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REPORT

Energy Efficiency and Carbon Footprint of the **Polygon Blockchain**

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Preamble

This commissioned report is prepared by CCRI for
Polygon Technology

Executive summary

- The **electricity consumption and carbon footprint of Proof of Work** (PoW)-based networks and cryptocurrencies such as Bitcoin and Ethereum **remain significant**.
- Existing research suggests that cryptocurrencies based on alternative consensus mechanisms such as **Proof of Stake (PoS)** are **more energy efficient**.
- **Layer 2 networks increase complexity** of **emission estimation** as they have to fully account for the emissions from their own network as well as the impact on the underlying layer 1.
- This report **assesses the electricity consumption** and **carbon footprint** of the layer 2 PoS network **Polygon**, which is a sidechain building on the PoW-based network Ethereum.
- From 01.08.2021 to 31.07.2022, it is estimated that the **activity of Polygon on Ethereum** has **caused 60.9 ktCO$_2$e** emissions.
- Consequently, **one transaction** on Polygon has to additionally account for **45.27 gCO$_2$e** of carbon emissions due to layer 1 activity.
- As of July 2022, the **yearly electricity consumption** of the Polygon PoS network sums up to **109,213.48 kWh**, which results in a carbon footprint of **50.13 tCO$_2$e**. Thereof, the majority (more than 99.9 %) of emissions originate from the activities of Polygon on Ethereum.
- The **electricity consumption** of the Polygon PoS network itself sits **within the range** of **previously studied PoS blockchain** networks.
- The **marginal electricity consumption** for a single transaction within the Polygon PoS network is **0.608776 Ws per Tx**.

I. Overview

1. Introduction

The electricity consumption and related carbon footprint of Bitcoin and other cryptocurrencies are subject to extensive discussion in public, academia, and industry. For these protocols, various estimations exist, comparing Bitcoin's electricity consumption to different mid-sized countries(CBECI, 2022; de Vries, 2021). 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)[1]. Previous research conducted by CCRI, calculated both the electricity consumption and carbon footprint of the Proof of Stake networks Algorand, Avalanche, Cardano, Polkadot, Tezos, and Solana (CCRI, 2022c) as well as TRON (CCRI, 2022d). There are also estimates for other PoS systems, albeit no actual hardware measurements took place (Platt et al., 2021).

Since the Proof of Stake network Polygon is a layer 2 sidechain that builds on the Ethereum network, one also needs to account for activities that Polygon is responsible for on its underlying base layer to conduct a proper carbon estimate. Ethereum itself uses a Proof of Work consensus algorithm.

An extensive analysis of the electricity consumption and carbon footprint is not yet available for the layer 2 cryptocurrency Polygon. Therefore, this report examines the electricity consumption, carbon footprint, and influencing factors of the Polygon Proof of Stake blockchain network and estimates Polygon’s impact on its PoW base layer Ethereum. Table 1, Table 2 and Table 3 summarize the most important results of base layer allocation, Polygon PoS network, and total carbon footprint, respectively.

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[1] Transparency notice: This paper was co-authored by the founders of CCRI.

Transactions [Tx/year][2]	Carbon emissions per transaction [gCO_2e/year]	Holding caused carbon emissions [tCO_2e/year]	Transaction caused carbon emissions [tCO_2e/year]	Total carbon emissions [tCO_2e/year]	Lifetime carbon emissions [tCO_2e/year][3]
1,345.44 M	45.27	42,932.81	17,970.33	60,903.13	94,692.77

Table 1: Overview of results for Polygon base layer allocation of the Ethereum PoW network in the period from 01st August 2021 to 31st July 2022.

Nodes [# total][4]	Transactions [Tx/year][5]	Total electricity consumption [kWh/year]	Electricity per node [kWh/year]	Electricity per transaction [Wh/Tx]	Marginal Electricity [Ws/Tx]	Total carbon emissions [tCO_2e/year]
200	1,058.73 M	109,213.48	546.07	0.1031	0.608776	50.13

Table 2: Overview of results for Polygon PoS network based on measurement as of July 2022.

	Total carbon emissions [tCO_2e/year]
Polygon total	60,953.26

Table 3: Overview of results for Polygon total in the period from 01st August 2021 to 31st July 2022.

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[2] Polygonscan, https://polygonscan.com/chart/tx, accessed 22nd August 2022.

[3] Lifetime carbon emissions range from 20th April 2019 to 31st July 2022.

[4] There are 100 validators in the Polygon PoS network at the time of measurement, however, we double this amount for our calculations since each validator needs to be connected to a sentry node to operate properly.

[5] We assume the number of transactions occurred during our measurement period of one day to extrapolate to a yearly transaction count which is needed to contextualize the electricity consumption.

2. Aim and scope

This report aims to provide insights into the electricity consumption and carbon footprint of the Polygon Proof of Stake network and its impact on the layer 1 network, Ethereum, which serves as the base layer of the Polygon side chain.

The Polygon PoS network investigated in our analysis takes the 13th position with regard to market capitalization of coinmarketcap.com on 31st July 2022[6]. We summarize important key figures for the Polygon (MATIC) cryptocurrency as per the specified date in the following:

Name:	Polygon
Symbol:	MATIC
Market Capitalization (Rank):	$ 7,458,425,921 USD (13th)
POLYGON Price:	$ 0.9296 USD
Circulating Supply:	8.03 B MATIC
24 Hours Trading Volume:	$ 1,102,958,859 USD

In order to fully assess the emissions generated by Polygon, two different aspects need to be considered: First, the devices participating in the network require electricity and thus cause emissions. Second, Polygon as a layer 2 side blockchain causes activities on its base chain Ethereum, which also must be attributed to the emissions generated by Polygon. Figure 1 depicts the two sources of emissions regarding Polygon, both the Polygon network layer itself and the relevant portion of the Ethereum base layer.

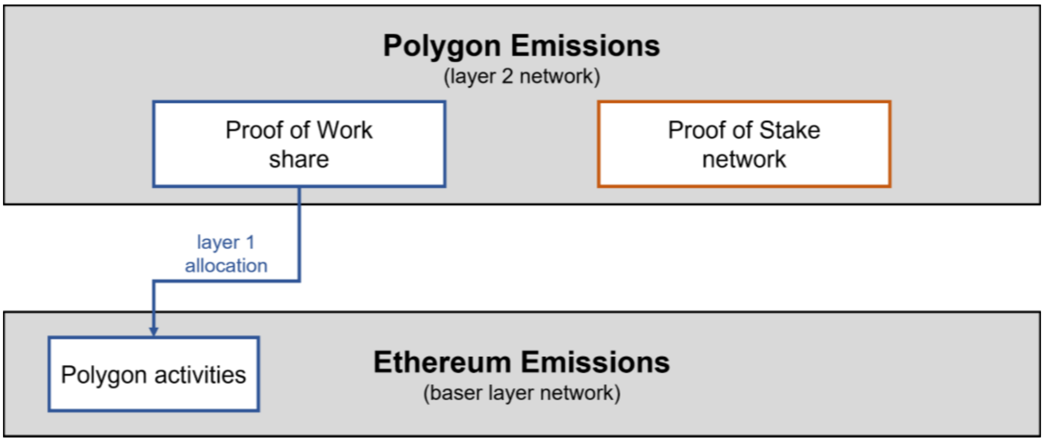

Figure 1: Emission allocation framework for Layer 2 networks such as Polygon

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[6] The data is taken from https://coinmarketcap.com/historical/20220718/.

The following of this report is divided into three chapters. Firstly, we analyze the emissions of Ethereum that are caused by the Polygon layer 2 blockchain, and thus attributable to it. Secondly, we examine the electricity consumption and the emissions generated by the Polygon PoS network itself. Thirdly, we compare these results and discuss our observations. The specific measurement 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 as well as the relative performance. 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 the most precise electricity consumption and carbon footprint estimates for the Polygon cryptocurrency, as we a) observe and measure the electricity consumption of single hardware components and use them as a proxy for the overall PoS network as well as b) use current estimates for the electricity consumption and carbon footprint of the Ethereum network to estimate the impact of the respective activities of the Polygon network on Ethereum.

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.

II. Proof of Work Component

1. Base layer allocation of Ethereum PoW

Polygon is a layer 2 Proof of Stake network built on Ethereum network which utilizes a Proof of Work consensus mechanism[7]. Polygon relies and utilizes Ethereum's security properties for the integrity of its own network by periodically committing the state of its own chain on Ethereum. To conduct a proper emission estimate of the Polygon PoS network, one also needs to account for any activities that the Polygon network is responsible for on the underlying Ethereum layer. For that, we deploy a five-step approach to understand and calculate the carbon emissions stemming from the activities on the Ethereum base layer.

Five-Step Emission Allocation for the Polygon network

1. **Electricity consumption of the Ethereum network**: In an initial step, we need to 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, one needs to 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.

3. **Framework selection**: There are a variety of frameworks available for allocating the overall network emissions to individual activities: holdings, transactions, and mining new coins. The selection of the framework influences the respective carbon allocation; therefore, one should select a framework that depicts the market mechanics as closely as possible.

4. **Determination of activities**: One needs to determine all activity of the second layer network on the base layer blockchain. In Polygon's case, the network employs a set of smart contracts on the Ethereum network to ensure the integrity of its own network. Depending on the previously selected allocation framework, transactions and historical balances need to be considered for the overall carbon footprint estimate.

5. **Allocation of activities:** As soon as a framework has been selected and all relevant activities have been determined, the respective share of carbon emissions can be calculated for the Polygon network. With this data, it is also possible to estimate the amount of carbon emissions per transaction on Polygon due to base layer activity.

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[7] To be more precise, PoW is a sybil control mechanism whereas the Nakamoto consensus with the longest tip selection is considered as a consensus mechanism. For the purposes of this report, we are referencing PoW as a consensus mechanism.

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.[8] 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[9] to the network and collect a mining reward containing a block subsidy as well as all transaction fees[10] 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. On the 29th of July 2022, Bitcoin miners received around 22.3 million USD in the last 24 hours[11] as mining reward whereas Ethereum miners received about 23.9 million USD for the same period[12].

