BIS Economics and Business
Volume 2 2025 | DOI: 10.31603/biseb.233
6th Borobudur International Symposium on Humanities and Social Science (BIS-HSS) 2024
UNIMMA PRESS
Universitas Muhammadiyah Magelang

Exploring sustainability in cryptocurrency protocols: environmental insights from PoW to PoS

Fuad Hasyim[1,2], Adelia Nur Hapsari[1*], Budi Sukardi[1], Waluyo[1], Luki Sri Anggorowati[3,4]

[1] UIN Raden Mas Said, Surakarta, Indonesia
[2] Universitas Airlangga, Surabaya, Indonesia
[3] Universitas Boyolali, Boyolali, Indonesia
[4] Universitas Muhammadiyah Surakarta, Surakarta. Indonesia
[*]Corresponding author email: adelianur90@gmail.com

Abstract

Cryptocurrency mining, especially Bitcoin's Proof of Work (PoW), significantly impacts the environment through high energy consumption, carbon footprint, and e-waste. Ethereum's adoption of Proof of Stake (PoS) in 2022 offers a potential solution to reduce these effects. This study compares the environmental impacts of PoW and PoS, focusing on energy consumption, mining efficiency, hash rate, and carbon footprint. Using regression analysis and t-tests on data from Bitcoin (PoW) and Ethereum (before and after PoS) from 2017 to 2024, the results show that PoS significantly reduces energy consumption, carbon footprint, and e-waste, while improving mining efficiency. The findings highlight that transitioning to PoS can mitigate the environmental impact of cryptocurrency mining and encourage its broader adoption to align with global sustainability goals.

Keywords

Cryptocurrency, Sustainability, Proof-of-work, Proof-of-stake, Carbon footprint

Introduction

Cryptocurrency mining has become a major global industry, and with its rapid growth, its environmental impacts have become a significant concern. Traditional Proof of Work (PoW) consensus mechanisms, such as those used in Bitcoin, are known to be energy-intensive, resulting in a substantial carbon footprint and significant electronic waste (e-waste) due to the high computational power required [7, 21, 23]. Mining operations under PoW consume massive amounts of electricity to solve complex mathematical puzzles, leading to increased greenhouse gas emissions and environmental degradation [11, 30]. In response, alternative consensus mechanisms like Proof of Stake (PoS), adopted by Ethereum in 2022, have emerged as potential solutions to reduce these environmental impacts [1, 10]. PoS consumes far less energy, as it eliminates the need

Published:
May 2, 2025

Selection and Peer-review under the responsibility of the 6th BIS-HSS 2024 Committee

for energy-intensive mining equipment and instead relies on staking to validate transactions [3, 13, 25]. However, while PoS promises environmental benefits, its practical implications in terms of energy use and environmental sustainability need further investigation, particularly in comparison to PoW [22, 23].

This study aims to address the gap in understanding the environmental implications of different consensus mechanisms used in blockchain technologies. Specifically, it investigates the differences between PoW and PoS in their effects on energy consumption, mining efficiency, carbon footprint, and e-waste. Previous studies have highlighted the energy consumption associated with PoW mining and its environmental costs, but there is limited research on how the transition to PoS impacts these environmental factors [1, 10, 26, 30]. This research focuses on analyzing the role of energy consumption and mining efficiency in shaping the environmental impact of cryptocurrency mining, particularly in the context of Ethereum's shift from PoW to PoS. By comparing these two consensus mechanisms, the study aims to offer a clearer understanding of the potential benefits and trade-offs associated with transitioning to more sustainable blockchain technologies.

The findings of this study have important implications for both the cryptocurrency industry and policymakers concerned with sustainability. The research will provide critical insights into how PoS can offer significant reductions in carbon footprint and e-waste compared to PoW, thus supporting a more sustainable future for blockchain technologies. Furthermore, this study will help inform decisions on regulatory frameworks and mining practices, encouraging the adoption of energy-efficient technologies and consensus mechanisms across the cryptocurrency ecosystem. By understanding the environmental implications of blockchain mining, stakeholders can take proactive steps toward reducing the ecological footprint of this growing industry [22, 30].

