CCRI

OCT 2023

REPORT

Energy Efficiency and
Carbon Footprint of
PoS Blockchain Networks and Platforms

PoS Benchmark Study 2023

CCRI

PoS Benchmark Study 2023: Energy Efficiency and Carbon Footprint of PoS Blockchain Networks and Platforms

October 2023

CCRI
carbon-ratings.com

Executive summary

- **Proof of Stake (PoS) protocols** are more **energy-efficient** compared to Proof of Work (PoW)-based networks such as Bitcoin.
- This report assesses the **electricity consumption** and **carbon footprint** of the **PoS protocols** Algorand, Avalanche, Cardano, Cosmos, Ethereum, Polkadot, and Solana.
- For the networks assessed in this study, we find a **variance in total annualized electricity consumption** of 37x - ranging from 154,202.1 kWh to 5,750,351.6 kWh.
- Electricity consumption can be **translated into carbon emissions** via **emission factors** of electricity generation to gauge climate impacts, taking the **node locations** into account.
- For the networks assessed in this study, we find a **variance in total annualized carbon footprint** - ranging from 70.8 tCO_2e to 2,088.4 tCO_2e.
- The result ranges of the networks assessed equal about the annual electricity consumption of **15 to 542 U.S. households** and carbon emissions of **12 to 342 roundtrip flights from MUC to SFO.**
- The **marginal power demand** per TPS (transactions per second) within the assessed blockchain networks ranges from **0.01 W to 0.81 W**.

1 Introduction

The electricity consumption and related carbon footprint of cryptocurrencies remain subject to extensive discussion in public, academia, and industry. Various estimations exist, for instance, comparing Bitcoin's carbon footprint to mid-sized countries (CBECI, 2023; De Vries, Gallersdörfer, Klaaßen, & Stoll, 2022). The consensus family of Proof of Stake (PoS) is superior regarding the electricity requirements compared to the Proof of Work (PoW) consensus mechanisms as applied, for example, by Bitcoin. Yet electricity requirements of individual PoS systems may differ significantly.

Instead of requiring computational power to solve mining puzzles for securing PoW networks, PoS networks require validators to lock in funds to propose or vote on new blocks. Due to the nature of the software engineering process and network architectures, PoS networks differ in terms of hardware requirements, programming language, network size, transaction throughput, and transaction complexity. Besides node count and transaction volume, these factors influence the network electricity consumption and carbon footprint.

Despite the relatively low absolute electricity consumption and carbon emission level of PoS networks and platforms benchmarked in this study, it remains essential to continue monitoring and disclosing energy efficiency and carbon emissions of PoS chains. Key reasons to do so include:

- **Transparency:** It is vital to inform users, regulators, policymakers, and the public about the climate costs and benefits of blockchain solutions.
- **Differentiator:** Sustainability indicators are a decision criterion for some developers, corporates, NFT creators, etc. to select an energy efficient chain.
- **High hardware requirements:** Carbon footprint calculations are the essential data basis to reach corporate climate goals via energy consumption reduction strategies and/or carbon offsetting.
- **Regulation:** Compliance with upcoming regulatory requirements entails disclosure of climate impact.

Compared to last year's CCRI PoS Benchmark study, we have developed a methodology to assess Avalanche Subnets, the Cosmos Ecosystem, and Polkadot Parachains. The results of the PoS Benchmark Study 2023 are summarized in **Figure 1**.

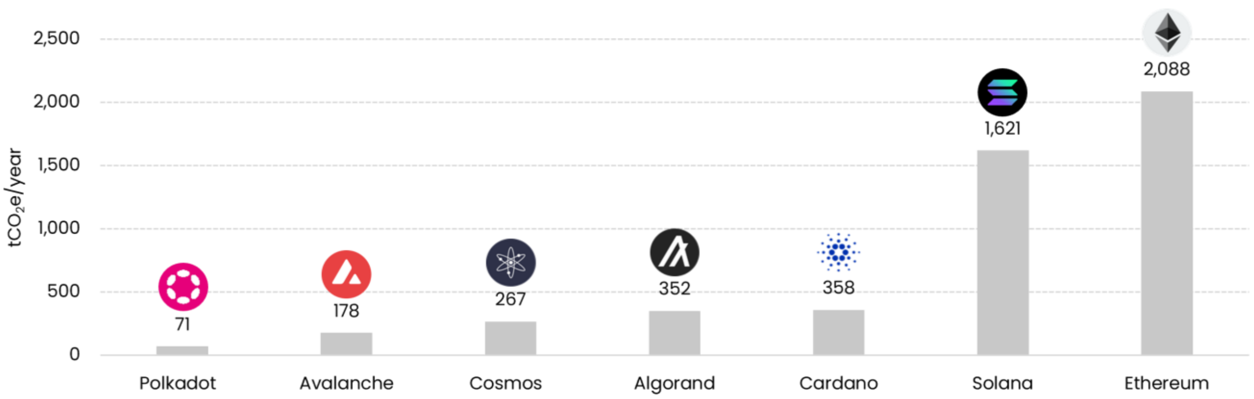

Figure 1: Total annualized network carbon emissions determined by 2023 PoS Benchmarking Study.

2 Aim and scope

This report aims to provide insights into the electricity consumption and carbon footprint of PoS networks. It is noteworthy that the approach applied in this report is a helpful tool to benchmark the total electricity consumption and the carbon emissions as well as the relative performance, however, any PoS network is associated with uncertainties that impede deriving exact numbers. Factors such as network size, varying hardware configurations, and network infrastructure influence the results. Nonetheless, we deem this report to produce precise electricity consumption and carbon footprint estimates for the analyzed systems, as we measure the electricity consumption of single hardware components and use those as a proxy for the overall network or platform of networks. The establishment of representative hardware, network sizes, and electricity measurements form the basis for future research, such as comparing further networks and their respective requirements and properties. In our analysis, we investigate the PoS networks Algorand, Cardano, Ethereum and Solana, as well as the network platforms Avalanche, Cosmos and Polkadot. For platform networks, we differentiate between the network base layer and side chains. Network characteristics are summarized in **Table 1**.

	Symbol	Rank[1]	Market capitalization [$]
Algorand	ALGO	42	1,088,622,236
Avalanche-Mainnet (platform base layer)	AVAX	16	4,941,980,762
Avalanche-DFK (platform upper bound)	JEWEL	823	8,693,655
Avalanche-DOS (platform lower bound)	DOS	-	-
Cardano	ADA	7	13,001,485,360
Cosmos-Hub (platform base layer)	ATOM	19	3,662,295,329
Cosmos-Injective (platform upper bound)	INJ	66	652,961,622
Cosmos-Bitsong (platform lower bound)	BTSG	5741	1,189,280
Ethereum	ETH	2	227,212,821,253
Polkadot-Relaychain (platform base layer)	DOT	13	6,269,855,108
Polkadot -Astar (platform upper bound)	ASTR	136	220,657,549
Polkadot -Composable (platform lower bound)	LAYR	-	-
Solana	SOL	10	220,657,549

Table 1: Key figures of measured networks. Values are taken from Coinmarketcap.com as of June 02, 2023.

[1] Rank in regard of market capitalization.

3 Methodology

Our methodology builds upon five steps to generate data on the electricity consumption and carbon footprint of a PoS system. Moreover, we develop metrics to enable a valid comparison between other PoS systems. Further details regarding our methodology can be found in (CCRI, 2023a).

In the **first step**, we analyze the selected PoS networks and their minimum hardware requirements. The hardware requirements are an indicator of the hardware composition of the network. We use this information and additional hardware data from PassMark (Passmark Software, 2021) to select and obtain hardware that we use to measure a single node's electricity consumption.

In the **second step**, we measure the electricity consumption of a single node and provide upper and lower bounds for each network. We start by running the software required by the respective network on all selected hardware devices and measure their electricity consumption while running the network and while idling. We also capture further data points, such as CPU utilization and processed blocks, to be able to evaluate additional metrics.

In the **third step**, we estimate the electricity consumption of the entire networks. Firstly, we collect information about the size of the network, as the node count significantly influences the total 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 the energy efficiency of transaction throughput for each network. We take samples of the nodes' electricity consumption periodically and examine the number of transactions that the single nodes handled during the respective time periods. This allows us to describe the marginal influence of the number of transactions on the electricity consumption of a node in a specific network. As a result, we establish a model to estimate a node's power consumption based on the number of transactions. This also enables us to track the electricity consumption of a network over time, as node count and transaction volume change.

In the **fifth step**, we estimate the CO_2 emissions arising from the operation of the PoS networks. To do so, we use our data on network electricity consumption and multiply it by carbon emission factors. In case the distribution of nodes in a network is available, we use the respective carbon intensity factors of the regions where the nodes are located to calculate the network's carbon footprint. Otherwise, we rely on an average global carbon intensity factor. For each network, we provide a best guess as well as an upper and a lower bound for the carbon footprint.

Note: To analyze the electricity consumption and carbon footprint of **platform networks** such as Avalanche, Cosmos, and Polkadot, we expand the above-introduced methodology as those networks consist of a base layer and side chains: For each platform, we first select a side chain that has a rather low transaction volume as a lower bound reference, and one with a high transaction volume as an upper bound reference for the electricity consumption of blockchains within the platform. We adhere to our standard approach to measure the electricity consumption of these two reference bounds. By relying on a linear approximation, we can determine the electricity consumption for networks of arbitrary transaction volumes within the corresponding platform. Since there are technical differences in how the platform networks are designed, we tailor our methodology for each platform network. For example, Avalanche requires all validators of Subnets to also participate in the base layer (Mainnet), which is not the case for the Cosmos ecosystem. The exact procedure we apply for each platform is described in Chapter 5.4.2.

4 Hardware requirements and test environment

In this chapter, we first establish a hardware pool for carrying out analyses of PoS networks. Secondly, we summarize the hardware requirements for a node participating in a respective network. For each network in scope of this study, we derive a hardware selection that satisfies the network-specific requirements. Thirdly, we provide details of the infrastructure required to measure the nodes' electricity consumption and describe our test environment.

4.1 Hardware selection

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

- **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.
- **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.
- **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), a MSI GeForce RTX 4090 graphics card, 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. 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, 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, 2022a), 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.

Compared to our PoS network benchmarking of last year (CCRI, 2022a), we largely stick to the same hardware selection. However, some adjustments have been conducted to better fit evolving hardware requirements. 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. Configuration 6 was equipped with a graphics card.

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 2 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	MSI GeForce RTX 4090
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 2: Overview of selected hardware configurations from lowest to highest requirement.

4.2 Hardware requirements of selected PoS networks

The PoS systems to be analyzed reveal different requirements for the hardware of their network participants. While some networks are precise regarding their minimal or recommended hardware requirements, others are partly unspecific: For the Cosmos-Hub network, as an example, no information on the CPU required to run their software is specified. Solana has the highest requirements in our sample, requiring 12 cores / 24 threads, 128 GB RAM, and a 2 TB NVMe SSD. Solana also recommends a specific CPU type (AMD Threadripper Zen3) and states that a node might profit from using a GPU in future. It is noteworthy that some networks (e.g., Polkadot or Cosmos-Hub) do not provide minimum hardware requirements but rather link to a recommended setup.

Furthermore, there are PoS networks that introduce different roles among their nodes, each executing varying tasks. These roles can lead to divergent hardware requirements within the network. In the Algorand network, for instance, a node can assume the role of a relay node (i.e., it is responsible for communication routing), a participation node (i.e., the node participates in the consensus mechanism), an archival node (i.e., the node stores the entire leger), or various combinations of these roles. In such cases, we apply the hardware requirements of a role that most closely resembles a normal full node of a standard PoS network.

Table 3 summarizes the hardware requirements at the time of our analysis (April 2023) for executing a node participating the selected PoS networks.

	CPU	RAM	Storage	SSD/NVMe	Source
Algorand	> 8x v	> 16 GB	> 100 GB	NVMe	(Algorand, 2023)
Avalanche (all platform chains)	> 8x v (AWS)	> 16 GiB	> 1 TiB	N/A	(Ava Labs, 2023a)
Cardano	> 2x1.6GHz	> 16 GB	> 75 GB	N/A	(Cardano Foundation, 2023)
Cosmos-Hub (platform base layer)	N/A	32 GB	> 500 GB	N/A	(Tendermint, 2023a)
Cosmos-Injective (platform upper bound)	> 4x2GHz v	> 32 GB	> 1 TB	SSD	(Injective Labs, 2023)
Cosmos-Bitsong (platform lower bound)	N/A	N/A	N/A	N/A	(BitSong, 2023)
Ethereum	Different configurations of client software possible, see detailed analysis in (CCRI, 2022b)				
Polkadot-Relaychain (platform base layer)	4x3.4GHz	32 GB	1 TB	NVMe	(Web3 Foundation, 2023b)
Polkadot-Astar (platform upper bound)	8x	16 GB	500 GB	NVMe	(Astar Developers Hub, 2023)
Polkadot-Composable (platform lower bound)	> 2x	> 6 GB	> 600 GB	N/A	(Composable Finance, 2023)
Solana	12x2.8GHz	> 128 GB	1 TB + 500 GB	NVMe	(Solana Foundation, 2023)

Table 3: Hardware requirements of the selected PoS networks. Minimal requirements are marked with a ">" sign. CPUs labeled with "v" denote virtual CPUs.