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[13]. 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*

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

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

[10] 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.

[11] https://bitinfocharts.com/de/bitcoin/, accessed on the 29th July 2022

[12] https://bitinfocharts.com/de/ethereum/, accessed on the 29th July 2022

[13] 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.

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 90% as of mid-August 2022. With these assumptions, his estimate of the Ethereum network derives an overall annual electricity consumption of ~90 TWh as of mid-August 2022 (de Vries, 2022a, 2022b).

The **bottom-up approach** was initially described in scientific literature by Krause / Tolaymat in 2018 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, 2022b). 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 2 displays an overview of both top-down method by de Vries (2022b) as well as both bottom-up estimates by Gallersdörfer et al. (2020)[14] and McDonald (2021)[15].

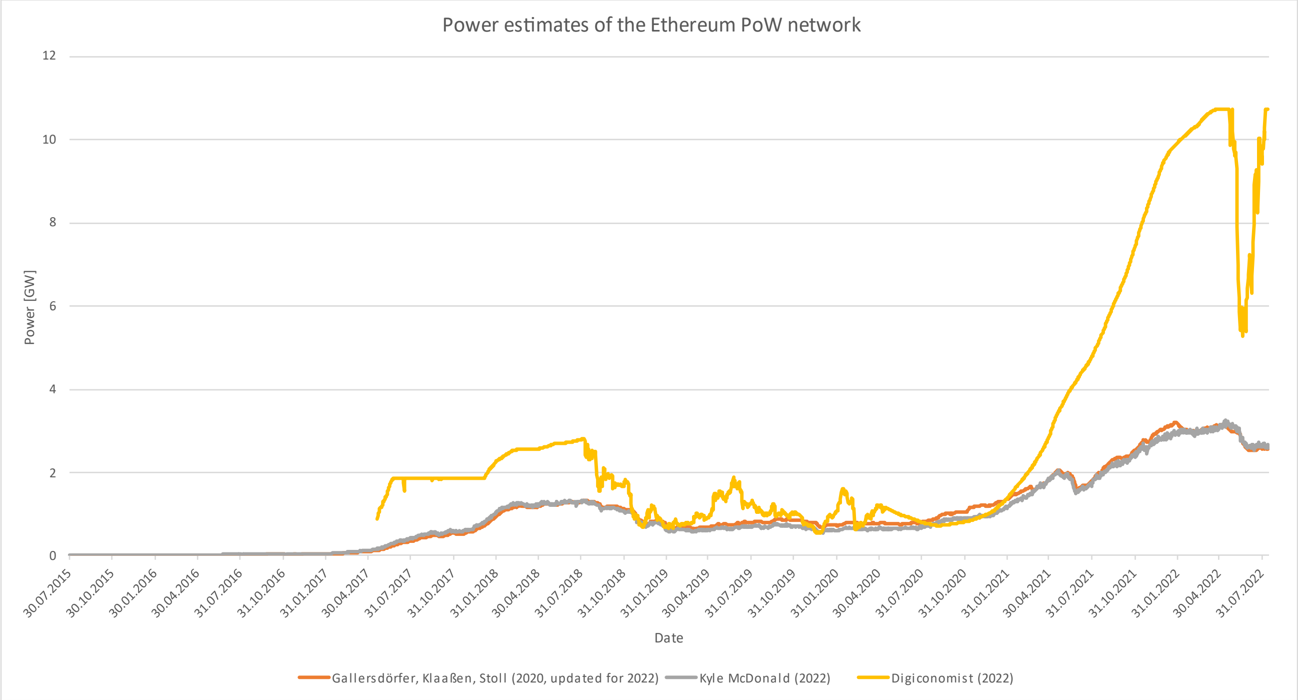

Figure 2: Estimates of power usage of the Ethereum network by Gallersdörfer et. al, Kyle McDonald and Digiconomist. Data from Digiconomist is transformed to GW to align.

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.

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

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

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[16], 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.

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[17]. 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 location and carbon intensity exist (CBECI, 2022; de Vries, Gallersdörfer, Klaaßen, & Stoll, 2022; Stoll, Klaaßen, & Gallersdörfer, 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

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[16] 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.

[17] 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.

self-reported location by miners[18] 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[19]. 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.

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[20], leading to an average carbon intensity for the relevant period of 501 gCO_2e/kWh, leading to the overall emissions of 23.15 $MtCO_2e$ for the period of 20th April 2019 to 31st July 2022.

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[18] 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.

[19] 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.

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

4. The allocation framework selection

As we estimate the overall carbon footprint of the Ethereum network, we need to understand how to properly distribute the carbon emissions to the individual activities within the network.

For that, we identify three different activities that take place in any cryptocurrency network:

Holding of cryptocurrency: In times in which Bitcoin is referred to as digital gold and more people invest in cryptocurrency, the holding of crypto becomes one of the central activities of an entity within a cryptocurrency. Whether holding itself can be determined as activity, given that the entity does not have to actively participate in the network, is analyzed in the next paragraph.

Execution of transactions: Transactions are the central building block of any cryptocurrency, enabling the shift of ownership of the respective crypto assets and also allowing further use cases such as data storage, smart contract setup and execution, creation and utilization of tokens, NFTs and many more. Independent of the underlying use case that is built on the blockchain, on-chain[21] transactions are required in any case.

Creation of new coins: New coins can be the result of a mining process; miners get rewarded for their activity and also contribute to the inflation of the supply. In Bitcoin, the total supply of 21,000,000 bitcoins is hard coded into the protocol whereas other networks, such as Ethereum, have a dynamic supply without a fixed target supply.

Overall, the major part of the emissions results from the production of the electricity that miners' use for their activities and therefore are part of miners' scope 2 emissions, according to the Greenhouse Gas Protocol (GHG Protocol). Consequently, these emissions form value chain emissions (so-called scope 3) of any other entity that is up- and downstream of the miners. This is the case in the cryptocurrency ecosystem: Entities that are involved in holding or transacting crypto need to account for respective emissions as well. The question is not if, but how to determine the respective to-be allocated emissions.

For allocating emissions from cryptocurrencies to single activities, several frameworks exist. We cover them briefly and discuss their advantages and disadvantages. Generally, it is difficult to credit these frameworks to their origin, as multiple entities came up with them independently and these approaches are rather straightforward in their thinking. Nonetheless, we give a non-exhaustive list of these frameworks.

The **transaction-based approach** allocates all emissions of the overall network to all transactions that took place in the same time frame. If an entity is responsible for 1 % of all transactions, it is also responsible for 1 % of all emissions of the respective network. This approach seems intuitive at first, as transactions are the main activity that is visible on-chain. Also, it is an often-cited metric in the media to display the electricity consumption of cryptocurrencies. Nonetheless, this approach is rather limited and one-sided, as it does not take the role of holders into account. The formula for the transaction-based approach is depicted in Figure 3.

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[21] Off-chain transactions exist as well, e.g., if an entity buys or sells crypto at a centralized service. As this shift of ownership on an exchange does not impact the network, we do not account for any of these activities.

$$\text{Entity-specific carbon footprint} = \text{Total network emissions} \times \left(\frac{\text{Executed transactions}}{\text{Total network transaction count}} \right)$$

Figure 3: Formula of the transaction-based allocation methodology. Blue-colored variables are entity-specific, whereas purple colors represent network-based values.

The **holding-based approach** takes the opposite route and instead of considering all transactions, it considers all holdings in a given time frame. If an entity holds 1 % of the entire supply of a cryptocurrency, it is also responsible for 1 % of the respective carbon footprint of the network. This approach shifts the responsibility to all holders, who significantly profit from a functioning network as well as contribute to the price increase of the cryptocurrency by reducing the supply of the currency. As outlined previously, an increasing price is a key driver for higher electricity consumption of a PoW network. Nonetheless, also the holding-based approach negates the responsibility of any transactions and therefore lacks a comprehensive view. The formula for calculating a holding-based share is given in Figure 4.

$$\text{Entity-specific carbon footprint} = \text{Total network emissions} \times \left(\frac{\text{Number of coins held in crypto}}{\text{Total supply of cryptocurrency}} \right)$$

Figure 4: Formula of the holding-based allocation methodology. Blue-colored variables are entity-specific, whereas purple colors represent network-based values.

The **hybrid approach**[22] acknowledges that both holdings and transactions contribute to the miners' rewards and therefore both need to properly be accounted for. From an incentive perspective, miners receive both block subsidies and transaction fees. While transaction fees are paid by entities that execute transactions, it might not be intuitive why the block subsidy is paid by all holders. To understand the relationship between holders and block subsidies, we need to consider the creation of new currency. As miners propose new blocks, they are rewarded with new coins. While the supply of the currency inflates, the value of the overall currency stays the same. Therefore, the value of the individual coin is decreasing; the value of every holding in the respective cryptocurrency gets devalued; the difference in form of new coins is paid to the miner as the block subsidy. This results in an indirect payment of all holders towards the miners which in turn use this money to purchase electricity to run their mining devices. Therefore, all holders are responsible for the share of the block subsidy of the overall reward. The hybrid approach accounts for these phenomena and distributes the total network emissions to both all holders and all entities executing transactions. The share between holders and transactions is weighted by the respective share of both components. A disadvantage of the hybrid approach is the additionally required data, both from the entity and network side, which might be difficult to obtain. Figure 5 displays the share of transaction fees on the overall mining reward of Bitcoin and Ethereum in 2021 (Gallersdörfer et al., 2021). Figure 6 contains the formula for the hybrid approach.

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[22] Transparency notice: The hybrid approach was developed by CCRI and South Pole under consultation with PayPal (CCRI, 2022a). A more technical whitepaper is also available (Gallersdörfer, Klaaßen, & Stoll, 2021).

