EU Blockchain
Observatory and Forum

Ethereum Merge Trend Report

Note

While we have done our best to incorporate the comments and suggestions of our contributors where appropriate and feasible, all mistakes and omissions are the sole responsibility of the authors of this report.

Disclaimer

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1 Introduction

1.1 Ethereum & consensus mechanism

Ethereum is a distributed computing platform enabling the development and execution of '*smart contracts*' using a virtual machine able to execute code of arbitrary algorithmic complexity; hence the term a Turing-complete machine. The data stored on the Ethereum chain include block and transaction-related information facilitating smart contract functions. Ethereum has recently transitioned from proof of work to proof of stake to increase the scalability of the network while reducing the environmental impact of mining. This transition is most commonly referred to as the Merge.

Proof of work (PoW) is one of the most widely used consensus mechanisms[1], despite having one of the highest overheads. In PoW, special nodes called '*miners*' collect transactions and network state information in data sets known as '*blocks*'. Miners then repeatedly apply cryptographic functions to this data until it meets certain criteria set by the network and is deemed acceptable. This process ensures that only valid information is recorded on the blockchain, relying on the cryptographic work done by miners instead of a designated entity or entities. The mining process is resource-intensive, which is necessary to prevent insufficient information from being included in the network, as blockchains, like all systems of value, operate in an adversarial environment.

The environmental impact of PoW has become a growing concern among regulators, as highlighted in a report by the Observatory. As a result, alternative consensus methods that claim to offer similar security and decentralisation to PoW but with lower overheads have gained attention, such as proof of stake (PoS). In PoS, participants pledge a certain amount of wealth, represented in the network's native token, in exchange for the ability to update the blockchain. Bad behaviour is discouraged through a process known as '*slashing*', in which the pledge of the offending party is (partially) destroyed. This process is substantially less resource intensive than PoW and may be less secure or decentralised, but this requires further analysis beyond the scope of the present. Ethereum's recent transition from PoW to PoS provides valuable insight into the energy consumption of blockchains.

1.2 The Merge

Understanding Ethereum's networking layer is crucial to grasping the Merge. The networking layer consists of different protocols forming a stack allowing the nodes to find each other and exchange information[2]. The node software has the execution client and consensus client, along with a connection between the two clients. Specifically:

- the **execution layer** permits a new node to find peers to connect with and enables nodes to exchange information;
- the **consensus layer** ensures the state of the blockchain, maintaining integrity and stability. The consensus layer involves the discovery and propagation of the blocks.

The Merge impacted the consensus layer without interfering with the execution layer; thus, the entire history since the genesis block remains intact. The consensus layer shifted from PoW to PoS, requiring nodes to update their software. For this reason, the Merge did not affect data like transactions and smart contracts. As

[1] Binance Academy. (2022, 12 December). What is Proof of Work (PoW)?. Source.
[2] Ethereum Documentation. (2023, 16 January). Networking Layer. Source.

cryptocurrencies are smart contracts, users did not have to take any action with their digital wallets after the Merge.

1.2.1 Merge quick facts

- **The Merge happened on 15 September 2022.**
- **The Merge moved Ethereum onto the proof of stake consensus mechanism.**
- **The Merge did not require users to exchange their tokens for new ones. The contracts were intact following the change.**
- **The Merge reduced Ethereum's energy consumption by 99.98%.**
- **Average block time decreased to 12 seconds, increasing the scalability by 13%**

2 Ethereum Energy Consumption: Before and After the Merge

2.1 Moving towards decentralisation

Decentralisation is one of the characteristics of blockchain and is often compared with the server-client architecture of conventional applications (Atlam et al., 2018). The server architecture results in the network's low decentralisation and constitutes a single point of failure for the entire system. Numerous sectors like supply chain and healthcare can benefit from decentralisation by radically transforming their methods (Hussien et al., 2019). The distributed ledger is responsible for achieving decentralisation, as each node holds a record of the transaction, making it impossible for bad actors to manipulate data. The study by Hussein et al. points to the reduction in the system's configuration, maintenance, modification, and arbitration with blockchain adoption. Overall, blockchain faces a trilemma between decentralisation, security, and scalability, as detailed by Makarov & Schoar (2022). Blockchains use consensus mechanisms that combine cryptography and game theory to update the ledger, resulting in higher overheads and costs.

