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REPORT

The Merge

Implications on the Electricity Consumption and Carbon Footprint of the Ethereum Network

CCRI

Crypto Carbon Ratings Institute (CCRI) is a brand of CCRI GmbH based in Dingolfing, Germany.

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Preamble

This commissioned report is prepared by CCRI for
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Executive summary

- Ethereum's **Merge** is one of the **largest and most complex upgrades** to any cryptocurrency network in history.
- The **Proof of Work** consensus mechanism Ethash is **replaced** by a **Proof of Stake** mechanism. Instead of miners, validators verify and propose new blocks after the Merge.
- This report establishes metrics for the **electricity consumption** and **carbon footprint** of both the Ethereum **Proof of Work** and **Proof of Stake** network.
- Given the complexity of the Ethereum Proof of Stake network, multiple consensus and execution clients exist. CCRI's **measurements cover 95.54 % of all clients** and provide an estimate for the number of nodes in the network.
- The **Merge reduces** the electricity consumption and carbon footprint of the Ethereum network by over **99.988 %** and **99.992 %**, respectively.

I. Overview

1. Introduction

The Merge, as one of the most important updates in the history of the Ethereum network is referred to, takes place in September 2022. After years of planning, software design and engineering, the largest smart contract platform switches its consensus engine from Proof of Work (PoW) to Proof of Stake (PoS). In the history of blockchain networks, such a complex update is unprecedented.

There are several factors that increase the complexity of the Merge. First, the Merge should not interrupt the operations of the network and is designed for a seamless switch between the consensus mechanisms. Second, the network is designed for resilience against individual node failure. Therefore, several teams work in different implementations of the respective clients. In case a single type of node fails due to any reason, the functionality of the network is not at stake, as the remainder of nodes are able to establish and keep consensus. However, this increases the complexity of testing and verifying any correct functionality, given that any combination of consensus and execution clients need to be properly tested. Before the core developers decided on a Total Terminal Difficulty[1], a plethora of merges of both testnets as well as shadow main nets took place. The findings during these tests were incorporated into the respective client software to sort out any potential problems due to the Merge.

Plans for switching from Proof of Work to Proof of Stake have existed since the first days of Ethereum in 2015. While many reasons exist for a switch to PoS (scalability, lower barriers of entry, reduced issuance of new ether and more), the sustainability of the PoW and PoS consensus mechanisms has significantly increased in relevance in the public debate as well as for the networks itself. Especially Bitcoin's electricity consumption and carbon footprint has sparked a broader debate. Proof of Stake is expected to reduce the electricity consumption and the carbon footprint significantly. Therefore, the Merge will substantially enhance the environmental sustainability of the Ethereum network.

Instead of requiring computational power to solve mining puzzles for securing the network in PoW, PoS requires validators to lock in funds for a specific period of time to propose or vote on new blocks. The cost to secure the network is decreasing, as electricity as a safeguard for the network is replaced by network participants' stake.

It remains the question: By how much will the Merge reduce the electricity consumption and carbon footprint of the Ethereum network due to the switch from Proof of Work to Proof of Stake? For both Proof of Work and Proof of Stake networks, previous research and methodologies to estimate electricity consumption and carbon footprint exist. CCRI, its team members and other institutions and researchers have put forward multiple studies, assessing the sustainability of Proof of Work networks such as Bitcoin, Ethereum, Litecoin and others (de Vries et al., 2022; Gallersdörfer et al., 2020; Krause & Tolaymat, 2018; Stoll et al., 2019), Proof of Stake networks such as Algorand, Avalanche, Cardano, Polkadot, Tezos, Solana (CCRI, 2022b), TRON (CCRI, 2022d) as well as Layer 2 networks involving PoW and PoS components such as Polygon (CCRI, 2022c; KlimaDAO, 2022).

In this report, we provide estimates on the electricity consumption and carbon footprint for Ethereum pre-Merge (PoW) and Ethereum post-Merge (PoS). For the PoW component, we rely on established literature and methodologies. For the PoS component, we leverage a research framework initially proposed in CCRI (2022b)

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[1] The Total Terminal Difficulty (TTD) is the value at which, when the network reaches it, the Merge takes place. The TTD is set to 58750000000000000000000.

and adapt it to cater for Ethereum's specific landscape of different client versions. We find that the Merge leads to a reduction of the electricity consumption and carbon emissions of 99.988 % and 99.992 %, respectively. Table 1-3 provides an overview of the main results.

Electrical power [MW]	Annualized electricity consumption [MWh/year]	Annualized carbon emissions [tCO_2e/year]
2,565	22,900,320	11,016,000

Table 1: Overview of results for Ethereum PoW network, annualized values as of August 2022 (pre-Merge)

Beacon Node Count [# total]	Transactions [Tx/year][2]	Total electricity consumption [MWh/year]	Electricity per node [kWh/year]	Total electricity per transaction [Wh/Tx]	Total carbon emissions [tCO_2e/year]
4,755	413,209,565	2,600.86	547.01	6.2943	869.78

Table 2: Overview of results for Ethereum PoS network, annualized values as of our measurements in August and September 2022 (post-Merge)

	Ethereum PoW	Ethereum PoS	Reduction factor
Electricity consumption [MWh/year]	22,900,320	2,600.86	0.99988
CO_2e emissions [t/year]	11,016,000	869.78	0.99992

Table 3: Overview of reduction factors as a result of the Merge

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[2] We count the transactions occurring during our measurements and thus estimate the number of transactions for a year.

2. Aim and scope

This report aims to provide insights into the electricity consumption and carbon footprint of both the Ethereum network pre-Merge (PoW) and post-Merge (PoS).

The Ethereum network investigated in our analysis takes the 2nd position with regard to market capitalization of coinmarketcap.com on 1st September 2022.[3] We summarize important key figures for the Ethereum (ETH) cryptocurrency as per 1st September 2022 in the following:

Name:	Ethereum
Symbol:	ETH
Market Capitalization (Rank):	193,834,454,492 USD (2nd)
ETH Price:	1,586.18 USD
Circulating Supply:	120,344,720 ETH
24 Hours Trading Volume:	387,409,445 USD

The following of this report is divided into three components. Firstly, we analyze the electricity consumption and carbon footprint of the Ethereum network pre-Merge. Secondly, we examine the electricity consumption and the emissions generated by the Ethereum network post-Merge. Thirdly, we compare these results and discuss our observations. The specific methodologies are defined and explained in the corresponding sections.

It is noteworthy that the approach applied in this report is a helpful tool to derive a ballpark estimate for total electricity consumption and carbon emissions. However, any cryptocurrency network is associated with uncertainties that impede deriving exact numbers of the electricity consumption or, respectively, of a network's carbon footprint. Numerous factors, such as the network size, varying hardware configuration, or network infrastructure, influence the overall electricity consumption. Nonetheless, we deem this report to produce a precise estimate for the electricity consumption and carbon footprint of the Ethereum pre- and post-Merge network, as we a) build on an established method for the PoW network, b) observe and measure the electricity consumption of single hardware components and use them as a proxy for the overall PoS network as well as c) use the network-specific carbon intensity of the Ethereum network to estimate the overall carbon footprint.

The establishment of methodology, representative hardware, network sizes, and electricity measurements form the basis for future research, such as comparing different networks and their respective requirements and properties.

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[3] The data is taken from https://coinmarketcap.com/currencies/ethereum/historical-data/

II. Ethereum's Proof of Work network

1. Overview

Since its inception, the Ethereum network has been based on the Proof of Work consensus mechanism and therefore requires computational power to secure the integrity of its blockchain. The electricity consumption and carbon footprint of the PoW component of the Ethereum network has been subject to extensive research (de Vries, 2022b; Gallersdörfer et al., 2020; McDonald, 2021). In this report, we deploy a two-step approach to derive the sustainability metrics of the network.

Two-Step Carbon Footprint Analysis of Ethereum Pre-Merge

1. **Electricity consumption of the Ethereum network**: In an initial step, we derive the overall electricity consumption of the Ethereum network by determining the hardware composition and device efficiency required for producing the hash rate the Ethereum network is running on.

2. **Carbon footprint of the Ethereum network**: As a second step, we translate the electricity consumption calculated in step 1 into a carbon footprint. For this, the locations of miners need to be determined and the carbon intensity of the respective electricity sources are utilized to calculate an overall carbon intensity of the network. With this value, one can determine the overall carbon footprint of the Ethereum network.

2. Electricity consumption of the Ethereum network

Ethereum is the second largest Proof of Work network as well as the largest platform that supports smart contracts in terms of market capitalization.[4] As such, it has received considerable attention on its sustainability performance, albeit Bitcoin's carbon footprint as the largest cryptocurrency in terms of market cap has been still in the center of the discussion.

Proof of Work protects the integrity of the network by relying on computationally intensive mining puzzles that require miners to run hardware devices that produce solutions for these puzzles. Once a puzzle is solved, a miner is allowed to propose a new block[5] to the network and collect a mining reward containing a block subsidy as well as all transaction fees[6] from the included transactions. PoW works as a sybil control mechanism in that regard, that an adversary is not able to control the next forthcoming block or is able to rewrite past blocks unless it controls more than 50 % of the overall computational power. Given the involved hardware requirements and electricity costs for such attacks, they are very expensive and thus very unlikely to occur.

This security mechanism comes with the cost of a comparatively high electricity consumption for any Proof of Work network. One key driver of the electricity consumption is the respective reward for the miners; if they receive a higher payment for their operations, they can allocate larger amounts of money for electricity costs.

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[4] Data available on https://coinmarketcap.com.

[5] A new block refers to a new state based on the transactions that are included in the respective block.

[6] Since 5th August 2021 (block 12,965,000), EIP-1559 forces the miner to burn a certain share of transaction fees in the Ethereum network.