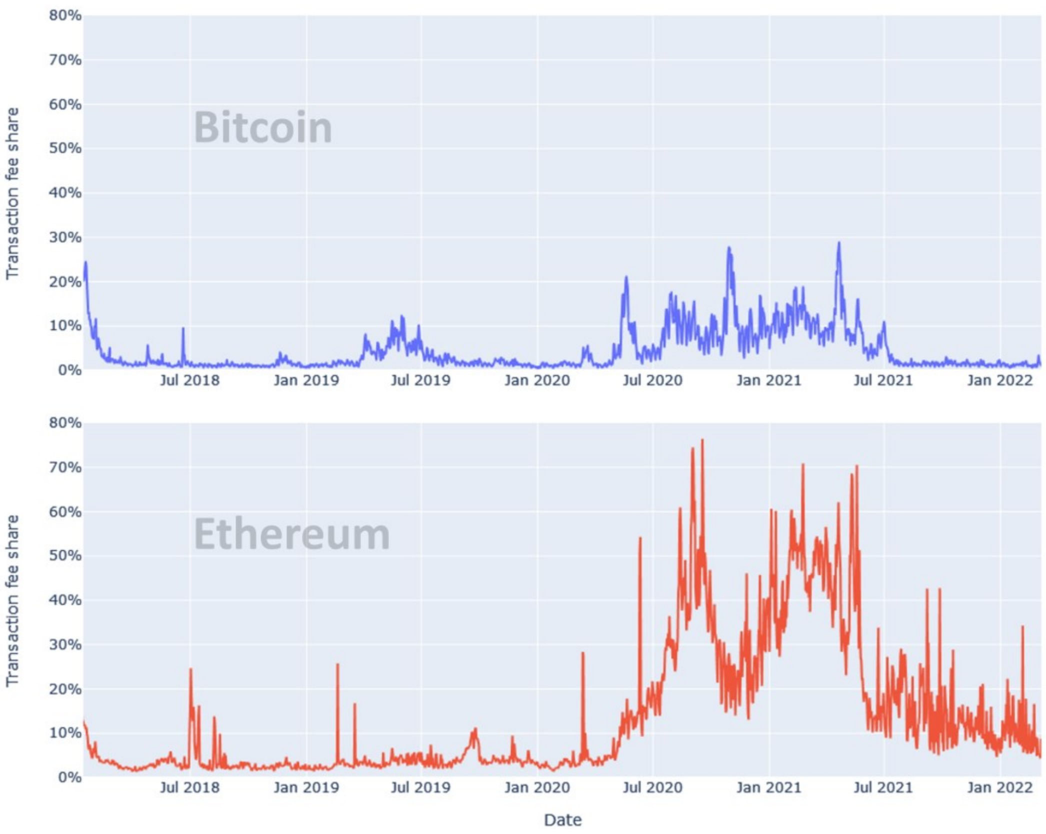

Figure 5: The share of the transaction fee of the overall miner reward. Top: Bitcoin, Bottom: Ethereum. Calculations from the CCRI Cryptocurrency Sustainability API (CCRI, 2022b; Gallersdörfer et al., 2021).

$$\text{Entity-specific carbon footprint} = \text{Total network emissions} \times \left(f \, \frac{\text{Value held in crypto}}{\text{Total supply of cryptocurrency}} + (1-f) \, \frac{\text{Paid transaction fee}}{\text{Total network transaction fee}} \right)$$

Figure 6: Hybrid approach that includes both transactions and holdings. f is the incentivization factor, meaning the share of block subsidy of the overall mining reward. 1-f therefore is the share of the transaction fees of the overall mining reward. 1-f is the variable displayed in Figure 5.

There are additional methodologies that we are not able to cover in this report; given the incentivization of miners, we opt for the hybrid approach, as it best represents the reality of mining economics.

A word on transaction fees and gas consumption

Moss.Earth[23] and Offsetra with their Carbon.FYI-service[24] utilize the gas consumption of a transaction as a denominator for the share of emissions (independently of their chosen allocation methodology). While we agree that gas consumption describes the computational complexity of a transaction, we believe it is not a suitable metric for allocating emissions to transactions in Proof of Work systems[25]. The reason is that a transaction with low gas consumption, but high gas fees, might contribute more to the miners' earnings than a more complex transaction with lower gas fees[26]. The electricity consumption during the calculation and verification of the transaction within the miner or full node is negligible (CCRI, 2022d); important is the incentivization of the miners and contributing to their income, which in turn gets spent on electricity and results in carbon emissions. Therefore, we take the transaction fees as the decision metric and additionally account for EIP-1559[27]; transaction fees and the respective miner incentivization is adjusted accordingly.

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[23] https://medium.com/@luisfelipeadaime/moss-crypto-carbon-index-v1-0-b05405955148

[24] https://github.com/Offsetra/ethereum-emissions-calculator

[25] In Proof of Stake systems, leveraging gas usage for an electricity consumption calculation is recommended, as in these systems there is no monetary incentive to consume more electricity.

[26] This can be the case when the network faces a high / low demand for transactions.

[27] EIP-1559 introduces a novel fee market in the Ethereum network (Buterin et al., 2019). With that, a part of the transaction fee is burned and not paid towards the miner. This also reduces the incentivization of the miner and thus leads to a reduced electricity consumption for transactions.

5. Determination of activities

The activities, both holdings and transactions, of the Polygon network on the Ethereum base layer needs to be properly understood to determine whether an activity should be accounted for or not. Given the complexity of the Polygon smart contract ecosystem on Ethereum, we account for any activity that takes place on Polygon's smart contracts on Ethereum.

Transactions, messages, internal transactions and others

Ethereum, as a turing-complete smart contract blockchain platform, is able to execute arbitrary computational tasks. These computations are handled within smart contracts, which code was defined previously at the time of the smart contract creation. The account model of Ethereum, therefore, requires the existence of a) smart contracts as well as b) externally owned accounts (EOAs), whereas EOAs represent the regular user account, which is associated with a private key. Generally, transactions can only be created by EOAs, but not by smart contracts. Smart contracts can create messages (sometimes called internal transactions) which have almost the same functionality as transactions but depend on the existence of a transaction of an EOA. The reason for this detailed explanation is that while a smart contract (SC A) can be the direct recipient of a transaction, they can also be an indirect recipient of a transaction, in case another smart contract (SC B) calls the smart contract (SC A) via a message. This involvement might not be clear as the transaction count on Etherscan does not include messages. Further, given the arbitrary complexity of smart contracts, a user could create a smart contract that facilitates multiple operations at once, both activities involving Polygon's smart contracts and other, unrelated smart contracts. We are not able to discern these activities and properly account only for the part that involves Polygon, therefore, if such complex transactions exist, we account for the entirety of the transaction, even if it contains parts that are not relevant for the Polygon network. Also, to prevent double counting, we consider each smart contract individually and decide whether it is a) a contract that is directly called by an EOA, b) only called by other smart contracts or c) received less than 10,000 transactions or messages in total. We account for any activity that takes place in contracts of type 1 (including messages), neglect activity of accounts of type 2, as these will lead to double counting and account for any activity on contracts of type 3, given that they likely do not play a major role in the overall emissions.

Polygon's smart contract ecosystem

Etherscan provides a list of, in total, 39 smart contracts of the Polygon ecosystem (Etherscan, 2022). We deem this list to be complete for the purposes of this report. We account for any additional smart contracts that are deployed because of the activity of these 39 smart contracts as well, as we consider any message involving any of these 39 contracts[28]. This approach also accounts for any activity of other smart contract ecosystems such as Uniswap, resulting from trading of Polygon tokens. A complete list of the addresses with the associated emissions is found in Appendix D.

Technical setup

To gather all smart contract transaction data and any holdings, we utilize a fully synced Erigon node on an Ubuntu 22.04 machine equipped with an AMD Ryzen 5950X processor, 128 gigabyte of memory and two 3.84 TB NVMe SSDs in RAID 1 as storage. We leverage *TrueBlocks* and *chifra* to access all transactional and holding data from the respective addresses (Trueblocks, 2022). For that purpose, we built a Python script accessing

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[28] Smart contracts can create other smart contracts.

chifra via CLI to gather, store, and analyze all data. We filter for duplicates, summarize the transactional data and submit it to our CCRI Sustainability API to receive the respective emission values (CCRI, 2022b).

Emission allocation results

The respective 39 contracts are involved both in transaction activity as well as holding cryptocurrency. Table 4 summarizes the results for both activities over a one-year period as well as the total network lifetime of Polygon.

Period	Emissions from transactions	Emissions from holdings	Total emissions
One year (01.08.2021 – 31.07.2022)	17,970.33 tCO_2e	42,932.81 tCO_2e	60,903.14 tCO_2e
Total (20.04.2019 – 31.07.2022)	41,604.26 tCO_2e	53,088.51 tCO_2e	94,692.77 tCO_2e

Table 4: Overview of emissions of the base layer allocation for both holdings, transactions and total for periods of one year and the total network lifetime.

We find that the Polygon network is responsible for 60.9 kt CO_2e emissions due to its activity on the base layer of Ethereum in the last year. In total, this number grows to about 94.7 kt of CO_2e emissions. The emissions are almost evenly distributed between transactions and holdings for the entire lifetime of the Polygon network, whereas most of the emissions from last year (~ 70 %) stem from holdings.

Figure 7 displays the emissions from individual contracts over the lifetime of the network.