Applying the networks' requirements to execute full nodes to our hardware pool presented in the previous section, we deduce that configuration 6 as shown in **Table 2** exceeds the hardware recommendations for all clients listed. Thus, this hardware configuration is included into all measurements.

Apart from Solana, configuration 5 likewise meets all requirements and is therefore included in all the other measurements. Since we do not enforce hardware requirements to be a strict lower bound, we also include configurations into a network's measurements that are slightly lower than the official requirements. For this reason, configuration 4 is involved in all experiments apart from Solana. Nodes representative for the low-tier category were only capable to run client software to measure a lower bound, an upper bound, and the base layer for the platform networks Polkadot and Cosmos. It is noteworthy that software might not be available for configuration 1 due to the Raspberry Pi's architecture.

Table 4 summaries which configurations of our hardware pool were included as a foundation to derive the electricity consumption of the different PoS networks selected.

	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6
Algorand	✗	✓	✓	✓	✓	✓
Avalanche-Mainnet (platform base layer)	✗	✗	✗	✓	✓	✓
Avalanche-DFK (platform upper bound)	✗	✗	✗	✓	✓	✓
Avalanche-DOS (platform lower bound)	✗	✗	✗	✓	✓	✓
Cardano	✗	✗	✗	✓	✓	✓
Cosmos-Hub (platform base layer)	✗	✓	✓	✓	✓	✓
Cosmos-Injective (platform upper bound)	✗	✓	✓	✓	✓	✓
Cosmos-Bitsong (platform lower bound)	✓	✓	✓	✓	✓	✓
Ethereum	✗	✗	✗	✓	✓	✓
Polkadot-Relaychain (platform base layer)	✗	✓	✓	✓	✓	✓
Polkadot-Astar (platform upper bound)	✗	✓	✓	✓	✓	✓
Polkadot-Composable (platform lower bound)	✗	✓	✓	✓	✓	✓
Solana	✗	✗	✗	✗	✗	✓

Table 4: Overview of configurations out of our hardware pool selected for the different PoS networks selected.

4.3 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 (Hennion, 2021) that allows us to collect additional system information such as temperature or system load during the experiment.

A separate Raspberry Pi, equipped with a Python script, collected and monitored the systems during executing the 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.

5 Benchmarking Results: Electricity consumption and carbon footprint

The hardware selection as described in the previous chapter allows us to establish single node electricity measurements. With these measurements, we provide upper and lower bounds for the electricity consumption of a single node running a specific network, and a best guess as a weighted average between the selected hardware devices for the network. On that basis, we calculate the overall electricity consumption of the respective PoS network or platform. Furthermore, we discuss additional metrics such as the electricity consumption of a node assuming the network is running but no transactions are executed, and the marginal power demand per transactions per second.

5.1 Single node electricity measurements

After defining and obtaining the hardware required for our analysis, we set up the hardware and install the node software for each PoS network to be measured. We use the following process:

- **Hardware setup**:
  We install the node with the respective Linux version, configure Glances and configure remote access.
- **Idle measurement**:
  We run the idle measurement for the devices without any additional software installed.
- **Node setup**:
  We download and install the software necessary for executing a specific PoS network and verify the correct installation.
- **Node bootstrap**:
  On each node, we run the respective software and wait for the synchronization to be completed since we do not want to skew the electricity consumption of the devices during the bootstrapping phase.
- **Electricity measurement**:
  We shut down the nodes, start the electricity measurement and then start the nodes again. The nodes run for 24 hours executing the respective network's client software, as this covers an entire day cycle. Appendix B contains an overview summarizing the result of every electricity measurement for each node and network.

To understand what exactly we are measuring, we need to describe a regular PoS network and its setup. In addition, we need to investigate the architecture of PoS platform networks.

A PoS network consists of nodes, either validators (participating in the consensus protocol and producing new blocks) or regular full nodes (broadcasting and verifying regular transactions). Validators are selected to propose new blocks based on their stake. 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 networks, usually 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 conduct our electricity measurement on regular full nodes running on the main networks of the selected PoS systems.

A platform network such as Avalanche, Cosmos, or Polkadot consists of multiple PoS networks that are mutually linked via inter-blockchain communication protocols. The core of the platform is formed by a base layer, i.e., a main network of the system, which is commonly responsible for managing the different networks of the platform and to allow for communication and transfers of assets between them. The terminology used among the different platforms is not standardized: In case of Avalanche, this base layer is referred to as the Avalanche-Mainnet, for Cosmos, it is called Cosmos-Hub, and for Polkadot, it is named the Polkadot-Relaychain. All other networks of the Avalanche network are denoted as Subnets, those of the Cosmos platform as Zones, and those of the Polkadot platform as Parachains. Moreover, the role of validators within these platforms varies. For instance, validators on the Cosmos platform can join an arbitrary number of zones. Unlike Avalanche, for which each validator of a Subnet also needs to join the Avalanche-Mainnet, validators of a particular Cosmos Zone do not necessarily have to participate in the base layer network. However, on Polkadot, the individual networks have their distinct set of validators, although validators of the Relaychain share responsibilities for the various Parachains among each other in order to enable communication across the different Polkadot networks.

5.1.1 Electricity consumption in idle state

We measure the electricity consumption of the devices idle. **Table 5** depicts the minimum, maximum, median, mean, and the first and third quartile of the electricity consumption for 24 hours. All values are rounded to two decimals. Interestingly, setups 2 and 3 consume less electricity than the Raspberry Pi (configuration 1), which we deemed the most energy-efficient solution beforehand.

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

Table 5: Power demand in Idle measured in Watt [W] – hardware selection for each of the six configurations can be found in Table 2.

5.1.2 Node electricity consumption

Due to the hardware requirements outlined in Chapter 4.2, we do not run all networks on all nodes. In **Table 4**, we give an overview about which measurements take place on which machines.

We outline the mean (**Table 6**) and the median (**Table 7**) power demand of the nodes during the measurement of all PoS networks selected. This includes the standard PoS systems Algorand, Cardano, Ethereum and Solana on the one hand, and, on the other hand, an upper and lower bound network as well as the base layer network for each of the platforms Avalanche, Cosmos, and Polkadot.

	1	2	3	4	5	6
Algorand	N/A	23.25	25.07	30.86	56.79	160.30
Avalanche-Mainnet (platform base layer)	N/A	N/A	N/A	7.29	27.22	109.61
Avalanche-DFK (platform upper bound)	N/A	N/A	N/A	13.86	34.00	120.67
Avalanche-DOS (platform lower bound)	N/A	N/A	N/A	7.73	27.73	112.61
Cardano	N/A	N/A	N/A	4.57	26.36	83.91
Cosmos-Hub (platform base layer)	N/A	12.95	17.02	13.37	34.40	125.69
Cosmos-Injective (platform upper bound)	N/A	15.71	18.32	19.35	42.24	132.89
Cosmos-Bitsong (platform lower bound)	3.63	5.69	7.70	10.18	30.90	120.43
Ethereum	Different configurations of client software possible, see detailed analysis in (CCRI, 2022b)					
Polkadot-Relaychain (platform base layer)	N/A	6.07	9.27	21.46	44.32	123.16
Polkadot-Astar (platform upper bound)	N/A	6.88	9.92	22.66	45.07	125.10
Polkadot-Composable (platform lower bound)	N/A	4.73	6.76	14.63	36.85	122.36
Solana	N/A	N/A	N/A	N/A	N/A	319.60

Table 6: Mean power demand of nodes in Watt [W].

	1	2	3	4	5	6
Algorand	N/A	23.07	24.90	29.94	56.74	160.25
Avalanche-Mainnet (platform base layer)	N/A	N/A	N/A	7.12	27.12	109.31
Avalanche-DFK (platform upper bound)	N/A	N/A	N/A	13.73	33.86	120.535
Avalanche-DOS (platform lower bound)	N/A	N/A	N/A	7.58	27.64	112.54
Cardano	N/A	N/A	N/A	4.18	25.81	82.63
Cosmos-Hub (platform base layer)	N/A	12.81	18.10	10.39	31.10	121.91
Cosmos-Injective (platform upper bound)	N/A	15.62	18.36	19.35	42.09	132.84
Cosmos-Bitsong (platform lower bound)	3.59	5.42	7.58	9.93	30.72	120.07

	1	2	3	4	5	6
Ethereum	Different configurations of client software possible, see detailed analysis in (CCRI, 2022b)					
Polkadot-Relaychain (platform base layer)	N/A	6.01	9.21	21.44	44.32	123.09
Polkadot-Astar (platform upper bound)	N/A	6.86	9.93	22.74	45.30	124.87
Polkadot-Composable (platform lower bound)	N/A	4.64	6.86	14.05	37.25	122.29
Solana	N/A	N/A	N/A	N/A	N/A	320.33

Table 7: Mean power demand of nodes in Watt [W].

5.2 Calculation of bounds for electricity consumption

To calculate the electricity consumption of an overall network or platform, we need to understand the average calculation for a single node. We measured the electrical power demand for different computers depending on the respective network's hardware requirements. 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 an average node best for the respective network. We apply this approach for each of the PoS networks as well as the three networks for each platform (base layer network and upper bound as well as lower bound in terms of transaction throughput) measured.

5.2.1 Upper and lower bound electricity consumption

The upper and lower bounds are measured by the least efficient and most efficient hardware, respectively. The lower bound therefore is constituted by the Raspberry Pi (configuration 1) for Cosmos-Bitsong. Configuration 2 is used for Algorand, Cosmos-Hub, Cosmos-Injective, Polkadot-Relaychain, Polkadot-Astar, and Polkadot-Composable. Configuration 3 does not represent any lower bound since each network that could be executed on this hardware set has also worked on configuration 2. Configuration 4 forms the lower bound for networks revealing more advanced hardware requirements, that is, all networks measured for the Avalanche platform as well as Cardano and Ethereum. Configuration 6 serves both as the lower bound for Solana and as an upper bound for all networks, since for Solana only one device is available. The respective lower and upper bounds are summarized in **Table 8**.

	Lower bound [W]	Lower bound [kWh/year]	Upper bound [W]	Upper bound [kWh/year]
Algorand	23.25	203.7	160.30	1,404.25
Avalanche-Mainnet (platform base layer)	7.29	63.82	109.61	960.17
Avalanche-DFK (platform upper bound)	13.86	121.4	120.67	1,057.11
Avalanche-DOS (platform lower bound)	7.73	67.7	112.61	986.46
Cardano	4.57	39.99	83.91	735.03

	Lower bound [W]	Lower bound [kWh/year]	Upper bound [W]	Upper bound [kWh/year]
Cosmos-Hub (platform base layer)	12.95	113.46	125.69	1,101.00
Cosmos-Injective (platform upper bound)	15.71	137.62	132.89	1,164.10
Cosmos-Bitsong (platform lower bound)	3.63	31.79	120.43	1,055.00
Ethereum[2]	20.00	175.19	150.06	1,314.75
Polkadot-Relaychain (platform base layer)	6.07	53.13	123.16	1,078.84
Polkadot-Astar (platform upper bound)	6.88	60.28	125.10	1,095.84
Polkadot-Composable (platform lower bound)	4.73	41.48	122.36	1,071.89
Solana	319.60	319.60	319.60	2,799.67

Table 8: Overview of lower and upper bounds of power demand and electricity consumption per single node.

5.2.2 Best guess electricity consumption

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 configuration for each network investigated is displayed in **Table 9**.

	1	2	3	4	5	6
Algorand	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Avalanche-Mainnet (platform base layer)	N/A	N/A	N/A	25.00%	50.00%	25.00%
Avalanche-DFK (platform upper bound)	N/A	N/A	N/A	25.00%	50.00%	25.00%
Avalanche-DOS (platform lower bound)	N/A	N/A	N/A	25.00%	50.00%	25.00%

[2] For Ethereum, different client software for both execution and consensus client are available, which impact the electricity consumption of the single network's nodes. CCRI has extensively analyzed the electricity consumption of the Ethereum network in (CCRI, 2022b) recently, the upper and lower bounds provided here are taken from this study and take the shares of the different client software into account.

	1	2	3	4	5	6
Cardano	N/A	N/A	N/A	25.00%	50.00%	25.00%
Cosmos-Hub (platform base layer)	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Cosmos-Injective (platform upper bound)	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Cosmos-Bitsong (platform lower bound)	3.125%	15.625%	31.25%	31.25%	15.625%	3.125%
Ethereum	N/A	N/A	N/A	25.00%	50.00%	25.00%
Polkadot-Relaychain (platform base layer)	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Polkadot-Astar (platform upper bound)	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Polkadot-Composable (platform lower bound)	N/A	6.25%	25.00%	37.50%	25.00%	6.25%
Solana	N/A	N/A	N/A	N/A	N/A	100.00%

Table 9: Overview of node distribution for the measured networks.

