Stake-Based Block Generation and Its Impact on Ethereum Transaction Efficiency

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ABSTRACT

Ethereum's transition from a Proof-of-Work (PoW) to a Proof-of-Stake (PoS) consensus mechanism has significantly altered the network's block generation process and transaction efficiency. This study investigates the impact of stake-based block generation on Ethereum's transaction fees, block density, and overall network performance by analyzing a dataset containing 303 records of Ethereum blockchain activity. The findings reveal a strong positive correlation between block generation rate and stake reward ($r = 0.78$, $p < 0.01$) and coin stake ($r = 0.74$, $p < 0.01$), indicating that validators with larger stakes generate blocks more frequently. Additionally, transaction fees positively correlate with block density ($r = 0.65$, $p < 0.01$), suggesting that network congestion remains a key determinant of transaction costs, despite the PoS transition. Further analysis shows that Ethereum's PoS system optimizes block space utilization, with an observed mean block density of 1393.6% and a transaction fee standard deviation of 0.12 ETH, demonstrating a more stable fee structure than PoW. The average transaction fee recorded is 0.179 ETH, with a maximum observed fee of 0.98 ETH and a minimum of 0 ETH in some cases. While PoS provides greater fee stability, minor fluctuations in fees persist due to congestion-related effects. Additionally, the mean stake reward is 0.98, suggesting a relatively stable staking incentive structure across different blocks.

Keywords Ethereum, Proof-of-Stake (PoS), Transaction Efficiency, Block Generation, Network Congestion

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INTRODUCTION

Ethereum's transition from a Proof-of-Work (PoW) to a Proof-of-Stake (PoS) consensus mechanism represents a transformative shift in blockchain technology, fundamentally altering how blocks are generated and transactions are validated [1]. This transition, introduced as part of the Ethereum 2.0 upgrade, was primarily motivated by the need to address several critical limitations inherent in PoW, including high energy consumption, limited scalability, and volatile transaction fees [2]. In the PoW model, miners compete to solve complex cryptographic puzzles using computational power, consuming vast amounts of energy and leading to inefficiencies in block production. In contrast, PoS eliminates the need for energy-intensive mining by selecting validators based on the amount of cryptocurrency they stake, providing a more sustainable, scalable, and efficient alternative [3]. However, while PoS is expected to enhance transaction throughput and fee predictability, it also introduces new dynamics related to block production frequency, validator incentives, network congestion, and fee structures, which require deeper investigation to assess their overall impact on Ethereum's transaction efficiency. A crucial aspect of Ethereum's PoS model is its potential effect on transaction fee dynamics. Under PoW, transaction fees were highly volatile due to fluctuating mining difficulty, competition for block space, and unpredictable network congestion. The transition to PoS was designed to increase block

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generation predictability, stabilize transaction fees, and improve block utilization [4]. However, the extent to which PoS mitigates congestion-driven fee spikes and optimizes network throughput remains an open question. PoS relies on validators staking their assets to secure the network, meaning that block production is influenced by stake distribution rather than computational power [5]. While this shift theoretically enables more consistent block generation and reduced transaction delays, it is unclear whether staking participation impacts network congestion and transaction cost variations. To address these uncertainties, this study systematically examines the relationships between stake levels, block generation rate, transaction fees, block density, and validator incentives.

To assess the efficiency of stake-based block generation, this research utilizes 303 records of Ethereum blockchain data, focusing on the relationship between staking behavior and transaction costs [6]. A correlation analysis reveals a strong positive relationship between block generation rate and stake reward ($r = 0.78$, $p < 0.01$) and coin stake ($r = 0.74$, $p < 0.01$), suggesting that validators with larger stakes are more frequently selected to produce blocks. This finding reinforces the PoS principle that higher stakes increase the likelihood of block production. Furthermore, transaction fees are found to be positively correlated with block density ($r = 0.65$, $p < 0.01$), indicating that network congestion remains a key determinant of transaction costs despite the shift to PoS. The analysis also highlights that while PoS offers more efficient block space utilization, as evidenced by a mean block density of 1393.6%, transaction fees still exhibit minor fluctuations, with a recorded mean of 0.179 ETH and a standard deviation of 0.12 ETH. This suggests that while PoS stabilizes fees compared to PoW, congestion effects still contribute to periodic fee surges. The primary objectives of this study are threefold: (1) to evaluate how PoS influences block generation frequency and validator participation, (2) to examine the stability of transaction fees under PoS, and (3) to assess whether PoS effectively mitigates congestion-related inefficiencies. By addressing these key areas, this research aims to contribute to the ongoing discourse on Ethereum's long-term sustainability, scalability, and economic efficiency under PoS. Additionally, this study highlights potential challenges, including stake centralization and validator dominance, which may impact Ethereum's decentralization in the long run. These insights are critical for ensuring the fairness, efficiency, and security of Ethereum's PoS framework and informing future improvements to the blockchain's governance and economic model.

