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White paper:

Determining the electricity consumption and carbon footprint of Proof of Stake networks

Crypto Carbon Ratings Institute (CCRI)[1]
https://carbon-ratings.com

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[1]*Crypto Carbon Ratings Institute* is a research-driven company providing data on sustainability aspects of cryptocurrencies, blockchain and other technologies. CCRI was founded by Ulrich Gallersdörfer, Lena Klaaßen and Christian Stoll in 2021. More information: https://carbon-ratings.com.

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INTRODUCTION

The electricity consumption and related carbon footprint of Bitcoin and other cryptocurrencies are subject to extensive discussion in public, academia, and industry. Various estimations exist, comparing Bitcoin's electricity consumption to different mid-sized countries (CCAF, 2022; Vries, Gallersdörfer, Klaaßen, & Stoll, 2022).[2] The problem has been known for several years, and other systems and technologies have emerged to solve the issue. The consensus family of Proof of Stake (PoS) is deemed superior regarding the electricity requirements compared to the traditional Proof of Work (PoW) consensus mechanisms (King & Nadal, 2012). While it is consensus in the broader scientific community that PoS does not exhibit the same electricity issues of PoW, the responsibility of individual PoS systems is typically less clear.

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. Due to the nature of the software engineering process and network architectures, different PoS systems rely on varying fundamentals regarding the hardware requirements, programming language, network size, transaction throughput, transaction complexity, and more. These factors influence the electricity consumption and, therefore, the carbon footprint of a respective network. While it is expected that the overall differences between PoS networks are minor, it is nonetheless essential to understand the absolute and relative energy efficiency of single networks (Gallersdörfer, Klaaßen, & Stoll, 2020).[3] In previous industry reports, CCRI calculated both the electricity consumption and carbon footprint of a wide range of Proof of Stake networks, namely Algorand, Avalanche, Cardano, Polkadot, Tezos, and Solana (CCRI, 2022a) as well as TRON (CCRI, 2022c), Polygon (CCRI, 2022b) and Ethereum (CCRI, 2022d).[4] There are also estimates for other PoS systems, albeit no actual hardware measurements took place (Platt et al., 2021).

This white paper aims to outline the methodology used by CCRI to derive the electricity consumption of PoS networks. By doing this, we aim to work towards more standardized approaches for assessing PoS networks and build the foundation for constant improvement based on established approaches summarized in this white paper.

[2] Transparency note: This article was co-authored by the founders of CCRI.
[3] Transparency note: This article was authored by the founders of CCRI.
[4] Transparency note: The industry reports have been commissioned by Avalanche, TRON, Polygon and ConsenSys.

OVERVIEW OF APPROACH

Our methodology builds upon five steps to generate data on the electricity consumption and carbon footprint of a PoS system.

(1) In the first step, we analyze the respective PoS network and its minimum hardware requirements. The hardware requirements are an indicator of the hardware composition of the network. We use this information to select and obtain hardware that we use to measure a single node's electricity consumption.

(2) In the second step, we estimate the electricity usage of a single node and provide upper and lower bounds as well as a best guess estimate for the network. We start by running the network's client software on all obtained hardware devices and measure their single electricity consumption while running the network and while idling. We also measure other data points, such as CPU utilization and processed blocks, to be able to evaluate additional metrics. These values allow us to produce reasonable upper and lower bounds for running a single node, as our hardware is selected accordingly.

(3) In the third step, we estimate the electricity consumption of the complete network. For this, we collect information about the size of the network, as the node count significantly influences the amount of electricity consumed. We then multiply the electricity consumption of the best guess estimate by the number of nodes in the network.

(4) In the fourth step, we analyze additional data (such as transactions and block information) to develop further metrics to explore energy efficiency in transaction throughput. We take samples of the nodes' electricity consumption periodically and examine the number of transactions that were handled by the single nodes during the respective time periods. This allows us to describe the marginal influence of the number of transactions on the electricity consumption of a node. As a result, we establish a model to estimate a node's electricity consumption based on the number of transactions. This enables us to put the electricity consumption of the analyzed network into perspective with other PoS networks and also other cryptocurrencies.