With these distributions, we calculate the weighted power demand of an average best guess node ($P_{bestGuessNode}$) for a specific network:

$$P_{bestGuessNode} = \sum_{hc}^{HardwareConfigurations} (meanEnergyConsumption_{hc} * share_{hc})$$

An average node in the different networks consumes from 15.18 watts for the Cosmos platform's lower bound reference network in terms of transaction throughput (Cosmos-Bitsong) to 319.60 watts for the Solana network. This difference of more than a factor of 21 implies that 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 10** gives an overview about the best guess power demand in watts and electricity consumptions per year in kWh for each network measured.

	Best guess [W]	Best guess [kWh/year]
Algorand	43.51	381.14
Avalanche-Mainnet (platform base layer)	42.83	375.23
Avalanche-DFK (platform upper bound)	50.64	443.57
Avalanche-DOS (platform lower bound)	43.95	384.9
Cardano	35.30	309.21
Cosmos-Hub (platform base layer)	26.53	232.42

	Best guess [W]	Best guess [kWh/year]
Cosmos-Injective (platform upper bound)	31.68	277.55
Cosmos-Bitsong (platform lower bound)	15.18	132.99
Ethereum[3]	62.44	547.01
Polkadot-Relaychain (platform base layer)	29.52	258.61
Polkadot-Astar (platform upper bound)	30.49	267.12
Polkadot-Composable (platform lower bound)	24.33	213.15
Solana	319.60	2,799.67

Table 10: Overview of best guess estimates for power demand and electricity consumption per single node.

Additionally, we summarize the single node power demand estimates of the upper bound, lower bound, and best guess for each network measured in **Figure 2**.

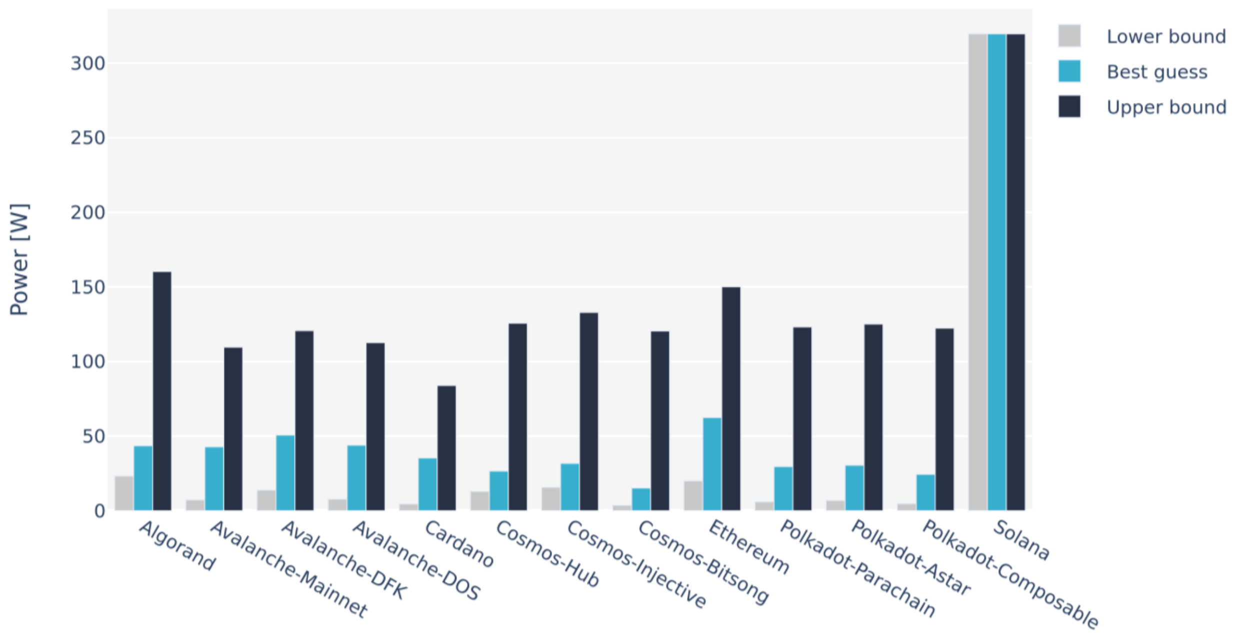

Figure 2: Overview of lower bound, upper bound and best guess power demand estimates for a single node of the respective network in watts.

[3] For Ethereum, different client software for both execution and consensus client are available, which impact the electricity consumption of the single network's nodes. CCRI has extensively analyzed the electricity consumption of the Ethereum network in (CCRI, 2022b) recently, the best guess provided here is taken from this study and takes the shares of the different client software into account.

5.3 Power per transaction: Node base power demand and marginal power demand per TPS

Discussion on electricity consumption per transaction metric

An often-used metric in comparing electricity consumption between systems is the electricity consumption per transaction, which is frequently calculated by dividing the total electricity consumption by the total number of transactions within a specific time period. The underlying idea is to compare systems that have different architectures, transaction throughput, and electricity requirements. However, such comparisons are associated with several challenges and complexities (CCRI, 2023a).

First, underlying definitions may influence the results significantly. For instance, some systems provide a theoretical electricity consumption per transaction, simulating the network at full speed. Other calculations are based on transaction rates measured in the networks, making comparisons skewed. Further, the definition of a transaction might vary from network to network.

Second, there is additional complexity caused by the attribution of the electricity consumption solely to the transactions. The system requires a base electricity consumption to keep up with the consensus without providing any transactions. Nonetheless, given the base load of a network, running a node in a "low-transaction"-period might yield higher electricity per transaction costs than usually to be expected and vice versa. This may also distort comparisons across networks when electricity consumption per transaction is used as the central metric. Consequently, albeit the metric may provide straightforward insights into different protocols, its base assumptions need to be understood and its results must be treated with care and in context of other metrics.

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

To address the above-mentioned challenges, we measure the power demand of our nodes in a real-world scenario and consider the transaction throughput that took place during the respective time period. We then derive the marginal power demand per transactions per second on a statistical regression model (CCRI, 2023a).

With this approach, we aim to obtain more accurate results than merely considering average values. Furthermore, it has the advantage that constant power demand, which is independent of the transaction count, can be differentiated from the power demand that is driven by transactions. The regression model is set up completely on the basis of our own measurements. We filter outliers and construct a regression line for each of the hardware configurations from **Table 2** selected for the considered PoS network, based on our periodically taken measurement samples that consist of the current power demand and the transactions per second throughput at that time.

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

$$P_{BG_{network}}(TPS)\ [W] = m_{BG} * TPS_{network} + basePower_{BG}$$

The annualized transaction counts, the transactions per second metric (both as of April 24, 2023), as well as es the measured networks' marginal power demands per TPS and base power demands of all networks investigated in this study are summarized in **Table 11**.

We were not able to derive a meaningful relationship between the transaction volume and the nodes' power demand for the upper and lower bound Parachains of Polkadot (Polkadot-Astar and Polkadot-Composable). This is presumed to be due to the architecture of the Polkadot platform (see Chapter 5.4.2): We assume that the majority of the load of a Parachain node is caused by the interconnection to the Polkadot-Relaychain and the inter-chain communication mechanism. Only a smaller fraction of the nodes' load stem from the transactions of the Relaychain itself. As a result, for the Polkadot Parachains, the relationship between the number of transactions and the electricity consumption of a node cannot be expressed meaningfully. The same holds true for the lower bound chain Avalanche-DOS measured to assess the Avalanche platform. Since each validator of an Avalanche Subnet is required to join the Avalanche-Mainnet entirely (see Chapter 5.4.2), a reasonable relationship between the nodes' power demand and the transaction volume of the considered Subnet can only be expressed if the traffic on the Subnet significantly exceeds that of the Avalanche-Mainnet itself. This applies to the measured upper bound Avalanche-DFK, but not for the lower bound Avalanche-DOS.

	Transactions (annualized) [Tx/year][4]	Transactions (TPS) [Tx/s][4]	Marginal power demand per TPS [W]	Base power demand [W]
Algorand	180,527,540	5.7245	0.0807	42.9984
Avalanche-Mainnet[5] (platform base layer)	297,252	3.4404	0.1092	42.5741
Avalanche-DFK (platform upper bound)	651,463	7.5401	0.4395	47.8678
Avalanche-DOS (platform lower bound)	394	0.0046	-	-
Cardano	16,534,135	0.5243	1.1158	34.6155
Cosmos-Hub (platform base layer)	18,338,695	0.5815	0.8095	26.0707
Cosmos-Injective (platform upper bound)	222,166,375	7.0448	0.2112	30.4125

[4] Transaction counts are as of April 24, 2023. For the Avalanche platform and its Subnet blockchains measured, transaction counts are as of June 01, 2023.
[5] The Avalanche Mainnet is composed of three blockchains (C-Chain, X-Chain, and P-Chain). We refer to the C-Chain (contract chain) for the transaction count since this chain is causes most of the traffic on the Avalanche-Mainnet.

	Transactions (annualized) [Tx/year][4]	Transactions (TPS) [Tx/s][4]	Marginal power demand per TPS [W]	Base power demand [W]
Cosmos-Bitsong (platform lower bound)	220,460	0.0070	0.7981	15.1185
Ethereum[6]	343,393,460	10.8889	0.1055	61.9741
Polkadot-Relaychain (platform base layer)	2,603,545	0.0826	0.3596	29.3472
Polkadot-Astar (platform upper bound)	732,190	0.0232	N/A	N/A
Polkadot-Composable (platform lower bound)	105,485	0.0033	N/A	N/A
Solana	11,843,554,310	375.5566	0.0130	313.9651

Table 11: Overview of marginal power demands per TPS and base power demands of a best guess node for each measured network.

Figure 3 illustrates the base power demand (left y-axis) and marginal power demand per one TPS (right y-axis) for each network that reveals a meaningful relationship between transaction volume and node power.

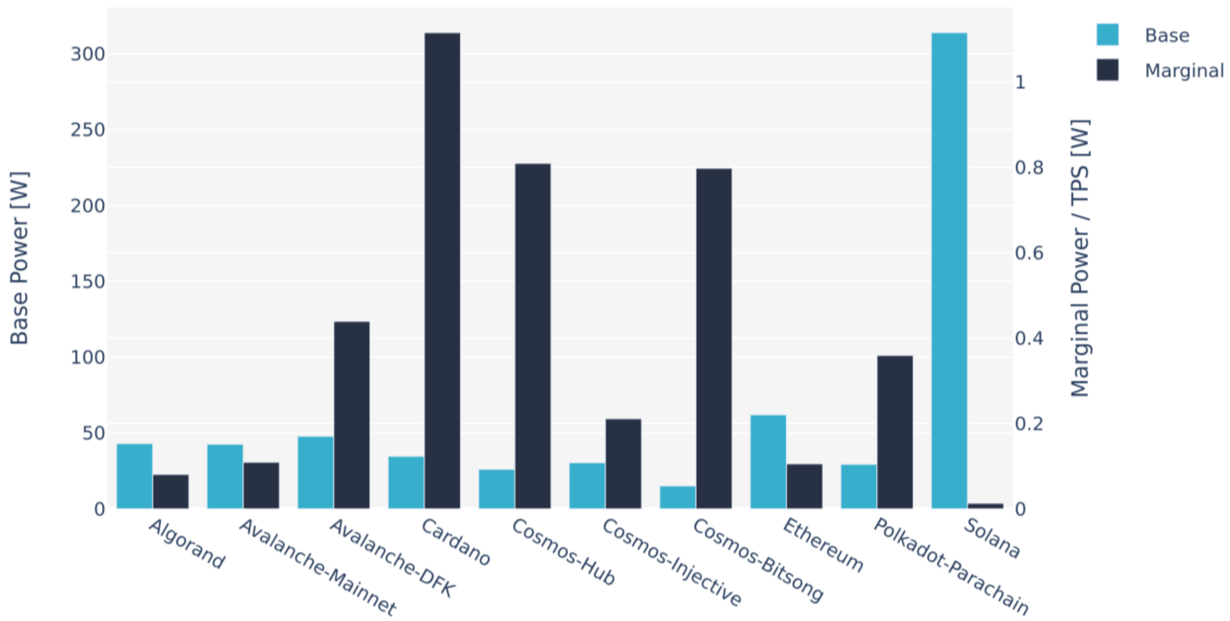

Figure 3: Base power demand and marginal power demand per TPS for a best guess single node of the respective network in watts.

[6] For Ethereum, different client software for both execution and consensus client are available, which impact the electricity consumption of the single network's nodes. CCRI has extensively analyzed the electricity consumption of the Ethereum network in (CCRI, 2022b) recently, both the marginal power demand per TPS and the base power demand are based on this study to take the shares of the different client software into account (as of April 24, 2023).

5.4 Electricity consumption of PoS networks and platforms

Based on the per-node electricity consumption, we can derive the overall electricity consumption of a PoS network or a PoS platform network. The composition of a network is an important factor when calculating its electricity consumption. In the following, we first determine the electricity consumption of the regular PoS networks Algorand, Cardano, Ethereum, and Solana. After that, we analyze the total electricity consumption of the platforms Avalanche, Cosmos, and Polkadot, based on the results of the three networks measured for each of these platforms (lower bound, upper bound, and base layer network). Since the platforms reveal technical differences, we tailor our methodology to address the respective platform characteristics.

