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SUSTAINABILITY CHALLENGES OF THE ETHEREUM NETWORK: POWER DEMAND, EMISSIONS AND ECONOMIC IMPLICATION

Vladimir Pavićević
College of Applied Economic Studies, Belgrade, Serbia

e-mail: vladimirvpavicevic@gmail.com
https://orcid.org/0000-0003-4848-6380

Suzana Balaban
Alfa BK University, Belgrade, Serbia

e-mail: suzana.balaban@alfa.edu.rs
https://orcid.org/0000-0001-8132-9120

Bojan Stoiljković
Alfa BK University, Belgrade, Serbia

e-mail: bojan.stoiljkovic@alfa.edu.rs
https://orcid.org/0000-0003-2796-8663

Aleksandar Rašović
Department for Local Public Revenues, Podgorica, Montenegro

e-mail: aco@eusky.net
https://orcid.org/0009-0006-7195-9966

Abstract: The Ethereum network, a leading blockchain platform for decentralized applications and smart contracts, has undergone significant transformations, particularly with the transition from Proof of Work (PoW) to Proof of Stake (PoS). This paper examines the sustainability challenges of Ethereum with a focus on its historical and current power consumption, associated carbon emissions, and broader economic implications. By critically analyzing Ethereum's environmental footprint pre- and post-Merge, we assess whether the network's shift to Proof of Stake constitutes a sustainable solution. Furthermore, we explore the trade-offs inherent in the decentrali-

zation-efficiency paradigm and consider Ethereum's position within the global movement toward greener technologies.

Key words: *Ethereum, blockchain, Proof of Stake (PoS), Proof of Work (PoW), sustainability, energy consumption, carbon emissions, decentralization, staking.*

1. INTRODUCTION

Ethereum is a decentralized, open-source blockchain platform that enables the development and execution of smart contracts and decentralized applications (dApps) without the need for centralized intermediaries. Proposed by Vitalik Buterin in late 2013 and launched in 2015, Ethereum extends the functionality of earlier blockchain systems, such as Bitcoin. It can be seen from its development that Ethereum was not created primarily as a cryptocurrency; on the contrary, it is much more focused on general and decentralized functionalities (Huang, 2023). This innovation allows developers to write and deploy self-executing code that can facilitate complex contractual agreements across a wide range of industries, including finance, supply chain management, healthcare, and governance.

One of the fundamental features of the Ethereum blockchain is that it is permissionless. This means that no single party has special privileges to add blocks to the chain. Instead, the ability to add blocks is distributed among many participants, who are selected randomly. At regular time intervals, Ethereum chooses one participant to act as the block proposers and several others to act as attesters. The proposer is the only one allowed to suggest a new block for that specific time slot. However, whether the proposed block becomes part of the blockchain depends on whether enough attesters approve it (John et al., 2025).

The growing popularity of blockchain technology has prompted scrutiny over its environmental and economic impacts. The exponential growth of cryptocurrency mining and crypto-trade, and the development and spread of modern technologies, as well as the rapid changes in the technological needs of human beings, have faced the existential problem of environmental sustainability and the impact of CO_2 emissions in the leading countries where cryptocurrency is mined and crypto-currency traded (Pavićević, 2023).

Using data from nearly 900 million blockchain transactions, authors found that the gas price is statistically significantly positively associated with the block utilization rate (Karaivanov, A., & Zarifian, S. 2024).

The native cryptocurrency of the Ethereum network, Ether (ETH), serves both as a digital currency and as a means of compensation for participants who perform computations and validate transactions. Unlike traditional centralized computing models, Ethereum's consensus is maintained through a distributed network of nodes, initially using Proof of Work (PoW) and, as of the 2022 "Merge" upgrade, transitioning to a more energy-efficient Proof of Stake (PoS) mechanism. This transition marks a significant milestone in blockchain scalability, sustainability, and security. Ethereum has played a significant role in the growth of the decentralized finance (DeFi) ecosystem and the emergence of non-fungible tokens (NFTs), contributing to the broader adoption of blockchain technologies.

Ethereum, second only to Bitcoin in terms of market capitalization, is a crucial case study due to its extensive ecosystem and utility. Despite the reduction in energy usage post-Merge, questions remain regarding Ethereum's broader sustainability, particularly in terms of emissions, resource distribution, and economic externalities. This paper critically explores these concerns by examining three central dimensions: power demand, emissions, and economic implications.