2.2 Energy consumption analysis

An event study of the Ethereum transition to PoS by Kapengut & Mizrach (2022) provides information about the energy consumption of the Ethereum network before and after the transition. Krause & Tolaymat (2018) found that the network's electricity consumption reached a peak of 93.975 terrawatt hours per year on 13 August 2022. To put this into context, this level of energy consumption is higher than the annual electricity usage of the entire Philippines[3]. However, after the transition to PoS, the energy usage of the network decreased significantly, by 99.98%, to 0.015 terrawatts, as shown in *Figure 1*. This is due to the fact that PoS eliminates the energy-intensive problem-solving characteristic of the initial consensus algorithm based on PoW.

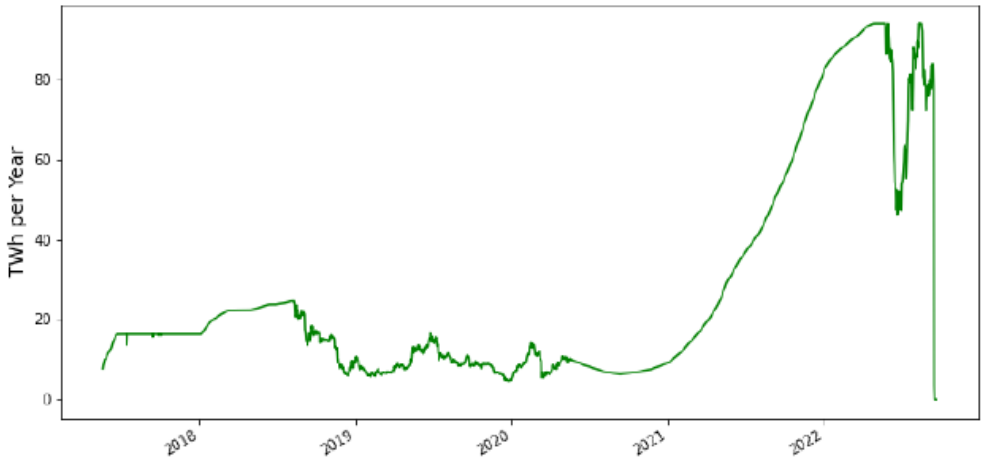

Figure 1: Ethereum Network's Electricity Consumption. Note: Data are collected by Digiconomist. Source

Prior to the Merge, the estimation for energy consumption decrease was around 99.95%[4] by comparing the node's consumption on the beacon chain. An Ethereum blog[5] presents the CCRI valuation to be in line with

[3] List of countries by electricity consumption. Source. Accessed: 14 February 2023.
[4] Ethereum Blog. (2021, 18 May). Ethereum's energy usage will soon decrease by ~99.95%. Source. Accessed: 14 February 2023.
[5] Ethereum Blog. Ethereum Energy Consumption. Source.

the Digiconomist, meaning the decrease is at 99,98% post the Merge. High consumption was an occurring event indicated by the previous high in May of 2022 indicating the frequency, with an estimated 93 TWh per year, or 19 minimum TWh per year. In contrast, the lowest energy consumption was observed after the Merge in October 2022, with approximately 0.0096 estimated TWh per year, or 0.00249 minimum TWh per year.

Before the transition from PoW to PoS, the average estimated TWh per year was approximately 28.5, or 8.2 minimum TWh per year. However, after the transition, the average estimated TWh per year is 0.57 or 0.1 minimum TWh per year based on data from January onwards. Undoubtedly, this significant decrease in energy consumption clearly demonstrates the effectiveness of the transition to PoS in reducing the energy consumption of the Ethereum network. This positive turn brings the Ethereum network, as well as the cryptocurrency industry as a whole, a few steps closer to sustainability. Ethereum.org visualises the difference as follows in Figure 2.

Additionally, the Crypto Carbon Ratings Institute (CCRI) conducted a study[6] to estimate the electricity consumption and carbon footprint of the Ethereum network using a bottom-up approach. It measured the electricity consumption of different nodes with various hardware and client software configurations. The tests yielded an estimate of 2.601 MWh (0.0026 TWh) for the network's annual electricity consumption (September 2022), corresponding to yearly carbon emissions of 870 tonnes of CO2e, applying regional-specific carbon intensity factors. Table 1 provides an overview of the electricity consumption of the Ethereum PoS network using the CCRI estimates. The number of nodes was obtained from an explorer called Beacon Chain Network Public Dashboard by Miga Labs[7] for 5 September 2022.