Method

This study analyzes the environmental impact of crypto mining, focusing on carbon footprint and e-waste from May 20, 2017 to October 26, 2024. It uses data from CBECI, Digiconomist, and Blockchain.com, employing two statistical models [5]. The first model uses panel regression to assess how independent variable influence the carbon footprint of Bitcoin and Ethereum. The equation is:

$$carbon\_footprint_{i,t} = \beta_0 + \beta_1\, energy\_consumption_{i,t} + \beta_2\, mining\_efficiency_{i,t} + \beta_3\, hash\_rate_{i,t} + \beta_4 consensus_{i,t} + \alpha_i + \gamma_t + \epsilon_{i,t} \quad \dots (1)$$

An independent t-test compares Bitcoin and Ethereum from September 15, 2022 to October 26, 2024 for energy consumption, mining efficiency, and hash rate. A paired sample t-test examines changes in these variables for Ethereum before and after September 15, 2022 [8]. Furthermore, the second model uses linear regression to analyze how independent variable influence Bitcoin mining e-waste [5, 8]. This approach aims to identify factors influencing carbon footprint and e-waste, providing insights into the environmental impact of PoW and PoS protocols. The equation is:

$$e_{waste} = \beta_0 + \beta_1\, energy_{consumption} + \beta_2\, mining_{efficiency} + \beta_3\, hash\_rate + \beta_4 consensus + \in \quad \ldots (2)$$

Results and Discussion

The regression analysis using the fixed effects model 1 (Table 1) demonstrates significant impacts of energy consumption, mining efficiency, hash rate, and a dummy variable on the carbon footprint. A coefficient of 0.751207 for energy consumption indicates that each unit increase in energy consumption leads to a 0.751207 unit rise in carbon emissions, consistent with prior research [17, 23, 28]. Mining efficiency has a negative coefficient of -2.15E-06, suggesting that decreased efficiency correlates with increased carbon emissions, aligning with Morrell's findings on the importance of efficiency [15]. The hash rate shows a positive coefficient of 3.56E-08, indicating that higher hash rates are associated with increased emissions, confirming literature conclusions [11, 17]. Lastly, the dummy variable reflects significant effects (15.13118), highlighting that changes in consensus protocols can notably reduce environmental impact [3, 6].

Table 1. Model 1

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	2.33367	0.37413	6.23756	0.0000
Energy Consumption	0.75121	0.00540	139.23890	0.0000
Mining Efficiency	-2.15E-06	1.30E-07	-16.56853	0.0000
Hash Rate	3.56E-08	1.57E-09	22.73014	0.0000
Dummy Consensus	15.13118	0.528257	28.64362	0.0000

The independent samples t-test (Table 2) reveals significant differences in key environmental and operational metrics between Bitcoin and Ethereum from September 15, 2022, to October 26, 2024. During this period, Bitcoin continued using Proof of Work (PoW), while Ethereum transitioned to Proof of Stake (PoS) post-merge. Bitcoin's average carbon footprint is 131.0947 MtCO2e, compared to Ethereum's 0.0020 MtCO2e ($t = 120.053$, $p = 0.000$). In terms of energy consumption, Bitcoin averages 131.0947 TWh, while Ethereum uses only 0.0086 TWh ($t = 120.047$, $p = 0.000$). Bitcoin's mining efficiency is 286.7117 J/TH versus Ethereum's 0 J/TH ($t = 65.585$, $p = 0.000$), and Bitcoin's hash rate (448,002,642.3380 TH/s) far exceeds Ethereum's (0 TH/s) ($t = 88.209$, $p = 0.000$). These results confirm that Ethereum's transition from PoW to PoS dramatically reduced its energy consumption and hash rate (Figure 1), consistent with recent studies on blockchain technology's environmental impacts [2, 3, 6].