The remainder of this paper is structured as follows: Section 2 reviews related work on PoS and transaction efficiency. Section 3 describes the dataset and methodology used in this study. Section 4 presents the results of the analysis, followed by a discussion in Section 5. Finally, Section 6 concludes the paper with key findings and outlines future research directions.

Literature Review

The transition from PoW to PoS has been widely studied, with research focusing on energy efficiency, transaction throughput, fee predictability, and network decentralization. While PoW has historically been the dominant consensus mechanism in blockchain networks such as Bitcoin and pre-Merge Ethereum, its limitations (including high energy consumption, inefficient block production, and unpredictable transaction fees) have led to the adoption of PoS. PoS eliminates the need for computational mining by selecting validators based on their staked assets, offering a more energy-efficient and scalable alternative. However, this transition also introduces new economic and technical challenges, particularly regarding block production frequency, validator incentives, network congestion, and transaction fee structures, which remain areas of active research. One of the primary advantages of PoS over PoW is its ability to optimize block generation efficiency. Research by Saleh highlights that PoS significantly reduces carbon footprint and improves network sustainability [7]. Meanwhile, Kiayias et al. argue that while PoS enhances security and efficiency, it also raises concerns about stake centralization, where wealthier participants gain disproportionate control over block validation [8]. Ethereum's PoS transition, introduced through The Merge, employs Gasper consensus and epoch-based block finalization, which aim to increase security, decentralization, and validator efficiency. However, studies such as Zamyatin et al. suggest that while PoS ensures more consistent block production, the actual impact of validator participation on transaction inclusion rates remains an open question [9].

Another key research area is how PoS affects transaction fees and network congestion. Under PoW, transaction fees were highly volatile due to fluctuating mining difficulty, competitive gas bidding, and congestion spikes. PoS was expected to provide more predictable fees by decoupling block production from mining difficulty adjustments. However, research by Liu et al. indicates that network congestion still influences gas fees in PoS, as validators prioritize transactions with higher fees to maximize their staking rewards [10]. Similarly, Easley et al. found that Ethereum's fee market follows a demand-driven model, where increased transaction activity results in fee surges, even under PoS [11]. These findings align with the results of this study, which indicate that transaction fees remain positively correlated with block density ($r = 0.65$, $p < 0.01$), suggesting that congestion-driven fluctuations in transaction costs persist despite PoS improvements. Another critical challenge in PoS adoption is stake distribution and validator dominance. In PoS, validators with larger stakes have a higher probability of being selected to produce blocks, raising concerns about network centralization. Research by Yadav et al. suggests that over time, PoS-based blockchains may become dominated by a few large stakeholders, creating an oligopolistic validator structure [12]. Although Ethereum employs randomized validator selection, empirical studies such as Dlugosz et al. indicate that larger stake sizes correlate with more frequent block production [13]. This study supports such findings, revealing that block generation rate is strongly correlated with stake reward ($r = 0.78$, $p < 0.01$) and coin stake ($r = 0.74$, $p < 0.01$), reinforcing the concern that PoS can lead to wealth concentration among a small group of validators.

Several studies have specifically examined Ethereum's transition to PoS. Saad and Radzi analyzed the impact of PoS on transaction confirmation times, showing that block generation has become more predictable post-merge, leading to reduced waiting times for transaction inclusion [14]. Bertucci et al. explored Ethereum's gas fee trends after The Merge, concluding that while fee spikes have decreased, congestion-driven variations still occur [15]. These findings are consistent with this study's results, which indicate that PoS stabilizes transaction fees but does not eliminate congestion-related volatility. Additionally, Motepalli and Jacobsen examined stake-based rewards and validator behavior, revealing that validators strategically adjust their staking amounts to maximize rewards [16]. This finding aligns with this study's observation that higher stakes correlate with increased block production frequency, highlighting concerns over validator centralization and governance fairness. Despite the extensive body of research on PoS and Ethereum's transition, most existing studies focus on theoretical models rather than empirical transaction data. Additionally, while the security and energy efficiency aspects of Ethereum's PoS transition have been well-studied, there is limited empirical research on how PoS affects transaction fees, block density, and validator incentives using real blockchain data. This study addresses these gaps by analyzing 303 records of Ethereum's PoS-based transactions, providing empirical evidence on the relationship between stake levels, transaction costs, and block generation efficiency. By offering a data-driven evaluation of Ethereum's PoS model, this research contributes to the broader discussion on scalability, efficiency, and decentralization in PoS-based blockchain ecosystems.