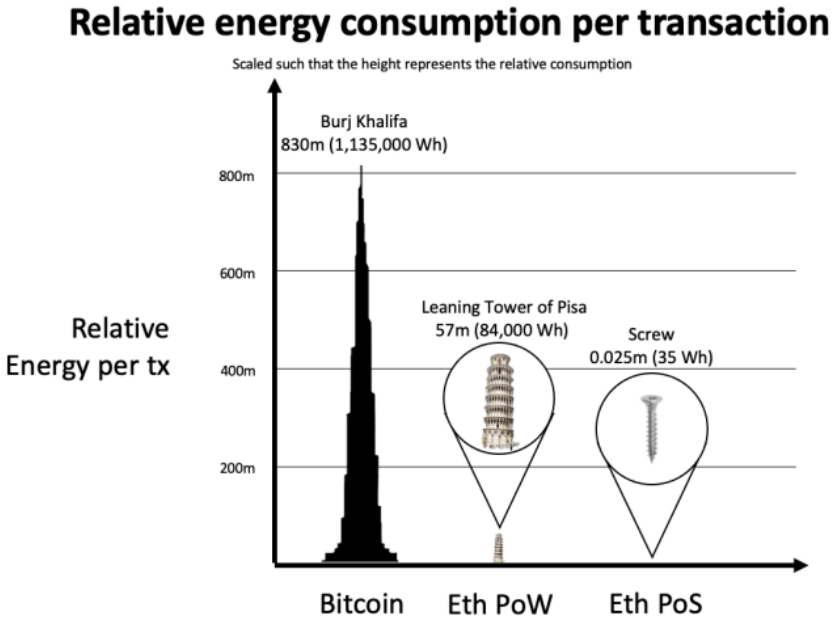

Figure 2: Relative Energy Consumption Per Transaction
Source: Ethereum.org

[6] CRI - Crypto Carbon Ratings Institute. (2022). CCRI - Understanding your climate impact. Source
[7] Miga Labs. Eth2 Client Analyzer. Source.

Table 1 Overview of electricity consumption of the Ethereum PoS network applying CCRI estimates

Ethereum PoS	
Beacon chain node count	4,755
Electrical power of network [W]	296,902.20
Consumption / day [kWh]	7,125.65
Consumption / year [kWh]	2,600,863.27

The CCRI 2022 report also presents results on electricity consumption per transaction of the Ethereum PoS network, although this metric is quite debatable. By applying the specific estimates described in the report, they presented the results in Table **2** below.

Table 2:Best guess electricity consumption of the Ethereum PoS network on a per-transaction basis. The transaction count amounts to the average number of transactions per 24h that took place during our measurements.

Ethereum PoS	
Wh/tx per node	0.0013237
Wh/tx per network	6.2943
Number of tx per day	1,132,081

Overall, Ethereum's transition to PoS has, by all measures, significantly reduced its energy consumption.

2.3 Reasons for PoW energy consumption

The energy consumed by PoW is a widely discussed topic, mainly due to the high energy usage of Bitcoin's PoW mechanism when compared to the energy consumption of some countries. To understand why PoW consumes so much energy, we need to first understand the importance of securing the network and the role of consensus algorithms.

The primary function of a consensus algorithm is to ensure that the state of the ledger is the same across the entire network. PoW mandates validators to solve complex mathematical problems to add new blocks to the chain. This mechanism ensures the validator's honesty on the basis of their willingness to consume energy to run the process on their node's hardware. In contrast, PoS validators are required to stake their crypto tokens as collateral to prove that they have a vested interest in being honest. It should be noted that block addition

differs between permissioned and permissionless networks, as the security requirements are more lenient for permissioned networks compared to the more sophisticated validation in permissionless ones, as concluded by Platt et al. (2021).

Another reason for the high energy consumption of PoW is the way it works in awarding the validators. Specifically, adding a block is a race between nodes to validate the block and consequently acquire the reward in the native token. As with any race, the winner gets the reward and leaves the rest of the nodes to consume resources without any compensation. While this may not have posed a problem in the initial stages of Bitcoin, as described by Forbes[8], the growing popularity now attracts miners and increases waste. Instead, PoS can randomly select a node to validate a block.