(5) In the fifth step, we estimate the carbon emissions arising from the operation of the considered PoS network. If data on the location of the network's nodes is available, we use country-specific emission intensities to calculate a network-specific emission intensity. If no information on the regional distribution of the nodes in the network is present, we rely on the world average emission intensity.

(1) Hardware requirements and test environment

We observe three general categories of hardware requirements across PoS systems 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.
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. In these cases, we include the respective results in our calculation. Nonetheless, hardware requirements typically give users who intend to run a node an indication of 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 an immense processing power required.

HARDWARE DESCRIPTION

We define a standardized hardware pool that covers the above-mentioned categories in order to ensure a high degree of hardware diversity for the analyses of PoS networks.

A detailed description of the single hardware configurations used in our test environment can be found in the CCRI API documentation:
https://docs.carbon-ratings.com/methodology/carbon-accounting/representative-hardware

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.

We consider our selection as representative to provide a balanced set of hardware for electricity measurements. As an operating system, we use Ubuntu Server 24.04 for all our devices.

HARDWARE SELECTION

For the analysis of a specific PoS network, it is important to decide on a case-by-case basis which hardware configurations to consider in the analysis. Depending on the hardware requirements of the network, we do not run the measurement on all hardware configurations. As we do not want to enforce the network's hardware requirements as a strict lower bound, we try to include hardware configurations that only barely satisfy the hardware requirements.

INFRASTRUCTURE FOR ELECTRICITY MEASUREMENTS

For the measurement of the electricity consumption, we use certified electricity measurement devices for each computer. These devices measure the electricity consumption as well as the room temperature and provide the values over a REST interface. The electricity measurements are made in Germany in an environment with near-constant room temperature.

All devices are equipped with the same software, a new Ubuntu server 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, collects and monitors the systems during executing the full nodes and analyses the data generated during the runs. All computers are only connected to the power outlet and LAN. All systems share an internet connection with 980 Mbit/s download and 340 Mbit/s upload.

(2) Electricity consumption of a single node

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, represented by the most and least efficient hardware, and the best guess as a weighted average between the selected computer devices. On that basis, we will then establish the electricity consumption of the overall PoS network.

SINGLE NODE MEASUREMENTS

After defining the hardware required for our analysis, we set up the hardware and install the node client software for the considered 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 full node of the PoS network to be analyzed and verify the correct installation.
4. **Node Bootstrap.** On each node we include in our analysis, we start the execution of the client software necessary to run a full node of the network to be analyzed. We wait until the node is fully synced since we do not want to skew the electricity consumption of the devices during the bootstrapping phase.
5. **Electricity Measurement.** We shut down the node, start the electricity measurement and then start the node again. The node runs for 24 hours executing the network's client software, as this covers an entire day cycle.

To understand what exactly we are measuring, we need to describe a standard PoS network and its common setup. It consists of nodes running a client service, either validators (participating in the consensus protocol and producing new blocks) or regular full nodes (broadcasting and verifying regular transactions). In an ideal setup, we would differentiate between full nodes and validators, as they have slightly different roles and responsibilities within the network, however, significant stakes are commonly required to run a validator. Furthermore, previous research suggests that participating in the PoS consensus mechanism has only a negligible effect on the device's electricity consumption (Sedlmeir, Buhl, Fridgen, & Keller, 2020). Therefore, we run our electricity measurement on regular full nodes running on the PoS network.

IDLE ELECTRICAL POWER

We measure the electricity consumption of all devices in idle mode.

CALCULATION OF BOUNDS AND A BEST GUESS FOR ELECTRICITY CONSUMPTION

With the measurements of the electricity consumption for each hardware configuration when running a full node in a respective PoS network, we can provide an upper bound (the highest electricity that a node consumes), a lower bound (the least electricity a node consumes), and a best guess that captures the consumption of the average node best for the network.

Upper and lower bound. The upper and lower bound are determined by the least efficient and most efficient hardware.

Best guess. The electricity consumption of an average node in a network is challenging to estimate. Typically, 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 hardware selected out of our pool for the network considered, based on a regular distribution for key questions. With this distribution, we calculate the electricity consumption of an average node by taking a weighted average of the single nodes' electricity consumptions.

