

Ethereum Proof-of-Stake Consensus Layer: Participation and Decentralization

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Abstract

In September 2022, Ethereum transitioned from *Proof-of-Work (PoW)* to *Proof-of-Stake (PoS)* during “the merge” — making it the largest PoS cryptocurrency in terms of market capitalization. With this work, we present a comprehensive measurement study of the current state of the Ethereum PoS consensus layer on the beacon chain. We perform a longitudinal study over the entire history of the *beacon chain*, which ranges from 1 December 2020 until 15 May 2023. Our work finds that all dips in network participation, unrelated to network upgrades, are caused by issues with major consensus clients or service operators controlling a large number of validators. Thus, we analyze the decentralization of staking power over time by clustering validators to entities. We find that the staking power is concentrated in the hands of a few large entities. Further, we also analyze the consensus client landscape, given that bugs in a consensus client pose a security risk to the consensus layer. While the consensus client landscape exhibits significant concentration, with a single client accounting for one-third of the market share throughout the entire history of the beacon chain, we observe an improving trend.

2012 ACM Subject Classification General and reference → Empirical studies; General and reference → Measurement; Security and privacy → Economics of security and privacy

Keywords and phrases blockchain, Ethereum, Proof-of-Stake, consensus layer, decentralization

1 Introduction

The global market capitalization of cryptocurrencies currently exceeds a staggering US\$ 1T [22]. This value is secured by nodes in an open *peer-to-peer (P2P)* network. These nodes follow the consensus protocol to record and verify transactions. The *decentralization*, i.e., fragmentation of control, of the node network is fundamental. Decentralization ensures that a small number of entities cannot manipulate the blockchain’s records. Moreover, enhancing the decentralization of the consensus layer enhances censorship resistance, as no single party can exert significant control over the inclusion of transactions on the ledger.

To safeguard the distributed network from Sybil attacks, where a party tries to gain an advantage by creating numerous nodes, most blockchains employ either *Proof-of-Work (PoW)* or *Proof-of-Stake (PoS)* mechanisms. In PoW *miners* solve computational puzzles, while in PoS *validators* must stake, i.e., lock, the cryptocurrency’s native token. In September 2022, Ethereum switched from PoW to PoS during “the merge”. Ethereum is the second biggest cryptocurrency in terms of market capitalization [22] and the largest PoS cryptocurrency. With its move from PoW to PoS, Ethereum targeted a reduction in energy usage but also an increase in decentralization by lowering the entry barriers for network participants [41].

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In Ethereum, PoS network participants wishing to partake in the consensus — be a validator — must deposit 32 ETH. Validators have three tasks: first, continuously attest to the validity of the blocks created by other validators, second, participate in sync committees, and third, occasionally propose a block. In contrast to PoW, PoS requires continuous active participation of more than two-thirds of the validators for the blockchain to make progress. Therefore, for a PoS blockchain, it is not only essential that the consensus layer is decentralized but also crucial that its validators participate actively even when it is not their turn to propose a block.

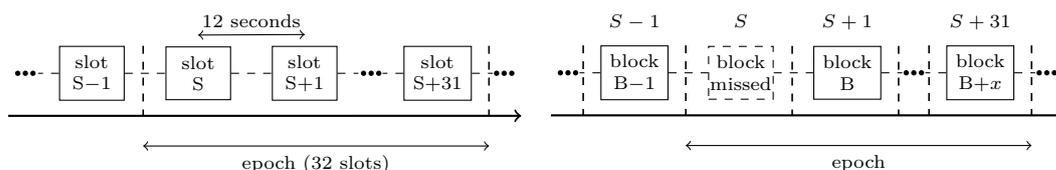
Additionally, the switch from PoW to PoS introduced additional consensus layer security concerns. *Maximal/miner extractable value (MEV)*, which refers to the maximum value that can be extracted through including, excluding, and re-ordering the transactions in a block, was prevalent in Ethereum PoW with more than US\$ 675M extracted value before the merge [16]. Thus, MEV poses consensus layer security concerns, as it incentivizes rational miners to fork the blockchain [42]. Not only does MEV remain a concern in Ethereum PoS, but there are also new types of MEV opportunities that arise as a result of knowing the block proposer minutes in advance [39].