Table 2. Independent sample t-test

	Consensus	N	Mean	Levene's Test for Equality of Variances		t-test for Equality of Means		
				F	Sig.	t	df	Sig.
Carbon footprint	Bitcoin	772	131.0947	2149.00	0.000	120.053	1542	0.000
	Ethereum	772	0.002			120.053	771	0.000
Energy consumption	Bitcoin	772	131.0947	2148.44	0.000	120.047	1542	0.000
	Ethereum	772	0.0086			120.047	771	0.000
Mining efficiency	Bitcoin	772	286.7117	1079.27	0.000	65.585	1542	0.000
	Ethereum	772	0			65.585	771	0.000
Hash rate	Bitcoin	772	4.48E+08	3170.91	0.000	88.209	1542	0.000
	Ethereum	772	0			88.209	771	0.000

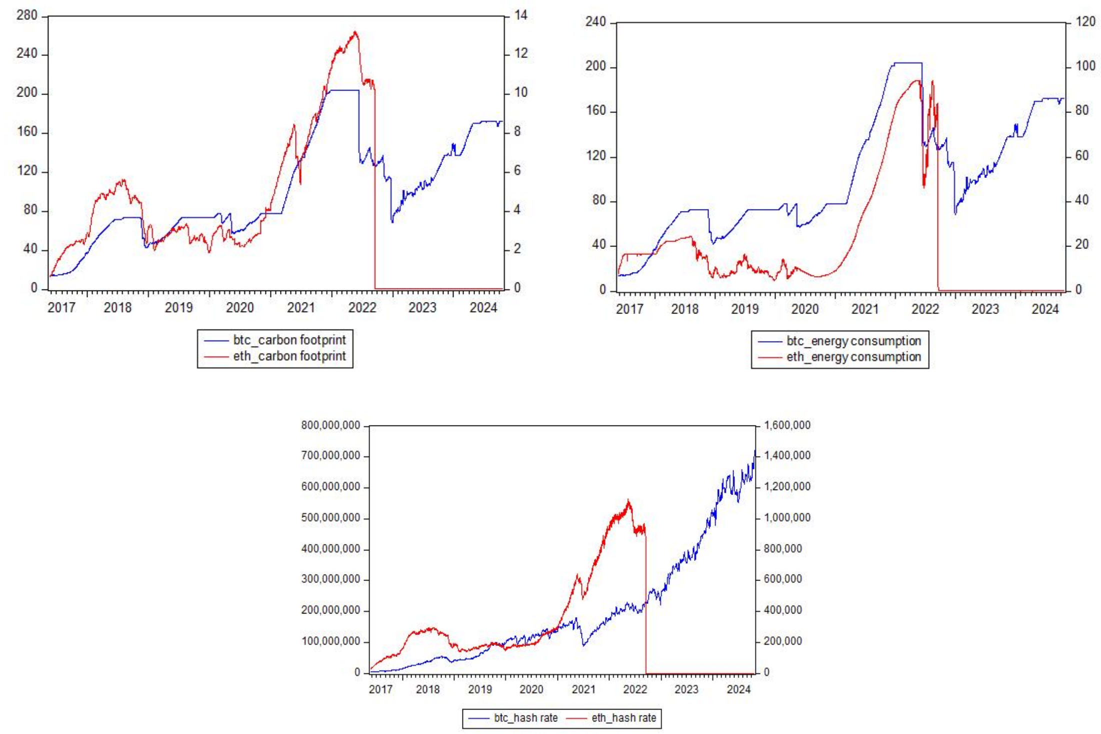

Figure 1. Comparison between Bitcoin and Ethereum

The paired sample t-test (Table 3) evaluated the significant changes in Ethereum's environmental impact and operational parameters during its transition from Proof of Work (PoW) to Proof of Stake (PoS). Results show substantial reductions in all variables post-transition. Carbon footprint decreased from 8.2113 MtCO2e (PoW) to 0.002 MtCO2e (PoS) ($t = 67.573$, $p = 0.000$). Energy consumption fell from 47.5971 TWh to 0.0086 TWh ($t = 40.908$, $p = 0.000$). Mining efficiency dropped from 501.4254 J/TH to 0 J/TH ($t = 387.438$, $p = 0.000$), and hash rate decreased from 664,078,894.6 TH/s to 0 TH/s ($t = 63.239$, $p = 0.000$). These findings underscore the significant environmental benefits of Ethereum's shift to PoS, drastically reducing its carbon footprint, energy consumption, mining efficiency, and hash rate (Figure 2) [3, 6, 15, 22].