2. ETHEREUM CONSENSUS MECHANISM

Ethereum's consensus mechanism is fundamental to how the network achieves agreement on the validity of transactions and the state of the blockchain, especially in the absence of a central authority. Initially, Ethereum used a consensus protocol called Proof of Work (PoW), similar to that of Bitcoin. In Proof of Work, network participants known as miners compete to solve complex cryptographic puzzles in order to validate block of transactions. The first miner to solve the puzzle adds the block to the blockchain and is rewarded with newly minted Ether (ETH). While Proof of Work is effective in securing decentralized networks, it is computationally intensive and energy-consuming, leading to growing concerns about its environmental impact.

To address these concerns and improve the scalability and sustainability of the network, Ethereum underwent a major upgrade in September 2022, known as "The Merge." This event marked the official transition from Proof of Work to a new consensus mechanism called Proof of Stake (PoS). In a Proof of Stake system, validators replace miners. These validators are selected to create new blocks and confirm transactions based on the amount of cryptocurrency (ETH) they have "staked". The selection process is pseudo-random but weighted by the size of each validator's stake, reducing the need for energy-intensive computations.

This shift has reduced Ethereum's energy consumption by over 99%, significantly lowering its environmental footprint.

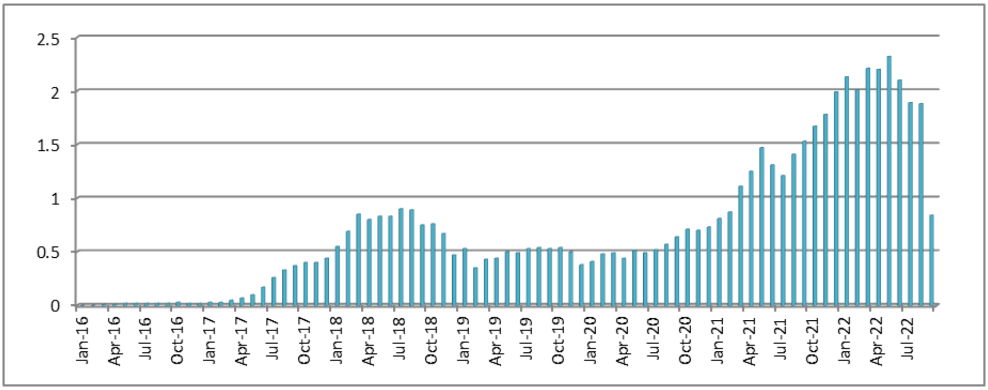
Additionally, Proof of Stake introduces new economic and security dynamics, as validators are financially incentivized to behave honestly and are penalized (through a process called slashing) for malicious behavior or failure to participate properly in the consensus process.

3. POWER DEMAND OF THE ETHEREUM NETWORK (ETHEREUM 1.0 VS ETHEREUM 2.0)

3.1 Pre-Merge Power Consumption (Ethereum 1.0)

Under the Proof of Work model, Ethereum relied on miners to validate transactions and secure the network through computationally intensive processes. Estimates prior to The Merge placed Ethereum's annual energy consumption at around 80-90 terawatt-hours (TWh) - comparable to the energy usage of countries such as Chile or Belgium.[1] This demand stemmed from the arms race in mining hardware efficiency, leading to widespread deployment of energy as we can see bellow on the Graph 1:

Graph 1. Total Ethereum 1.0 (PoW) electricity consumption (in GWh)



Source: https://ccaf.io/cbnsi/ethereum

This graph shows the Ethereum network's energy consumption (in GWh/month) in the period from January 2016 to September 2022. In the graph, we can see a steady growth from 2016 to early 2018: indicating an increase in usage or demand - a possible expansion of Ethereum mining. Then we can notice peaks around January-May 2018: it coincides with the first major Ethereum price increase, indicating higher mining activity or energy consumption.