Additionally, based on the opinion of Nair & Dorai (2021), the mathematical problems in PoW become progressively harder to solve as the number of network participants increases. Subsequently, this requires miners to update their hardware to run more computations quickly while maintaining security.

Furthermore, it is essential to understand that evaluating the environmental impact of PoW solely on the basis of energy consumption may not be entirely accurate since this excludes many parameters. While energy consumption is an indicator, it needs to incorporate the way energy is produced, as energy produced from renewable sources has a lower environmental impact than energy produced from non-renewable sources. In the New York Times article[9], China's mining ban may have made mining even more harmful to the environment due to the shift to alternatives from China's cheap hydro energy. All in all, minimising the environmental impact of PoW is a matter of energy strategies and constant effort to produce energy from greener means.

In conclusion, there are three key points when it comes to PoW energy consumption: 1) the energy consumption of PoW is high due to the security requirements of the consensus algorithm and the race between nodes to validate the block and acquire rewards first; 2) the mathematical problems in PoW become more complex as the number of participants increases, obliging miners to acquire updated hardware; and 3) it is essential to consider other parameters of energy production to evaluate the environmental impact of PoW correctly.

2.4 Drawbacks of PoS

PoS adoption is not concern-free by blockchain practitioners. A Forbes article[10] points out the track record between the PoW and PoS in deployed applications. Despite the energy consumption, PoW has been employed to protect the Bitcoin network for over a decade with a limited number of forks in the chain. PoS will have to consider and deal with issues during its deployment. The 'nothing at stake' attack, for instance, is rationally possible due to the game theory of PoS. Essentially, PoS validators are incentivised to work on multiple forks for the rewards, and they can introduce conflicting blocks for generating the forks and continuing the cycle. Forks in the chain make it less secure since it takes longer to do checks, providing opportunities for fraud. There are suggestions for improving the security of PoS algorithms for possible attacks by Li et al. (2017) and Kiayias et al. (2016).

Concerns have also been raised about the administration of the network, as the proposed changes will have far-reaching effects on the reward allocation criteria in place. PoW was an essential component of an open and decentralised protocol for securing the network by allowing miners to allocate their hardware. In contrast,

[8] Forbes. (28 July 2022). Why Does Bitcoin Use So Much Energy?. Source.
[9] The New York Times. (25 February 2022). China Banished Cryptocurrencies now, 'Mining' is even dirtier. Source.
[10] Forbes. (2023, 16 February). Proof of Stake Explained. Source.

PoS relies on validators staking an amount of the native token for participating in the block addition. Fanti et al. (2019) argue that PoS consensus encourages the phenomenon of the richer getting richer, as wealth concentrates in a smaller team of users, as the validation, and its resulting rewards, would be awarded to nodes affording to stake a higher number of tokens. The validator's selections will be skewed towards the nodes with the highest stakes resulting in the centralisation of the network (Shifferaw & Lemma, 2021). However, there are counterarguments, such as the one presented by Roşu & Saleh (2021), who demonstrate that, for buy-and-hold investors in the PoS blockchain, the proportion of staked money remains consistent.

PoS algorithms are less straightforward in nature than their PoW counterparts. PoW is anchored to the physical world with its reliance on computing devices for securing the network, even for new users. This property is referred to as being an objective mechanism, as any set of related and unrelated parties can accurately reach an agreement for the chain's state. On the other hand, PoS is inherently subjective and necessitates the addition of security mechanisms[11] (Ethereum blog). Essentially, new users can not dependently define the chain's state solely relying on protocol rules. The additional social components in PoS enhance its complexity for users.

[11] Ethereum Foundation Blog. (2014). Proof of Stake: How I Learned to Love Weak Subjectivity. Source.

3 Merge Impact: Beyond Energy Consumption

3.1 Mining competition and migration outside of Ethereum

PoW is a consensus algorithm with demanding requirements for processing. As the valuation of cryptocurrency kept rising, hardware competition intensified due to the rewards for mining becoming more lucrative. The ferocity of the competition is evident in the machines used for mining. When Bitcoin launched in 2009, mining required only CPUs. Soon, the transition of mining to using GPUs and publicly available GPU mining software allowed anyone to join. The public had found another way to use graphics cards other than machine learning problems or leisure activities like gaming, and demand went up. In 2012, machinery specially and solely designed for mining was introduced. These specialised machines are called application-specific integrated circuits (ASICs) and can only be used for mining specific cryptocurrencies.