Table 3. Paired Samples Test

		Mean	N	Paired Differences Mean	Paired Differences Std. Dev.	t	Sig.
Pair 1	PoW_carbon_footprint	8.2113	772	8.20937	3.37555	67.573	0.000
	PoS_carbon_footprint	0.002	772				
Pair 2	PoW_carbon_footprint	47.5971	772	47.58846	32.32258	40.908	0.000
	PoS_carbon_footprint	0.0086	772				
Pair 3	PoW_carbon_footprint	501.4254	772	501.4254	35.95943	387.438	0.000
	PoS_carbon_footprint	0.000	772				
Pair 4	PoW_carbon_footprint	664078.8946	772	664078.9	291771.8	63.239	0.000
	PoS_carbon_footprint	0.000	772				

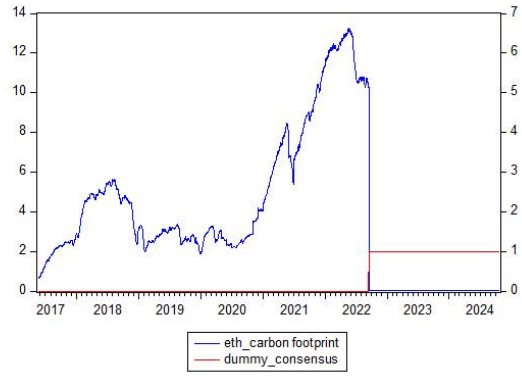

Figure 2. Comparison between PoS and PoW

The regression analysis (Model 2) in Table 4 unveils the significant impact of key operational parameters on electronic waste generation in cryptocurrency mining. This model examines how various aspects of the mining process contribute to the production of e-waste, shedding light on the environmental consequences of different mining practices. Energy consumption positively influences e-waste production, with a coefficient of 0.1504, indicating that higher energy use leads to more e-waste, consistent with previous studies [23, 25, 26, 30]. Mining efficiency negatively impacts e-waste (coefficient -3.51E-06), suggesting that improved efficiency reduces e-waste, aligning with Morrell's findings [12, 15, 24]. Hash rate also positively affects e-waste generation (coefficient 1.63E-07), indicating that greater computational power contributes to increased e-waste, as noted in the literature [9, 14, 22]. These findings underscore the need for enhanced mining efficiency and a shift to sustainable consensus mechanisms like Proof of Stake (PoS) to mitigate the environmental impact of cryptocurrency mining.

Table 4. Model 2

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	37.54044	0.566968	66.21264	0.000
Energy_Consumption	0.1504	0.005618	26.77219	0.000
Mining_Efficiency	-3.51E-06	1.17E-07	-29.9428	0.000
Hash_Rate	1.63E-07	1.45E-09	112.4749	0.000

The analysis reveals a significant relationship between energy consumption, mining efficiency, and hash rate with the environmental impact of cryptocurrency mining, particularly in terms of carbon footprint and e-waste [23, 26, 30]. It is evident that energy consumption plays a critical role in increasing the environmental burden, as higher energy consumption correlates with a larger carbon footprint and more e-waste. This finding aligns with existing literature that identifies energy consumption as a key determinant of environmental damage in blockchain technologies [3, 4, 16, 18, 20, 29, 30]. On the other hand, mining efficiency is shown to mitigate this effect, where improved efficiency in mining processes leads to a reduction in both emissions and waste generation. This supports the notion that more efficient mining technologies can reduce the environmental impact of cryptocurrencies [3, 4, 15, 27]. In contrast, hash rate, although necessary for computational power, has a direct positive effect on the environmental impact, indicating that higher computational demands result in more energy usage and, consequently, more e-waste and carbon emissions. This reinforces the findings of Zhang et al, who suggest that increased hash rate contributes to greater energy consumption and, in turn, worsens environmental outcomes [30].