On the 6th of September 2022, Bitcoin miners received around 19.1 million USD in the last 24 hours[7] as mining reward whereas Ethereum miners received about 22.2 million USD for the same period[8].

There are two key mechanisms to determine the electricity consumption of a Proof of Work network, namely a **top-down** calculation and a **bottom-up** calculation.

The **top-down approach** starts by assessing the income of miners both from block reward and transaction fees. Second, it estimates the share of income that is spent on electricity. Given the incentive structure and market conditions of cryptocurrency mining, the share for electricity costs can be a substantial amount of the overall cost structure. With the assumption of an average electricity price miners pay, one can determine the overall network electricity consumption.

The **bottom-up approach** starts by looking at the metric of the hash rate of the respective network. The hash rate is the required computational power to produce the number of blocks in the respective time frame with the given difficulty for that period of time[9]. In a second step, the amounts and types of hardware are determined that can operate profitably under current computational requirements in the network. Given the variety of different hardware devices and efficiencies, the selection of hardware influences the overall result significantly. The overall electricity consumption of the network is then determined by summing up the electricity consumption of all the devices considered in the previous step.

The **top-down approach** was initially presented and widely promoted by Alex de Vries. His website digiconomist.net provides both a *Bitcoin Energy Consumption Index* and an *Ethereum Energy Consumption Index*. He assumes that a certain share of the miners' revenue is spent on electricity consumption while assuming a price of 0.1 USD / kWh for the Ethereum network. This share is regularly adjusted depending on market conditions and lies at almost 100 % as of the beginning of September 2022. With these assumptions, his estimate of the Ethereum network derives an overall annual electricity consumption of ~78 TWh as of the beginning of September 2022 (de Vries, 2022a, 2022b).

The **bottom-up approach** was initially described in scientific literature by Marc Bevand in 2017[10] and since then has been adopted by several researchers (Krause & Tolaymat, 2018). In 2020, (Gallersdörfer et al., 2020) have utilized this methodology to determine the electricity consumption of, amongst other currencies, Ethereum. Based on this methodology, CCRI developed up-to-date calculations for the electricity consumption and carbon footprint of Ethereum and other major PoW protocols. The estimates feed into the CCRI Cryptocurrency Sustainability API (CCRI, 2022a). In 2021, Kyle McDonald also utilized the bottom-up approach to determine the electricity consumption and carbon footprint of the Ethereum network (McDonald, 2021). The results have aligned with previously conducted studies.

Figure 1 displays an overview of both top-down method by de Vries (2022b) as well as both bottom-up estimates by Gallersdörfer et al. (2020)[11] and McDonald (2021)[12].

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[7] https://bitinfocharts.com/de/bitcoin/, accessed on the 6th September 2022

[8] https://bitinfocharts.com/de/ethereum/, accessed on the 6th September 2022

[9] The hash rate is a stochastic metric, meaning that a lower or higher hash rate can exist in reality. Depending on the time frame that is considered, the hash rate can vary significantly, but if sufficiently long periods of time are selected, the hash rate becomes a reliable metric.

[10] http://blog.zorinaq.com/bitcoin-electricity-consumption, accessed on the 7th September 2022

[11] CCRI has leveraged the initial research methodology and updated all values for 2022.

[12] Current values have been obtained from https://kylemcdonald.github.io/ethereum-emissions/

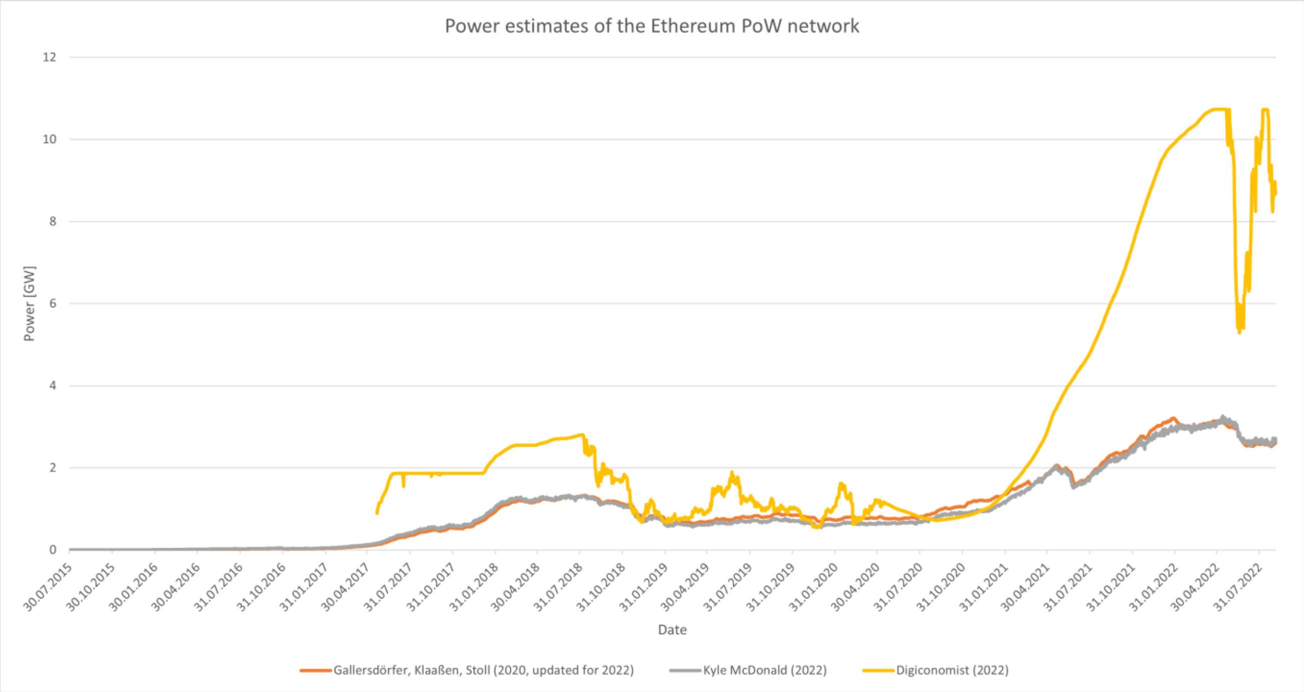

Figure 1: Estimates of power usage of the Ethereum network by Gallersdörfer et. al, Kyle McDonald and Digiconomist. Data from Digiconomist is transformed to GW to align.

While the estimates from the bottom-up approaches are closely aligned, the top-down approach from digicomist.net is around fourfold in terms of electricity consumption as of mid-August 2020. As such, we believe the bottom-up approach to derive more realistic estimates as it is directly based on actual metrics of the network (i.e., hash rate) and the market (i.e., hardware profitability). Therefore, CCRI uses it for its own calculations which also serve as the underlying foundation in this report.

3. The carbon footprint of the Ethereum network

In comparison to the use-phase of the hardware, the production and disposal of cryptocurrency mining devices play a subordinate role of carbon emissions in PoW networks (De Vries & Stoll, 2021; Köhler & Pizzol, 2019). Especially for ASIC-resistant PoW algorithms[13], general purpose hardware can be repurposed afterward and is available for secondary markets. Therefore, the carbon footprint of a PoW network largely depends on the utilized electricity sources during the mining process and their respective carbon intensities.

To properly identify the carbon intensity of the respective cryptocurrency network, one needs to determine the locations and, ideally, the electricity sources of miners. This is an inherently difficult endeavor due to the nature of mining:

> One of the key variables that miners can influence is the **price paid for the electricity** for their operations; selecting locations with a high availability of electricity as well as cheap rates can make or break a business and are therefore a well-kept secret. Miners have no interest in sharing their location or their electricity prices, as this only would attract competition.

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[13] An ASIC-resistant PoW algorithm is an algorithm that, in theory, prevents the development of specialized hardware aimed at solving the respective puzzle in a more efficient way than general purpose devices such as CPUs or GPUs. For Bitcoins *double-SHA 256* algorithm, the market is dominated by Application specific integrated circuits (ASICs), whereas Ethereum's *Ethash* algorithm is mainly dominated by GPUs.

Miners might even be **required to keep their operations a secret**, if they are operating in locations that have banned the usage of mining devices, such as China. In such cases, miners use technologies such as VPN and other approaches to disguise their business and remain under the radar.

Miners **connect to larger mining pools** in order to enhance the predictability of their income stream[14]. Mining pools provide a raw block including details such as transactions and payouts and the individual miners try to solve the respective mining puzzle for the block. Given the network structure, miners cannot be observed directly when they create a valid block (e.g., by IP-addresses), making it harder to determine the location of the mining devices.

Even if a location is known, it is **unclear which electricity is exactly used**. Miners could operate behind the meter, utilize electricity that is otherwise stranded or their electricity usage is leading to displacement effects. Therefore, if locations are available, average grid intensities are leveraged to balance between different potential situations.

For Bitcoin as the largest PoW network, various estimates on the locations and carbon intensity exist (CBECI, 2022; de Vries et al., 2022; Stoll et al., 2019). In these cases, mining pools have provided data on the location of the connected miners or other information such as IoT search engines have been leveraged for location determination. Nonetheless, these data points face the same issues as previously mentioned, allowing only for a rough estimate of the carbon intensity of the network.

To the best of our knowledge, only one estimate on the carbon intensity of the Ethereum network exists. In his paper, Kyle McDonald also analyzed the miner location of Ethereum miners to determine an overall carbon intensity (and thus carbon footprint) of the network (McDonald, 2021). He thereby uses data partly relying on self-reported location by miners[15] as well as further information about mining pools, blog posts, and other sources such as Reddit. In his article, he comes up with a carbon intensity of 320 gCO_2/kWh. In comparison, the world average carbon intensity lies at 459 gCO_2/kWh (International Energy Agency, 2021), which is significantly higher than McDonald's estimate. Furthermore, estimates for the Bitcoin network are significantly higher ranging from 480 gCO_2/kWh to 560 gCO_2/kWh (de Vries et al., 2022; Stoll et al., 2019).