Contributions In this work, we present the first comprehensive measurement study on the participation level and decentralization of the Ethereum PoS consensus layer. We summarise our contributions as follows:

- We study the participation level of validators in the Ethereum PoS and find that the participation levels are very high — exceeding 98%. Dips in participation levels generally coincide with network upgrades or bugs in one or more consensus clients.
- We investigate the prevalence of slashable offenses, i.e., instances of equivocation by a validator. In our measurement period, which spans more than two years, only 248 slashable offenses were discovered.
- We cluster Ethereum validators into entities and study the decentralization of the validator landscape. Our analysis finds that the level of decentralization of the Ethereum consensus layer has not significantly increased since the merge.
- We conduct an entity performance analysis to find that validators in large entities, on average, tend to have higher success rates for proposals and attestations.
- We also investigate the consensus client landscape, given that bugs in dominant consensus clients are the cause of the majority of the participation drops in the Ethereum PoS consensus. Even though the centralization of the consensus client landscape is immense, we observe a promising decreasing trend.

2 Ethereum Proof-of-Stake

During the merge on 15 September 2022 [1], Ethereum transitioned from PoW to PoS as Sybil resistance. Ethereum now runs two layers: the execution and consensus layer. The execution layer, resembling the previous PoW protocol, retains the responsibility of validating and executing transactions. On the other hand, the consensus layer, constructed atop the beacon chain, focuses on achieving consensus among validators. Importantly, in the PoS paradigm, participants known as validators have replaced traditional miners. Validators are responsible for proposing and validating blocks in the Ethereum network. To become a validator, one must *stake* (i.e., lock) 32 ETH into the designated deposit contract.



(a) Relationship between epochs and slots on the beacon chain. Each epoch consists of 32 slots and each slot lasts 12 seconds. (b) Connection between slots and blocks, where $x = 31 - M$, and M represents the total of all missed and orphaned blocks in the epoch.

■ **Figure 1** Relationship of beacon chain epochs and slots (cf. Figure 1a) with execution layer blocks (cf. Figure 1b). There is a chance for an execution layer block in every beacon chain slot.

2.1 Block Generation

In contrast to PoW, where the timing of blocks is dictated by mining difficulty, PoS operates with a fixed tempo for block generation. To be precise, time is split into epochs. An epoch represents a fixed period in the Ethereum network, consisting of 32 slots (cf. Figure 1a). Each slot, in turn, is a time interval during which a single block can be proposed and validated. The duration of a slot is fixed at 12 seconds [35], i.e., block production is synchronous.

As previously mentioned, there is a chance for a single block to be added to the blockchain in every slot. As used to be the case with PoW Ethereum, a block contains a collection of transactions [44]. In each slot, a validator is selected pseudo-randomly as the blocks proposer. If a slot's proposer fails to propose a block within the allotted time, the slot remains empty (cf. Figure 1b). We note here that the probability of a validator being chosen as a proposer is inversely proportional to the number of active validators in the network at the time of selection [4]. In addition to being tasked with block proposals, validators are also assigned to committees to validate newly proposed blocks. We note here that validators chosen to propose or validate blocks are determined at least one epoch and at most two epochs in advance [25]. Finally, validators participate in sync committees to allow light client to determine the head of the beacon chain.

2.2 Validator Duties

In the following, we provide additional details for the tasks performed by Ethereum PoS validators. Besides having to deposit 32 ETH, a validator must also operate three distinct software components: an execution client, a consensus client, and a validator client. Following the deposit, users enter an activation queue, which serves to control the influx of new validators joining the network. Once a validator joins the network, they are assigned three primary tasks, each of which is critical to the overall operation and integrity of the network [7]:

Block proposal. Validators are sporadically selected as a block's proposer, which involves proposing new blocks and making them available for attestation. A pseudo-random selection process for block proposers ensures a fair distribution of block proposal opportunities among all validators. This task is fundamental in facilitating the constant addition of new blocks to the Ethereum blockchain, thereby securing its ongoing expansion and stability. At the present state of the network, an individual validator typically gets an opportunity to propose a block approximately every 2.5 months.