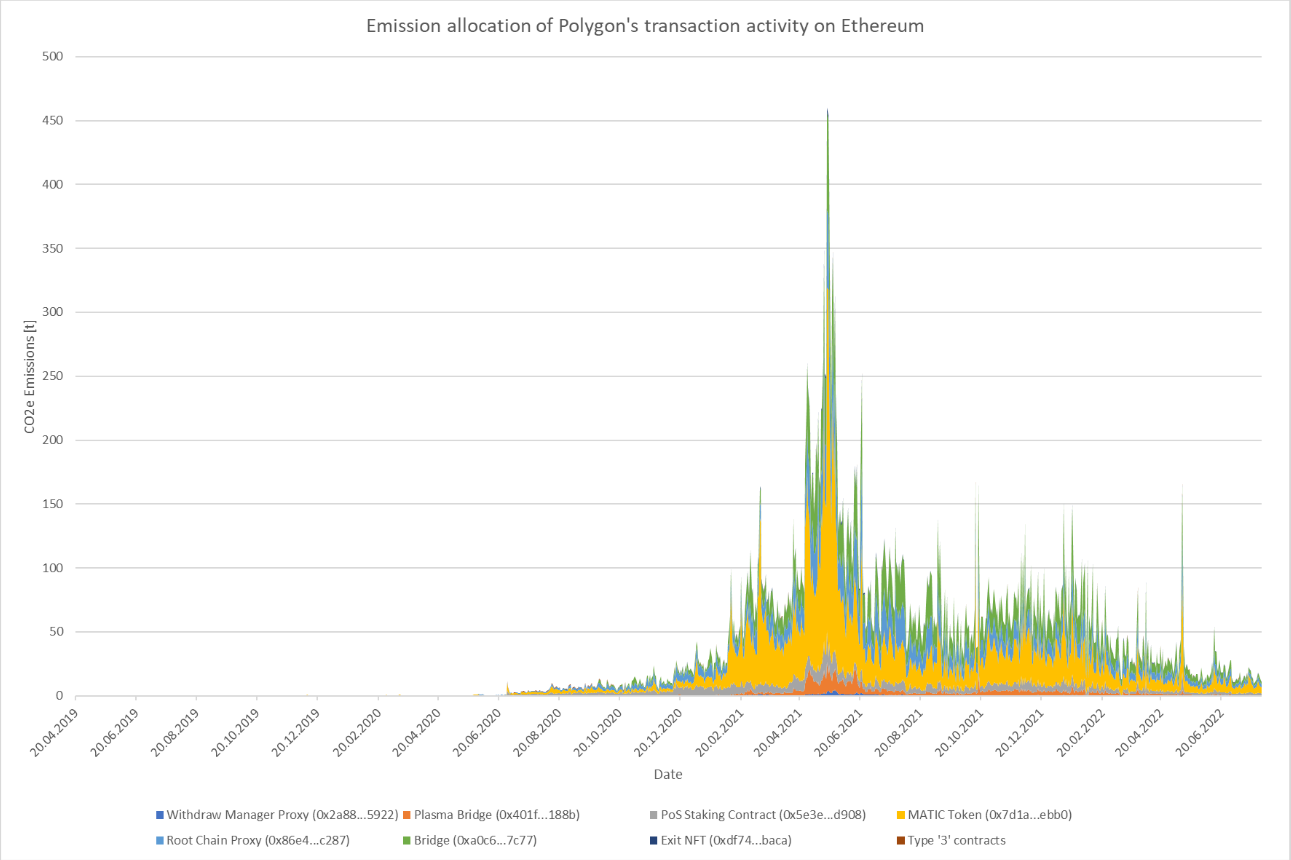

Figure 7: Daily allocated emissions in tonnes of smart contract activity grouped by address.

Overall, we see that the emissions from transactions are a result of several smart contracts, whereas most of the emissions come from three smart contracts: Root Chain Proxy (0x86e4…c287) with 20 %, Bridge (0xa0c6…7c77) with 24 %, and MATIC Token (0x7d1a…ebb0) with 41 % of overall emissions.

For holdings, only one smart contract ("Ether Bridge") is responsible for almost the entirety of emissions. Figure 8 displays the daily emissions of the three smart contracts holding ether.

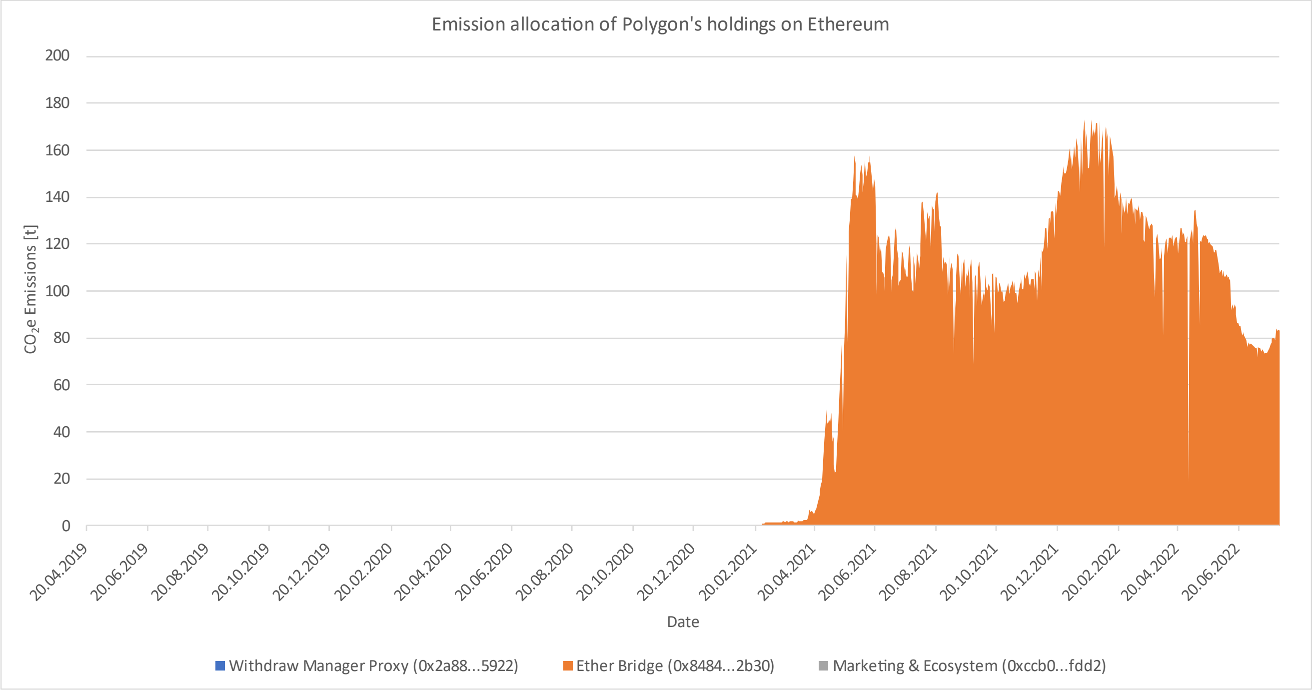

Figure 8: Daily allocated emissions in tonnes of smart contracts holdings.

Figure 9 displays the accumulated allocated carbon emissions over time for both holdings and transactions.

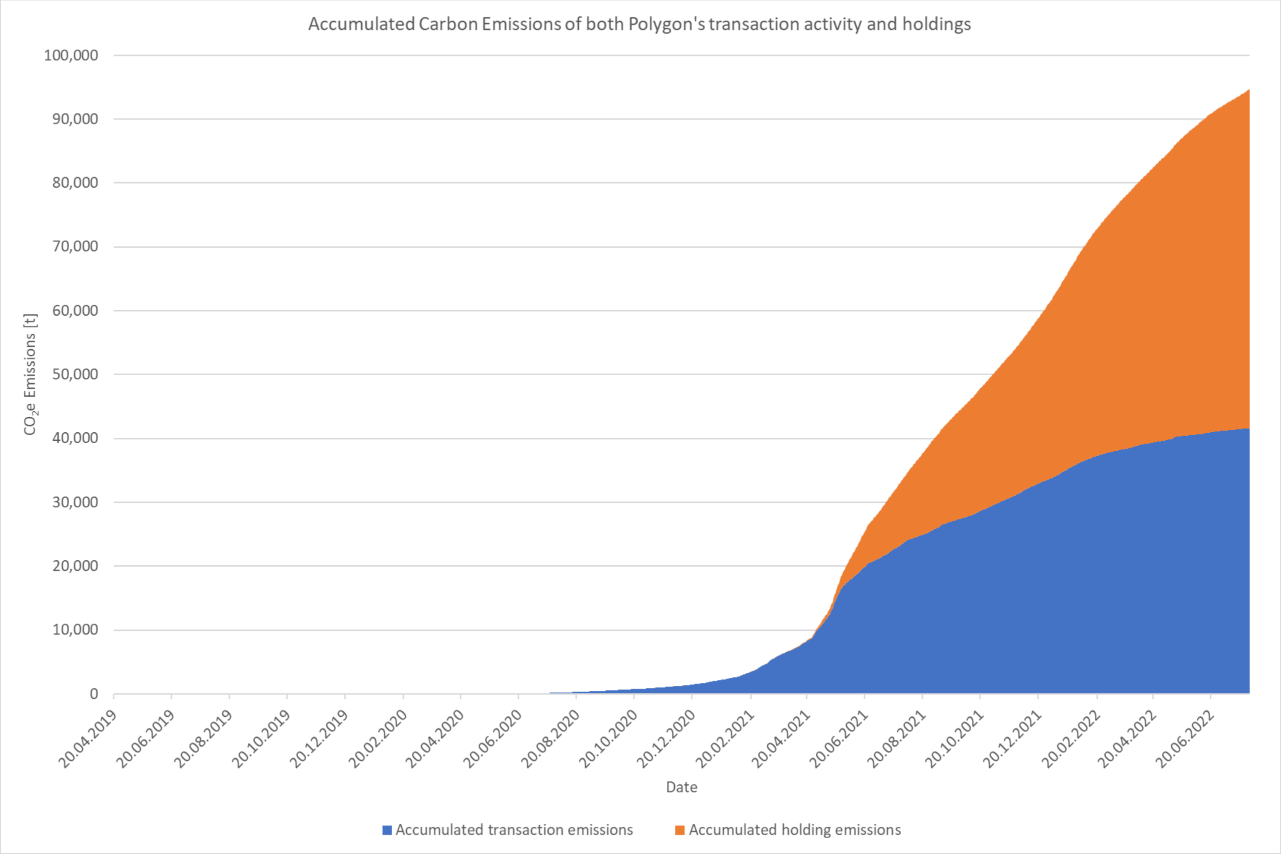

Figure 9: Accumulated emissions in tonnes of smart contracts holdings and transactions.