We see two challenges with McDonald's carbon intensity data:

Self-reported data: It is unclear how reliable self-reported location data is. Given that the blocks might contain the location of the respective mining pool, it is entirely unclear if miners select their mining pool based on proximity and whether this approach leads to a fair approximation of miner locations.

PoW incentives: The consensus mechanisms of Bitcoin and Ethereum differ in their selected hash function, resulting in different utilized hardware[16]. Nonetheless, the underlying incentive structure for the cheapest electricity should lead to similar locations and thus carbon intensities for both networks. Given also that both types of mining businesses are rather investment-intensive, it seems incongruent that McDonald's estimate resides significantly below the world average and most of Bitcoin's estimates reside significantly above the world average.

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[14] Miners with a low hash rate cannot reliably expect to mine a block in a given timeframe; instead of finding one block and receiving a large payout, they connect to mining pools that distribute earnings depending on the respective hash rate of the miner.

[15] Miners are able to store information in an extra field of the block they mined. Some blocks contain the information of the location of the mining pool; assuming that a miner selects the nearest mining pool, regions and a geographical distribution can be determined.

[16] Bitcoin relies on a Double-SHA256 hash function, allowing the broad deployment of ASIC devices. Ethereum relies on a more complex hash function that severely restricts the usage of ASIC devices, therefore it is believed that most of the hash rate of Ethereum is provided by GPUs.

We use a conservative approach here to avoid underestimating emissions. Therefore, we select the carbon intensities of the Bitcoin network and apply them to Ethereum's electricity consumption. We utilize an updated carbon intensity based on the methodology presented in (de Vries et al., 2022) and additional data available from the Cambridge Mining map[17], leading to an average carbon intensity for the relevant period of 501 gCO_2e/kWh, leading to the overall emissions of 12.721 $MtCO_2e$ for the period of 1st August 2021 to 31st July 2022. Figure 2 gives an overview of the annualized emissions of the Ethereum network pre-Merge.

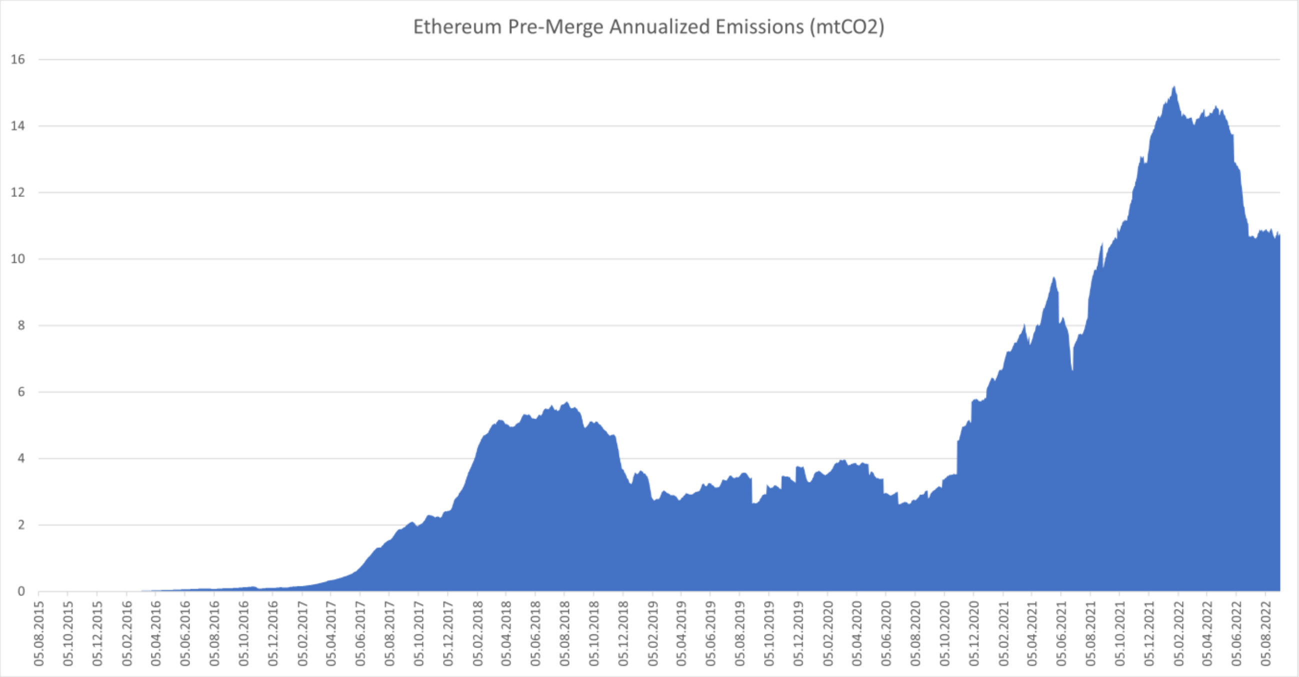

Figure 2: Estimates of annualized carbon emissions in $MtCO_2e$ of the Ethereum network based on (de Vries et al., 2022; Gallersdörfer et al., 2020)

4. Conclusion

Table 4 displays the key results of the analysis of the electricity consumption and carbon footprint of the Ethereum pre-Merge network. We opt for a one-month period from 1st August to 31st August 2022 and annualize the values for later comparison in chapter IV: The annualized average power for the given time period is 2,565 MW, the annualized consumed electricity amounts to 22,900,320 MWh, whereas the respective annualized carbon footprint amounts to 11,016,000 tCO_2e.

	Electrical power [MW]	**Electricity consumption [MWh/year]**	**Carbon emissions [tCO_2e/year]**
Ethereum pre-Merge	2,565	22,900,320	11,016,000

Table 4: Overview of the annualized electrical power, electricity consumption and carbon emissions for the Ethereum pre-Merge network for the time period from 1st August to 31st August 2022.

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[17] Available at https://ccaf.io/cbeci/mining_map

III. Ethereum’s Proof of Stake network

The upcoming Merge event will change Ethereum’s consensus engine to a Proof of Stake mechanism. This event is claimed to be the most significant upgrade in the history of Ethereum, aiming for less electricity consumption and to prepare the blockchain for future scaling upgrades.

The PoS based Beacon chain was launched on 1st December 2020 and has been running in parallel to Ethereum’s PoW based mainnet since then. After the Merge, the Beacon chain will be used as the consensus engine for the Ethereum mainnet, and thus be the engine for block production. Instead of mining, PoS validators will verify transactions and propose new blocks.

Since the Beacon chain is already in operation without actually processing transactions, the power consumption of participating consensus and execution nodes can already be determined. This allows an estimate for the electricity consumption of the Ethereum network after the Merge took place.

1. Client diversity of Ethereum

Generally, after the Merge, an Ethereum client consists of two different layers: On the one hand, the so-called consensus layer, which is responsible for participating in the consensus mechanism. On the other hand, the so-called execution layer, which is in charge of executing and bundling transactions as well as handling the state management. For both layer types, several different and independently developed client software exist, each built in different programming languages and offering different advantages.

At the time of writing (05th of September 2022), Prysm is the most widely used consensus client (44.15 %), and Geth is the dominant execution client (80.74 %). The data describing the client diversity stem from the Blockprint Public API[18] concerning the consensus clients and from Ethernodes[19] for the execution clients. Table 5 gives an overview of the distribution among the most important clients in the network as of September 2022.

Consensus Clients	
Prysm	44.15 %
Lighthouse	33.99 %
Teku	17.49 %
Nimbus	4.33 %
Lodestar	0.05 %
Others	0.00 %

Execution Clients	
Geth	80.74 %
Erigon	8.55 %
Besu	6.24 %
Nethermind	4.01 %
Others	0.45 %

Table 5: Client diversity within the Ethereum network. Data from Blockprint Public API (consensus clients) and Ethernodes (execution clients).

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[18] https://github.com/sigp/blockprint

[19] https://ethernodes.org/

2. Methodology for analyzing Ethereum PoS network

Our methodology builds upon four steps to generate data on the electricity consumption and carbon footprint of the Ethereum PoS network.

In the **first step**, we analyze the different client solutions and their minimum hardware requirements. The hardware requirements are an indicator of the hardware composition of the network. We use this information and additional hardware data from PassMark to select and obtain hardware that we use to measure a single node's electricity consumption.

In the **second step**, we estimate the electricity usage of a single node participating in the network that runs a specific combination of one consensus and one execution client. For this, we first determine the electricity usage of the hardware devices while idling. Secondly, we measure the execution of different consensus and execution clients on their own on the hardware devices selected. We provide upper and lower bounds as well as a best guess metric for each client software considered. Thirdly, we subtract the idle electricity usage from the results obtained for each client, allowing us to calculate the power consumption for arbitrary combinations of consensus with execution clients. Taking the idle power consumption into account, these values allow us to produce reasonable upper and lower bounds and a best guess for running a full node applying different client software combinations, as our hardware is selected accordingly. We also measure other data points, such as CPU utilization and processed blocks, to be able to evaluate additional metrics.

In the **third step**, we estimate the electricity consumption of the complete network. Firstly, we collect information about the size of the network, as the node count significantly influences the amount of electricity consumed. Thereby, we consider the client diversity within the Ethereum network as presented in Table 5 since the various combinations differ in terms of electricity usage. We thus weight the electricity consumption of client combinations according to their frequency of occurrence in the network. Secondly, we develop a weighting between the single hardware devices. Lastly, we multiply the electricity consumption, adjusted for the client diversity, of the weighted nodes by the number of accounts in the network.