Block attestation. Attestation involves validators confirming the validity and accuracy of the data contained within a block. Validators are expected to attest to their view of the head of the beacon chain, the most recent fully validated block, once per epoch. During each epoch, every validator submits an attestation, a signature expressing their opinion on

the head of the chain. Timeliness is essential, as attestations must be included within 32 slots to be eligible for rewards. Occasionally, validators are assigned the task of aggregating attestations from other validators in the same committee. This process involves combining multiple attestations into a single aggregated attestation, which helps reduce the overall amount of data being transmitted and stored on the network.

Sync committee participation. Sync committees play a crucial role in enabling light clients to efficiently and trustlessly determine the head of the beacon chain. These committees have a duration of 27 hours, ensuring a lower frequency of change compared to the attestation committees, which change every slot. This stability reduces the computational load on light clients. Validators are pseudo-randomly selected to participate in a sync committee, with their selection odds being less than those of being assigned to propose a block [23]. Validators in a sync committee create signatures on a slot-by-slot basis, signing the root of the previous beacon block. Their signatures attest to the chain's head. Light clients can then use these signatures to determine the head of the beacon chain.

2.3 Validator Rewards and Penalties

For the previously outlined tasks, validators receive rewards for the previously outlined tasks. Their rewards can be divided into consensus and execution layer rewards. Note consensus layer rewards were received by validators since the start of the beacon chain in December 2020, while execution layer rewards only became available to validators after the merge, i.e., when PoS replaced PoW on Ethereum.

Consensus layer rewards. Validators receive consensus layer rewards for block proposal, attestation (i.e., attesting to the source epoch, attesting to the target epoch, and attesting to the head block), and participation in sync committees [23]. Additionally, validators receive whistle-blowing rewards for providing evidence of dishonest validators, such as proposing multiple blocks in a single slot or submitting contradictory attestations. These consensus layer rewards decrease on an individual validator basis as more validators join the network and do not change depending on network activity. Currently, a validator receives approximately 0.04 ETH for a successful proposal and 0.00001 ETH for a successful attestation [27].

Execution layer rewards. A block proposer also receives rewards from priority fees and direct payments to their fee recipient address. To maximize their consensus layer rewards, many validators run MEV-Boost. MEV-Boost is a sidecar service that essentially operates as a block builder under the framework of *proposer-builder separation (PBS)*, creating profitable blocks for the block proposer [11]. These rewards are consensus layer rewards, which were introduced after the merge. On average, the execution layer reward of a proposal is around 0.1 ETH per block [46].

Penalties and slashing. To incentivize network participation and honest behavior, validators receive penalties for missing target and source votes. These penalties are equal in amount to the rewards received for successful attestation. Additionally, validators can also be slashed for serious offenses (e.g., proposing and signing two different blocks for the same slot). Slashing removes at least $1/32$ of a validator's staked Ether.

2.4 Staking Services

Staking services facilitate user participation in Ethereum's consensus by giving users easier access to Ethereum staking. Generally, staking services are either *custodial*, where the service

holds the user's keys, or *non-custodial*, where the user retains control of the keys. Liquid staking further enhances these services by offering tokenized representations of staked assets, enabling their use in DeFi applications.

Custodial staking services. Custodial staking services, e.g., Binance, Bitcoin Suisse, Coinbase, and Kraken, hold the user's private keys and manage the technical aspects of staking. Users gain convenience, but besides paying a fee, they must also place trust in the service provider to safeguard their assets. This type of service is suitable for those who prefer a hands-off approach to staking, with the platform handling all the staking operations.

Further, custodial staking services such as Lido and Rocket Pool are staking pools governed by on-chain communities. In Lido, 30 permissioned companies provide staking services to the protocol, while in contrast, Rocket Pool employs over 2,500 permissionless node operators for staking user funds.

Non-custodial staking services. Non-custodial staking services, such as Stakefish and Staked, provide the infrastructure for staking but allow users to keep control of their assets. The service runs the validator nodes, but users interact directly with smart contracts to stake their assets. Thus, even though the service is running the technical aspects of the staking process, the control and ownership of the assets remain with the user.