5.4.1 Electricity consumption of regular PoS networks

Algorand, Cardano, Ethereum, Solana

To determine the overall electricity consumption of a regular, non-platform PoS network, we multiply the best guess node estimate with the number of validator nodes in the respective network:

$$P_{network}\,[W] = P_{BG_{network}} * validatorCount_{network}$$

We obtain the number of nodes from block explorers as specified in Appendix C. The results are depicted in **Table 12**. From the networks' electrical power demands, we derive the daily and annualized electricity consumption.

	Nodes [# total][7]	Electrical power [W]	Electricity consumption [kWh/day]	Electricity consumption [kWh/year]
Algorand	2,013	87,585.63	2,102.01	767,234.82
Cardano	3,177	112,148.10	2,691.40	982,360.17
Ethereum[8]	10,856	685,257.33	16,446.16	5,750,351.57
Solana	1,772	566,331.20	13,591.82	4,961,015.24

Table 12: Overview of electricity consumption of analyzed regular PoS networks applying the respective best guess estimate.

Figure 4 summarizes the yearly electricity consumption of the analyzed PoS networks Algorand, Cardano, Ethereum, and Solana in comparison with their respective node count. We find the consumption per year of a standard PoS system to amount from 767,235 kWh for Algorand to 6,003,585 for Ethereum.

[7] Validator counts are as of April 24, 2023. Due to unavailability of data for Algorand at the time of analysis, we rely on an average value taken from January 17 to February 05, 2023.
[8] For Ethereum, different client software for both execution and consensus client are available, which impact the electricity consumption of the single network's nodes. CCRI has extensively analyzed the electricity consumption of the Ethereum network in (CCRI, 2022b) recently. The results on network level shown are based on this study to take the shares of the different client software into account (as of April 24, 2023).

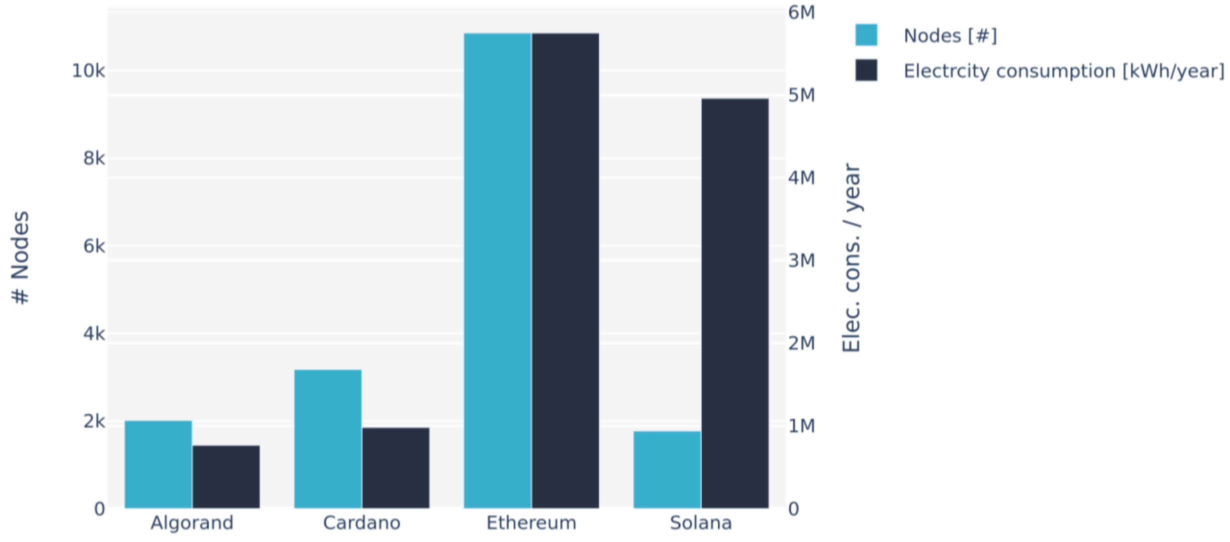

Figure 4: Electricity consumption per year [kWh] and node counts of non-platform networks.

5.4.2 Electricity consumption of PoS platform networks

Avalanche, Cosmos, Polkadot

Platform networks such as Avalanche, Cosmos, and Polkadot are composed of multiple interconnected blockchains. Thus, to determine the electricity consumption of a platform, we need to extend our approach applied for standard PoS systems, that is, multiplying the electricity consumption of a best guess node in the network by the overall node count. The power demand per node in a platform differs depending on the specific network of the platform to which the node is connected to. This is the case since a platform's networks can differ significantly in terms of transaction throughput, transaction complexity, and state size. For some platforms, it is common that a node validates multiple networks' blockchains simultaneously. In this case, a node's electricity consumption also depends on the number of networks in which it participates. To analyze the total electricity consumption of a platform, we use a five-step approach:

In the **first step**, we collect information about the platform's topology. This means that we analyze of how many blockchains the platform is composed, how these are interconnected, and how the individual blockchains perform in terms of size, complexity, and transaction throughput.

In the **second step**, we analyze the nodes of the respective platform. This means that we capture data about the overall number of nodes, a mapping of which node has joined which blockchain, and whether validators of the platform can participate in several blockchains simultaneously.

In the **third step**, we estimate the power demand per node for each of the platform's blockchains. To do so, we identify a blockchain with a rather high transaction volume as an upper bound for the power demand of nodes within this platform, and one with a rather low transaction volume as a lower bound. We measure these two blockchains adhering to our approach explained in Chapter 5.1, i.e., by running full nodes on representative hardware configurations conforming to the requirements listed in **Table 2.** As a result, we obtain the power demand of a best guess node for both chains investigated, that is, the upper and the lower bound blockchain selected for the platform. We then establish a linear function model by fitting a line through the determined best guess power demand per node of the upper and lower bound blockchains towards the respective blockchain's daily transaction volume. This linear model allows us to derive an estimate of the power demand of a best guess node for an arbitrary blockchain of the platform based on its daily transaction volume.

In the **fourth step**, we apply these estimates to calculate the power demand of a single best guess node for each blockchain of the platform.

In the **fifth step**, we calculate the total electricity consumption of the entire platform. We iterate over all validators of the platform and sum up their estimated power demand, which results in the total power demand of the entire platform. Depending on the platform examined, a validator might participate in more than one platform. In this case, we furthermore need to correct each validator's total power demand by its repeatedly counted idle power.

Table 13 summarizes the results of measuring the upper and the lower bound networks for the platforms Avalanche, Cosmos, and Polkadot. Furthermore, for each of these platforms, we provide the measurement results for the respective base layer chain, that is, the Avalanche-Mainnet for Avalanche, the Cosmos-Hub for Cosmos, and the Polkadot-Relaychain for Polkadot. In the remainder of this chapter, we will determine the total electricity consumption of the three platforms based on these measurement results. For this, we tailor our general methodology just introduced to address the specific characteristics of the respective platform appropriately.

	Nodes [# total][9]	Electrical power [W]	Electricity consumption [kWh/day]	Electricity consumption [kWh/year]
Avalanche-Mainnet (platform base layer)	1,247	53,409.01	1,281.95	467,911.81
Avalanche-DFK (platform upper bound)	8	405.12	9.72	3,548.56
Avalanche-DOS (platform lower bound)	9	395.55	9.49	3,464.10
Cosmos-Hub (platform base layer)	175	4,642.75	111.43	40,673.50
Cosmos-Injective (platform upper bound)	60	1,900.80	45.62	16,653.00
Cosmos-Bitsong (platform lower bound)	99	1,502.82	36.07	13,166.01
Polkadot-Relaychain (platform base layer)	297	8,767.44	210.43	76,807.17
Polkadot-Astar (platform upper bound)	75	2,286.75	54.89	20,034.00
Polkadot-Composable (platform lower bound)	4	97.32	2.34	852.60

Table 13: Overview of electricity consumption of analyzed platforms' upper bound, lower bound, and base layer chain references applying the respective best guess estimate.

[9] Validator counts are as of April 24, 2023. For the Avalanche platform and its Subnet blockchains measured, validator counts are as of June 01, 2023.

Figure 5 illustrates the relationship between the node count and the yearly electricity consumption of the examined platforms' lower bound, upper bound, and base layer blockchains.

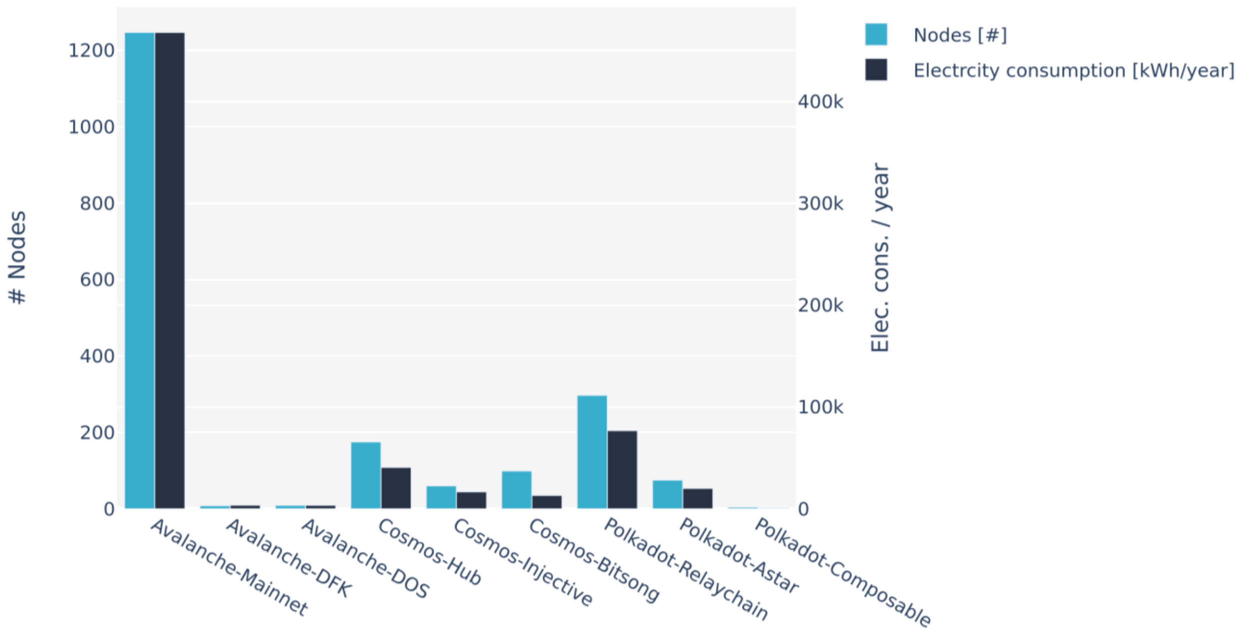

Figure 5: Electricity consumption per year [kWh] and node count of analyzed platforms' lower bound, upper bound, and base layer chains.

Avalanche Platform

Since it has become possible to launch so-called Subnets in the Avalanche ecosystem, it can be regarded as a platform network. Nodes of one single Subnet can validate multiple blockchains at once, however, a blockchain can only belong to exactly one Subnet. Subnets are independent networks, allowing to specify a custom membership regularity, define an own execution logic, and maintain a custom state. In contrast to some other platform networks, Subnets running within the Avalanche platform do not rely on the security of the base layer, but rather need to maintain their own network security. Communication between Subnets is facilitated by the *Avalanche Warp Messaging* protocol. The primary base layer network of Avalanche is referred to as the Mainnet; it is compiled of three different blockchains: the P-Chain (platform chain responsible for platform-level operations), the C-Chain (EVM-based contract chain for executing smart contracts), and the X-Chain (exchange chain for operations on digital smart assets) (Ava Labs, 2023b).

Each validator of any Subnet on the Avalanche platform is required to additionally join the Avalanche-Mainnet. Furthermore, it is theoretically possible for a validator to participate in multiple Subnets simultaneously, although this was not the case for any node at the time of our analysis. Hence, to calculate the total electricity consumption of the Avalanche platform ($P_{Avalanche}$), we need to iterate over all validator nodes of the platform and sum up their power demands:

$$P_{Avalanche}\ [W] = \sum_{Validator}^{Validators} P_{Validator}$$

For each node, we determine its individual power demand ($P_{Validator}$) by examining which Subnets this node has joined. If the node is not participating in any Subnet, i.e., it only validates the Avalanche-Mainnet, its power demand corresponds to the best guess for a node in Avalanche-Mainnet ($P_{bestGuess_{Mainnet}}$) base layer, which we have determined through a dedicated measurement (see Chapter 5.2.2). However, if the node participates in one or more Subnets, we sum up the best guess power demand of the Avalanche-Mainnet on the one hand, and, on the other hand, the *additional power demand* caused by running each blockchain of the respective Subnet or Subnets ($P_{networkMarginal_{SubnetChain}}$):

$$\forall\, Validator:$$
$$P_{Validator}\,[W] = P_{bestGuess_{Mainnet}} + (\sum_{sc}^{SubnetChains} (P_{networkMarginal_{sc}}\; if\; Validator\; in\;\; sc\; else\; 0))$$

To estimate the additional power demand ($(P_{networkMarginal_{SubnetChain}}$) that a node incurs by joining a specific Subnet, we rely on a linear approximation. Through our measurements of the upper bound Subnet blockchain Avalanche-DFK and the lower bound Avalanche-DOS, we can model the power demand of a best guess node participating in an arbitrary Avalanche-Subnet blockchain ($P_{bestGuess_{SubnetChain}}$) based on its daily transaction volume. Since each node of a Subnet also joins the Mainnet as described above, we subtract the best guess power demand of an Avalanche-Mainnet node to obtain a node's additional power demand for participating in the corresponding Subnet blockchain:

$$\forall\, SubnetChain:$$
$$P_{networkMarginal_{SubnetChain}}\,[W] = P_{bestGuess_{SubnetChain}}(txCount_{SubnetChain}) - P_{bestGuess_{Mainnet}}$$

The linear models applied are shown in **Figure 6**. The x-axis indicates the daily transaction volume of Subnet blockchains within the Avalanche platform, the y-axis the corresponding power demand in watts. The lower bound measurement results are represented by the orange dots (Avalanche-DOS), the upper bound measurement results by the blue dots (Avalanche-DFK). The red function plot indicates the best guess power consumption of a node running an arbitrary Subnet blockchain ($P_{bestGuess_{SubnetChain}}$) in parallel to the Avalanche-Mainnet towards the daily transaction count of the respective Subnet blockchain. To finally derive the additional power demand caused by joining an arbitrary Subnet blockchain ($P_{networkMarginal_{SubnetChain}}$), we subtract the power demand of the Avalanche-Mainnet represented by the green marker from the red line, which results in the purple linear function. The gray markers on the purple plot show different Subnet blockchains as of June 01, 2023.