After that we have the 2018-2019 decline: it coincided with the "crypto winter" when prices and activity declined. Rapid rise starting from mid-2020 to mid-2022: this aligns with the DeFi boom, NFT expansion, and general blockchain adoption surge. On the right side of graph, we can see sharp drop after mid-2022 is likely due to The

[1] Digiconomist (2022). Ethereum Energy Consumption Index. Retrieved from https://digiconomist.net/ethereum-energy-consumption

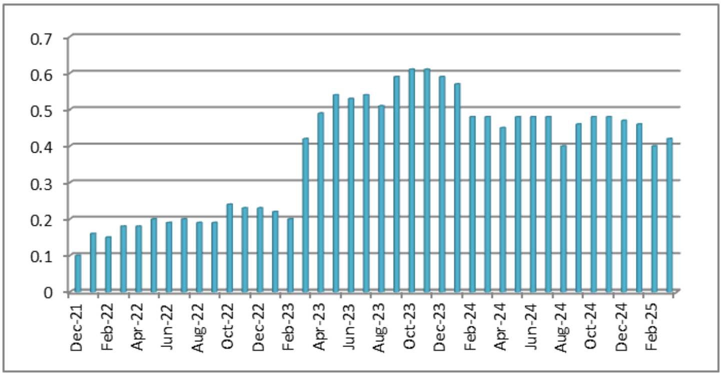
Merge (Ethereum's shift from Proof of Work to Proof of Stake in September 2022), which reduced energy consumption by over 99.95%.

Finally, this graph very likely depicts Ethereum's energy usage, total network power demand, or mining difficulty from 2016 to 2022. The sharp decline around mid-to-late 2022 strongly suggests it's reflecting the impact of The Merge, when Ethereum moved away from energy-intensive mining.

3.2 Post-Merge Energy Efficiency (Ethereum 2.0)

The transition to Proof of Stake has drastically reduced Ethereum's energy demand. According to data from the Ethereum Foundation, the network's energy consumption dropped by over 99.95%, reducing annual usage to less than 0.01 TWh.[1] Validators in the Proof of Stake model are selected based on staked assets rather than computational work, eliminating the need for massive energy expenditure as we can see on the Graph 2:

Graph 2. Total Ethereum 2.0 electricity consumption (in GWh)



Source: https://ccaf.io/cbnsi/ethereum

As we can see on the graph above, we have initial increase in the period from December 2021 to the February 2023. This period is characterized by steady growth in electricity consumption from ~0.1 GWh/month to around 0.25 GWh/month. This period reflects growing validator participation as more users staked ETH in anticipation of Ethereum's full transition to Proof of Stake.

After previous period follows sharp rise in the period from March 2023 to August 2023. We can see noticeable jump in consumption to ~0.5 GWh/month by April 2023 and peaking near 0.6 GWh/month by October 2023. This happened likely due to next facts:

- increased validator counts after The Merge (completed in September 2022);
- post-Merge staking incentives driving more users to run validator nodes;

[1] Ethereum Foundation. (2022). The Merge: Energy Impact. Retrieved from https://ethereum.org

- possible changes in validator infrastructure (use of more resource-demanding setups or increased cloud reliance).

Finally, after the peak, energy consumption stabilizes around 0.45-0.5 GWh/month with slight fluctuations. This suggests that while the number of validators remains high, improvements in energy efficiency, network upgrades, or better hardware may be reducing per-node power usage. Even at the peak (~0.6 GWh/month), Ethereum 2.0's consumption is orders of magnitude lower than during its Proof of Work era (~80-90 TWh/year, or ~6.5 TWh/month).

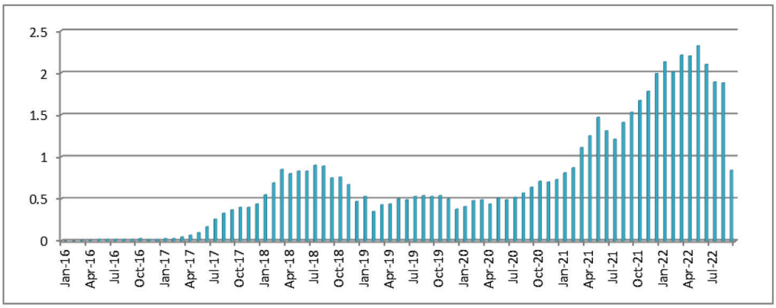
This graph illustrates the rise and stabilization of energy usage in Ethereum's Proof-of-Stake system. A peak around October 2023 (~0.6 GWh/month) reflects increased validator participation post-Merge.

Energy use remains consistently low compared to Ethereum's pre-Merge Proof of Work model, supporting claims of Proof of Stake sustainability. However, power consumption is only one part of the sustainability equation.