The shift from Proof of Work (PoW) to Proof of Stake (PoS) presents a potential solution to reduce these environmental impacts significantly [15, 22]. The transition to PoS offers substantial reductions in energy consumption, e-waste, and carbon emissions, highlighting its advantages over the energy-intensive PoW mechanism. This is consistent with the work of Baur & Karlsen, who argue that PoS mechanisms are more energy-efficient and environmentally friendly compared to PoW [6]. These results point to the broader implications of transitioning to more sustainable consensus mechanisms for blockchain networks. In practice, adopting PoS could not only improve the energy efficiency of cryptocurrency mining but also reduce the environmental harm associated with excessive electronic waste generation [3, 6, 11, 15]. This transition is crucial for the cryptocurrency industry, as it seeks to align with global sustainability goals and mitigate its contribution to climate change and electronic waste accumulation [3, 6, 10, 26, 27]. Further studies emphasize that blockchain systems moving to PoS will significantly lessen their ecological footprint, offering long-term sustainability benefits for the industry [3, 19].

Conclusion

This study demonstrates that Proof of Work (PoW) significantly contributes to higher energy consumption, carbon footprint, and e-waste compared to Proof of Stake (PoS). The transition to PoS offers a more sustainable solution by reducing energy usage and environmental impact. The findings emphasize the importance of improving mining efficiency and adopting PoS as an eco-friendlier alternative in cryptocurrency mining. Theoretically, this study contributes to the understanding of the environmental implications of blockchain technologies, highlighting the benefits of PoS in mitigating environmental damage. Practically, it offers actionable insights for cryptocurrency mining operations, policymakers, and developers to promote sustainable mining practices by transitioning to PoS and enhancing mining efficiency to reduce environmental harm. Future research should assess the long-term impacts of PoS on blockchain performance and sustainability. The cryptocurrency industry should focus on energy-efficient mining technologies and implement governance frameworks that promote sustainability, aligning the sector with global environmental goals.

References

1. Ahn, J. et al.: Blockchain Consensus Mechanisms: A Bibliometric Analysis (2014–2024) Using VOSviewer and R Bibliometrix. Information. 15, 10, (2024). https://doi.org/10.3390/info15100644.
2. Almeida, D. et al.: Information flow dynamics between cryptocurrency returns and electricity consumption: A comparative analysis of Bitcoin and Ethereum. Financ Res Lett. 68, 105997 (2024). https://doi.org/https://doi.org/10.1016/j.frl.2024.105997.
3. Alzoubi, Y.I., Mishra, A.: Green blockchain – A move towards sustainability. J Clean Prod. 430, 139541 (2023). https://doi.org/https://doi.org/10.1016/j.jclepro.2023.139541.
4. Anandhabalaji, V. et al.: Energy consumption by cryptocurrency: A bibliometric analysis revealing research trends and insights. Energy Nexus. 13, 100274 (2024). https://doi.org/https://doi.org/10.1016/j.nexus.2024.100274.
5. Asteriou, D., Hall, S.G.: Applied econometrics. Bloomsbury Publishing (2021).
6. Baur, D.G., Karlsen, J.R.: Do crypto investors care about energy use and climate change? Evidence from Ethereum's transition to proof-of-stake. J Environ Manage. 369, 122299 (2024). https://doi.org/https://doi.org/10.1016/j.jenvman.2024.122299.
7. Ghazouani, I. et al.: Powering perception, echoing green voices: The interplay of Cryptocurrency's energy footprint and environmental discourse in steering the direction of the market. Borsa Istanbul Review. (2024). https://doi.org/https://doi.org/10.1016/j.bir.2024.12.020.
8. Gujarati, D.N.: Gujarati: Basic Econometrics, Fourth Edition. (2004).
9. Jain, M. et al.: Review on E-waste management and its impact on the environment and society. Waste Management Bulletin. 1, 3, 34–44 (2023). https://doi.org/https://doi.org/10.1016/j.wmb.2023.06.004.
10. Kapengut, E., Mizrach, B.: An Event Study of the Ethereum Transition to Proof-of-Stake. Commodities. 2, 2, 96–110 (2023). https://doi.org/10.3390/commodities2020006.
11. Kohli, V. et al.: An analysis of energy consumption and carbon footprints of cryptocurrencies and possible solutions. Digital Communications and Networks. 9, 1, 79–89 (2023). https://doi.org/https://doi.org/10.1016/j.dcan.2022.06.017.
12. Kumari, P. et al.: The changing dynamics of crypto mining and environmental impact. International Review of Economics & Finance. 89, 940–953 (2024). https://doi.org/https://doi.org/10.1016/j.iref.2023.08.004.
13. Li, C. et al.: The optimal asset trading settlement based on Proof-of-Stake blockchains. Decis Support Syst. 166, 113909 (2023). https://doi.org/https://doi.org/10.1016/j.dss.2022.113909.
14. Liu, K. et al.: A global perspective on e-waste recycling. Circular Economy. 2, 1, 100028 (2023). https://doi.org/https://doi.org/10.1016/j.cec.2023.100028.
15. Morrell, S.: Helping to reduce mining industry carbon emissions: A step-by-step guide to sizing and selection of energy efficient high pressure grinding rolls circuits. Miner Eng. 179, 107431 (2022). https://doi.org/https://doi.org/10.1016/j.mineng.2022.107431.
16. Mulligan, C. et al.: Blockchain for sustainability: A systematic literature review for policy impact. Telecomm Policy. 48, 2, 102676 (2024). https://doi.org/https://doi.org/10.1016/j.telpol.2023.102676.
17. Papp, A. et al.: Bitcoin and carbon dioxide emissions: Evidence from daily production decisions. J Public Econ. 227, 105003 (2023). https://doi.org/https://doi.org/10.1016/j.jpubeco.2023.105003.
18. Qin, M. et al.: Are energy consumption and carbon emission caused by Bitcoin? A novel time-varying technique. Econ Anal Policy. 80, 109–120 (2023). https://doi.org/https://doi.org/10.1016/j.eap.2023.08.004.
19. Rani, P. et al.: Toward a greener future: A survey on sustainable blockchain applications and impact. J Environ Manage. 354, 120273 (2024). https://doi.org/https://doi.org/10.1016/j.jenvman.2024.120273.
20. Sai, A.R., Vranken, H.: Promoting rigor in blockchain energy and environmental footprint research: A systematic literature review. Blockchain: Research and Applications. 5, 1, 100169 (2024). https://doi.org/https://doi.org/10.1016/j.bcra.2023.100169.
21. Sapra, N. et al.: Impact of Proof of Work (PoW)-Based Blockchain Applications on the Environment: A Systematic Review and Research Agenda, (2023). https://doi.org/10.3390/jrfm16040218.
22. Sapra, N. et al.: Impact of Proof of Work (PoW)-Based Blockchain Applications on the Environment:

A Systematic Review and Research Agenda. Journal of Risk and Financial Management. 16, 4, (2023). https://doi.org/10.3390/jrfm16040218.

23. Sarkodie, S.A. et al.: Assessment of Bitcoin carbon footprint. Sustainable Horizons. 7, 100060 (2023). https://doi.org/https://doi.org/10.1016/j.horiz.2023.100060.
24. Siddik, M.A.B. et al.: The water and carbon footprint of cryptocurrencies and conventional currencies. J Clean Prod. 411, 137268 (2023). https://doi.org/https://doi.org/10.1016/j.jclepro.2023.137268.
25. De Vries, A.: Cryptocurrencies on the road to sustainability: Ethereum paving the way for Bitcoin. Patterns. 4, 1, 100633 (2023). https://doi.org/https://doi.org/10.1016/j.patter.2022.100633.
26. de Vries, A., Stoll, C.: Bitcoin's growing e-waste problem. Resour Conserv Recycl. 175, 105901 (2021). https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105901.
27. Wendl, M. et al.: The environmental impact of cryptocurrencies using proof of work and proof of stake consensus algorithms: A systematic review. J Environ Manage. 326, 116530 (2023). https://doi.org/https://doi.org/10.1016/j.jenvman.2022.116530.
28. Xiao, Z. et al.: The environmental cost of cryptocurrency: Assessing carbon emissions from bitcoin mining in China. Journal of Digital Economy. 2, 119–136 (2023). https://doi.org/https://doi.org/10.1016/j.jdec.2023.11.001.
29. Yang, Z. et al.: Blockchain technology in building environmental sustainability: A systematic literature review and future perspectives. Build Environ. 245, 110970 (2023). https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110970.
30. Zhang, D. et al.: Implications of cryptocurrency energy usage on climate change. Technol Forecast Soc Change. 187, 122219 (2023). https://doi.org/https://doi.org/10.1016/j.techfore.2022.122219.