Bearing in mind the method of mining and the machines involved, one must consider the impact on the market. Firstly, miners using GPUs must reflect on their choices after the Merge. The most straightforward choice is to abandon mining by repurposing their GPUS for other tasks or selling them. A cross-market comparison should be made on the hash rates of the other cryptocurrencies to determine how miners have operated since the Merge. While Ethereum may consume less energy, the case in the overall market may differ if miners operate in other networks.

The case is different for ASIC miners, as the sole purpose of their machines is to mine Ethereum. The Merge has rendered ASIC miners obsolete, as their aim is to solve PoW problems efficiently. In other words, the Merge and its shift to PoS has made these miners redundant. The positive effect on the environmental impact is that ASIC mining accounted for 10% of Ethereum's computer power (Forbes[12], 2022), and there is only limited availability.

There is scepticism about the reduction of the carbon footprint of the cryptocurrency market as a whole, as documented by the miners' choices in blog posts[13]. Competition with other blockchains may have intensified after the Merge. For instance, the hash rate in PoW chains like Ethereum Classic (see *Figure 3* left), Ravencoin (see *Figure 3* right), and Litecoin (see *Figure 4*) have increased, meaning that miners have shifted their operations to other chains. The following charts indicate a spike in the hash rate after Ethereum's Merge.

Figure 3: Hashrate of Ethereum Classic (left) and Ravecoin (right)

[12] Forbes. (21 April 2022). Ethereum Miners Will Have Few Good Options After The Merge. Source.
[13] DSHR's Blog. (18 October 2022). The power of Ethereum's Merge. Source.

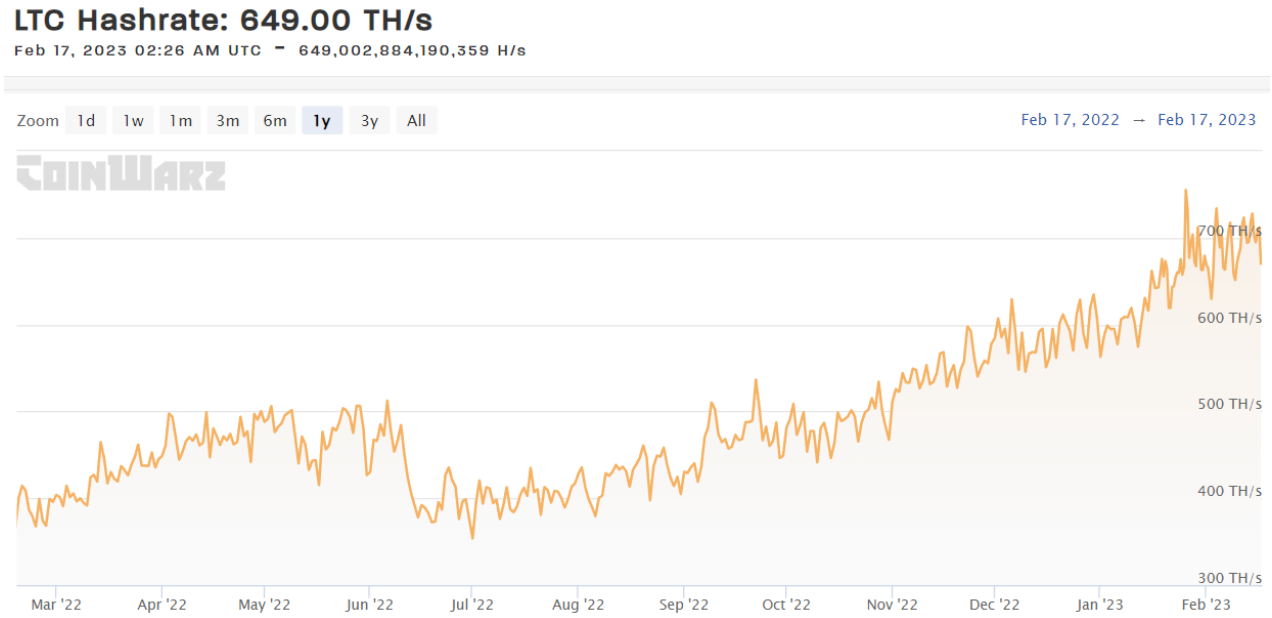

Figure 4: Litecoin Hashrate, Period 17/02/2022-17/02/2023

All in all, the Merge may have raised the competition between miners even further, as indicated by a podcast interview with Alex de Vries[14]. Miners select areas with access to the most efficient and cost optimal areas for electricity to optimise their operations.