(3) Electricity consumption of the entire network

To calculate the electricity consumption of the overall network, we take the number of all nodes in the considered PoS network and multiply it by our best guess estimate of the electricity consumption of an average node. By using the lower and upper bound of the electricity consumption of a single node, we may also derive a respective lower and upper bound for the network's electricity consumption. Usually, we obtain the number of nodes of the network from a publicly accessible source.

(4) Analysis of efficiency in transaction throughput

DISCUSSION ON ELECTRICITY CONSUMPTION PER TRANSACTION METRIC

An often-used metric in comparing electricity consumption between systems is the electricity consumption per transaction, which is frequently calculated by dividing the total electricity consumption by the total number of transactions within a specific time period. The underlying idea is to compare systems that have different architectures, transaction throughput, and electricity requirements. However, such comparisons are associated with several challenges and complexities.

First, underlying definitions may influence the results significantly. For instance, 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.

Second, there is additional complexity caused by 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 and vice versa. This may also distort comparisons across networks when electricity consumption per transaction is used as the central metric. Consequently, albeit the metric may provide straightforward insights into different protocols, its base assumptions need to be understood and its results must be treated with care and in context of other metrics.

Third, the electricity consumption per transaction is only one 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.

MARGINAL ELECTRICITY CONSUMPTION PER TRANSACTION

To address the above-mentioned challenges, we measure the power demand of our nodes in a real-world scenario and consider the transactions per second throughput that took place during the respective time period. We then derive the marginal electricity consumption per transaction based on a statistical regression model.

With this approach, we aim to obtain more accurate results than merely considering average values. Furthermore, it has the advantage that constant power demand, which is independent of the transaction count, can be differentiated from the power demand that is driven by transactions. The regression model is set up completely on the basis of our own measurements. We filter outliers and construct a regression line for each of the hardware configurations selected for the considered PoS network, based on our periodically taken measurement samples that consist of the current power demand and the transactions per second throughput at that time.

Based on this, we can establish a linear equation for a regression line to predict the power demand of a best guess node operating in a PoS network (P_{BG}) for a given transactions per second (tps) throughput. To determine a general slope (m_{BG}) for a network's best guess node, which represents the electricity consumption per transaction in Watt seconds, we weigh the slopes of the individual regression lines of all hardware configurations included in our measurements. Likewise, we derive a weighted y-axis intercept ($base_{BG}$), which represents the node's power demand while executing no transactions but running the client software of the network. As a result, we obtain a linear regression equation to determine the power demand of a best guess node in the considered network depending on the transactions per second the best guess node processes:

$$P_{BG}(tps)\ [W] = m_{BG} * tps + base_{BG}$$

Multiplying a network's node count by the resulting power demand of a best guess node allows us to estimate the overall network's power demand for a specific transaction per second throughput based on our model:

$$P_{network}\ [W] = P_{BG}(tps) * nodeCount$$

(5) Estimation of the network's carbon emissions

The electricity consumption of any system has no direct climate impact, as mere usage does not necessarily cause any emissions. However, the impacts due to the potential emissions of the underlying energy sources may cause damage to the climate 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 commonly do not have any information on whether or to what extent the electricity consumption of a PoS 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 a PoS 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. It depends on the specific network to be analyzed whether information on the node location is available

or not. If data on where the single nodes are located is present, we calculate a network-specific emission intensity utilizing location-specific emission factors. If there is no data on node locations, we assume the latest available world average emission intensity.

With that, we derive the carbon footprint of the network by multiplying the determined carbon intensity with the sum of the best guess electricity consumption over all nodes in the network:

$$CarbonIntensity * \sum_{i \in node}^{NetworkNodeCount} ElectricityConsumption_i$$

Likewise, by applying the lower and the upper electricity consumption bounds, a lower and an upper bound for the overall network's carbon emissions can be estimated.

CONCLUSION

In this white paper, we outlined the methodology proposed by CCRI to derive the electricity consumption and carbon footprint of PoS networks. By relying on actual measurements instead of a purely model-based approach, this methodology allows to base the estimate on empirical data. The described approach is very well suited to provide a detailed snapshot of the respective timeframe. By monitoring the node and transaction count, the assessment can serve as basis to provide dynamic estimates of the electricity consumption and carbon footprint of PoS networks.

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About CCRI

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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