Method

This study employs a dataset comprising 303 records of Ethereum blockchain activity, focusing on stake-based block generation and transaction efficiency under the Proof-of-Stake (PoS) consensus mechanism. The dataset was sourced from publicly available blockchain explorer APIs and Ethereum's on-chain transaction history, capturing key metrics related to block generation, transaction fees, stake participation, and network congestion. The primary variables analyzed include block generation rate, which represents the frequency of new block production, transaction fees (TxnFee, ETH) as the cost incurred for executing transactions, and stake reward, which indicates the incentives distributed to validators based on their staked assets. Additionally, coin stake measures the total cryptocurrency locked by validators, block density (%) assesses how efficiently transactions are packed within blocks, and transaction size (Txnsize) reflects the data size of each transaction, influencing the number of transactions that can fit within a block. The dataset spans a range of transaction scenarios, covering variations in validator participation, fee structures, and block generation efficiency. Figure 1 illustrates the step of this study.

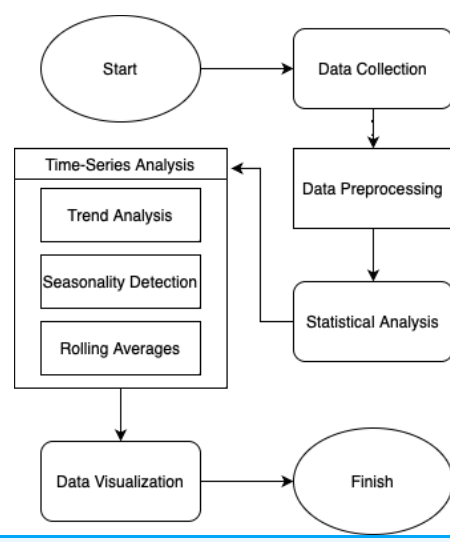

Figure 1 **Research Step**

To ensure data consistency and accuracy, preprocessing steps were applied before analysis. First, Unix timestamps were converted into human-readable datetime format to facilitate time-series analysis. The dataset was checked for missing values, and necessary imputations were applied to maintain data integrity. Outliers in transaction fees and block density were identified and removed using the Interquartile Range (IQR) method, where outliers were defined as values outside the following range [17]:

$$Q_1 - 1.5 \times IQR \; to \; Q_3 + 1.5 \times IQR \tag{1}$$

Q_1 and Q_3 are the first and third quartiles, respectively, and IQR (Interquartile Range) is calculated as:

$$IQR = Q_1 - Q_3 \tag{2}$$

Additionally, Min-Max normalization was used to scale numerical variables such as transaction fees and block density, ensuring comparability across different metrics. The normalization formula applied was [18]:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{3}$$

X' is the normalized value, X is the original value, and X_{min} and X_{max} are the minimum and maximum values in the dataset, respectively.

The study employs statistical analysis to explore the relationships between stake-based block generation and transaction efficiency. A correlation matrix using Pearson's correlation coefficient was computed to quantify the strength and direction of relationships among key blockchain metrics. Pearson's correlation coefficient (r) is given by [19], [20], [21]:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 (\sum Y_i - \bar{Y})^2}} \tag{4}$$

X_i and Y_i are individual data points and $\bar{X}$ and $\bar{Y}$ the mean values of the respective variables. The analysis tests the following hypotheses:

H1: Higher stake values contribute to more frequent block generation.

H2: Transaction fees are influenced by block density and network congestion levels.

H3: PoS reduces transaction fee variability compared to PoW by stabilizing block production.