3.2 Performance, scalability, and security after the Merge

Software deployment is an iterative process where deployment is the final phase of a product after an exhaustive cycle of changes, tests, and debugging. The end goal of all the work that goes into making software is a reliable, bug-free product for end users.

The Ethereum network and its consensus algorithm's recent update are analogous to the software deployment. On December 1, 2020, the Ethereum Foundation marked the first step of its transition to PoS by launching the Beacon Chain. Between the debut of Beacon Chain and the Merge, two parallel networks operating with the two different consensus algorithms existed. While users generally transacted on the Proof of Work network called Ethereum Mainnet, Ethereum's developers worked on the functionalities of the Beacon Chain. The Bellatrix and Paris update announcement[15] depicts the transition from the Beacon Chain to Ethereum 2.0.

[14] Marketplace. (7 December 2022). An environment friendly model for crypto mining shows promise. Source.
[15] Ethereum Foundation Blog. (2022, 22 August). Mainnet Merge Announcement.

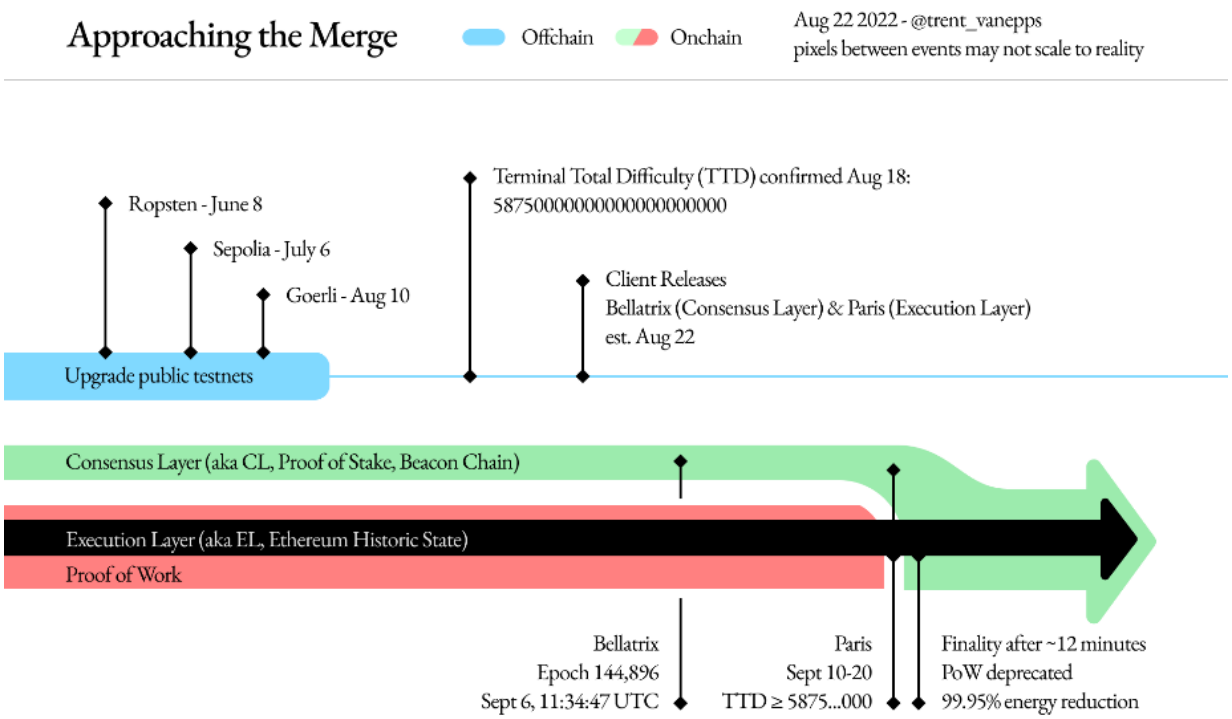

Figure 5: Ethereum's chains and upgrades timeline[15]

The change of the consensus algorithm mandates the replication of the existing blocks on the PoW network to the Beacon Chain. The changes can be summarised in the transaction storage, block headers, and difficulty of the addition of the block. A reason for the change is that data fields are irrelevant for PoS as ommer blocks are almost impossible to exist in the new consensus. Moreover, the difficulty shifts from block hash to another feature, PREVRANDAO, which indicates the randomness in creating a block. A detailed explanation by Ethereum[16] presents the updates mentioned earlier, along with the following figure.