4. EMISSIONS AND ENVIRONMENTAL IMPACT

4.1 Historical Emissions (Ethereum 1.0)

Prior to The Merge, Ethereum's carbon footprint was significant. Estimates suggested that the network emitted between 30 to 40 million metric tons of CO_2 annually (Mora et al., 2018), primarily due to coal-powered mining operations in regions like China, Kazakhstan, and parts of Eastern Europe. So, we can notice data for the period from January 2016 to March 2019:



Graph 3. Total Ethereum 1.0 (PoW) Greenhouse Gas Emissions (in KtCO2e)

Source: https://ccaf.io/cbnsi/ethereum

This bar chart illustrates the total greenhouse gas emissions (in kilotonnes of CO_2 equivalent, or $KtCO_2e$) generated by the Ethereum 1.0 blockchain under its original Proof-of-Work (PoW) consensus mechanism, over time from January 2016 to March 2019.

Firstly, we have an early period from January 2016 to February 2017 characterized by very low emissions, close to zero. Ethereum was still relatively new and not heavily mined, leading to minimal energy consumption and emissions. After that follows period of growth during 2017 year featured by steady increase in emissions, especially in mid-to-late 2017. The rise is supported by:

- Ethereum's popularity and usage;
- mining activity, as more miners joined the network;
- energy consumption, driving up emissions.

The peak period from early to middle 2018 is characterized with emissions peaked around middle of 2018, reaching close to 0.45 $KtCO_2e$. This coincides with:

- Ethereum's price surge from late 2017 to early 2018;
- increased network activity and high mining difficulty and energy.

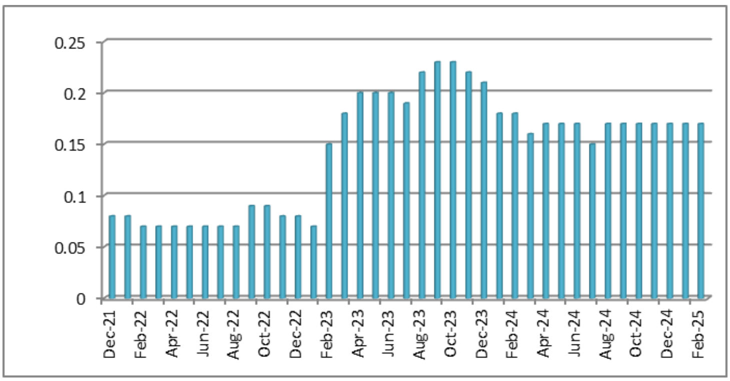
This period is followed by significant decline in emissions after middle of 2018, caused by Ethereum's price drop (bear market), when miners shutting down unprofitable operations or exit of high-energy mining farms.

We can notice a small increase in emissions again by March 2019, possibly due to: network events, temporary rise in activity and changes in mining hardware.

4.2 Post-Merge Emissions Profile (Ethereum 2.0)

Following the transition to Proof of Stake, Ethereum's direct emissions plummeted. However, indirect emissions persist. Validator nodes, although not computationally intensive, still rely on energy sources that may not be renewable. This period is described by graph bellow:

Graph 4. Total Ethereum 2.0 Greenhouse Gas Emissions (in KtCO2e)



Source: https://ccaf.io/cbnsi/ethereum

As we clearly noticed, initial period from December 2021 to February 2023 characterizes next features:

- emissions remain relatively low, fluctuating around 0.07 to 0.1 $KtCO_2e$/month;
- reflects early validator participation with low power usage typical of Proof of Stake.

Previous period followed by sharp increase from March 2023 to August 2023, caused with emissions increase steeply to a peak around 0.23 $KtCO_2e$/month by August 2023 and possibly due to increased validator numbers, greater network activity, or slightly higher energy demand per validator.

Finally, we have decline and stabilization during period from September 2023 to February 2025, characterized by:

- emissions drop to about 0.15-0.17 $KtCO_2e$/month and remain relatively stable;
- suggests improvements in efficiency or the effects of energy optimization.

Compared to Proof of Work emissions that peaked in thousands of $KtCO_2e$/month, these values show the drastic emissions reduction thanks to Proof of Stake model. The peak emissions for Ethereum 2.0 are under 0.25 $KtCO_2e$/month, highlighting Proof of Stake's sustainability. The emissions stabilize at low levels, supporting Ethereum 2.0's long-term viability as an eco-friendly blockchain. Moreover, Ethereum's sustainability depends on the lifecycle emissions of hardware used in validation and the environmental cost of staking infrastructure such as data centers and cloud hosting services.