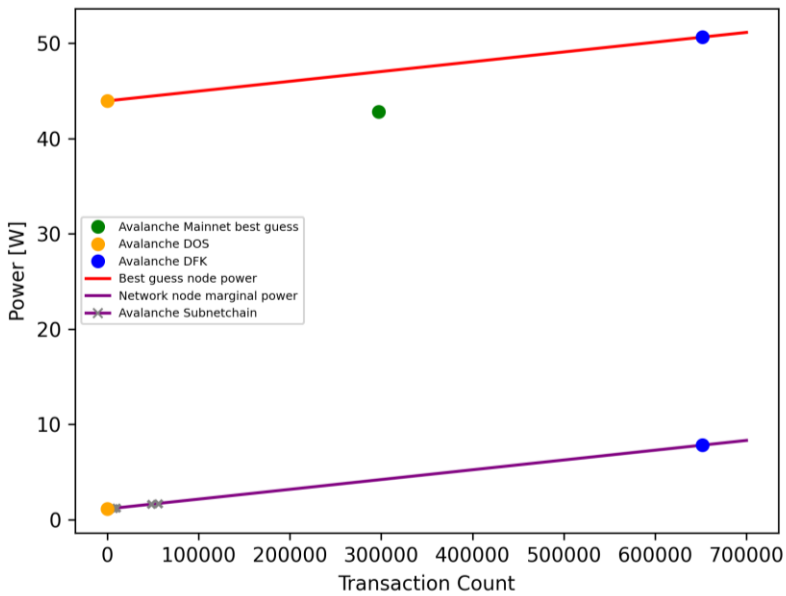

Figure 6: Linear models built out of upper and lower bound measurements to estimate the power demand of arbitrary Subnets of the Avalanche platform based on daily transaction volume.

Table 14 lists the results of our calculations to estimate the total power demand and electricity consumption of the Avalanche platform. Validator counts, transaction counts, as well as the mapping of which validator participates in which Subnet blockchain are taken from the block explorer Avascan.info[10] (as of June 01, 2023). Some blockchains are not yet indexed by the block explorer at the time of our analysis; for these chains we assume the same daily transaction volume as for our lower bound Subnet blockchain (Avalanche-DOS) selected, since we consider the unindexed chains to be rather small in size and low in throughput.

	Nodes [# total][11]	Electrical power [W]	Electricity consumption [kWh/day]	Electricity consumption [kWh/year]
Avalanche (platform total)	1,247	53,630.41	1,287.13	469,802.39

Table 14: Electricity consumption of the Avalanche platform.

Cosmos Platform

In the Cosmos ecosystem, the base layer blockchain is called Cosmos-Hub, all other chains are referred to as Zones (Tendermint, 2023b). A characteristic of the Cosmos platform is that validators of a zone do not necessarily have to join the Cosmos-Hub. Hence, for an individual node that has joined only one single Zone, a meaningful correlation between the electricity consumption and the transaction volume on the respective blockchain can be established. For this reason, we enhance our methodology: Instead of merely estimating the electricity consumption of a best guess node on a Cosmos Zone via a linear model, we can determine the relationship between transaction volume and power demand for each of our upper and lower bound blockchains measured (Cosmos-Injective and Cosmos-Bitsong, respectively). This allows us to calculate the marginal power consumption per TPS and the base load of a best guess node running the respective Zone as described in Chapter 5.3. For both metrics, the marginal power consumption per TPS and the base load, we establish a linear function through the two power demands we have obtained by measuring the upper and lower bound Zone towards the Zones' daily transaction counts ($zoneBasePower(txCount_{Zone})$ and $zoneMarginalTxPower(txCount_{Zone})$). We can thus determine the power demand of a best guess node of an arbitrary Zone at a given daily transaction volume ($P_{bestGuess_{Zone}}$) for each Zone in the Cosmos ecosystem by adding these two functions while applying the Zone's TPS metric:

$$\forall\ Zone:$$
$$P_{bestGuess_{Zone}}\ [W] = zoneBasePower(txCount_{Zone}) + (zoneMarginalTxPower(txCount_{Zone})\ \times\ TPS_{Zone})$$

Many nodes of the Cosmos platform are validators of multiple Zones at the same time. For this reason, we need to further adapt our methodology to estimate the power consumption of those nodes that validate multiple blockchains. Merely counting their estimated best guess power demand for each Zone would lead to an overestimation, as the nodes' idle consumption should only be included once. To address this, we calculate the *additional power demand* a node might require as soon as it has joined a specific Cosmos Zone ($P_{networkMarginal_{Zone}}$): We subtract the estimated idle power demand of the hardware of a best guess node in the Zone ($idle(txCount_{Zone})$) from the power demand of that Zone determined through our just introduced linear model. For the idle power demand of the hardware, we also rely on a linear model through our two

[10] https://avascan.info/ by AvascanExplorer

[11] The total validator count of the entire Avalanche platform provided here equals the validator count of the Avalanche-Mainnet since each validator of a Subnet must additionally join the Avalanche-Mainnet. This means a validator that participates in one or more Subnets is counted only once. The value is determined as of June 01, 2023.

points measured; we assume a linear distribution of the idle power demand between the hardware from our lower bound to our upper bound Zone.

$$\forall\ Zone: \\ P_{networkMarginal_{Zone}}\ [W] = P_{bestGuess_{Zone}} - idle(txCount_{Zone})$$

Based on the additional power demand that a node incurs when it joins a Zone, we can compute the total power demand for each individual validator ($P_{Validator}$). For this, we sum all additional network power demands of the Zones the node runs on the one hand, and the average idle consumption of estimated for these Zones on the other ($idle_{Validator}$):

$$\forall\ Validator: \\ P_{Validator}\ [W] = idle_{Validator} + (\sum_{z}^{Zones} (P_{networkMarginal_z}\ if\ Validator\ in\ z\ else\ 0))$$

$$idle_{Validator} = \frac{\sum_{z}^{Zones}(idle(txCount)\ \ if\ \ v\ in\ z\ else\ 0)}{|Zones_v|}$$

To finally determine the total power demand of the Cosmos platform (P_{Cosmos}), we iterate over all validators and sum up their individual power demands approximated:

$$P_{Cosmos}\ [W] = \sum_{Validator}^{Validators} P_{Validator}$$

We note that we have conducted an additional measurement of the base layer Zone Cosmos-Hub as provided in **Table 11**. For those validators participating in the Cosmos-Hub, we rely on the real measurement results to determine the base power demand and the marginal power demand per TPS instead of the estimation we would obtain through our linear models.

The results of our analysis of the Cosmos platform applying the tailored methodology just introduced are summarized in **Table 15**. All underlying transaction counts, validator counts, and the mapping of which validator is part of which Zone are taken from the block explorer Mintscan.io[12] (as of April 24, 2023).

	Nodes [# total][13]	Electrical power [W]	Electricity consumption [kWh/day]	Electricity consumption [kWh/year]
Cosmos (platform total)	1,914	66,401.5	1,593.64	581,677.14

Table 15: Electricity consumption of the Cosmos platform.

Figure 7 illustrates the linear functions that we have applied in our calculations for the Cosmos platform. The orange data points result from measuring the lower bound Zone Cosmos-Bitsong, the blue ones from measuring the upper bound Zone Cosmos-Injective. The x-axis represents the absolute number of transactions within 24 hours (as of April 24, 2023). The orange line indicates the base power demand of a Zone for a given 24-hour transaction volume ($zoneBasePower(txCount_{Zone})$). The blue function shows the marginal power demand per one transaction per second for a Zone ($zoneMarginalTxPower(txCount_{Zone})$), likewise for a given 24-hour transaction volume. By multiplying the result of the blue function with the transactions per

[12] https://hub.mintscan.io/ by Cosmostation

[13] A validator in the Cosmos platform can participate in multiple Zones simultaneously. The total validator count of the Cosmos platform provided here is the overall number of machines in the entire platform. This means a validator that participates in more than one Zone is counted only once. The value is determined as of April 24, 2023.

second (TPS) of the corresponding Zone, and adding the orange function to this result, we obtain the red line, which represents the power demand of a best guess node for a Zone towards a daily transaction count ($P_{bestGuess_{Zone}}$). We subtract the green idle function from this best guess to determine the additional power demand for a node that joins a specific Zone ($P_{networkMarginal_{Zone}}$) as shown by the purple function. The gray markers on the purple plot indicate the different Zones as of April 24, 2023.

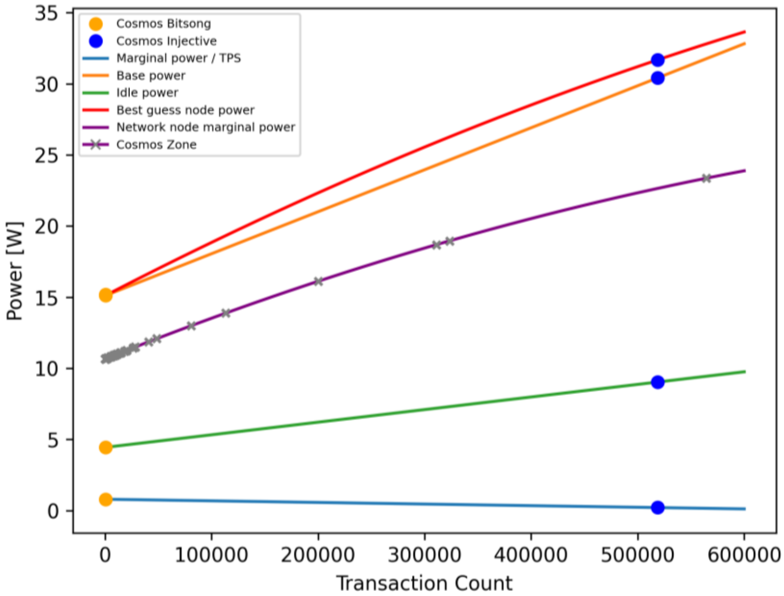

Figure 7: Linear models built out of upper and lower bound measurements to estimate the power demand of arbitrary Zones of the Cosmos platform based on daily transaction volume.

Polkadot Platform

Similar to Avalanche and Cosmos, Polkadot is also a platform for multiple blockchains. In addition to the base layer, which is referred to as the Relaychain, there are so-called Parachains. In contrast to the Subnets of Avalanche and the Zones of Cosmos, Parachains are relying on the security of the Relaychain (shared security) since they are validated by the nodes of Polkadot's base layer blockchain. Nodes maintaining a Parachain are called collators. Unlike traditional validators, they do not provide security guarantees; instead, among other things, they are responsible for propagating the state of their Parachain to the Relaychain. In addition, they are in charge of handling the communication between the different Parachains, which is accomplished via the XCM (Cross-Consensus-Message) protocol (Web3 Foundation, 2023a).

For our analysis of the Polkadot platform, we opt for the Parachain Astar as the upper bound and the Parachain Composable as the lower bound to estimate the power demand of a best guess collator node participating in an arbitrary Parachain, based on the Parachains' daily transaction volumes (as of April 24, 2023). As mentioned in Chapter 5.3, we were unable to establish a meaningful relationship between the power demand of the collator nodes measured and the transaction volume on the corresponding Parachain for either bound. This suggests that the activities of the collators associated with the Relaychain are more decisive for the power demand than the transactions taking place on the actual Parachain. Consequently, we cannot determine a marginal power demand per TPS nor a base power demand for the individual Parachains of the Polkadot ecosystem.