[16] Ethereum Foundation Blog. (2021, 29 November). How The Merge Impacts Ethereum's Application Layer. Source.

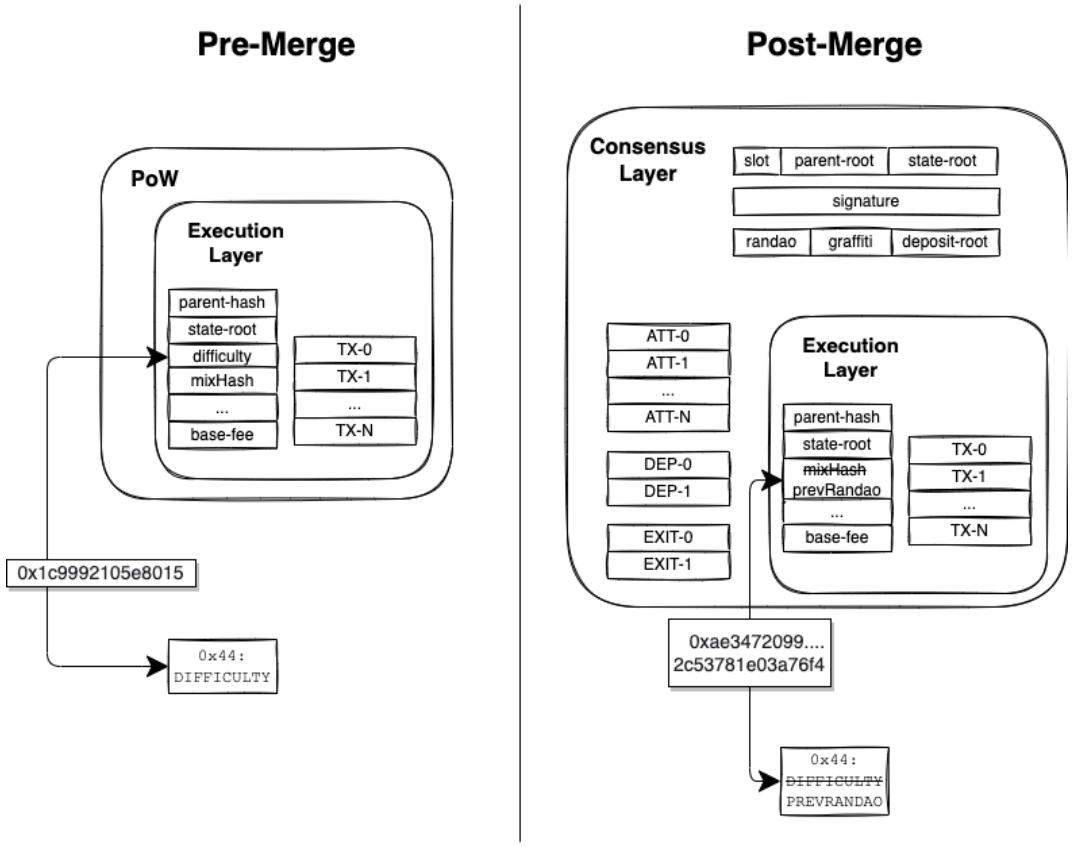

Figure 6: Block structure pre and post Merge[16]

Another effect of the Merge on the Ethereum network is a shorter block time. The block time is the time necessary for adding a new block on the chain and is a characteristic closely related to scalability and security. Block time has decreased in its average value by roughly 13%[17], along with the wide fluctuations indicating a decrease in variance. During PoW, the average time for creating a block was approximately 13 seconds, whereas it is consistently 12 seconds under PoS. According to YCharts' figures, the daily block creation has increased as a result of the decreased block time.

[17] Cointelegraph. (2022, 02 October). Ethereum Merge spikes block creation with a faster average block time. Source.