In the **fourth step**, we estimate the CO_2 emissions arising from the operation of the Ethereum PoS network. For this, we use our weighted data on electricity consumption calculated and multiply it with a carbon intensity factor adjusted to the regional distribution of the nodes in the network. We provide a best guess as well as an upper and a lower bound for the carbon footprint of the Ethereum PoS network.

3. Ethereum PoS hardware requirements and test environment

In this section, we first establish our selected hardware pool for carrying out analyses of PoS networks. Secondly, we summarize the hardware requirements for the different Ethereum clients and derive a hardware selection out of our pool that satisfies the requirements for all clients considered. Thirdly, we provide details of the infrastructure applied to measure electricity consumption and further describe our test environment.

Hardware selection

For analyses of PoS systems, we generally define three different categories of hardware requirements for nodes participating in a network:

1. **Low hardware requirements:** For PoS networks with rather low hardware requirements, we assume that computational power is not a concern for the systems, and users should be comfortable running the software on any system they have available. Typically, such networks recommend using low-energy hardware for running nodes, as for example the well-known Raspberry Pi. In today's average consumer desktop PC, 4-8 GB RAM and 200 GB of storage (even an SSD) are not uncommon anymore.

2. **Specific hardware requirements:** Some networks specify quite precise hardware requirements, for instance stating the exact CPU type as well as RAM and storage. For such networks, we normally aim for using hardware that satisfies the requirements, but we also test hardware that does not meet the recommendations if they are able to run a node reliably and include these tests in our calculation. Nonetheless, hardware requirements typically give users who intend to run a node an indication about what to expect regarding demand, influencing their final choice of hardware.

3. **High hardware requirements:** Some few PoS systems exhibit surprisingly high hardware requirements. The CPU, RAM, and storage requirements can be at the highest level of standard desktop computers (besides servers). Graphic cards can be required in such networks, which hints at the immense processing power required.

We define a hardware pool that covers the above-mentioned categories in order to ensure a high degree of hardware diversity. For the analysis of specific networks, it is important to decide on a case-by-case basis which hardware configurations to use. Based on the hardware requirements, both an upper and a lower bound of hardware are evident.

For the lower bound, we select a Raspberry Pi 4 Model B with 8 GB RAM and 128 GB SD-card given that the popularity of the Raspberry Pi computers is high within all communities. We opt for an official Raspberry Pi full kit, including fan and power supply.

As an upper bound, we opt for an average system within the Threadripper specifications consisting of an AMD Ryzen Threadripper 3970X, 32C/64T, 256GB RAM (DDR4-3600), and a Samsung 970 Evo Plus 2TB in order to address high hardware requirements. As the processor does not have an onboard graphics processor, we need a graphics card. However, as graphics cards are not always required at that time, we opt for a card that does not support CUDA and cannot participate in the calculations of any network. We select an appropriate mainboard as well as a power supply.

The upper and lower bounds highly deviate from each other in terms of computational power and electricity consumption. Further, the two computers may not capture the complete picture of the hardware used within networks to be analyzed. Therefore, we decided to add four additional computers to ensure a well-balanced set of hardware for electricity consumption measurements.

As there are millions of different computer configurations, thousands of variables, and other factors that influence the electricity consumption of devices, we opt for one key variable and derive other specifications of the system from it: The central processing unit (CPU). Nonetheless, the CPU also has several variables such as the number of cores, threads, speed, turbo speed, thermal design power (TDP), and others. Further, identical variables do not necessarily lead to the same computational power or electricity consumption. To get an in-depth view and understanding of the CPU landscape, we obtain a data set from PassMark. PassMark provides a software suite able to benchmark varying types of hardware, including CPUs. The obtained data set contains over 3,100 CPU models as well as over 1 million results of their benchmarking suite (Passmark Software, 2021). Based on this data set, we select four CPUs to derive our final configurations. We thereby aim at three categories of performance (high, mid, and low) and select one or more CPUs with the average efficiency for their class. A detailed description of our approach to select CPUs can be found in Appendix A.

For the high-tier (configuration 5), we identified the Intel Core i5-10400F as being closest to the average efficiency. As Intel's F-models only have a deactivated onboard graphics chip (Intel, 2021), we decided to opt for the non-F variant, as otherwise, a dedicated GPU would add unnecessary electricity consumption to the system. The non-F variant is almost identical to the F variant regards to benchmarking results. We opted for 64 GB DDR4 RAM and a Samsung 970 Evo Plus 2 TB NVMe SSD to complement the system. Mainboard, power supply unit, and case have been selected appropriately.

Regarding the mid-tier section, we have extended our hardware selection with an additional device compared to our previous measurements (CCRI, 2022b), as we assume that most standard users apply hardware from this range. Since the Intel NUC series is becoming increasingly popular for running blockchain nodes, we decided on an Intel NUC with medium equipment (configuration 4). We chose an Intel Core i5-1135G7 laptop processor with included graphics chip, which represents the upper mid-range of typically used devices quite well. This additional mid-tier computer is equipped with a 32 GB DDR4 RAM and a 2 TB NVMe SSD. Furthermore, we still stick to the Intel Core i5-8400T since it has the best fit for the average electricity consumption in the mid-tier section (configuration 3). The T-model means the CPU has a "power-optimized lifestyle", resulting in lower performance and less electricity consumption. We could not directly obtain the CPU in the market and instead opted for a completed build: The Lenovo ThinkCentre M720q Tiny 10T8S3KD00. Besides the processor as mentioned above, it includes a 256 GB NVMe SSD as well as 8 GB RAM.

In the low-tier section (configuration 2), we identify the Intel Core i3-8109U as the processor with an average energy efficiency for its class. The U-label refers to a "Mobile power-efficient" CPU but is nonetheless included in MiniPCs. To our knowledge, this CPU was never sold separately on the consumer market but is available in Intel's NUC series. We obtain the Intel NUC Kit NUC8i3BEK2 Barebone and augment it with the Samsung 970 Evo Plus 512 GB NVMe SSD as well as 8 GB RAM.

To ensure comparability with our previous analyses of other PoS systems, we largely stick to the same hardware selection as defined in CCRI (2022b). However, some minor adjustments to better fit the assumed hardware diversity in the Ethereum network have been conducted. Besides including a further mid-tier setup into the hardware pool with configuration 4, configuration 5 was enhanced regarding both RAM and storage capacity ensuring a significant difference to the new configuration 4 not only in terms of the CPU.

We consider our selection as representative to provide a balanced set of hardware for electricity measurements with these six computers. As an operating system, we use for all our devices Ubuntu Server 20.04, except for configuration 5. Due to driver issues, we had to opt for Ubuntu Server 21. Table 6 displays an overview of the hardware configurations just introduced. Other factors than CPU are also relevant for the electricity consumption of the systems. Nonetheless, this set of hardware yields a broad overview of used hardware within such networks.

	1	2	3	4	5	6
CPU	Broadcom BCM2711	Intel i3-8109U	Intel i5-8400T	Intel i5-1135G7	Intel i5-10400	AMD 3970X
Cores/Threads	4/4	2/4	6/6	4/8	6/12	32/64
Architecture	ARM	x86/x64	x86/x64	x86/x64	x86/x64	x86/x64
RAM	8 GB	8 GB	8 GB	16 GB	64 GB	256 GB
Storage	128 GB SD	512 GB SSD	256 GB SSD	2 TB SSD	2 TB SSD	2 TB SSD
GPU	Onboard	Onboard	Onboard	Onboard	Onboard	AM 6970
PSU	USB-C	65 Watt	65 Watt	65 Watt	650 Watt	1000 Watt
Case	Integrated	Integrated	Integrated	Integrated	Custom	Custom
OS	Ubuntu 20.04	Ubuntu 20.04	Ubuntu 20.04	Ubuntu 20.04	Ubuntu 21	Ubuntu 20.04

Table 6: Overview of selected hardware configurations from lowest to highest requirement

It is very likely that a considerable share of nodes in the network are hosted on cloud providers such as Amazon Web Services (AWS) or similar. Establishing precise data metrics for the hardware in use in such data centers, its energy efficiency and electrical consumption goes beyond the scope of this report. Especially hyperscale data centers tend to exhibit a comparatively high degree of efficiency. Therefore, the approach based on self-hosted hardware as presented in this report may overestimate the electricity consumption of Ethereum's PoS networks and hence represents a rather conservative estimate.

Hardware requirements of Ethereum clients

Different hardware requirements are recommended for the various Ethereum clients. There are considerable differences between consensus and execution clients, also within the same client type the requirements can vary. Consensus clients tend to have higher hardware requirements than consensus clients, which is why the hardware required to run a full node is often determined by the execution client. Table 7 summarizes the recommended minimum hardware requirements for consensus clients we have considered in our analyses. Likewise, Table 8 lists the recommendations for the regarded execution clients.

Consensus Client	CPU	RAM	Storage
Prysm[20]	4 cores, 2.8 GHz	16 GB	2 TB SSD
Lighthouse[21]	2 cores, 2015 or newer	8 GB	128 GB SSD
Teku[22]	2 cores, Intel Core i5–760 / AMD FX-8100 or better	4 GB	20 GB SSD
Nimbus[23]	N/A	4 GB	200 GB
Lodestar[24]	Intel Core i5–760 / AMD FX-8100 or better	4 GB	20 GB SSD

Table 7: Hardware requirements for measured Ethereum consensus clients

Execution Client	CPU	RAM	Storage
Geth[25]	2 cores	4 GB	320 GB
Erigon[26]	N/A	16 GB	400 GB SSD
Besu[27]	N/A	8 GB	750 GB SSD

Table 8: Hardware requirements for measured Ethereum execution clients

Applying the client's requirements for executing full nodes to our hardware pool presented in the previous section, we deduce that configurations 5 and 6 shown in Table 6 exceed the hardware recommendations for all clients listed. Consequently, these configurations are chosen to be included in our analysis. Moreover, since we avoid treating hardware recommendations as a strict lower bound, we also involve configuration 4 into our experiment, as it closely fulfills the minimum recommendations for the most demanding client (Prysm). As a result, we also examine a node representative of the mid-tier category. Table 9 summaries which configurations of our hardware pool were included as a foundation to derive the electricity consumption of the Ethereum PoS network.