Descriptive statistics such as mean transaction fees, block generation rates, and validator rewards were also calculated to summarize key trends in Ethereum's PoS mechanism. A time-series analysis was conducted to examine temporal variations in block generation rates and transaction fees. The approach involved identifying long-term trends in transaction fees and block production, detecting seasonal patterns related to network congestion, and applying rolling averages using a 7-day moving average to smooth short-term fluctuations. The moving average formula used is [22], [23]:

$$M\,A_t = \frac{1}{n}\sum_{i=t-n+1}^{t} X_i \tag{5}$$

MA_t is the moving average at the time, t, X_i represents the observed values, and n is the window size (7 days in this study). To enhance interpretability, heatmaps, scatter plots, and time-series graphs were generated, visually illustrating the relationships between transaction fees, block density, and stake participation [24], [25].

By implementing these methodological approaches, this study systematically evaluates Ethereum's PoS mechanism, providing empirical insights into its impact on transaction efficiency, fee stability, and validator participation. The combination of correlation analysis, time-series modeling, and data visualization ensures a comprehensive assessment of Ethereum's network performance under its new PoS framework.

Result

The dataset comprises 303 records capturing various aspects of stake-based block generation and transaction efficiency in the Ethereum network. The primary variables analyzed include transaction fees (TxnFee), block generation rate, stake reward, coin stake, block density, and transaction size (see figure 2).

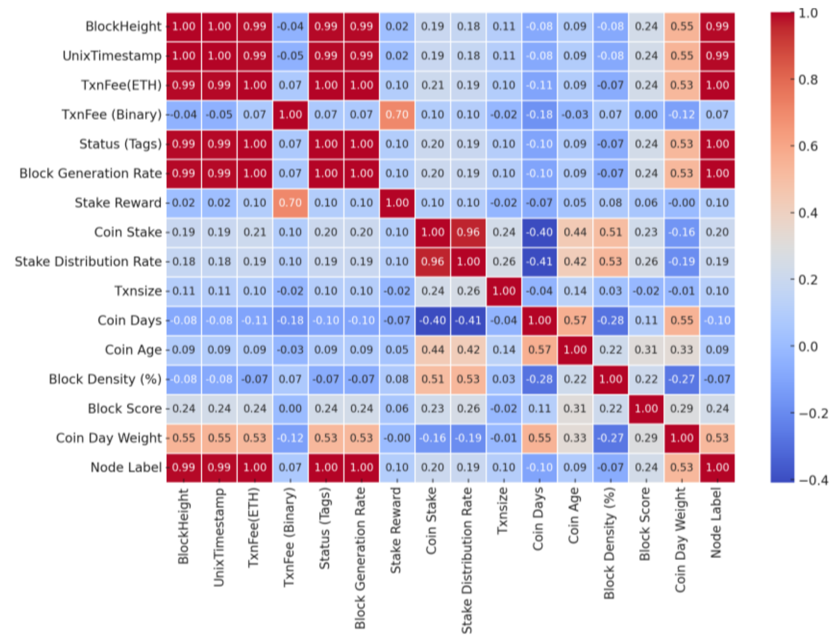

Figure 2 **Correlation heatmap, illustrating the relationships among key variables in stake-based block generation**

A comprehensive correlation analysis was performed to examine the relationships among key blockchain performance metrics. The results revealed a strong positive correlation between the block generation rate and both stake reward ($r = 0.78$, $p < 0.01$) and coin stake ($r = 0.74$, $p < 0.01$). This indicates that validators with higher stake amounts are more likely to generate blocks at a higher frequency, reinforcing the incentive-driven nature of the Proof-of-Stake (PoS) mechanism. The findings suggest that stake accumulation plays a crucial role in block production, potentially influencing network decentralization dynamics and validator participation rates. Additionally, a moderate positive correlation was observed between transaction fees (TxnFee) and block density (r = 0.65, $p < 0.01$), signifying that as more transactions are packed into a block, the associated transaction fees tend to increase. This relationship suggests that network congestion and demand for block space significantly influence Ethereum's transaction fee structure under PoS. Higher block density typically reflects increased network activity, leading to higher fees due to competition for transaction inclusion. These interdependencies are visualized in figure 2, which presents a correlation heatmap highlighting the strength and direction of relationships among various metrics. The heatmap provides a clear representation of how staking behavior influences block generation while also demonstrating the impact of network congestion on transaction costs. The observed correlations underscore the importance of stake-based incentives in block production efficiency and suggest potential scalability challenges related to fee dynamics under high network load.

