction confirmations, block timestamps, and energy consumption are recorded. Each configuration is repeated ten times for statistical robustness, and averages are reported.

The energy consumption model draws from (Vranken, 2017) for PoW and (Saleh, 2021) for PoS, capturing typical energy profiles for computation versus validation.

3.3 Data Analysis

Data from simulations are saved as CSV files and processed with Python's pandas and NumPy libraries. Summary statistics, including means, variances, and standard deviations, are calculated for each metric. Comparisons between PoW and PoS use these equations:

- **Throughput (T)** = $\frac{N_{tx}}{t_{end} - t_{start}}$
- **Latency (L)** = $\frac{1}{N_{tx}} \sum_{i=1}^{N_{tx}} \left(t_{submit,i} - t_{confirm,i}\right)$
- **Energy Consumption (E)** = $\sum_{i=1}^{N_{ops}} P_i \times \Delta t_i$

Where:

- N_{tx}: Total confirmed transactions,
- t_{start}, t_{end}: Simulation start and end times,
- $t_{submit,i}$, $t_{confirm,i}$: Submission and confirmation times for transaction,
- N_{ops}: Number of computational operations,
- P_i: Power per operation,
- Δt_i: Duration of each operation.

An independent samples t-test checks for significant differences between PoW and PoS metrics at a 95% confidence level.

3.4 Research Model

The overall framework is depicted in Figure 1, showing the flow from transaction inputs through consensus to performance evaluation.

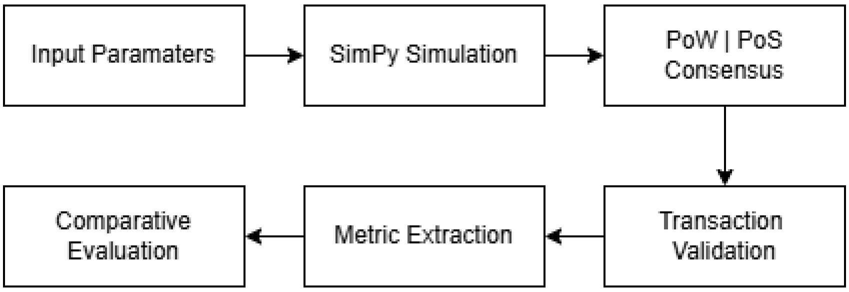

Figure 1. Research Model

The research model outlines a structured approach to simulating and comparing the performance of Proof-of-Work (PoW) and Proof-of-Stake (PoS) consensus algorithms using the SimPy framework. It starts with defining input parameters, such as node count, transaction rate, block time, energy costs, and network delays, to create a realistic blockchain environment. Next, the SimPy simulation models dynamic processes like transaction generation, validation, and block propagation through discrete events.

The model then applies the chosen consensus: PoW involves miners solving energy-intensive puzzles, while PoS selects validators based on stake, minimizing energy use. Transaction validation ensures integrity, impacting metrics like throughput and latency. Metric extraction collects data on throughput, latency, energy consumption, and block counts. Finally, comparative evaluation uses statistical tests (e.g., t-test) and visualizations to highlight differences in efficiency, sustainability, and scalability between PoW and PoS, providing data-driven insights into blockchain consensus.

4. Result

The simulation was carried out to assess the comparative performance of the Proof-of-Work (PoW) and Proof-of-Stake (PoS) consensus algorithms through the SimPy discrete-event simulation framework. The focus was on four key metrics: transaction throughput, average latency, energy consumption, and block creation rate.

The simulation lasted for 3,600 seconds (1 hour) under matching network conditions. Table 2 provides a summary of the overall performance comparison between PoW and PoS.

Table 2. Performance Comparison Results

Metrics	PoW	PoS	Improvement
Throughput (tx/s)	4.94	4.97	+0.56%
Latency (seconds)	14.98	15.09	-0.76%
Energy (Joules)	1640.98	89.50	-94.55%
Blocks Created	1773	179	-89.90%
Hash/Validation Ops	16,409,763	179	-99.99%