	Ethereum
Configuration 1	✗
Configuration 2	✗
Configuration 3	✗
Configuration 4	✓
Configuration 5	✓
Configuration 6	✓

Table 9: Overview of nodes of our hardware pool selected for running a Ethereum full node

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[20] Source: https://docs.prylabs.network/docs/install/install-with-script

[21] Source: https://lighthouse-book.sigmaprime.io/system-requirements.html

[22] Source: https://www.coincashew.com/v/spanish/coins/overview-eth/guide-how-to-stake-on-eth2-with-teku-on-ubuntu

[23] Source: https://nimbus.guide/hardware.html

[24] Source: https://chainsafe.github.io/lodestar/

[25] Source: https://docs.ethhub.io/using-ethereum/ethereum-clients/geth/

[26] Source: https://github.com/ledgerwatch/erigon

[27] Source: https://besu.hyperledger.org/en/stable/public-networks/get-started/system-requirements/

Infrastructure for electricity measurements

For the measurement of the electricity consumption, we use a Mystrom WiFi Switch for each computer. These switches measure the electricity consumption as well the room temperature and provide the values over a REST interface. The electricity measurements are made in Munich, Germany in a separate server room with near-constant room temperature.

All devices were equipped with the same software, a fresh Ubuntu server 20.04/21 installation, and the monitoring tool Glances that allows us to collect additional system information such as temperature or system load during the experiment (Hennion, 2021).

A separate Raspberry Pi, equipped with a Python script, collected, and monitored the systems during executing the Ethereum full nodes and analyzed the data generated during the runs. All computers are only connected to the power outlet and LAN. All systems share an internet connection with 350 Mbit/s download and 110 MBit/s upload.

4. Electricity consumption and carbon footprint of the Ethereum PoS network

The definition of the to-be used hardware allows us to establish single node measurements. With these measurements, we provide upper and lower bounds for the electricity consumption of a single node running a specific client, and a best guess as a weighted average between the selected computer devices. On that basis, we establish the electricity consumption of the overall Ethereum PoS network assuming each node executes both a consensus and an execution client and taking the client diversity as introduced in section 1 of chapter III. We furthermore discuss additional metrics such as the electricity use per transaction.

Single node measurements

After defining and obtaining the hardware required for our analysis, we set up the hardware and install the node software for the Ethereum PoS network. For that, we use the following process:

1. **Hardware Setup**: We install the node with the respective Linux version, configure Glances and configure remote access.
2. **Idle Measurement**: We run the idle measurement for the devices without any additional software installed.
3. **Node Setup**: We download and install the software necessary for executing a specific Ethereum client and verify the correct installation.
4. **Node Bootstrap**: On each node, we run the respective client software and wait for the synchronization to be completed since we do not want to skew the electricity consumption of the devices during the bootstrapping phase.
5. **Electricity Measurement**: We shut down the nodes, start the electricity measurement and then start the nodes again. The nodes run for 48 hours executing the respective Ethereum client, as this covers two entire day cycles. Appendix B contains an overview of every electricity measurement for each node executing each client.

To understand what exactly we are measuring, we need to describe the Ethereum PoS network and its setup. It consists of nodes running either just a single client software or both a consensus and an execution client.

However, to execute a consensus client exclusively, a connection to one or more remote execution clients is required. While consensus clients are responsible for state synchronization, execution clients manipulate the state and handle smart contracts. The combination of both clients is what we refer to as a full node in this report. Furthermore, a limited number of validators exist, which receive blocks and re-execute included transactions to verify block validity before submitting a vote on the verified block to the network. To operate a validator node, 32 ETH need to be deposited and, along with operating a full node, a validator software must be executed. In an ideal setup, we measure the electricity consumption of consensus clients that run validators, but given the costs we decide not to. Furthermore, previous research suggests that participating in the PoS consensus mechanism has only a negligible effect on the device's electricity consumption (Sedlmeir et al., 2020). Therefore, we run our electricity measurements on nodes executing either a consensus or an execution client, thereby determining the electricity consumption of various full node configurations consisting of different consensus and execution client pairs.

Idle electrical power

We measure the electricity consumption of the devices idle. Table 10 depicts the minimum, maximum, median, and the first and third quartile of the electricity consumption for 24 hours. All values are rounded to one decimal. Interestingly, the setup 2 and 3 consumes less electricity than the Raspberry Pi (configuration 1), which we deemed the most energy-efficient solution beforehand.

	1	2	3	4	5	6
Mean [W]	3.04	2.70	2.95	3.66	25.04	78.17
Min [W]	2.92	2.60	2.57	3.55	24.53	77.52
Q1 [W]	3.00	2.64	2.87	3.65	24.75	77.85
Median [W]	3.05	2.69	2.94	3.66	24.87	78.04
Q3 [W]	3.06	2.70	3.00	3.66	25.15	78.34
Max [W]	3.96	17.78	17.33	4.37	26.64	118.14

Table 10: Electrical power in Idle measured in Watt [W] – hardware selection for each of the six clusters can be found in Table 2

Node electrical power

Due to the hardware requirements outlined in section 3, we do not run the Ethereum clients on all nodes. While the hardware setups 5 and 6 of Table 6 exceed the recommended configurations even for the most demanding client software, we also test configuration 4 as we do not want to enforce the recommended hardware requirements as a strict lower bound. However, we exclude hardware configurations 1-3 from our measurements since these do not satisfy the requirements of all clients.

In Table 11 and 12, we outline the mean and the median electrical power of the nodes during the measurements of the single Ethereum clients. We also provide the electrical power consumption less the devices' idle consumption during the executions in order to obtain the marginal power consumption per client software. These values are necessary for our calculation of estimations for the execution of different consensus and execution client combinations later in this chapter.

Execution Client		4		5		6	
		Total	Marginal	Total	Marginal	Total	Marginal
Geth	Mean	14.89	11.23	34.74	9.70	125.87	47.70
	Median	14.86	11.20	34.58	9.71	125.93	47.89
Erigon	Mean	22.26	18.60	42.63	17.59	122.79	44.62
	Median	22.20	18.54	42.44	17.57	121.20	43.16
Besu	Mean	33.91	30.25	56.06	31.02	153.21	75.04
	Median	33.73	30.07	55.42	30.55	153.19	75.15

Table 11: Electrical power of nodes executing different execution clients in Watt [W].
The most consuming clients per node are highlighted.

Consensus Client		4		5		6	
		Total	Marginal	Total	Marginal	Total	Marginal
Prysm	Mean	7.17	3.51	27.91	2.87	102.50	24.33
	Median	7.13	3.47	27.86	2.99	102.36	24.32
Lighthouse	Mean	6.41	2.75	28.18	3.14	97.01	18.84
	Median	6.26	2.60	28.03	3.16	96.74	18.70
Teku	Mean	7.37	3.71	28.36	3.32	105.63	27.46
	Median	7.44	3.78	28.02	3.15	105.31	27.27
Nimbus	Mean	5.33	1.67	27.12	2.08	95.28	17.11
	Median	5.17	1.51	26.89	2.02	94.99	16.95
Lodestar	Mean	6.80	3.14	28.93	3.89	111.72	33.55
	Median	6.68	3.02	28.80	3.93	111.86	33.82

Table 12: Electrical power of nodes executing different consensus clients in Watt [W].
The most consuming clients per node are highlighted.

In summary, the measurements show that Besu requires the most electrical power within the execution clients. Among the consensus clients, Teku was the most expensive on hardware configuration 4, and Lodestar on configurations 5 and 6. However, we note that the measurements took place sequentially and, therefore, some minor differences in the transaction numbers during the single measurements occur.

5. Calculation of best guess and bounds for electricity consumption

To calculate the electricity consumption of the overall network, we need to understand the average consumption for a single node participating with a specific combination of a consensus and an execution client. We measured the electrical power for three different hardware configurations several times running various consensus and execution clients. Thus, with these measurements, we can compute a best guess that captures the consumption of a node for arbitrary configurations of one consensus and one execution client best. Since we know about the distribution of clients among the network as explained in section 1 of chapter III, we can finally weight the best guesses for the single client configuration possibilities and come up with an overall best guess for the electrical consumption of the average node in the network.

Furthermore, we can provide upper bounds, meaning the highest electricity that a node consumes, and lower bounds, meaning the least electricity a node consumes.

Best guess

The electricity consumption of an average node in the network is challenging to estimate. There is no empirical data on the concrete hardware that nodes are running on or indicating users' preferences. For node owners, several factors are relevant for their decision on which hardware to run their node on. First, owners stake tokens to receive rewards and want their revenue to be stable, aiming for hardware designed for long-term operations. Second, due to the profit structure, they do not intend to spend all their revenue on hardware and might rather opt for barely sufficient hardware within the hardware requirements. These thoughts might influence their decision in one way or another but might not directly translate to a hardware selection. Therefore, we opt for a binomial distribution for the hardware selection, based on a regular distribution for key questions. The distribution for each hardware type is displayed in Table 13.