Distribution of allocated emissions to Polygon transactions

Some activities on the layer 2 network can be directly attributed to the activity on the layer 1 network, e.g., in case of bridging of tokens. Nonetheless, this is a highly complex endeavor and therefore is out of scope for this report. Nonetheless, we present a figure of the average emissions per layer 2 transaction by dividing the allocated emissions of the last year by the amount of layer 2 transactions that took place during the respective time. For that, we access polygonscan.com and leverage their daily transaction volume numbers from 01.08.2021 until 31.07.2022 with 1,345,443,534 transactions[29]. By that figure, for every transaction taking place on Polygon, one has to account for an additional 45.27 g CO_2e emissions as seen in Table 5.

Period	Number of transactions	Emission allocation per transaction
One year (01.08.2021 – 31.07.2022)	1,345,443,534	45.27 g CO_2e

Table 5: Number of transactions taking place on Polygon and respective emission allocation for each transaction.

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[29] https://polygonscan.com/chart/tx, accessed on 22nd August 2022.

III. Proof of Stake network

Aiming for high network throughput and scalability, as well as to overcome drawbacks of Proof of Work systems, the Polygon side chain utilizes a Proof of Stake consensus mechanism. In the following chapter of this report, we focus on the Polygon PoS network itself rather than its impact on its base layer Ethereum which has been the focus of the second chapter of this report. We analyze the electricity consumption of participating nodes, the entire network and estimate the carbon emissions generated.

1. Methodology for analyzing Polygon PoS network

Our methodology builds upon five steps to generate data on the electricity consumption and carbon footprint of the Polygon PoS system. We furthermore develop metrics to enable a valid comparison between previously analyzed PoS systems (CCRI, 2022c, 2022d).

In the **first step**, we analyze the Polygon PoS network and its 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 and provide upper and lower bounds for the network. We start by running the required 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.

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. Secondly, we develop a weighting between the single hardware devices for each network. Lastly, we multiply the electricity consumption of the weighted nodes by the number of nodes in the network.

In the **fourth step**, we analyze additional data (such as transaction 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 amount of transactions on the electricity consumption of a node. As a result, we establish a model to estimate a node's power consumption based on the number of transactions. This enables us to put the electricity consumption of the Polygon network into perspective with other PoS networks and also other cryptocurrencies such as Bitcoin and even Polygon's base layer Ethereum.

In the **fifth step**, we estimate the CO_2 emissions arising from the operation of the polygon PoS network. For this, we use our data on electricity consumption calculated and multiply it by the world average carbon intensity, since no information of the regional distribution of the nodes in the network is available. We provide a best guess as well as an upper and a lower bound for the carbon footprint of the Polygon PoS network.

2. Polygon 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 a node participating in the Polygon PoS network. Thirdly, we provide details of the infrastructure required 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, 2022c), 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 (2022c). However, some minor adjustments to better fit the assumed hardware diversity in the Polygon 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	AMD 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

Hardware requirements of Polygon PoS network

Compared to the hardware requirements of the PoS systems previously analyzed (CCRI, 2022c), those for nodes participating in the Polygon network are comparatively advanced. Different hardware requirements are recommended for Polygon, depending on whether the user runs a regular full node or a validator node. Table 7 summarizes the recommended hardware for executing Polygon at the time of our analysis (July 2022).

	Polygon (Full Node, Minimal)	Polygon (Validator, Minimal)	Polygon (Validator, Recommended)
CPU	4-8 core CPU (t3 xLarge)	8 cores	16 cores
RAM	16-32 GB	32 GB	64 GB
Storage	1.2 TB SSD	2 TB SSD	3-4 TB SSD

Table 7: Hardware requirements for Polygon PoS network

Applying the requirements for executing a Polygon full node to our hardware pool as presented in the previous section, we deduce that configurations 5 and 6 shown in Table 6 fulfill and even exceed the hardware recommendations. 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 to examine a representative of the mid-tier category. Table 8 summaries which configurations of our hardware pool were included as a foundation to derive the electricity consumption of the Polygon network.

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

Table 8: Overview of nodes of our hardware pool selected for running a Polygon full node

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 new 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 Polygon 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.

3. Electricity consumption and carbon footprint of the Polygon 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 and the best guess as a weighted average between the selected computer devices. On that basis, we establish the electricity consumption of the overall Polygon PoS network assuming each node executes both Bor and Heimdall. 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 Polygon 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 Polygon and verify the correct installation.
4. **Node Bootstrap**: On each node, we first run Heimdall and wait for it to be fully synced. After that, we execute Bor. Likewise, we wait for the synchronization to be completed on every node 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 both Heimdall and Bor, as this covers an entire day cycle. Appendix B contains an overview of every electricity measurement.

To understand what exactly we are measuring, we need to describe the Polygon network and its setup. It consists of nodes running both the Heimdall and Bor service, either validators (participating in the consensus protocol, producing new blocks, and committing checkpoints on the Ethereum mainnet) or regular full nodes (broadcasting and verifying regular transactions). We would differentiate between full nodes and validators in an ideal setup, as they have slightly different roles and responsibilities within the network, however, on the Main network, significant stakes are 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 Polygon PoS Main network.

Idle electrical power

We measure the electricity consumption of the devices idle. Table 9 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
Min [W]	2.9	2.6	2.6	3.6	24.5	77.5
Q1 [W]	3.0	2.6	2.9	3.7	24.8	77.9
Median [W]	3.0	2.7	2.9	3.7	24.9	78.0
Q3 [W]	3.0	2.7	3.0	3.7	25.1	78.3
Max [W]	3.9	17.8	17.3	4.4	26.6	118.1

Table 9: 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 2, we do not run Polygon on all nodes. While the hardware setups 5 and 6 of Table 6 exceed the recommended configurations for executing a Polygon full node, we also test configuration 4 as we do not want to enforce the hardware requirements as a strict lower bound. We exclude hardware configurations 1-3 from our measurements since these clearly do not satisfy the requirements required by Polygon.

In Table 10, we outline the mean and the median electrical power of the nodes during the measurement. There is no value available for those configurations not sufficient for executing Polygon.

	1	2	3	4	5	6
Mean	N/A	N/A	N/A	25.76	46.46	130.67
Median	N/A	N/A	N/A	25.78	46.23	130.34

Table 10: Mean and median electrical power of nodes in Watt [W]

4. Calculation of bounds for electricity consumption

To calculate the electricity consumption of the overall network, we need to understand the average consumption for a single node. We measured the electrical power for three different computers. With these measurements for the electricity consumption, we can provide upper bounds, meaning the highest electricity that a node consumes, lower bounds, 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, respectively. The lower bound therefore is constituted by configuration 4 from Table 2. Accordingly, configuration 6 serves as an upper bound. These bounds are summarized in Table 11.

	Polygon
Lower bound [W]	27.76
Lower bound [kWh / year]	225.68
Upper bound [W]	130.67
Upper bound [kWh / year]	1,144.65

Table 11: Overview of lower and upper bounds of electrical power and electricity consumption per single node

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 12.

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

Table 12: Overview of node distribution for the six networks

With this distribution, we calculate the weighted electricity consumption of an average node:

$$\sum_{i \in hardware} avgEnergyConsumption_i * share_i$$

Not only the number of nodes is relevant for the electricity consumption of a PoS network, but also the underlying software and its requirements. Table 13 gives an overview of the best guess electricity consumption for the Polygon network.

	Polygon
Best guess [W]	62.34
Best guess [kWh / year]	546.07

Table 13: Best guess estimates for Polygon PoS network per single node

5. Electricity consumption of the Polygon PoS network

We apply our lower bound, upper bound as well as our best guess at the number of validator nodes in the Polygon network multiplied by the factor of 2, as each validator needs to be connected to a further full node (sentry node). We obtain the number of nodes from a block explorer as specified in Appendix C. The results are depicted in Table 14.

	Polygon
Validator count	200
Electrical power of network [W]	12,468
Consumption / day [kWh]	299.22
Consumption / year [kWh]	109,213.48

Table 14: Overview of electricity consumption of the Polygon network applying the best guess estimate

We find that the electricity consumption of the network amounts to 109,213.48 kWh annually in our best guess.

6. Electricity consumption per transaction of the Polygon 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. As we have outlined in chapter II section 4, 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 also apply the transaction numbers that took place during the respective time period. Again, we weigh the single nodes for the overall network applying the previously described binomial distribution. The results can be found in Table 15.

	Polygon
Wh/tx per node	0.00051580
Wh/tx per network	0.1031
Number of tx	2,900,637

Table 15: *Best guess electricity consumption of the Polygon PoS network on a per-transaction basis. The transaction count amounts to the number of transactions that took place on the blockchain 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 Polygon network. Generally, these numbers are expected to go down with an increase in the transaction rate, regardless which blockchain is in use.

Another approach to estimate a node's and thus the network's electricity consumption based on the number of transactions is to rely on a statistical regression model. This methodology typically allows for more accurate results than merely considering average values. Furthermore, it has the advantage that constant power consumptions, which are independent of the transaction count, can be included in the model (e.g., the node's idle power consumption to be represented as the y-axis intercept). The regression model can be set up completely on the basis of our own measurements. We apply the Z–score methodology to filter our measured data for strong outliers. We only consider measured time periods for which the power consumption lies within the range $-3 \leq Z \leq 3$. Regarding the transaction count, we opt to filter only the coarsest outliers and thus take all periods within $-5 \leq Z \leq 5$ into account.