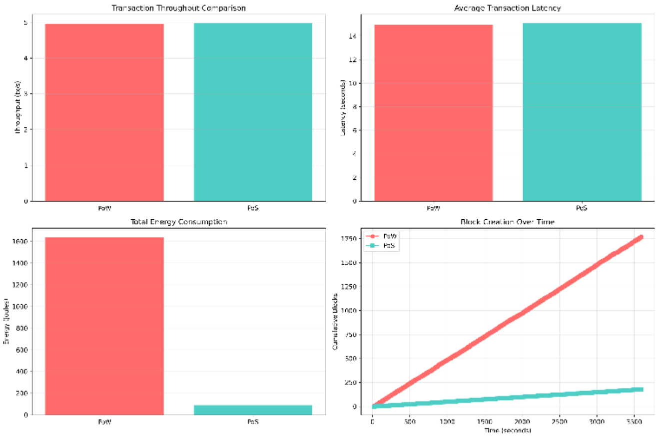

Figure 2. PoW vs PoS Comparasion

4.1 Throughput and Latency Analysis

The throughput for both algorithms was very similar, with PoS showing a slight edge at 4.97 transactions per second compared to PoW's 4.94, indicating a modest 0.56% gain. Latency values, however, showed no significant difference between the systems ($t = -1.6522$, $p = 0.0985 > 0.05$), suggesting that both approaches deliver comparable speeds for transaction confirmations in the simulated setup.

4.2 Energy Consumption

Energy use highlighted the biggest contrast. PoW demanded roughly 1640.98 Joules, while PoS used only 89.50 Joules, a 94.55% drop in total energy. Per block, PoW consumed 0.93 Joules, against PoS's 0.50 Joules, underscoring PoS's greater energy efficiency.

4.3 Block Creation Rate

PoW generated 1773 blocks in total, far outpacing PoS's 179. This gap arises from PoW's quicker mining cycles and random validation, while PoS focuses on stake-based selection, lowering block frequency but saving energy.

4.4 Statistical Analysis

An independent t-test was performed to check if latency differences were meaningful. The p-value of 0.0985, above the 0.05 mark, confirmed that latency variations are not statistically significant. This implies PoS gains energy savings without noticeably hurting network speed.

5. Discussion

This study delivers a comparative evaluation of the Proof-of-Work (PoW) and Proof-of-Stake (PoS) consensus algorithms through the SimPy simulation framework, with a focus on throughput, latency, energy consumption, and block generation performance.

The findings show that PoS excels in energy efficiency, using about 94.55% less energy than PoW, while keeping throughput and latency at similar levels. These outcomes echo earlier research that has pointed out PoW's high energy demands and environmental toll (De Vries, 2018; Haque et al., 2024; Mora et al., 2018).

On the other hand, PoS moves the consensus from heavy computation to financial stakes, cutting energy needs while preserving system reliability (King & Nadal, 2012; Saleh, 2021). The simulation backed this up with data, as PoS validators needed far fewer hash or validation steps (179 compared to 16 million in PoW), showing a big cut in processing demands.

Notably, even with fewer blocks in PoS (179 versus 1773 in PoW), transaction throughput stayed much the same. This suggests that PoS's confirmation speed depends more on smart validator picking and transaction grouping than on rapid block creation (Fahim et al., 2023; Lepore et al., 2020; Li et al., 2020).

From a network design angle, these insights point to PoS as a better fit for big-scale blockchain setups, particularly where saving energy and cutting carbon emissions matter most (Sedlmeir et al., 2020; Wadhwa et al., 2022). That said, PoW still holds edges in decentralization and security strength, thanks to its random mining that fights against centralization (Bonneau et al., 2015).

Statistical checks found no major gap in latency ($p = 0.0985$), confirming that PoS gains efficiency without hurting network speed. This backs up work by (Kin Chan et al., 2020) and (Syamsuddin et al., 2025), who noted that newer consensus methods can slash energy use while matching PoW's transaction handling.

In summary, the results position PoS as a step forward in consensus design, tackling PoW's energy issues while keeping solid performance.

6. Conclusion, Implication, and Recommendation

6.1 Conclusion

This research finds that the Proof-of-Stake (PoS) algorithm clearly beats Proof-of-Work (PoW) in energy savings, dropping usage by over 94% in matching simulation setups. At the same time, throughput and latency showed small, non-significant differences. These results back PoS as a greener option for blockchain networks without losing operational quality.

6.2 Implications

Theoretically, this work deepens our grasp of blockchain consensus by offering simulation-driven proof. It aligns with the literature's view that PoS can lessen blockchain's environmental harm (Sedlmeir et al., 2020; Truby et al., 2022). Practically, it urges system builders and policymakers to shift to PoS or mixed models for better efficiency and eco-friendliness.

6.3 Recommendations

Future studies could build on this by:

- Adding more consensus types like Delegated Proof-of-Stake (DPoS) or Proof-of-Authority (PoA) to weigh decentralization and security trade-offs.
- Testing varied network setups (different node numbers, transaction loads, and delays) to check stability in complex real-world scenarios.
- Using detailed energy tracking tools to measure power per transaction, for better match with actual blockchain data.
- Blending simulations with testnet trials to merge theory with real deployments.

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