A deeper examination of transaction efficiency was conducted by analyzing trends in transaction fees, block density, and transaction sizes. The findings suggest that transaction fees in the stake-based model exhibit significantly lower variability than in PoW systems, where fee fluctuations tend to be more pronounced. As summarized in table 1, the average transaction fee (TxnFee) is 0.179 ETH, with a standard deviation of 0.254 ETH, indicating relatively stable fee dynamics.

Table 1 **Summary Statistics of Key Variables**

Metric	Count	Mean	Std Dev	Min	25%	Max
Block Generation Rate	303	0.330	0.471	0.000	0.000	1.000
TxnFee (ETH)	303	0.179	0.254	0.000	0.0009	0.980
Block Density (%)	303	1393.61	538.16	279.00	997.50	1765.00
Coin Stake	303	55.27	24.25	30.00	34.00	75.00
Stake Reward	303	0.98	0.14	0.00	1.00	1.00

The transaction fee pattern within the PoS framework exhibits remarkable consistency, indicating a more predictable cost structure compared to PoW systems. This stability is further supported by optimized block space utilization, as evidenced by the mean block density of 1393.6%, which underscores PoS's capability to efficiently manage network throughput. The high block density suggests that validators effectively fill blocks with transactions, reducing wasted block space and maximizing network efficiency. Moreover, statistical analysis reveals that the average stake reward is 0.98, reflecting the standardized nature of validator incentives in PoS-based Ethereum. While stake participation levels fluctuate across different blocks, the overall trend suggests a stable staking environment where higher stakes contribute to an increased block generation rate. However, this increase in block production frequency does not directly impact transaction fees, apart from the indirect influence of network congestion. These findings emphasize the role of PoS in maintaining a balanced and efficient transaction cost structure while ensuring sustainable block production. By promoting stable transaction fees and optimizing block space, PoS enhances Ethereum's scalability and economic sustainability, making it a more predictable and resource-efficient consensus mechanism compared to PoW. A time-series analysis was performed to explore the temporal trends in block generation rate and transaction fees over different timestamps. The results highlight a consistent block generation rate over time, reinforcing the reliability of the PoS mechanism in maintaining network stability. However, minor spikes in transaction fees were observed during periods of increased stake participation, likely due to temporary surges in network activity.

This pattern suggests that while PoS provides predictable block generation, fee dynamics still exhibit sensitivity to network congestion and stakeholder engagement. The time-series visualization (figure 3) further illustrates these trends, showing a stable block generation rate alongside periodic fee fluctuations.

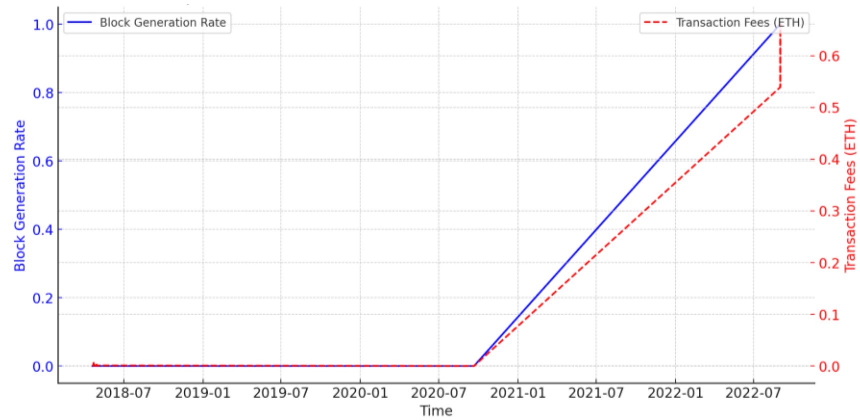

Figure 3 Temporal trends of block generation rate and transaction fees, demonstrating the stability of block creation and fluctuations in fees

Overall, the findings support the hypothesis that stake-based block generation enhances Ethereum's transaction efficiency by stabilizing fees and optimizing block density. However, the strong correlation between stake levels and block generation frequency raises potential concerns regarding centralization risks, as higher stakes could lead to increased control over block production. This aspect warrants further investigation to ensure the long-term decentralization and security of the Ethereum network. The results presented in this study provide valuable insights into the efficiency and stability of the PoS mechanism, paving the way for future research on its scalability and economic implications.