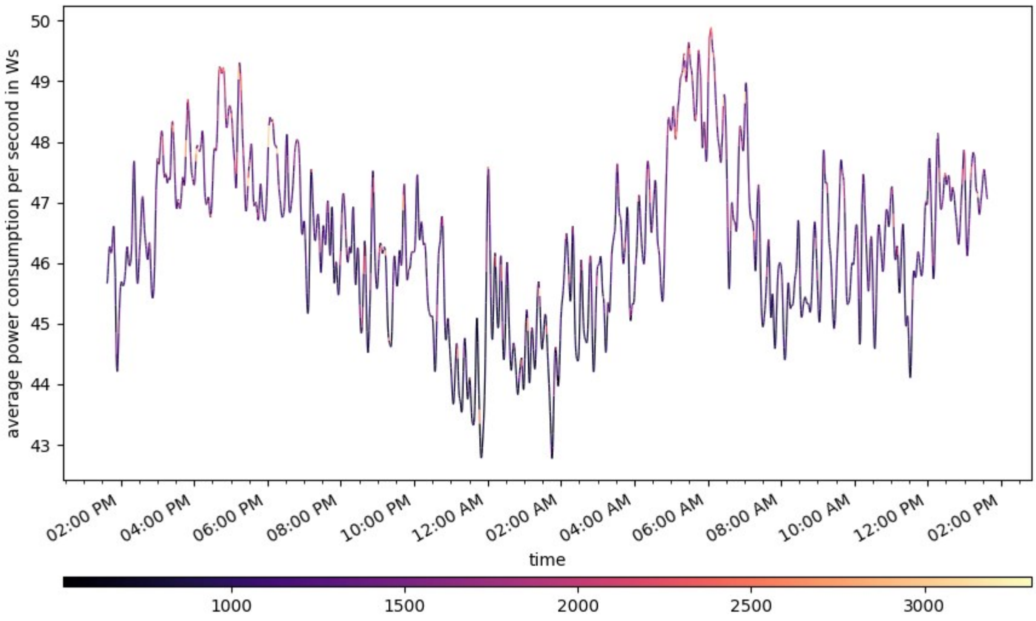

Figure 10: Average power consumption in Ws of hardware configuration 5 (y-axis) over time of measurement (x-axis). The color of the line represents the transaction count at the corresponding point in time.

Figure 10 indicates the power consumption of hardware configuration 5 (see Table 6) over the course of the measurement time frame. As a third dimension, the coloring of the line depicts the number of transactions that the node processed at the respective point in time. We find that the color of the line becomes brighter at the peaks, i.e., at points with high power consumption. Therefore, we suppose that the increased power consumption can probably be explained by a comparatively higher number of transactions occurring in the corresponding time periods.

For this reason, we constructed a regression that indicates the relationship between transaction count and power consumption for each of the three hardware configurations. The model is based on our periodically taken measurement samples (every 30 seconds) that consist, among further values, of the current power consumption and the number of transactions to be processed at that time.

As an example, Figure 11 provides the regression line to estimate the power consumption of hardware configuration 5 for any given number of transactions. The model reveals an increase in power consumption with a rising number of transactions.

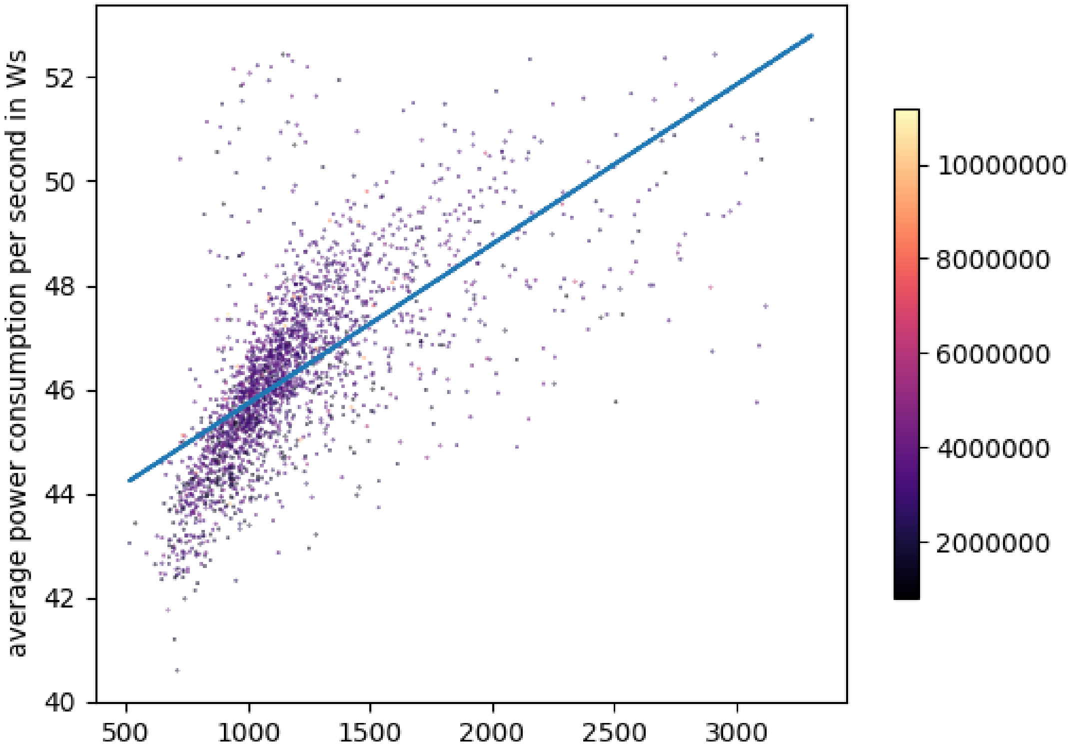

Figure 11: Plotted samples consisting of average power consumption per second in Ws (y-axis) and number of transactions processed per 30 seconds (x-axis) taken for hardware configuration 5. The color of the points indicates the average gas used by the blocks belonging to the corresponding sample. The resulting regression line to estimate the node's power consumption for an arbitrary amount of transaction is drawn in blue.

Based on this approach, we can establish a linear equation for a regression line to predict the power consumption (P_{BG}) for a given number of transactions (tx_{count}) for a best guess node operating in the Polygon network. To determine a general slope (m_{BG}) for a best guess node, we weight the slopes of the regression lines emerging for the three hardware configurations measured based on the distribution of Table 9. Likewise, we calculate a best guess y-axis intercept (t_{BG}) out of the three lines. Aa result, we obtain the following linear regression equation to determine the power consumption of a best guess validator node in the Polygon network depending on the number of transactions the node processes:

$$P_{BG}(tx_{count})\ [Ws] = m_{BG} * tx_{count} + t_{BG} = 0.00304388 * tx_{count} + 58.53252137$$

Multiplying the best guess marginal electricity consumption of a single node (m_{BG}) with the validator count of the Polygon network (including a further sentry node for each validator), we obtain an overall best guess for a single transaction's marginal electricity consumption of the whole network for the time of measurement of 0.608776 Ws, as Table 16 summarizes:

	Polygon
Validator count	200
Marginal electricity consumption per tx of single node [Ws]	0.00304388
Marginal electricity consumption per tx of network [Ws]	0.608776

Table 16: Overview of marginal electricity consumption of the Polygon network applying the best guess estimate

7. Carbon footprint of the Polygon 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 Polygon 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 Polygon 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. Unfortunately, structured data on the location of nodes in the Polygon network is not available. Due to the absence of such data, we rely on the average grid intensity worldwide. A formula to calculate the respective carbon footprint is shown.

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

We assume the carbon intensity of the grid to be the world average of 459 gCO_2e/kWh as indicated by the IEA (International Energy Agency, 2021). With that, we can infer the carbon footprint of the Polygon PoS network. The respective values are depicted in Table 17.

Polygon	CO_2e emissions / year [t]
Lower bound	20.72
Best guess	**50.13**
Upper Bound	105.08

Table 17: Overview of CO_2e emissions of the networks on an annual basis as of time of measurement (July 2022)

IV. Results and discussion

In this chapter of the report, we discuss and contextualize the results of our work. We compare Polygon's two sources of emissions, that is, the emissions caused on the Ethereum base layer (see chapter II.) and those arising from its own PoS network (see chapter III.), putting the results in relation to each other. After that, we discuss how future developments of Ethereum will influence the overall carbon emissions of the Polygon network and contextualize the results.

1. Comparison of emission volumes caused by Polygon's two emission sources

Overall, our report finds that the PoS network of Polygon is responsible for 50.13 tonnes of CO_2e emitted on a yearly basis, whereas the PoW emission allocation on Ethereum leads to significantly higher emissions with 60,903 tonnes of CO_2e for the timeframe 1st August 2021 to 31st July 2022. Historically, as stated in chapter II, all emissions allocated to the PoW base layer from the period of 20th April 2019 to 31st July 2022 sum up to 94,692 tonnes of CO_2e. We cannot provide historical data for emissions generated by the PoS network of Polygon since those measurements are not available.

Consequently, over 99.9 % of Polygon's emissions are resulting from the Polygon-related activities on the underlying layer 1 network, Ethereum.

Figure 12 displays the ratio of emissions from both sources.

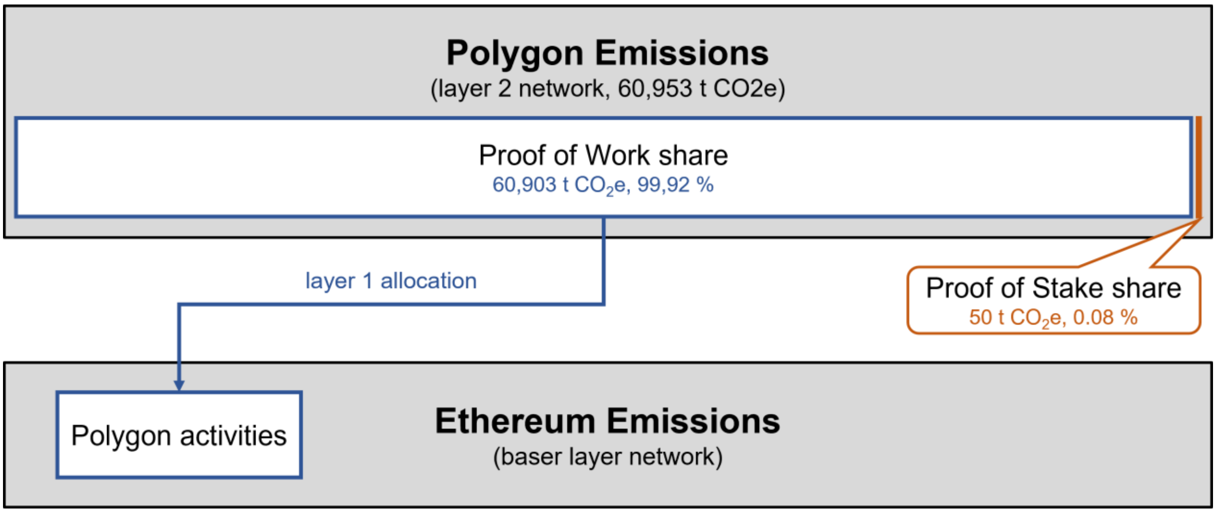

Figure 12: Comparison of Polygon's two sources of emissions and their respective shares in the timeframe of 1st August 2021 to 31st July 2022.