During the observed period structure of electricity consumption by source remained similar and did not significantly affect the reduction of greenhouse gas emissions, which means that it is almost 100% caused by the change in the consensus mechanism. These data are presented in the table below:

Table 1. Electricity consumption by source (in %)

	2022	2023	2024	Jan 2025
Coal	19.77	19.19	19.38	19.46
Gas	28.98	30.43	29.12	28.38
Oil	2.35	2.42	2.36	2.45
Nuclear	16.98	15.56	16.17	16.14
Hydro	8.47	9.73	10.68	10.44
Wind	13.00	12.38	12.13	12.48
Solar	5.75	5.59	5.54	5.66
Other	4.06	4.19	4.15	4.51

Source: https://ccaf.io/cbnsi/ethereum

The table above shows the global electricity mix by source for the years 2022 - 2025 (January) and is crucial for assessing the indirect carbon footprint of Ethereum 2.0, which now relies on general electricity grids due to its shift to Proof of Stake.

Fossil fuels (Coal + Gas + Oil) still account for ~50% of electricity generation, posing sustainability concerns for Ethereum Proof of Stake validators operating in regions dependent on these sources. Gas remains the dominant fossil fuel source, peaking in 2023 at over 30%, then declining slightly in 2024-2025.

Nuclear energy remains a stable contributor (~16%), offering a lower-emissions alternative of energy by source.

Renewables (Hydro + Wind + Solar) collectively rise slightly from ~27% in 2022 to ~28.6% in January 2025, suggesting slow but positive growth in clean energy adoption. Hydro and solar increase marginally, but wind energy slightly declines, which could affect future validator emissions depending on geographic distribution.

Even though Ethereum 2.0 uses a fraction of the power of its Proof of Work predecessor, its true environmental impact now depends on the source of electricity used by validators. The carbon intensity of Ethereum's Proof of Stake system is therefore indirectly tied to global and regional energy mixes, making this table a vital part of sustainability analysis.

5. ECONOMIC IMPLICATIONS

5.1. Tokenomics and Market Dynamics

The shift to Proof of Stake consensus mechanism also altered Ethereum's monetary policy. With the EIP-1559 implementation and reduced issuance post-Merge, Ethereum became potentially deflationary.[1] This has implications for long-term investor behavior, asset valuation, and economic sustainability. Additionally, staking has introduced a new economic model where returns are generated through asset locking, potentially favoring wealthier participants with more capital as stake (Wust and Gervais, 2018). This raises questions about centralization and the democratization of economic opportunity on the network.

5.2. Cost Externalization and Infrastructure

While Proof of Stake significantly reduces direct environmental costs, the economic costs of developing, securing, and maintaining Proof of Stake infrastructure are substantial. Institutional staking services, staking pools, and centralized exchanges now control significant portions of Ethereum's staking supply, introducing new vectors for centralization and economic inequality.[2]

Moreover, the reliance on financial instruments and services built atop Ethereum (e.g., DeFi platforms, NFTs) presents further economic externalities, including high

1 Ethereum Improvement Proposal 1559. Available at: https://eips.ethereum.org/EIPS/eip-1559

2 Ethereum Staking Concentration. Retrieved from https://messari.io

transaction fees during periods of congestion and market volatility driven by speculative activity.[1]

5.3. The Decentralization–Sustainability Trade-off

One of the core challenges facing Ethereum is balancing decentralization with sustainability. While Proof of Stake addresses energy concerns, it may unintentionally erode decentralization by concentrating power among large holders and validators. This "green but oligarchic" structure undermines the original ethos of blockchain systems, prompting concerns over governance, censorship resistance, and economic inclusivity (Buterin, 2020).

6. CONCLUSION

Ethereum's transition from Proof of Work to Proof of Stale consensus mechanism represents a key moment in blockchain sustainability. The dramatic reduction in energy consumption and emissions is a significant achievement, yet it does not resolve all sustainability concerns. Economic centralization, indirect emissions, and structural inequalities in staking remain critical challenges. To fully realize a sustainable future, Ethereum must continue evolving: technically, economically, and socially.

Future research should explore the long-term effects of staking centralization, the integration of renewable energy in validator operations, and the development of equitable governance models within decentralized networks.

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