Therefore, to determine the total power demand of the Polkadot platform, we rely on the best guess power metric from our measurements of the upper bound and the lower bound Parachain. We establish a linear model through the two measured best guess power demands towards the 24-hour transaction counts of the Parachains. This enables us to approximate the best guess power demand of an arbitrary Parachain node based on the daily transaction volume. The resulting linear function is plotted in **Figure 8**. The orange dot represents the best guess power demand of the lower bound Parachain Polkadot-Composable, the blue dot that of the upper bound Parachain Polkadot-Astar. The gray markers on the function plot indicate the model-based estimates of best guess power demands of the remaining Polkadot Parachains as of April 24, 2023.

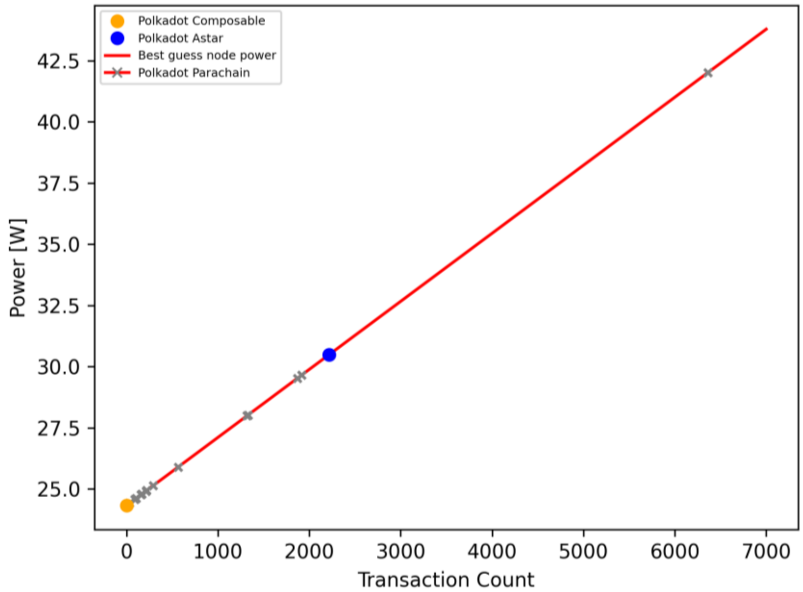

Figure 8: Linear model built out of upper and lower bound measurements to estimate the power demand of arbitrary Parachains of the Polkadot platform based on daily transaction volume.

Finally, to obtain the total power demand of the Polkadot platform ($P_{Polkadot}$), we iterate through each Parachain and multiply the node count with the best guess power demand of that Parachain determined via our linear model, and sum up the results:

$$P_{Polkadot}\ [W] = \sum_{p}^{Parachain} \left(\left|Validators_p\right| \times P_{bestGuess_p}(txCount) \right)$$

The results of our analysis to estimate the total power demand and electricity consumption of the Polkadot Platform are presented in **Table 16**. All transaction and validator/collator counts are taken from the block explorer Subscan.io[14] as of April 24, 2023. At the time of our analysis, no information about the node counts of the Parachains Acala, Crust-Parachain, Darwinia2, Efinity, Equilibrium, Kilt-Spiritnet, Nodle, Unique, and Zeitgeist was available on Subscan. For this reason, we assume the average node count of the other Parachains as a proxy for the analysis of these.

[14] https://www.subscan.io/ by Subscan Team

	Nodes [# total][15]	Electrical power [W]	Electricity consumption [kWh/day]	Electricity consumption [kWh/year]
Polkadot (platform total)	624	17,602.98	422.47	154,202.10

Table 16: Electricity consumption of the Polkadot platform.

Comparison of Platforms Electricity Consumptions

Figure 9 compares the calculated yearly electricity consumption as well as the validator counts of the analyzed platform networks Avalanche, Cosmos, and Polkadot. With 154,202.10 kWh per year, the Polkadot ecosystem reveals the lowest electricity consumption among the analyzed platforms, however, the total validator/collator count of Polkadot is remarkably below those of Avalanche and Cosmos.

Similar to the standard PoS networks analyzed in Chapter 5.4.1, the validator count of a platform appears to be a crucial driver for the total electricity consumption. However, for platforms such as Cosmos, we note that the relationship between node count and electricity consumption must be treated with care: As discussed above, it is common for a validator to participate in multiple networks of the platform simultaneously, which increases the power demand per node on the one hand but decreases the overall number of single nodes within the platform on the other hand. This results in additional complexity in determining the power demand of a single node and ultimately in calculating the total electricity consumption of the platform.

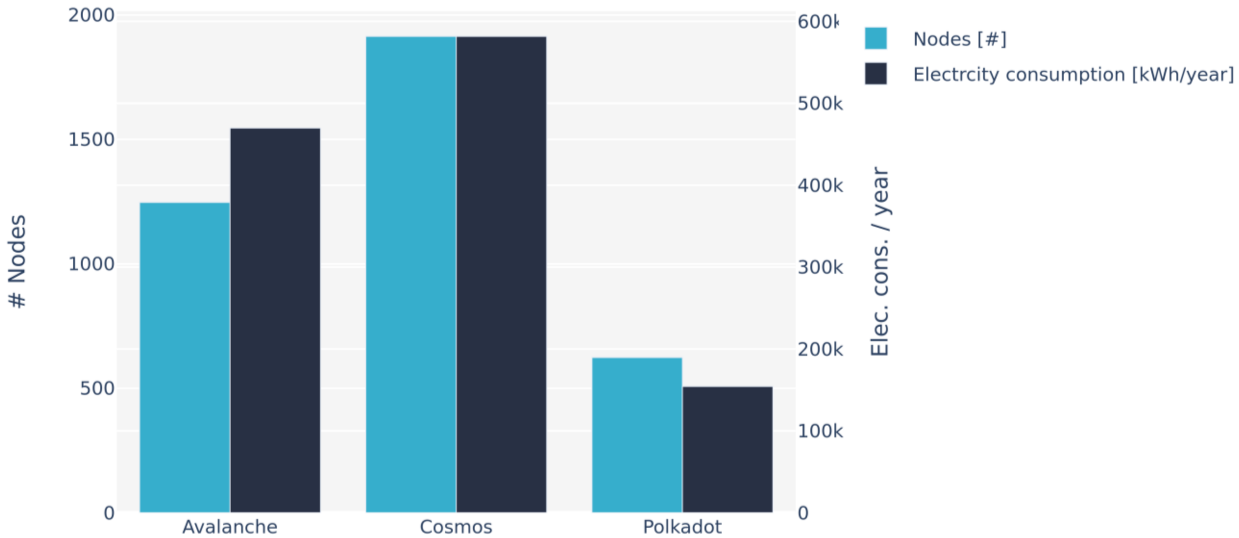

Figure 9: Electricity consumption per year [kWh] and node counts of platform networks.

[15] The total validator count of the entire Polkadot platform provided here equals the sum of the validator count of the Polkadot-Relaychain and each Parachain's collator count. The value is determined as of April 24, 2023.

5.5 Carbon footprint of PoS networks and platforms

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 PoS networks or PoS platform networks 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 PoS networks and platforms.

Previous research localized nodes in other protocols by relying on internet search machines aimed at ASIC devices, IP addresses, or pool addresses. These approaches allowed for an estimate of how the nodes are distributed worldwide.

For some PoS networks, data on the node locations is publicly available. In that case, we calculate the average carbon intensity of the countries in which the nodes are located utilizing country specific emission factors (carbon footprint, 2022). For the U.S., in which commonly a comparatively high number of a network's nodes are located, we even resort to state level carbon intensities. For unavailable carbon intensities or unavailable node locations, we assume the world average of 459 gCO_2e per kWh in accordance with the IEA (International Energy Agency, 2021).

Table 17 summarizes the carbon intensities for the different networks and platforms we apply to determine their carbon footprint. Furthermore, we provide the sources of the node locations that we have used to calculate the location specific carbon intensity factors.

	Carbon intensity [gCO_2e/kWh]	Node location source	Location specific intensity factor
Algorand	459	N/A	✗ (world avg)
Avalanche (platform total)	379	Avascan.info[16]	✓
Cardano	365	Adatools.io[17]	✓
Cosmos (platform total)	459	N/A	✗ (world avg)
Ethereum	348	Migalabs.es[18]	✓

[16] https://avascan.info/stats/staking
[17] https://adatools.io/earth
[18] https://migalabs.es/beaconnodes#geo-dist

	Carbon intensity [gCO_2e/kWh]	Node location source	Location specific intensity factor
Polkadot (platform total)	459	N/A	✗ (world avg)
Solana	327	Validators.app[19]	✓

Table 17: Carbon intensity factors applied for networks and platforms to determine their carbon footprints (as of April 24, 2023).

With that, we can derive the carbon footprints of the single networks and platforms: For each node of a network or platform, we determine the carbon footprint by multiplying its energy consumption with the respective carbon intensity factor of the network. Summing up the emissions caused by each validator node gives us the total carbon footprint of the network or platform ($CF_{Network|Platform}$):

$$CF_{Network|Platform} = \sum_{node}^{Nodes} (electricityConsumption_{node} \times carbonIntensity_{Network|Platform})$$

Table 18 summarizes the resulting carbon footprints of the analyzed standard PoS networks Algorand, Cardano, Ethereum, and Solana. Since our approach to measure the electricity consumption of a single node of a standard PoS network provides upper and lower bounds in addition to a best guess estimate (see Chapter 5.1.2), we can likewise establish a lower bound, an upper bound, and a best guess for the carbon footprint of each network.

	Emissions (best guess) [$tCO_2e/year$]	Emissions (lower bound) [$tCO_2e/year$]	Emissions (upper bound) [$tCO_2e/year$]
Algorand	352.16	188.21	1,297.48
Cardano	358.30	46.34	851.71
Ethereum	2,088.40	661.58	4,964.97
Solana	1,620.79	1,620.79	1,620.79

Table 18: Overview of annualized best guess, lower bound, and upper bound CO_2e emissions analyzed of the standard PoS networks.

For the investigated platform networks Avalanche, Cosmos, and Polkadot, the calculation of the total energy consumption is more complex; our methodology as described in Chapter 5.4.2 provides an annualized best guess for the electricity consumption of the platforms. We multiply this by the respective platform's carbon intensity factor as listed in **Table 17** to obtain a best guess for the total yearly CO_2e emissions. **Table 19** summarizes the results.

The annual CO_2e emissions of the examined standard PoS networks and those of the PoS platform networks lie in a similar range. **Figure 10** compares the annualized lower bound, best guess, and upper bound emissions of the standard PoS networks from **Table 18** and the best guess emissions of the platform networks from **Table 19.**

[19] https://www.validators.app/

	Emissions (best guess) [tCO_2e/year]
Avalanche (platform total)	178.27
Cosmos (platform total)	266.99
Polkadot (platform total)	70.78

Table 19: Overview of annualized best guess CO_2e emissions of the analyzed PoS platform networks.

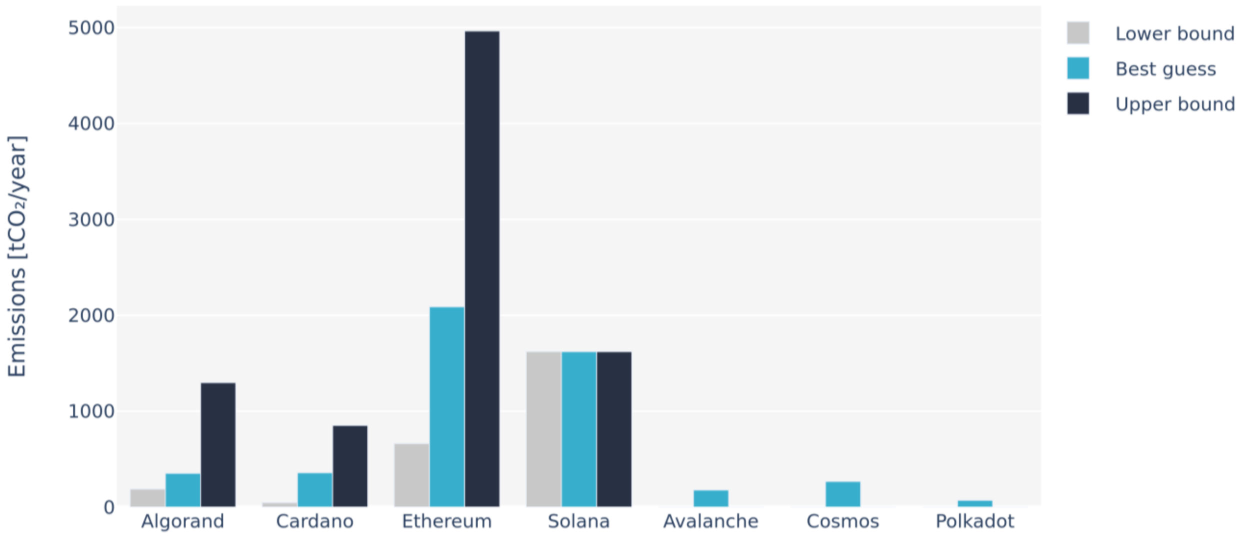

Figure 10: Comparison of annualized carbon emissions of standard PoS networks (lower bound, best guess, and upper bound) and PoS platform networks (best guess).

6 Discussion and comparison of results

In the previous chapters, we introduced our methodology and conducted measurements to derive the electricity consumption and carbon footprint of the Proof of Stake networks Algorand, Cardano, Ethereum, and Solana as well as the PoS platform networks Avalanche, Cosmos, and Polkadot. In this chapter, we contextualize the results.