	Ethereum
1	N/A
2	N/A
3	N/A
4	25.00 %
5	50.00 %
6	25.00 %

Table 13: Overview of node distribution for the six networks

With this distribution, we calculate the weighted electricity consumption of an average node for each combination of one consensus and one execution client. For this, we sum up the weighted marginal electricity consumption of the respective consensus and execution client, and add the weighted idle consumptions:

$$\sum_{i \in hardware} (avgMarginalEnergyConsumption_{i,cc} + avgMarginalEnergyConsumption_{i,ec} + avgIdleEnergyConsumption_{i}) * share_{i}$$

$$\forall \ cc \in [Prysm, Lighthouse, Teku, Nimbus, Lodestar], ec \in [Geth, Erigon, Besu]$$

Table 14 lists the per node best guess electricity consumption weighted according to Table 13 for each combination of consensus and execution client that we can compute with our measurements conducted. Additionally, the share of each client configuration within the network is indicated, which was computed based on Table 5.

Client configuration		Best guess [W]	Best guess [kWh / year]	Configuration share [%]
Consensus Client	Execution Client			
Prysm	**Geth**	60.96	533.97	35.65
Prysm	**Erigon**	65.97	577.91	3.77
Prysm	**Besu**	83.21	728.88	2.75
Lighthouse	**Geth**	59.53	521.47	27.44
Lighthouse	**Erigon**	64.54	565.41	2.91
Lighthouse	**Besu**	81.78	716.38	2.12
Teku	**Geth**	62.01	543.24	14.12
Teku	**Erigon**	67.03	587.18	1.50
Teku	**Besu**	84.26	738.15	1.09
Nimbus	**Geth**	58.29	510.66	3.50
Nimbus	**Erigon**	63.31	554.59	0.37
Nimbus	**Besu**	80.54	705.57	0.27
Lodestar	**Geth**	63.68	557.80	0.04
Lodestar	**Erigon**	68.69	601.74	0.00
Lodestar	**Besu**	85.93	752.71	0.00
				Sum: 95.54

Table 14: Best guess estimates per single node for different client configurations. The most electricity consuming configuration is highlighted.

The values show that the combination of Lodestar as the consensus and Besu as the execution client consumes most electricity for a best guess node in the network (85.93 W). However, this combination represents a negligible share in the network. The two most popular client combinations are Prysm and Geth (36.65 %) followed by Lighthouse and Geth (27.44 %). Both are rather efficient in terms of their power consumption (60.96 W and 59.53 W).

Since we know the shares of the individual client combinations, we can weight the power consumption of the single best guess nodes per client configuration accordingly, and thus obtain the electricity consumption of an average best guess node in the network:

$$\frac{\sum_{cc,ec \in clientConfigurations}(bestGuess_{cc,ec} * configurationShare_{cc,ec})}{\sum_{cc,ec \in clientConfigurations} configurationShare_{cc,ec}}$$

Both the estimated electrical power and the yearly electricity consumption of an average best guess node in the Ethereum PoS network are provided in Table 15.

	Ethereum PoS per node
Best guess [W]	62.44
Best guess [kWh / year]	547.01

Table 15: Best guess estimates for electrical power and electricity consumption of the Ethereum PoS network per single node

Upper and lower bound

Apart from this best guess estimate for an average node in the network, we can determine upper and lower limits for the power consumption of nodes participating in the network. These upper and lower bounds are determined by the least efficient and most efficient hardware, respectively. The lower bound therefore is constituted by configuration 4 from Table 6. Accordingly, configuration 6 serves as an upper bound. The resulting bounds, weighted by the share of the different client configurations, are summarized in Table 16.

	Ethereum PoS per node
Lower bound [W]	20.00
Lower bound [kWh / year]	175.19
Upper bound [W]	150.06
Upper bound [kWh / year]	1,314.75

Table 16: Weighted lower and upper bounds of electrical power and electricity consumption of the Ethereum PoS network per single node

6. Electricity consumption of the Ethereum PoS network

To estimate the electrical power and the yearly consumption of the entire network, we apply our best guess estimation to the number of active beacon chain nodes. The number of nodes is obtained from an explorer called Beacon Chain Network Public Dashboard of Miga Labs[28] for the 5th of September 2022. The results are depicted in Table 17. We find that the electricity consumption of the network amounts to 2,600,863.27 kWh annually in our best guess:

	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

Table 17: Overview of electricity consumption of the Ethereum PoS network applying the best guess estimate

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[28] https://migalabs.es/eth2-client-analyzer/

7. Electricity consumption per transaction of the Ethereum PoS network

An often-used metric in comparing electricity consumption between systems is the electricity consumption per transaction. This allows comparing systems that have different architectures, transaction throughput, and electricity requirements. Still, companies that want to report emissions associated with cryptocurrency exposure should not necessarily rely on a transaction-based allocation approach but should also consider other methodologies in order to avoid potential underreporting (Gallersdörfer et al., 2021).

The complexity of this metric is based on the fact that some systems provide a theoretical electricity consumption per transaction, simulating the network at full speed. Other calculations are based on transaction rates measured in the networks, making comparisons skewed. Further, the definition of a transaction might vary from network to network.

An additional complexity is the attribution of the electricity consumption solely to the transactions. The system requires a base electricity consumption to keep up with the consensus without providing any transactions. Nonetheless, given the base load of a network, running a node in a "low-transaction"-period might yield higher electricity per transaction costs than usually to be expected. While this metric provides a straightforward insight into different protocols, its base assumptions need to be understood and its results must be treated with care.

Lastly, the electricity consumption per transaction is only a single metric describing the sustainability of a network. It is of utmost importance to understand that this metric needs to be seen in the context of other metrics such as decentralization, security, transaction complexity, state size and others. This metric alone is not sufficient to decide whether a cryptocurrency is sustainable or if a cryptocurrency is worth investing in; in an extreme case, a network consisting of a single, high-performance computer, would be the most sustainable cryptocurrency, however making nonsense of the decentralization idea.

As we measured the electricity consumption of our nodes in real-world scenarios, we can rely on the transaction count that took place during the respective time periods. We consider the measurements of the three execution clients (Geth, Erigon, and Besu) and calculate the average number of transactions that took place during these three measurements that took place sequentially. Since the measurements were taken over 48 hours, we divide the resulting value by two in order to obtain an average number of transactions per day. To calculate the power consumption per transaction, we apply our best guess node for the entire network as defined in chapter III section 5. Hence, the results of individual node measurements are weighted for both the binomial distribution and the client diversity within the Ethereum network. The results can be found in Table 18.

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

Table 18: 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.

As expected, this metric depends on the number of transactions taking place on the blockchain, also the overall electricity consumption per transaction further depends on the number of nodes connected to the

Ethereum Beacon Chain. Generally, these numbers are expected to go down with an increase in the transaction rate, regardless which blockchain is in use.

8. Verification of approach to estimate electricity consumptions

In order to estimate the electricity consumption of the Ethereum PoS network accurately, the diversity of client software must be considered in the calculation. As explained in section 4 of chapter III, we execute several consensus and execution clients separately to conduct measurements. By subtracting the previously measured average electricity consumption of the hardware in idling state from the measured results, we can determine the marginal electricity consumption for each client software per computer. Hence, by summing up both clients' marginal electricity consumption and adding the respective idle consumption, we can investigate various combinations of one consensus and one execution client. This allows us to quantify the electricity consumption of multiple different client setups.

To verify this approach, we have additionally measured the simultaneous execution of the most popular client configuration, i.e., Prysm as the consensus and Geth as the execution client (35.65 %, see Table 14). Relying on the binomial hardware distribution as introduced in section 5, we calculated the electricity consumption of a best guess node in the Ethereum PoS network that runs this specific configuration. Table 19 summarizes the results in comparison to the results we obtain for the same best guess node by our combinatorial approach, which means by adding up the idle as well as the marginal electricity consumption of Prysm and Geth, as provided in Table 14.

		Ethereum PoS
Combinatorial determination (Prysm + Geth + Idle)	Best guess [W]	60.96
	Best guess [kWh / year]	533.97
	Number of tx (Geth measurement)	2,431,505
Direct measurement (Prysm & Geth)	Best guess [W]	54.91
	Best guess [kWh / year]	481.00
	Number of tx	2,138,612

Table 19: Comparison between combinatorial approach and concrete measurement of best guess estimates for a client configuration executing Prysm and Geth

The results show that both estimates for the same best guess node are quite close to each other, but the combinatorial calculation we apply slightly overestimates the electricity consumption in comparison to the direct measurement of the same client configuration (9 %). However, it should be noted that the measurements were not taken at the same points in time and, therefore, are not perfectly comparable. During the verification measurement, which means while monitoring the simultaneous execution of Prysm and Geth, 292,893 transactions less have occurred compared to the time of collecting data for our combinatorial calculation. This corresponds to a reduction of over 12 % regarding the number of transactions, which is most probably one reason for the slightly lower electricity consumption and thus the difference between both estimation approaches. If the best guess power consumption of the verification measurement were reduced by 12 %, the difference between both approaches would be almost negligible.

9. Carbon footprint of the Ethereum PoS network

The electricity consumption of any system has no direct environmental impact, as mere usage does not cause any emissions. However, the impacts due to the potential emissions of the underlying energy sources may cause damage to the environment and need to be considered for sustainable business operations.

Depending on the underlying energy sources, the respective carbon footprint of the electricity consumption can vary. For a precise estimate of the carbon footprint, two pieces of data are essential: The location of the electricity consumers as well as the carbon intensity of the respective grid.

There are several ways for local electricity consumers to claim that their electricity consumption is carbon neutral. This includes corporate Power Purchase Agreements (PPAs), unbundled energy attribute certificates (EACs) – also often referred to as Renewable Energy Certificates (RECs) –, or off-grid electricity production for self-consumption. As we do not have any information on whether or to what extent the electricity consumption of the Ethereum network is backed by such instruments, we rely on the average grid intensity factor. As these instruments are also often aimed at energy-intensive industries or large corporations, we find the application of the average grid intensity factor to be plausible for a solid estimate of the carbon footprint of the Ethereum network.