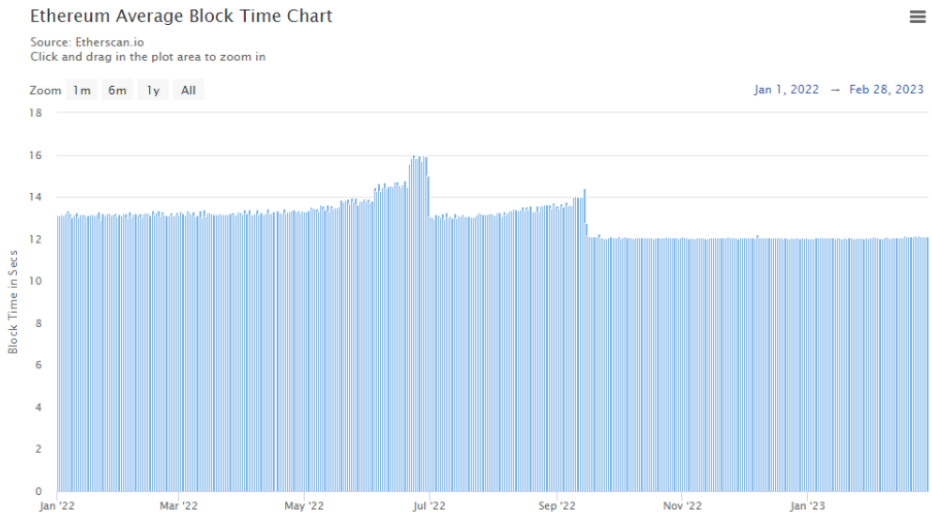

Figure 7: Ethereum average block time, https://etherscan.io/chart/blocktime

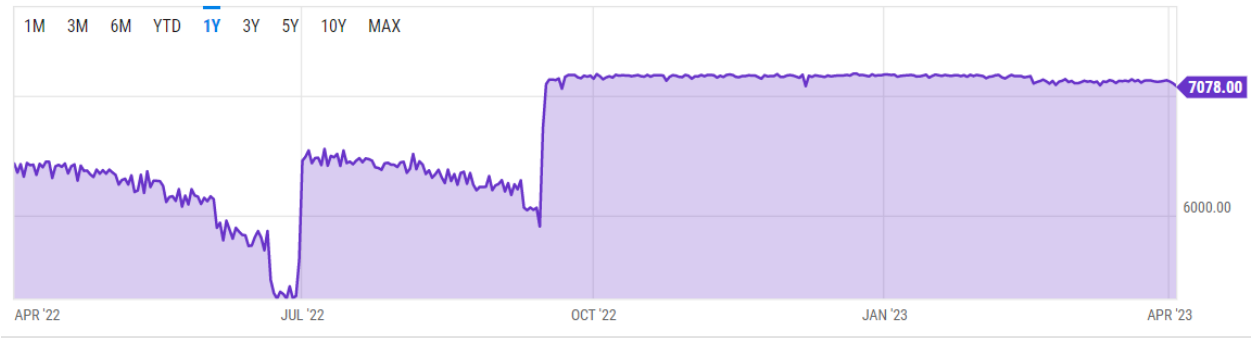

Figure 8: Ethereum daily block number, YChart

The Merge is an important update in terms of Ethereum's scalability, security, and longevity. Even though it has been hinted as a potential inclusion to the roadmap as far back as 2014[18,19], it is just one aspect of Ethereum's recent roadmap[20]. For example, Layer 2 solutions are to increase the transactional throughput, but they need access to cheaper gas fees to interact with the basis chain[21]. This is why it is crucial to think about scalability, and sharding[22] is one viable option for increasing scalability by minimising the stored data on each node. All in all, the Ethereum network is to add more updates over time to answer scalability, security, and sustainability.

[18] Ethereum Foundation Blog. (2014, 15 January). Slasher: A Punitive Proof-of-Stake Algorithm. Source.
[19] Ethereum Foundation Blog. (2014, 25 November). Proof of Stake: How I Learned to Love Weak Subjectivity. Source.
[20] Tweet by Vitalik Buterin. Updated roadmap diagram!. Source.
[21] Ethereum. Ethereum vision. Source.
[22] Ethereum. (2023, 30 March). Danksharding. Source.

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