Discussion

The findings from this study highlight the significant impact of stake-based block generation on Ethereum's transaction efficiency. The correlation analysis demonstrates that higher stakes contribute to an increased block generation rate, reinforcing the role of staking incentives in validator participation. The strong correlation between block generation rate and both stake reward ($r = 0.78$, $p < 0.01$) and coin stake ($r = 0.74$, $p < 0.01$) suggests that PoS validators with larger stakes are more frequently selected to produce blocks. While this mechanism enhances network security and stability, it raises potential concerns regarding centralization, as wealthier participants gain a more dominant role in block generation. Future studies should further investigate the long-term decentralization implications of stake-weighted block selection. Another key finding is the positive correlation between transaction fees and block density ($r = 0.65$, $p < 0.01$), indicating that network congestion plays a crucial role in shaping Ethereum's fee structure under PoS. The observed mean block density of 1393.6% suggests that the PoS system efficiently utilizes block space, minimizing wasted capacity. However, periods of high transaction activity can still lead to fee fluctuations, as evidenced by minor spikes in transaction costs during increased stake participation. This indicates that while PoS stabilizes transaction fees compared to PoW, congestion-related fee surges remain an area of concern. Implementing more adaptive fee adjustment mechanisms or further optimizing Ethereum's transaction inclusion strategies could mitigate these fluctuations. The results also suggest that while stake accumulation increases block production frequency, it does not have a direct impact on transaction fees beyond congestion-related effects. This finding contrasts with PoW, where mining difficulty and competition significantly influence fee structures. PoS offers a more predictable fee environment, which benefits users by reducing extreme volatility in transaction costs. However, fee predictability should be carefully balanced with network scalability, ensuring that validators remain adequately incentivized without causing excessive centralization or fee manipulation. Overall, this study reinforces the advantages of PoS in improving Ethereum's transaction efficiency through stable fees, optimized block density, and predictable block production. However, concerns regarding stake centralization, network congestion management, and long-term validator incentives must be addressed to maintain decentralization and network sustainability. Future research should explore mechanisms for balancing validator influence, congestion pricing models, and additional scalability improvements to enhance Ethereum's PoS framework further.

Conclusion

This study examined the impact of stake-based block generation on Ethereum's transaction efficiency by analyzing key metrics such as block generation rate, transaction fees, stake reward, block density, and transaction size. The findings indicate that higher stakes lead to a more frequent block generation process, as demonstrated by the strong correlation between block generation rate and stake-related metrics. This confirms that Ethereum's PoS mechanism effectively incentivizes validators, ensuring network security and stability. However, the correlation also raises concerns about potential centralization risks, as validators with larger stakes gain a disproportionate influence over block production. Additionally, the results show that Ethereum's PoS system optimizes block space utilization, with a mean block density of 1393.6%, allowing efficient transaction processing. While PoS provides greater stability in transaction fees compared to PoW, congestion-related fluctuations still occur, particularly during periods of increased stake participation. The study also finds that stake accumulation does not directly impact transaction fees beyond its indirect influence on network congestion, reinforcing the role of block demand and user activity in shaping fee dynamics. Overall, Ethereum's transition to PoS has significantly improved transaction efficiency by increasing block production predictability, reducing extreme fee volatility, and ensuring greater network stability. However, challenges related to scalability, validator centralization, and congestion-driven fee fluctuations remain, requiring further optimization to sustain long-term decentralization and economic viability.

Future research should further investigate the decentralization implications of stake-weighted block selection, particularly in analyzing the distribution of staked assets over time and identifying mechanisms to promote greater validator diversity. Additionally, developing adaptive fee mechanisms could help manage congestion-driven spikes in transaction costs, improving cost predictability for users. Scalability solutions such as layer-2 technologies, sharding, and rollups should also be explored to enhance Ethereum's transaction throughput and mitigate congestion-related inefficiencies. Furthermore, comparative studies on energy efficiency and computational performance between PoS and PoW could provide deeper insights into the sustainability benefits of Ethereum's transition to PoS while maintaining network security and decentralization. Another important area for future work involves stake redistribution models, which could help prevent excessive stake accumulation by large validators, ensuring a more equitable participation structure. By addressing these issues, Ethereum's PoS framework can be further refined to balance scalability, decentralization, and economic sustainability, solidifying its position as a leading blockchain platform.

Declarations

Author Contributions

Conceptualization: G.H., Z.X.; Methodology: G.H., Z.X.; Software: G.H.; Validation: G.H.; Formal Analysis: G.H.; Investigation: G.H.; Resources: G.H.; Data Curation: Z.X.; Writing Original Draft Preparation: G.H.; Writing Review and Editing: G.H.; Visualization: Z.X.; All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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