These results highlight again the magnitudes of differences between emissions of Proof of Work and Proof of Stake networks, as even just the allocation of the activity on Ethereum lead to an entirely different level of emissions than the PoS network itself.

Nonetheless, this will change with the upcoming merge of Ethereum scheduled for mid-September 2022. Ethereum will undergo a historic change and switch its consensus mechanism from Proof of Work to Proof of Stake, eliminating the entirety of emissions from mining. While it is unclear what the emissions of the remaining PoS Ethereum network will be, it is safe to assume that emissions will drop by well over 99 %. This also results in a significant reduction for the emission allocation of Polygon.

2. Comparison of Polygon "Post-Merge" network to other PoS systems

If Ethereum's electricity consumption and therefore carbon footprint drops because of the change to a Proof of Stake based consensus mechanism by 99.99 %[30], the emissions of Polygon's activity on Ethereum still amount to about 6.1 tonnes CO_2e, which is about 12 % of the Polygon PoS emissions. We add up both hypothetical emission allocation and emissions from the PoS network and put them in context with other Proof of Stake based systems in the following figures. We also put the electricity consumption in context; for that we leverage the previously established carbon intensity of 501 gCO_2/kWh.

We clearly point out that comparing different Proof of Stake networks is challenging, among other things because the data for the specific currencies were taken at different points in time, and the measurement scope is difficult to define and often unequal. Furthermore, we emphasize that the merge has not taken place yet and it is unclear by how much the electricity consumption of Ethereum will be reduced.

Yearly electricity consumption in the context of other systems

In section 5 of chapter III, we outline that the yearly electricity consumption of the network amounts to roughly 109,213 kWh, in addition to the 12,166 kWh from the base layer allocation. An average US household consumes about 10,600 kWh per year and therefore, the Polygon PoS network consumes about 10.3 times the electricity, and the base layer allocation of Ethereum adds roughly one household (U.S. Energy Information Administration, 2021). In comparison to the decentralized cryptocurrency Bitcoin, the PoS network consumes less than 0.00015 % of the Bitcoin network assuming 83.87 TWh on the 01st July 2022 (CBECI, 2022). Bitcoin consumes much more electricity than Proof of Stake systems due to its Proof of Work consensus mechanism, resulting in the deployment of energy-intensive hardware.

In Figure 13, we compare the Bitcoin network, the Ethereum network assuming 22.37 TWh (including the share Polygon causes on the network) on the 01st July 2022 (CCRI, 2022b), TRON (CCRI, 2022d), and further PoS networks we have analyzed in CCRI (2022c) as well as an average US household. Note that the networks drawn in gray are limited in their comparability given the age of the analysis (conducted in August to October 2021).

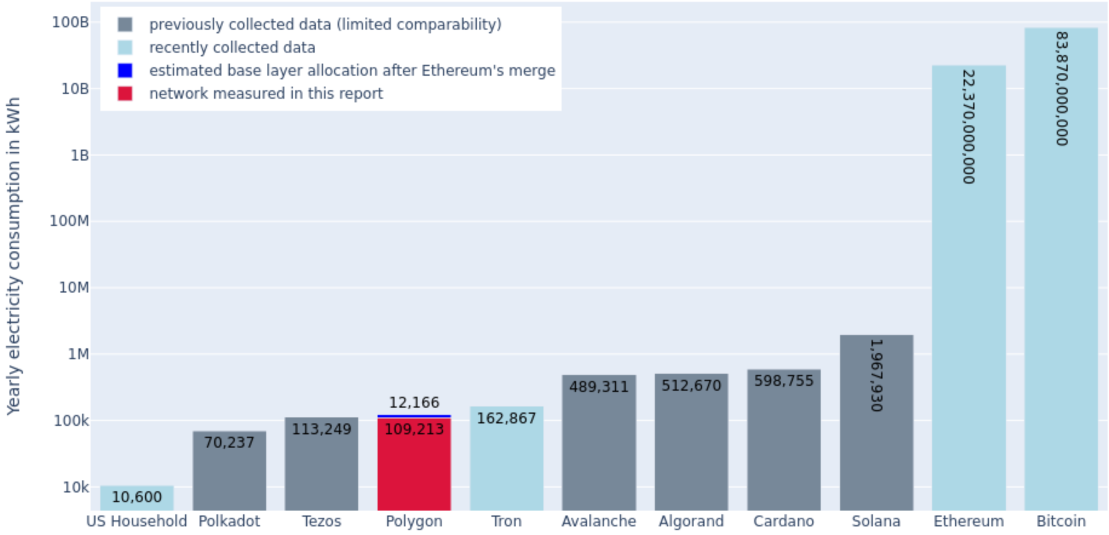

Figure 13: Yearly electricity consumption Polygon, Bitcoin, Ethereum, Proof of Stake networks TRON, Polkadot, Tezos, Avalanche, Algorand, Cardano and Solana, and an average US household in kWh. Logarithmic scale.

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[30] This results in a reduction by the factor of 10,000, similar to the difference between the PoS network with the highest electricity consumption (Solana) and the current Ethereum PoW network.

Carbon footprint in the context of other systems

Overall, the emissions of PoS networks are very low. As outlined in section 7 of chapter III, the Polygon PoS network emits 50.13 tons of CO_2e yearly. For example, 8 round trips from Munich (MUC) to San Francisco (SFO) in business class emit about the same amount of carbon dioxide (MyClimate, 2021) produced by the PoS network of Polygon, the base layer allocation equals an additional round trip. It can be assumed that the carbon emissions of companies behind the networks are higher than the emissions from the network itself. We highlight that Polygon is additionally responsible for a non-negligible amount of emissions on its base layer Ethereum, which currently utilizes a Proof of Work consensus algorithm. If we assume a reduction of Ethereum's emissions by 99.99% after the merge to a PoS based consensus protocol, Polygon will be responsible for roughly 6.09 tonnes of CO_2e on its base layer. Figure 14 compares the carbon footprints of Polygon PoS after the merge event of Ethereum, further PoS networks from our previous research (CCRI, 2022c, 2022d) and to a roundtrip MUC – SFO in business class. Again, the gray-colored networks are only comparable to a limited extent due to the age of the analysis.

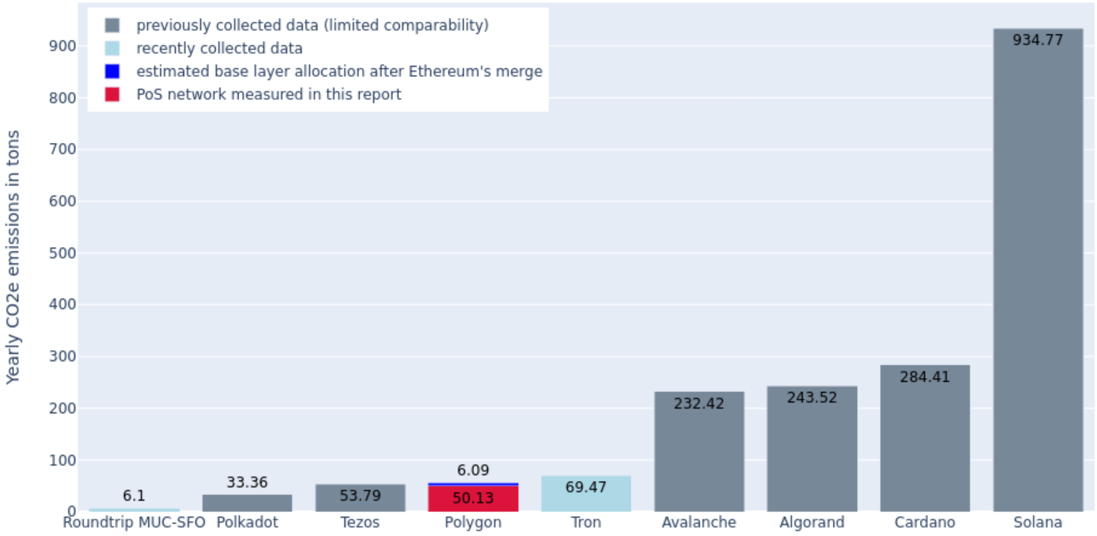

Figure 14: Yearly carbon footprint of Polygon compared to other PoS networks and to a roundtrip flight in business class

V. Conclusion

In this report, we outline an approach for calculating the electricity consumption and carbon footprint of the Polygon layer 2 network, including those emissions it causes on its base layer Ethereum. We elaborated on activities that happen through Polygon on Ethereum and assessed them in terms of their carbon footprint. Moreover, to provide an estimate of the emissions generated by Polygon's PoS network itself, we selected hardware, made measurements of the PoS protocol, and calculated the respective metrics. We discussed our results by comparing both two sources of emission generation for Polygon and introduced several other key metrics, such as the Bitcoin and Ethereum network for comparison. Furthermore, we provided estimates for the additional carbon footprint of a single transaction taking place on Polygon due to the base layer allocation.

For the PoS network of Polygon, our best guess estimates the yearly electricity consumption to be 109,213.48 kWh assuming a node count of 100 validators of which each is connected to a further full node. This results in a carbon footprint of 50.13 tons of CO_2e annually. Compared to other electricity consumers such as an average US household, the PoS network consumes roughly 10 times more electricity, and produces 8 times the amount of an intercontinental round-trip flight.

Regarding Polygon’s PoW activities on Ethereum, our calculations show that Polygon causes approximately 60,903 tonnes of CO_2e in the timeframe of 1st August 2021 to 31st July 2022 on its base layer Ethereum.

In total, i.e., summing up both the impact of Polygon's PoS network and its PoW activities, Polygon thus has generated 60.953 tons of CO_2e in the timeframe of 1st August 2021 to 31st July 2022. Ethereum’s merge will reduce the carbon emissions of the network significantly, and thus also Polygon’s overall emissions.