Previous research localized nodes in other protocols by relying on internet search machines aimed at ASIC devices, IP addresses, or pool addresses. These approaches allowed for an estimate of how the nodes are distributed worldwide. For the Ethereum Beacon Chain, information on the node location is collected by Miga Labs and presented on their public dashboard (Miga Labs, 2022). Figure 3 displays the node locations on the world map provided by Miga Labs on the 6th of September 2022.

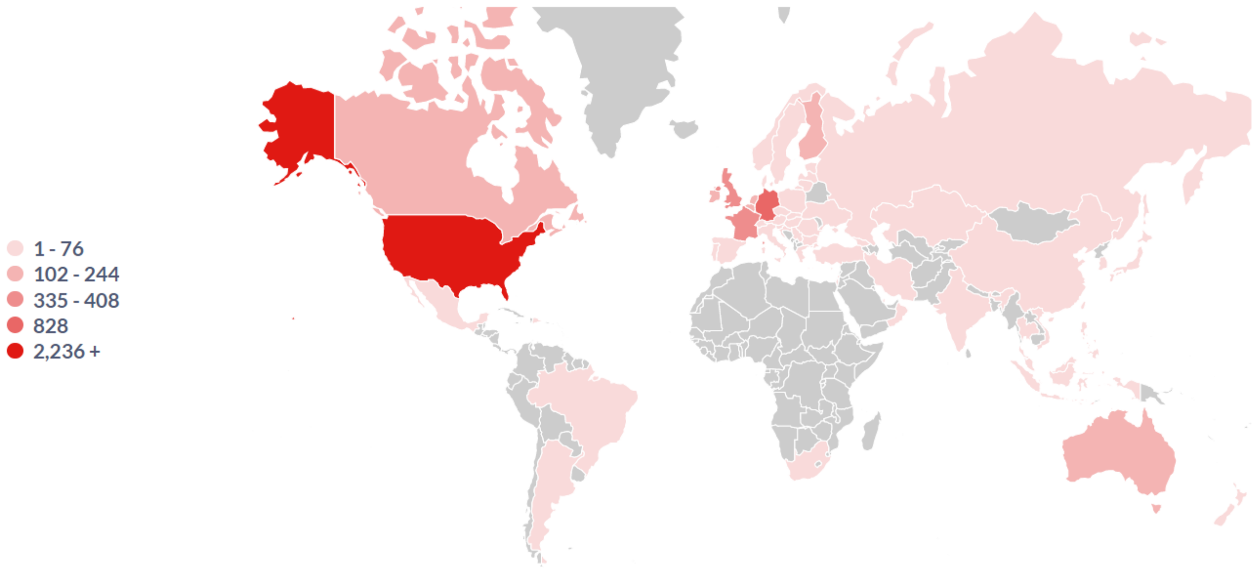

Figure 3: Distribution of Beacon nodes in the
Ethereum PoS network (September 2022) (Miga Labs, 2022)

Utilizing country specific emission factors (carbon footprint, 2022), we calculate the average carbon intensity of the network to be 334.42 gCO_2e/kWh. For unavailable carbon intensities and unavailable node locations, we assume the world average of 459 gCO_2e/kWh in accordance with the IEA (International Energy Agency,

2021) which is the case for 1.95 % of all nodes in the dataset. With that, we can derive the carbon footprint of the network using the following formula:

$$\sum_{i \in node} EnergyConsumption_i * CarbonIntensity$$

The resulting values are depicted in Table 20.

Ethereum PoS	CO_2e emissions / year [t]
Lower bound	278.60
Best guess	**869.78**
Upper Bound	2,090.32

Table 20: Overview of CO_2e emissions of the networks on an annual basis as of time of measurement (August-September 2022)

IV. Results and discussion

In this chapter of the report, we discuss and contextualize the results of our work.

The Merge will result in a significant reduction of the electricity consumption and carbon footprint of the Ethereum network, putting it in a similar range with other Proof of Stake networks. The detailed values for both the pre-Merge (PoW) Ethereum network, the post-Merge (PoS) Ethereum network, and the reduction of the respective sustainability metric are depicted in Table 21.

	Ethereum PoW	Ethereum PoS	Reduction factor
Electricity consumption [MWh/year]	22,900,320	2,600.86	0.99988
CO_2e emissions [t/year]	11,016,000	869.78	0.99992

Table 21: Comparison of annualized electricity consumption and CO_2e emissions of the Ethereum network before (PoW) and after (PoS) the Merge

According to our estimates, the Merge reduces the annualized electricity consumption of the Ethereum network from **22,900,320 MWh to 2,600.86 MWh by over 99.988 %.** This is a reduction by a factor of over 8,639. In addition to the electricity consumption, the carbon footprint is reduced from **11,016,000 tCO_2e to 869.78 tCO_2e**, a reduction by 99.992 %, a factor of over 12,425.

The difference between the reduction factors for the electricity consumption and carbon footprint for pre- and post-Merge are a result of different emission factors. For Ethereum's Proof of Work network, we assume a significantly higher emission factor of ~523 gCO_2e/kWh, whereas we estimate the carbon intensity of Ethereum's PoS network to be ~334 gCO_2e/kWh. Miners in Proof of Work networks seek cheapest electricity, as the electricity costs are a significant business expense. In contrast, validators in Proof of Stake networks do not need to cater to electricity costs in the same manner, as their main expense is, besides the initial stake of 32 ETH, hardware and maintenance costs.

Following figure might help to visualize the electricity consumption reduction the Merge will result in. The Eiffel Tower (330 meters) represents the total electricity consumption of the pre-Merge Ethereum network for one month, the resulting electricity consumption of the post-Merge Ethereum network will be ~3.8 cm high, about the same height as a single plastic toy figure.

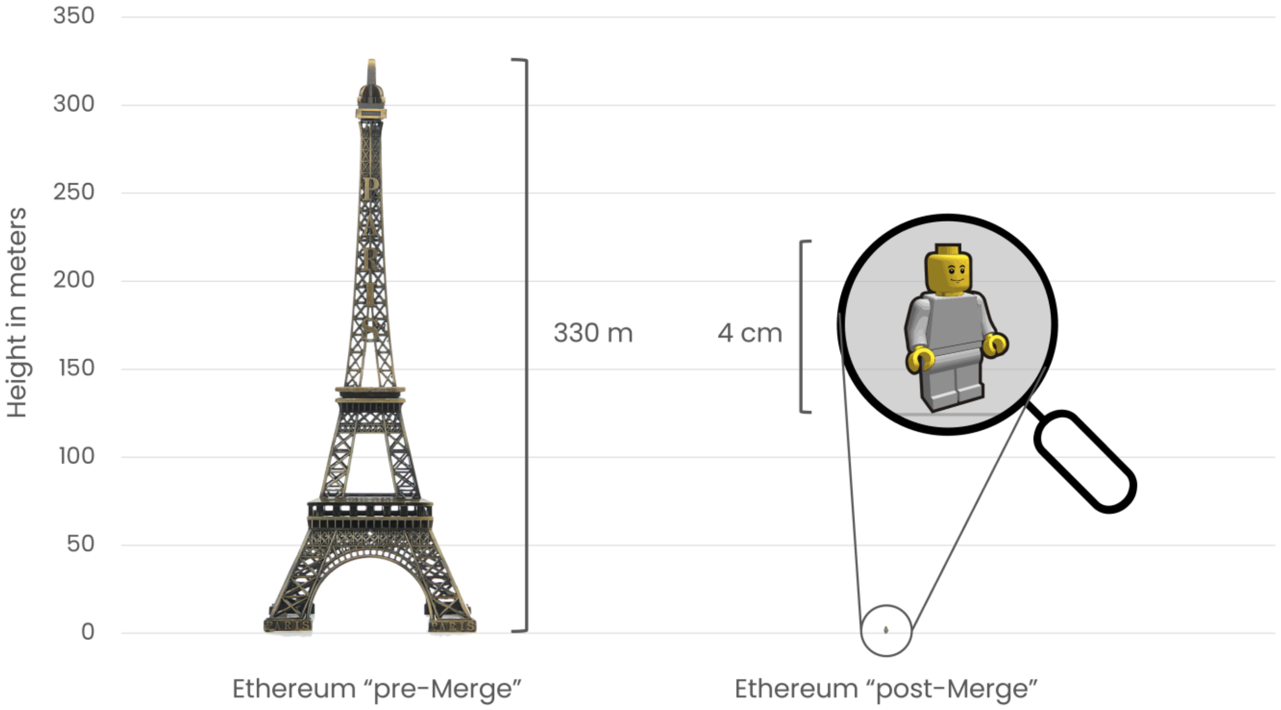

Figure 4: Comparison of the reduction of the electricity consumption of Ethereum pre-Merge and post-Merge on the example of the Eiffel tower and a plastic toy figure[29].

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[29] Eiffel tower image from https://wikipng.net/photo/7939/architecture-eiffel-tower-png-free,
Plastic toy figure taken from https://publicdomainvectors.org/en/free-clipart/Plastic-toy-vector-drawing/31404.html.

V. Conclusion

The Merge is the most significant update for the Ethereum network and the cryptocurrency space in general. It changes the consensus mechanism of Proof of Work to Proof of Stake, reducing the electricity consumption and carbon footprint of the network significantly.