6.1 Yearly electricity consumption in the context of other systems

The electricity consumption of a single network or platform is often meaningless without any context to compare the system. In Chapter 5.4, we outline that the yearly electricity consumption of networks or platforms range from 154,202.10 kWh (Polkadot platform) to 5,750,351.57 kWh (Ethereum network). An average US household consumes about 10,600 kWh per year and, therefore, the least electricity consuming system Polkadot requires about 14.5 times the electricity, and the most electricity consuming network Ethereum about 542.5 times the electricity (U.S. Energy Information Administration, 2021).

In comparison to the decentralized and PoW-based cryptocurrency Bitcoin, these two PoS systems consume about 0.0001 % (Polkadot) or 0.0042 % (Ethereum) of the Bitcoin network assuming an annualized consumption of 137.79 TWh as of April 24, 2023 (CBECI, 2023). Bitcoin consumes much more electricity than Proof of Stake systems due to its Proof of Work consensus mechanism, which results in the deployment of energy-intensive hardware.

In **Figure 11**, we compare the Bitcoin network (as of April 24, 2023), the average US household as introduced above (as of 2021), and the standard PoS networks and the PoS platform networks we have analyzed in this study.

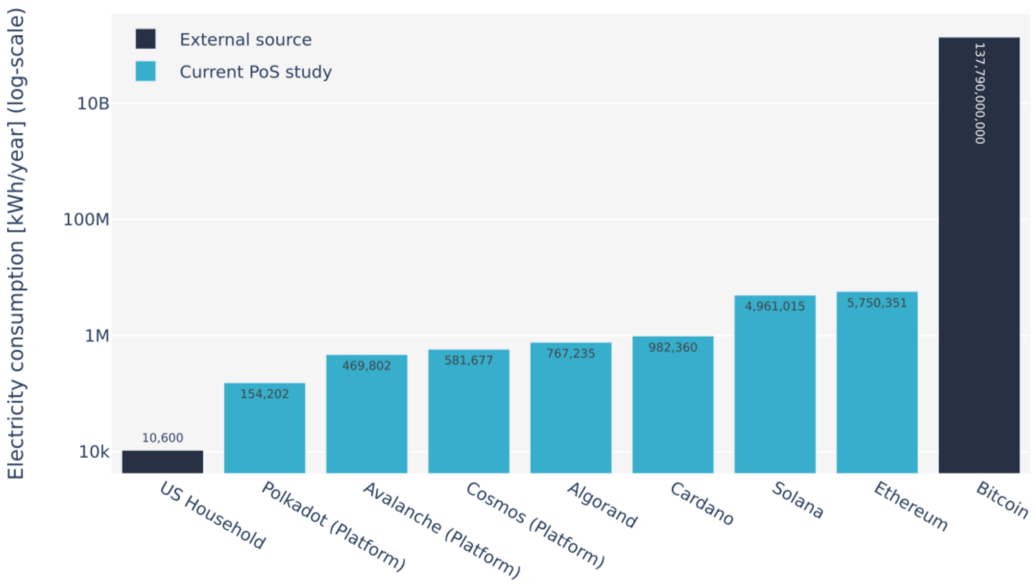

Figure 11: Comparison of the yearly electricity consumption of an average US household (as of 2021), the PoW network Bitcoin (as of April 24, 2023), and the PoS networks as well as platforms analyzed in this study.

6.2 The carbon footprint of Proof of Stake networks

In absolute terms, the emissions of the PoS networks are rather small. As outlined in Chapter 5.5, the networks or platform networks emit between 70.78 tonnes (Polkadot) and 2,088.40 tonnes (Ethereum) of CO_2e per year. As a reference point for comparison, one round trip flight from Munich (MUC) to San Francisco (SFO) in business class emits about 6.1 tonnes CO_2e (MyClimate, 2021). As a result, the networks or platforms assessed emit the same amount of carbon dioxide as 12 to 342 roundtrip flights**.** It can be assumed that the carbon emissions of companies behind the networks or platforms are higher than the emissions from the network itself (e.g., due to business travel).

Figure 12 compares the carbon footprints of the PoS networks and platforms examined in this study to a roundtrip flight MUC – SFO in business class.

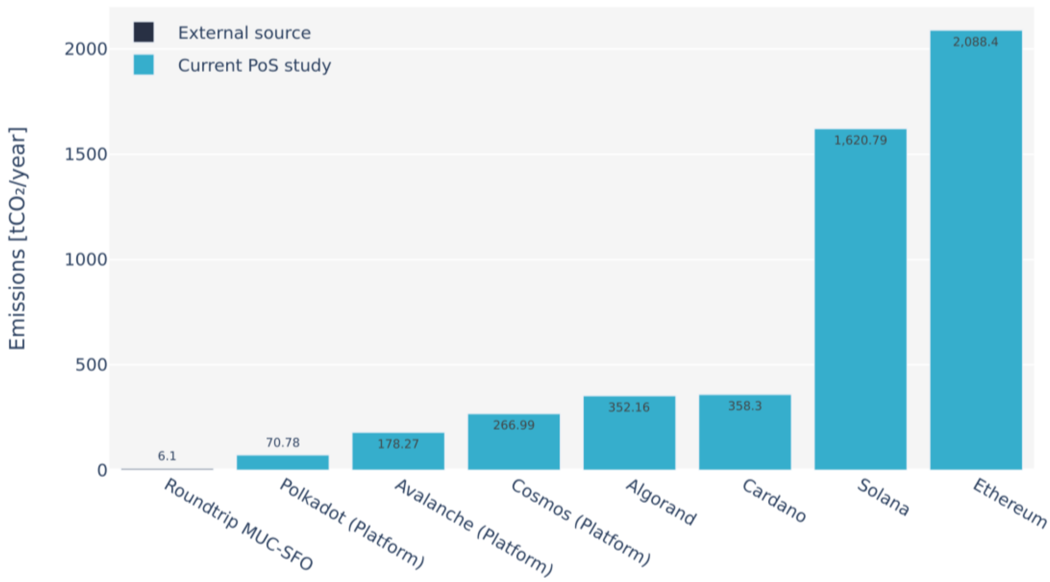

Figure 12: Comparison of the yearly carbon footprint of a MUC-SFO roundtrip flight in business class and the PoS networks as well as platforms analyzed in this study.

7 Conclusion

In this report, we benchmark the electricity consumption and carbon footprint of the Proof of Stake networks Algorand, Cardano, Ethereum, and Solana as well as the platform networks Avalanche, Cosmos, and Polkadot. Our results are based on a selection of representative hardware devices, measurements of node electricity consumption, and calculations of carbon emissions via emission factors.

Our best guess estimates the yearly electricity consumption of the Proof of Stake systems from 154,202.10 kWh for the Polkadot platform to 5,750,351.57 kWh for the Ethereum network. The electricity consumptions result in a carbon footprint between 70.78 and 2,088.40 tonnes of CO_2e annually. Compared to other electricity consumers such as an average US household, the most consuming network Ethereum requires roughly 542x more electricity and produces 342x the amount of an intercontinental round trip flight.

Given the continuous development and evolution of Proof of Stake networks, our results can only be taken as a snapshot of the respective timeframe. Additional 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. Moreover, other networks employing different consensus mechanisms as well as second layer networks (CCRI, 2023b) 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 (Rieger, Roth, Sedlmeir, & Fridgen, 2022).

Despite the relatively low absolute electricity consumption and carbon emission level of PoS networks and platforms as benchmarked in this study, it remains essential to continue monitoring and disclosing energy efficiency and carbon emissions of PoS chains. **Transparency** in terms of informing stakeholders, such as users, regulators, policymakers, and the public, about the climate costs and benefits of blockchain solutions is vital. In addition, sustainability indicators might be a **fundamental decision criterion** for developers, corporates, NFT creators, etc. to select an energy efficient chain. Finally, **compliance with upcoming regulatory** requirements entails disclosure of climate impact. In general, carbon footprint calculations can be considered as the **essential data basis** to reach corporate climate goals via energy consumption reduction strategies and/or carbon offsetting.

References

Algorand. (2023). Algorand - Hardware Requirements. Retrieved from https://developer.algorand.org/docs/run-a-node/setup/install/#hardware-requirements

Astar Developers Hub. (2023). Astar Docs - Requirements. Retrieved from https://docs.astar.network/docs/nodes/archive-node/#requirements

Ava Labs. (2023a). Avalanche - Computer Hardware and OS. Retrieved from https://docs.avax.network/nodes/build/run-avalanche-node-manually#computer-hardware-and-os

Ava Labs. (2023b). What Is a Subnet? Retrieved from https://docs.avax.network/learn/avalanche/subnets-overview

BitSong. (2023). BitSong - What are the hardware requirements? Retrieved from https://docs.bitsong.io/validators/validator-faq#what-are-hardware-requirements

Cardano Foundation. (2023). Cardano - Prerequisites Retrieved from https://developers.cardano.org/docs/get-started/installing-cardano-node/#prerequisites

CBECI. (2023). Cambridge Bitcoin Electricity Consumption Index. Retrieved from https://ccaf.io/cbnsi/cbeci

CCRI. (2022a). Energy efficiency and carbon emissions of PoS Networks. Retrieved from https://carbon-ratings.com/dl/pos-report-2022

CCRI. (2022b). The Merge - Implications on the Electricity Consumption and Carbon Footprint of the Ethereum Network. Retrieved from https://carbon-ratings.com/dl/eth-report-2022

CCRI. (2023a). Determining the electricity consumption and carbon footprint of Proof of Stake networks. Retrieved from https://carbon-ratings.com/dl/whitepaper-pos-methods-2023

CCRI. (2023b). Energy Efficiency and Carbon Footprint of the Polygon Blockchain. Retrieved from https://carbon-ratings.com/dl/polygon-report-2022

Composable Finance. (2023). Collator Set-up Guide. Retrieved from https://docs.composable.finance/developer-guides/collator-guide/#select-virtual-hardware

De Vries, A., Gallersdörfer, U., Klaaßen, L., & Stoll, C. (2022). Revisiting Bitcoin's carbon footprint. *Joule, 6*(3), 498-502.

Hennion, N. (2021). Glances - An eye on your system. Retrieved from https://github.com/nicolargo/glances

Injective Labs. (2023). Injective Docs - Hardware Specification. Retrieved from https://docs.injective.network/nodes/RunNode/mainnet/#hardware-specification

MyClimate. (2021). Carbon Footprint calculator. Retrieved from https://co2.myclimate.org/en/flight_calculators/new

Passmark Software. (2021). Hardware & Software Market Trends. Retrieved from https://www.passmark.com/services/market-analysis.php

Rieger, A., Roth, T., Sedlmeir, J., & Fridgen, G. (2022). We need a broader debate on the sustainability of blockchain. *Joule, 6*(6), 1137-1141.

Sedlmeir, J., Buhl, H. U., Fridgen, G., & Keller, R. (2020). The energy consumption of blockchain technology: Beyond myth. *Business & Information Systems Engineering, 62*(6), 599-608.

Solana Foundation. (2023). Solana - Validator Requirements. Retrieved from https://docs.solana.com/de/running-validator/validator-reqs

Tendermint. (2023a). Cosmos Hub - Hardware. Retrieved from https://hub.cosmos.network/main/hub-tutorials/join-mainnet.html#hardware

Tendermint. (2023b). What is Cosmos? Retrieved from https://v1.cosmos.network/intro

U.S. Energy Information Administration. (2021). How much electricity does an American home use? Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

Web3 Foundation. (2023a). Parachains. Retrieved from https://wiki.polkadot.network/docs/learn-parachains

Web3 Foundation. (2023b). Polkadot - Reference Hardware. Retrieved from https://wiki.polkadot.network/docs/maintain-guides-how-to-validate-polkadot#reference-hardware

List of Figures

List of Tables

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.

Algorand

	1	2	3	4	5	6
Min [W]	N/A	22.61	24.51	29.47	54.32	152.63
Q1 [W]	N/A	22.94	24.77	29.87	56.67	159.69
Median [W]	N/A	23.07	24.9	29.94	56.74	160.25
Mean [W]	N/A	23.25	25.07	30.86	56.79	160.30
Q3 [W]	N/A	23.2	25.03	33.14	56.81	160.85
Max [W]	N/A	33.47	36.34	41.06	70.6	175.19

Table 20: Power demand while running an Algorand full node measured in Watt [W].

Avalanche

Avalanche-Mainnet

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	6.66	26.67	104.64
Q1 [W]	N/A	N/A	N/A	7.04	26.99	108.37
Median [W]	N/A	N/A	N/A	7.12	27.12	109.31
Mean [W]	N/A	N/A	N/A	7.29	27.22	109.61
Q3 [W]	N/A	N/A	N/A	7.38	27.32	110.51
Max [W]	N/A	N/A	N/A	13.72	39.28	121.52

Table 21: Power demand while running an Avalanche-Mainnet full node measured in Watt [W].