Given the continuous development and evolution of Proof of Stake and second layer networks, 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, especially given in the light of the upcoming merge. 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, Bitcoin has faced harsh criticism for its electricity demand and carbon emissions. In the public, these fears and accusations have often been applied to other blockchain protocols, regardless of their technical foundations or capabilities, harming the adoption of blockchain protocols in the industry, public sector, and private investors. Based on the emissions calculated for the Polygon PoS network, one may conclude that Proof of Stake based blockchain protocols consume an amount of electricity that does not justify the discussions about their environmental footprints at current levels. However, in the case of layer 2 networks, it is important not to ignore the emissions that may be generated at the base layer. Nonetheless, further monitoring of the situation and analysis is required as Web3 and blockchain technologies receive increased attention and usage. Furthermore, an extensive perspective, including corporate footprints and the ecosystem, must be taken. For practitioners selecting a PoS blockchain protocol, other factors such as decentralization, network throughput and functionality (e.g., Smart Contracts) should play a vital role as decision criteria.

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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 nodes

All electricity measurements are conducted in Watt.

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	19.43	40.60	122.08
Q1 [W]	N/A	N/A	N/A	24.65	45.18	128.60
Mean [W]	N/A	N/A	N/A	25.76	46.46	130.67
Median [W]	N/A	N/A	N/A	25.78	46.23	130.34
Q3 [W]	N/A	N/A	N/A	26.80	47.44	132.17
Max [W]	N/A	N/A	N/A	34.61	58.72	151.36

Table 18: Electrical power while running a Polygon full node measured in Watt [W]

Appendix C: Data sources for Polygon network

Market capitalization is taken from https://coinmarketcap.com.

Polygon	Information
Measurement period	2022-07-30 13:37:04 to 2022-07-31 13:37:37
Number of nodes	https://polygon.technology/staking/ => “Global Validators”
Transaction Count	Transaction count taken from Node API (https://ethereum.org/en/developers/docs/apis/json-rpc/)
Software version	Heimdall: v0.2.10; Bor: 0.2.16-stable amd64; go: 1.18.1 linux/amd64

Table 19: Data sources

Appendix D: Smart contract addresses

For the calculations in chapter II, we collect smart contract data from Etherscan with the Tag "Polygon (Matic)"[31]. As outlined in the respective section, we do account for the entirety of all contract interactions as well as all holdings. We categorize the smart contracts into three groups, 1) a contract that is directly called by an EOA, 2) only called by other smart contracts or 3) received less than 10,000 transactions or messages in total. In following table, we give an overview of all smart contracts, whether we sort them in group a, b, or c, respective transactions, and holdings. Due to technical reasons, we were not able to gather transaction data for the 29th September 2021. For that day, we use an average gas consumption of the day before and the day after.

#	Address	Name Tag	Balance (Wei)	No. of tx	Creation Date	Group
1	`0x1d21facfc8cad068ef0cbc87fdacdfb20d7e2417`	Bytes Lib	0	1	30.05.2020	3
2	`0x31851aaf1fa4cc6632f45570c2086adcf8b7bd75`	Common	0	1	30.05.2020	3
3	`0xd505c3822c787d51d5c2b1ae9adb943b2304eb23`	Deposit Manager	0	146,119	30.05.2020	2
4	`0x71d91a8988d81617be53427126ee62471321b7df`	EC Verify	0	6,641	30.05.2020	2
5	`0x158d5fa3ef8e4dda8a5367decf76b94e7effce95`	ERC20 Predicate	0	9,914	11.08.2021	2
6	`0xdf74156420bd57ab387b195ed81eca36f9fabaca`	Exit NFT	0	19,674	30.05.2020	1
7	`0x98165b71cddea047c0a49413350c40571195fd07`	Governance	0	74	30.05.2020	3
8	`0x6e7a5820bad6ceba8ef5ea69c0c92ebbdac9ce48`	Governance Proxy	0	81	30.05.2020	3
9	`0x8b90c7633f1f751e19e76433990b1663c625b258`	Merkle	0	65	30.05.2020	3
10	`0x8e51a119e892d3fb324c0410f11f39f61dec9dc8`	Merkle	0	1	30.05.2020	3
11	`0x53e0bca35ec356bd5dddfebbd1fc0fd03fabad39`	POS Dummy State Sender	0	32	26.08.2020	3
12	`0x499a865ac595e6167482d2bd5a224876bab85ab4`	POS Ether Predicate	0	562,158	13.11.2020	2
13	`0x62414d03084eeb269e18c970a21f45d2967f0170`	POS Mintable ERC1155 Predicate	0	41	26.02.2021	2
14	`0x58adfa7960bf7cf39965b46d796fe66cd8f38283`	POS Mintable ERC721 Predicate	0	1,597	01.04.2021	3

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[31] https://etherscan.io/accounts/label/polygon-matic

#	Address	Name Tag	Balance (Wei)	No. of tx	Creation Date	Group
15	0x61addcd534bdc1721c91740cf711dbece936053e	Priority Queue	0	1	30.05.2020	3
16	0x33a02e6cc863d393d6bf231b697b82f6e499ca71	Registry	0	443,943	30.05.2020	2
17	0x021c2bf4d2941ce3d593e07317ec355937bae495	RLP Encode	0	1	30.05.2020	3
18	0xd75f1d6a8a7dc558a65c2f30ebf876ddbee035a2	RLP Reader	0	1	30.05.2020	3
19	0x536c55cfe4892e581806e10b38dfe8083551bd03	Root Chain	0	264,920	26.03.2021	2
20	0x86e4dc95c7fbdbf52e33d563bbdb00823894c287	Root Chain Proxy	0	792,655	30.05.2020	1
21	0x01f645dcd6c796f6bc6c982159b32faaaebdc96a	Slashing Manager	0	6,497	26.06.2020	3
22	0xd6f5c46d4e1a02f9d145cee41d2f8af30d8d2d76	Stake Manager	0	60,397	14.06.2021	2
23	0xa59c847bd5ac0172ff4fe912c5d29e5a71a7512b	Staking Info	0	120,463	26.06.2020	2
24	0x47cbe25bbdb40a774cc37e1da92d10c2c7ec897f	Staking NFT	0	2,011	26.06.2020	3
25	0x01d5dc56ad4206bb0c132d834644d57f51fed5ec	Validator Share	0	65,948	26.03.2021	2
26	0xc4fa447a0e77eff9717b09c057b40570813bb642	Validator Share Factory	0	147	26.06.2020	3
27	0x2a88696e0ffa76baa1338f2c74497cc013495922	Withdraw Manager Proxy	3,8216E+17	21,136	30.05.2020	1
28	0xa0c68c638235ee32657e8f720a23cec1bfc77c77	Bridge	0	2,358,573	26.08.2020	1
29	0x70bca57f4579f58670ab2d18ef16e02c17553c38	EIP1559 Burn	0	285	10.01.2022	3
30	0x40ec5b33f54e0e8a33a975908c5ba1c14e5bbbdf	ERC20 Bridge	0	942,859	26.08.2020	2
31	0x8484ef722627bf18ca5ae6bcf031c23e6e922b30	Ether Bridge	3,4672E+23	1,603,556	26.08.2020	2
32	0xb316fa9fa91700d7084d377bfdc81eb9f232f5ff	Foundation Contract	0	507	20.04.2019	3
33	0x0305c18771cd11b36dcfa610bcc8837f814746f1	HEZ to MATIC	0	595	20.08.2021	3
34	0xccb04768f3abcf1af1e749085ef67d8ec7c5fdd2	Marketing & Ecosystem	9,2808E+16	66	24.04.2019	3
35	0x7d1afa7b718fb893db30a3abc0cfc608aacfebb0	MATIC Token	0	4,698,574	20.04.2019	1

#	Address	Name Tag	Balance (Wei)	No. of tx	Creation Date	Group
36	`0x401f6c983ea34274ec46f84d70b31c151321188b`	Plasma Bridge	0	449,273	30.05.2020	1
37	`0x5e3ef299fddf15eaa0432e6e66473ace8c13d908`	PoS Staking Contract	0	214,535	26.06.2020	1
38	`0x28e4f3a7f651294b9564800b2d01f35189a5bfbe`	State Syncer	0	2,222,575	30.05.2020	2
39	`0xcbfe11b78c2e6cb25c6eda2c6ff46cd4755c8fca`	Vesting Contract	0	87	20.04.2019	3

Table 20: All smart contract addresses with the label "Polygon" on Etherscan (Etherscan, 2022)

Following table contains all major smart contracts and their respective emissions from the first occurrence until the 31st of July 2022 both from holdings as well as from transactions and messages.

#	Address	Tx emissions total [tCO_2e]	Tx emissions / year [tCO_2e]	Holding emissions total [tCO_2e]	Holding emissions / year [tCO_2e]
1	`0xdf74156420bd57ab387b195ed81eca36f9fabaca`	279.20	95.89	0	0
2	`0x86e4dc95c7fbdbf52e33d563bbdb00823894c287`	8,528.03	3,820.50	0	0
3	`0x2a88696e0ffa76baa1338f2c74497cc013495922`	284.73	98.73	0.032	0.030
4	`0xa0c68c638235ee32657e8f720a23cec1bfc77c77`	10,180.07	5,325.80	0	0
5	`0x7d1afa7b718fb893db30a3abc0cfc608aacfebb0`	17,086.93	6,465.24	0	0
6	`0x401f6c983ea34274ec46f84d70b31c151321188b`	1,735.90	722.98	0	0
7	`0x5e3ef299fddf15eaa0432e6e66473ace8c13d908`	3,441.94	1,419.47	0	0
8	`0x8484ef722627bf18ca5ae6bcf031c23e6e922b30`	n.A.	n.A.	53,088.464	42,932.77
9	`All contracts of type ‘3’`	67.46	21.70	0.014	0.009

Table 21: Smart contract addresses with major emissions. Emissions per year are calculated from the period 1st August 2021 to 31st July 2022.

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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