In this report, we first discuss, analyze, and calculate the electricity consumption and carbon footprint of the pre-Merge (PoW) Ethereum network. Second, we outline an approach for calculating the electricity consumption and carbon footprint of the post-Merge (PoS) Ethereum network, accounting for Ethereum's high client diversity and node locations. Third, to provide an estimate of the emissions, we selected hardware, made measurements of the individual nodes, and calculated the respective metrics.

For the pre-Merge Ethereum network, we calculate the **electricity consumption to be 24.10 TWh** and the **carbon footprint to be 13.64 MtCO$_2$e** for the period from 1st August 2021 to 31st July 2022. The respective annualized metrics based on the last month of the pre-Merge network amount to 22,900,320 MWh and 11,016,000 tCO$_2$e, respectively.

For the post-Merge Ethereum network, we estimate the annualized **electricity consumption to be 2,600.86 MWh** and the **carbon footprint to be 869.78 tCO$_2$e** based on the measurements taken place in August and September 2022.

Therefore, t**he Merge reduces the electricity consumption and carbon emissions of the Ethereum network by 99.988 % and 99.992 %, respectively**. Applying this reduction of electricity consumption to the height of the Eiffel tower, it would shrink to about the size of a plastic toy figure.

Given the continuous development and evolution of the Ethereum network, our results can only be taken as a snapshot of the respective timeframe. Further measurements and analyses are required to update and further enhance the validity of the metrics for electricity consumption and carbon footprint of Proof of Stake and other networks. Additionally, other networks employing different consensus mechanisms need to be taken into account to gain a holistic picture of the environmental impact of cryptocurrencies and tokens.

In recent years, Ethereum has faced harsh criticism for its electricity demand and carbon emissions. The Merge and its reduction of electricity consumption and carbon footprint by over 99.98 % marks a significant milestone in both the Ethereum network as well as for the entirety of the cryptocurrency space. After the Merge has taken place, a major step towards environmental sustainability has been done.

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Appendix A: Hardware selection

We use the Passmark CPU Benchmark Dataset. Our methodology to select three CPUs consists of the following steps:

1) The data set contains many processor types that are not relevant to us. We filter out:

    A) CPUs with less than 50 benchmarking results, as we expect that they are not relevant for the validator community.

    B) CPUs that were released before 1/1/2015, as we consider less usage of outdated hardware and a practical reason: We cannot buy these CPUs in the market.

    C) CPUs with missing or incomplete data.

    D) CPUs of AMD. Intel is the dominating manufacturer of CPUs with over 80 % market share over the last years. Not all values in the data set are consistent between both producers, and already one AMD system is included in our data set. Therefore we decided not to consider AMD processors.

    E) CPUs intended for servers or notebooks. We think that the share of server hardware is low and notebooks nonexistent. Some CPUs are marked as "Laptop only" in our dataset; however, we find them included in MiniPCs, e.g., the Intel NUC. To account for these CPUs, we consulted geizhals.de as a source of CPU models sold within MiniPCs and did not remove them from the data set.

2) After obtaining a cleaned data set, we can separate the data set into three equally large categories for later selection: High-level, mid-level, and low-level. While the hardware within the networks might not be equally distributed among these three categories, this approach allows us to shift the allocation for single networks between the devices depending on their hardware requirements.

3) We are confronted with the fact that older, high-level CPU models might have the same computational power as recent low-level CPU models but different energy efficiencies, leading to entirely different results. Therefore, we introduce an additional variable in our data set called *energy efficiency*. The energy efficiency of a processor is the average benchmarking result divided by the TDP. The TDP serves as a proxy for a processor's energy demand capabilities, as it describes the maximum amount of heat measured in Watts the CPU cooling system has to deal with.

4) This variable allows us to calculate the average energy efficiency for each category of CPUs (4-high/3-mid/2-low) and select an average processor from the respective tier. This approach ensures that we a) cover three different performance categories and b) select an average energy efficiency for their respective class.

Appendix B: Electricity measurements of single consensus and execution clients

All electricity measurements are conducted in Watt.

Prysm	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	6.32	27.07	96.37
Q1 [W]	N/A	N/A	N/A	6.99	27.69	100.93
Median [W]	N/A	N/A	N/A	7.13	27.86	102.36
Mean [W]	N/A	N/A	N/A	7.17	27.91	102.50
Q3 [W]	N/A	N/A	N/A	7.32	28.06	103.89
Max [W]	N/A	N/A	N/A	13.09	34.08	118.42
Software version		beacon-chain-v2.1.4-linux-amd				
Measurement period		2022-07-17 03:14:57,349 to 2022-07-19 03:14:59,194				

Table 22: Electrical power while running a node with Prysm consensus client measured in Watt [W]

Lighthouse	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	5.62	27.18	89.97
Q1 [W]	N/A	N/A	N/A	6.11	27.82	95.45
Median [W]	N/A	N/A	N/A	6.26	28.03	96.74
Mean [W]	N/A	N/A	N/A	6.41	28.18	97.01
Q3 [W]	N/A	N/A	N/A	6.42	28.29	98.25
Max [W]	N/A	N/A	N/A	14.28	38.09	118.39
Software version		v2.4.0-21dec6f				
Measurement period		2022-08-04 11:39:26,451 to 2022-08-06 11:39:26,552				

Table 23: Electrical power while running a node with Lighthouse consensus client measured in Watt [W]

Teku	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	5.97	27.50	100.16
Q1 [W]	N/A	N/A	N/A	6.46	27.88	104.15
Median [W]	N/A	N/A	N/A	7.44	28.02	105.31
Mean [W]	N/A	N/A	N/A	7.37	28.36	105.63
Q3 [W]	N/A	N/A	N/A	7.80	28.24	106.65
Max [W]	N/A	N/A	N/A	26.46	41.43	130.58
Software version		22.8.0 (JDK: OpenJDK 11.0.16 2022-07-19)				
Measurement period		2022-08-13 11:08:35,624 to 2022-08-15 11:08:35,726				

Table 24: Electrical power while running a node with Teku consensus client measured in Watt [W]

Nimbus	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	4.72	26.08	84.67
Q1 [W]	N/A	N/A	N/A	5.09	26.69	92.71
Median [W]	N/A	N/A	N/A	5.17	26.89	94.99
Mean[W]	N/A	N/A	N/A	5.33	27.12	95.28
Q3 [W]	N/A	N/A	N/A	5.31	27.29	97.55
Max [W]	N/A	N/A	N/A	9.52	36.95	111.10
Software version		22.7.0				
Measurement period		2022-08-17 11:02:03,248 to 2022-08-19 11:02:04,123				

Table 25: Electrical power while running a node with Nimbus consensus client measured in Watt [W]

Lodestar	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	5.82	27.64	100.94
Q1 [W]	N/A	N/A	N/A	6.48	28.52	110.02
Median [W]	N/A	N/A	N/A	6.68	28.80	111.86
Mean [W]	N/A	N/A	N/A	6.80	28.93	111.72
Q3 [W]	N/A	N/A	N/A	7.01	29.20	113.58
Max [W]	N/A	N/A	N/A	9.98	33.91	131.68
Software version		v1.0.0/d78131b (Node: 16.17.0, Yarn: 1.22.19)				
Measurement period		2022-08-26 13:01:03,054 to 2022-08-28 13:01:03,156				

Table 26: Electrical power while running a node with Lodestar consensus client measured in Watt [W]

Geth	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	4.77	26.32	81.94
Q1 [W]	N/A	N/A	N/A	13.53	33.24	123.71
Median [W]	N/A	N/A	N/A	14.86	34.58	125.93
Mean [W]	N/A	N/A	N/A	14.89	34.74	125.87
Q3 [W]	N/A	N/A	N/A	16.18	36.07	128.00
Max [W]	N/A	N/A	N/A	26.71	54.63	152.12
Software version		1.10.21-stable (Go: 1.18.04)				
Measurement period		2022-08-20 11:57:46,076 to 2022-08-22 11:57:46,177				

Table 27: Electrical power while running a node with Geth execution client measured in Watt [W]

Erigon	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	16.97	39.33	117.72
Q1 [W]	N/A	N/A	N/A	21.30	41.96	119.88
Median [W]	N/A	N/A	N/A	22.20	42.44	121.20
Mean [W]	N/A	N/A	N/A	22.26	42.63	122.79
Q3 [W]	N/A	N/A	N/A	23.06	43.00	124.73
Max [W]	N/A	N/A	N/A	34.40	55.90	152.19
Software version		2022.99.99-dev-15ca3d25 (Go: 1.18.04)				
Measurement period		2022-08-09 18:08:23,164 to 2022-08-11 18:08:23,762				

Table 28: Electrical power while running a node with Erigon execution client measured in Watt [W]

Besu	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	31.70	51.73	104.84
Q1 [W]	N/A	N/A	N/A	33.16	54.76	151.39
Median [W]	N/A	N/A	N/A	33.73	55.42	153.19
Mean [W]	N/A	N/A	N/A	33.91	56.06	153.21
Q3 [W]	N/A	N/A	N/A	34.36	56.41	155.05
Max [W]	N/A	N/A	N/A	40.36	70.40	169.27
Software version		22.7.1 (JDK: OpenJDK 11.0.16)				
Measurement period		2022-09-02 09:06:38,844 to 2022-09-04 09:06:38,854				

Table 29: Electrical power while running a node with Besu execution client measured in Watt [W]

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CCRI – *Crypto Carbon Ratings Institute* – is a research-driven company providing data on sustainability aspects of cryptocurrencies, blockchain and other technologies. The interdisciplinary team has built a multi-year research track record with a specific focus on cryptocurrencies and their sustainability impacts. CCRI uses the most up-to-date data sources as well as methods based on formerly peer-reviewed studies published in renowned scientific journals*.* CCRI provides insights that help their clients to understand and manage crypto-related ESG exposure. They serve a broad range of clients including institutional investors, exchanges and blockchain networks.

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