Avalanche-DFK

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	9.41	29.15	113.41
Q1 [W]	N/A	N/A	N/A	12.81	32.89	118.89
Median [W]	N/A	N/A	N/A	13.73	33.86	120.54
Mean [W]	N/A	N/A	N/A	13.86	34.00	120.67
Q3 [W]	N/A	N/A	N/A	14.77	34.96	122.18
Max [W]	N/A	N/A	N/A	32.03	52.67	144.76

Table 22: Power demand while running an Avalanche-DFK full node measured in Watt [W].

Avalanche-DOS

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	6.86	26.98	105.62
Q1 [W]	N/A	N/A	N/A	7.32	27.38	111.16
Median [W]	N/A	N/A	N/A	7.58	27.64	112.54
Mean [W]	N/A	N/A	N/A	7.73	27.73	112.61
Q3 [W]	N/A	N/A	N/A	7.97	27.91	114.00
Max [W]	N/A	N/A	N/A	15.16	35.89	122.31

Table 23: Power demand while running an Avalanche-DOS full node measured in Watt [W].

Cardano

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	3.85	25.22	81.11
Q1 [W]	N/A	N/A	N/A	4.11	25.62	82.23
Median [W]	N/A	N/A	N/A	4.18	25.81	82.63
Mean [W]	N/A	N/A	N/A	4.57	26.36	83.91
Q3 [W]	N/A	N/A	N/A	4.24	26.21	83.17
Max [W]	N/A	N/A	N/A	31.37	59.36	144.98

Table 24: Power demand while running a Cardano full node measured in Watt [W].

Cosmos

Cosmos-Hub

	1	2	3	4	5	6
Min [W]	N/A	5.48	7.32	8.95	28.62	118.28
Q1 [W]	N/A	12.09	15.47	9.93	30.43	120.25
Median [W]	N/A	12.81	18.10	10.39	31.10	121.91
Mean [W]	N/A	12.95	17.02	13.37	34.40	125.69
Q3 [W]	N/A	13.86	19.30	11.04	31.96	123.86
Max [W]	N/A	29.61	30.13	37.84	63.47	158.37

Table 25: Power demand while running a Cosmos-Hub full node measured in Watt [W].

Cosmos-Injective

	1	2	3	4	5	6
Min [W]	N/A	12.35	14.44	10.75	36.99	124.27
Q1 [W]	N/A	14.77	17.52	17.44	40.45	130.65
Median [W]	N/A	15.62	18.36	19.35	42.09	132.84
Mean [W]	N/A	15.71	18.32	19.35	42.24	132.89
Q3 [W]	N/A	16.53	19.02	21.05	43.99	135.13
Max [W]	N/A	21.37	23.14	26.20	49.03	149.00

Table 26: Power demand while running a Cosmos-Injective full node measured in Watt [W].

Cosmos-Bitsong

	1	2	3	4	5	6
Min [W]	3.33	4.57	6.73	9.08	29.08	117.99
Q1 [W]	3.59	4.96	7.12	9.60	30.26	119.25
Median [W]	3.59	5.42	7.58	9.93	30.72	120.07
Mean [W]	3.63	5.69	7.70	10.18	30.90	120.43
Q3 [W]	3.72	5.88	7.84	10.39	31.30	121.30
Max [W]	4.18	10.72	12.09	13.47	35.36	127.84

Table 27: Power demand while running a Cosmos-Bitsong full node measured in Watt [W].

Ethereum

For Ethereum, different client software for both the execution and the consensus client are available, which impact the electricity consumption of the network's nodes. CCRI has recently analyzed the electricity consumption of the Ethereum network in (CCRI, 2022b); all calculations conducted for Ethereum are based on the measurements and findings of this report.

Polkadot

Polkadot-Relaychain

	1	2	3	4	5	6
Min [W]	N/A	5.49	8.69	20.85	43.01	121.59
Q1 [W]	N/A	5.88	9.15	21.31	44.06	122.74
Median [W]	N/A	6.01	9.21	21.44	44.32	123.09
Mean [W]	N/A	6.07	9.27	21.46	44.32	123.16
Q3 [W]	N/A	6.14	9.34	21.57	44.57	123.48
Max [W]	N/A	22.94	15.49	23.53	46.80	131.05

Table 28: Power demand while running a Polkadot-Relaychain full node measured in Watt [W].

Polkadot-Astar

	1	2	3	4	5	6
Min [W]	N/A	5.55	7.97	19.60	36.67	120.78
Q1 [W]	N/A	6.53	9.67	22.48	44.53	124.08
Median [W]	N/A	6.86	9.93	22.74	45.30	124.87
Mean [W]	N/A	6.88	9.92	22.66	45.07	125.10
Q3 [W]	N/A	7.12	10.19	22.94	45.82	125.76
Max [W]	N/A	18.42	16.47	25.55	49.68	141.41

Table 29: Power demand while running a Polkadot-Astar full node measured in Watt [W].

Polkadot-Composable

	1	2	3	4	5	6
Min [W]	N/A	3.72	4.57	7.97	28.04	109.98
Q1 [W]	N/A	4.37	5.62	11.89	34.19	121.47
Median [W]	N/A	4.64	6.86	14.05	37.25	122.29
Mean [W]	N/A	4.73	6.76	14.63	36.85	122.36
Q3 [W]	N/A	4.96	7.57	17.25	39.74	123.23
Max [W]	N/A	12.74	12.81	22.55	44.90	140.75

Table 30: Power demand while running a Polkadot-Composable full node measured in Watt [W].

Solana

	1	2	3	4	5	6
Min [W]	N/A	N/A	N/A	N/A	N/A	289.86
Q1 [W]	N/A	N/A	N/A	N/A	N/A	312.16
Median [W]	N/A	N/A	N/A	N/A	N/A	320.33
Mean [W]	N/A	N/A	N/A	N/A	N/A	319.60
Q3 [W]	N/A	N/A	N/A	N/A	N/A	327.15
Max [W]	N/A	N/A	N/A	N/A	N/A	362.47

Table 31: Power demand while running a Solana full node measured in Watt [W].

Appendix C: Data sources for single networks

All market capitalizations are taken from https://coinmarketcap.com.

Algorand

	Information
Measurement period	2023-02-26 18:19 to 2023-02-27 18:19
Number of nodes	https://metrics.algorand.org/#/decentralization/ → *"Nodes"* (Number unavailable at time of analysis, average value taken from January 17 to February 05, 2023)
Transaction Count	https://algoexplorer.io/top-statistics → *"Transaction Metrics" → "Total Transactions"*
Software version	algorand-3.14.2 (non-relay node in non-archival mode) (https://github.com/algorand/go-algorand/releases/tag/v3.14.2-stable)

Table 32: Data sources for analysis of Algorand.

Avalanche

Avalanche-Mainnet

	Information
Measurement period	2023-02-19 19:44 to 2023-02-20 19:44
Number of nodes	https://avascan.info/blockchain/c/info → "Subnet Validators"
Transaction Count	https://avascan.info/blockchain/c/info → "Total transactions" (24h difference)
Software version	*avalanchego-1.9.8* (https://github.com/ava-labs/avalanchego/releases/tag/v1.9.8)

Table 33: Data sources for analysis of Avalanche-Mainnet.

Avalanche-DFK

	Information
Measurement period	2023-05-30 09:57 to 2023-05-31 09:57
Number of nodes	https://avascan.info/blockchain/dfk/info → "Subnet Validators"
Transaction Count	https://avascan.info/blockchain/dos/info → "Total transactions" (24h difference)
Software version	*avalanchego-1.10.1 (subnet-evm 0.5.1)* (https://github.com/ava-labs/avalanchego/releases/tag/v1.10.1)

Table 34: Data sources for analysis of Avalanche-DFK.

Avalanche-DOS

	Information
Measurement period	2023-05-31 19:29 to 2023-06-01 19:29
Number of nodes	https://avascan.info/blockchain/dos/info → "Subnet Validators"
Transaction Count	https://avascan.info/blockchain/dos/info → "Total transactions" (24h difference)
Software version	*avalanchego-1.10.1 (subnet-evm 0.5.1)* (https://github.com/ava-labs/avalanchego/releases/tag/v1.10.1)

Table 35: Data sources for analysis of Avalanche-DOS.

Cardano

	Information
Measurement period	2023-01-03 13:03 to 2023-01-04 13:03
Number of nodes	https://cardanoscan.io/ → *"Total stake pools"*
Transaction Count	https://explorer.bitquery.io/cardano/transactions → *"Transactions By Date"*
Software version	*cardano-node-1.35.4* (https://github.com/input-output-hk/cardano-node/releases/tag/1.35.4)

Table 36: Data sources for analysis of Cardano.

Cosmos

Cosmos-Hub

	Information
Measurement period	2023-03-22 23:02 to 2023-03-23 23:02
Number of nodes	https://www.mintscan.io/cosmos/validators → "Validators"
Transaction Count	https://www.mintscan.io/cosmos → "Transactions" (24h difference)
Software version	*gaiad-9.0* (https://github.com/cosmos/gaia/releases/tag/v9.0.1)

Table 37: Data sources for analysis of Cosmos-Hub.

Cosmos-Injective

	Information
Measurement period	2023-03-31 18:53 to 2023-04-01 18:53
Number of nodes	https://www.mintscan.io/injective/validators → "Validators"
Transaction Count	https://www.mintscan.io/injective → "Transactions" (24h difference)
Software version	*mainnet-1.10.0-1679065799* (https://github.com/InjectiveLabs/injective-chain-releases/releases/tag/v1.10.0-1679065799)

Table 38: Data sources for analysis of Cosmos-Injective.

Cosmos-Bitsong

	Information
Measurement period	2023-04-07 00:10 to 2023-04-08 00:10
Number of nodes	https://www.mintscan.io/bitsong/validators → "Validators"
Transaction Count	https://www.mintscan.io/bitsong → "Transactions" (24h difference)
Software version	*bitsongd-0.14.0* (https://github.com/bitsongofficial/go-bitsong/releases/tag/v0.14.0)

Table 39: Data sources for analysis of Cosmos-Bitsong.

Ethereum

	Information
Measurement period	*different for each client software, see (CCRI, 2022b)*
Number of nodes	https://migalabs.es/beaconnodes#act-nodes → *"ACTIVE NODES"*
Transaction Count	Dune Dashboard (https://dune.com/browse/dashboards)
Software version	*different for each client software, see (CCRI, 2022b)*

Table 40: Data sources for analysis of Ethereum.

Polkadot

Polkadot-Relaychain

	Information
Measurement period	2023-03-04 21:01 to 2023-03-05 21:01
Number of nodes	https://polkadot.subscan.io/validator → "Validators"
Transaction Count	https://polkadot.subscan.io/extrinsic → "Extrinsic History"
Software version	*polkadot-0.9.38* (https://github.com/paritytech/polkadot/releases/tag/v0.9.42)

Table 41: Data sources for analysis of Polkadot-Relaychain.

Polkadot-Astar

	Information
Measurement period	2023-03-14 17:12 to 2023-03-15 17:12
Number of nodes	https://astar.subscan.io/collator → "Candidate Collators"
Transaction Count	https://astar.subscan.io/extrinsic → "Extrinsic History"
Software version	*astar-collator-4.49.0* (https://github.com/AstarNetwork/Astar/releases/tag/v4.49.0)

Table 42: Data sources for analysis of Polkadot-Astar.

Polkadot-Composable

	Information
Measurement period	2023-03-18 01:55 to 2023-03-19 01:55
Number of nodes	https://composable.subscan.io/collator → "Candidate Collators"
Transaction Count	https://composable.subscan.io/extrinsic → "Extrinsic History"
Software version	*composable-node-2.10009.0* (https://github.com/ComposableFi/composable/releases/tag/release-v2.10009.0)

Table 43: Data sources for analysis of Polkadot-Composable.

Solana

	Information
Measurement period	2023-02-01 12:40 to 2023-02-02 12:40
Number of nodes	https://www.validators.app/ → "Cluster" → *"Validators"*
Transaction Count	Dune Dashboard (https://dune.com/browse/dashboards)
Software version	*solana-1.13.6* (https://github.com/solana-labs/solana/releases/tag/v1.13.6)

Table 44: Data sources for analysis of Solana.

Disclaimer

Purpose

The CCRI PoS Benchmark Study 2023 provided herein is intended for informational purposes only. The PoS Benchmark Study 2023 does not constitute a recommendation or suggestion, directly or indirectly, to buy, sell, hold, make, or undertake any investment or trading strategy with respect to any investment, loan, commodity, security, or any issuer. It should not be construed as financial, investment, legal, or tax advice. CCRI does not provide personalized advice, and the study should not be considered as a substitute for professional advice tailored to your specific circumstances. It is important to note that investment decisions should be based on your own assessment and understanding of the market, and not rely on the information presented in this study. You should conduct your own research and seek guidance from independent financial, tax, or legal advisors before making any investment decisions. CCRI shall not be held accountable for any financial losses or damages incurred as a result of following or relying on the study's content. CCRI does not guarantee the sequence, accuracy, completeness, or timeliness of any information provided in this PoS Benchmark Study. The content speaks only as of the indicated date, and any projections, estimates, forecasts, targets, prospects, and/or opinions expressed herein are subject to change without notice and may differ or be contrary to opinions expressed by others.

Competing interests

This CCRI report was created with financial support of Avalanche.

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.

CCRI

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