3 Data Collection

We collect data from Ethereum's execution and consensus layer by running a Lighthouse consensus client and an Erigon execution client. Our consensus layer data set covers the period from the genesis of the beacon chain on 1 December 2020 (i.e., slot 0) to the last slot of 15 May 2023 (i.e., slot 6,447,598). Notice that the beacon chain launched well in advance of the merge. In the time before the merge, the beacon chain was reaching consensus on its state without processing mainnet transactions [1]. Additionally, our execution layer data covers the period from the genesis of Ethereum on 30 July 2015 to the last slot of 15 May 2023 (i.e., block 17,268,587). We further enhance our data set through validator and address labels from Rated Network API [18], `beaconcha.in` [13], and Etherscan [6] to allow for validator clustering.²

3.1 Beacon Chain Data

We collect the majority of our data from the beacon chain with our Lighthouse client and provide an overview of the data collected in the following.

Validator data. For each validator that was in the network at some time or eligible for activation until the end of our data collection period, we query our Lighthouse client to collect the epoch in which they became eligible for activation (i.e. when they staked 32 ETH in the beacon chain deposit contract), their activation epoch (i.e., when they joined the network), and where applicable the exit epoch (i.e., when they left the network).

Attestations and proposals. We collect all attestations and proposals assigned to each validator. Then, we record the success status of each. For proposals, we collect data on all validators responsible for a proposal and the success or failure of each block proposal. We

² As a result of rate limits imposed by one of the APIs, we only obtain labels for all validators until the end of 15 April 2023 (i.e., slot 6,231,598). Thus, our results related to clustering (cf. Section 5) span only until 15 April 2023. We will extend this data in a future version.

further differentiate between missed blocks and orphaned blocks. Orphaned blocks are valid blocks that were proposed but not included in the main chain, as they were outcompeted by another block at the same height. This can occur due to near-simultaneous block proposals, causing temporary chain splits. We use the API provided by `beaconcha.in` to classify missed proposals [13]. Regarding attestations, we gather information on all epoch committees and block attestations. In total, our data set encompasses 62,951,944,703 attestations and 6,447,599 proposals. Out of the 64,385 missed proposals, we identify 6,584 as orphaned.

Slashing. We analyze all beacon chain blocks to identify any slashings for proposer and attestation violations. For each, we record the slashed validator, the slot in which the slashable offense took place, and the slot in which the proposer was slashed.

Blocks and graffiti. Depending on the consensus client, the order in which attestations are included and whether there is any redundancy in the included attestations varies [21]. Thus, we download all beacon chain blocks to identify the consensus client used by the block’s validators. We further extract the block’s graffiti as some validators indicate what client they are running in the graffiti.

3.2 Validator Clustering

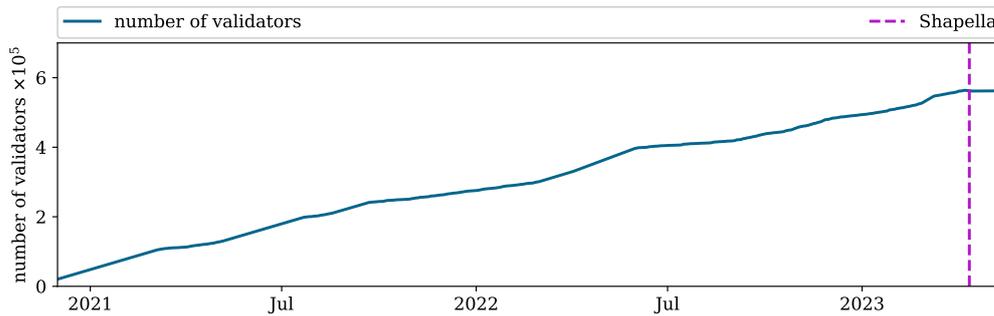
As of slot 6,447,598, we identify 625,193 validators that have participated in at least one attestation duty. For each validator, we collect additional metrics such as labels, deposit addresses, and fee recipient addresses. This information aids us in clustering these validators into distinct entities in subsequent analysis steps.

Deposit addresses. Deposit addresses are those that provide the 32 ETH required to fund a validator. Note that a validator can be associated with multiple deposit addresses. We collect all such addresses by monitoring the logs from the beacon chain deposit contract. In total, we identify 94,148 distinct deposit addresses in our dataset.

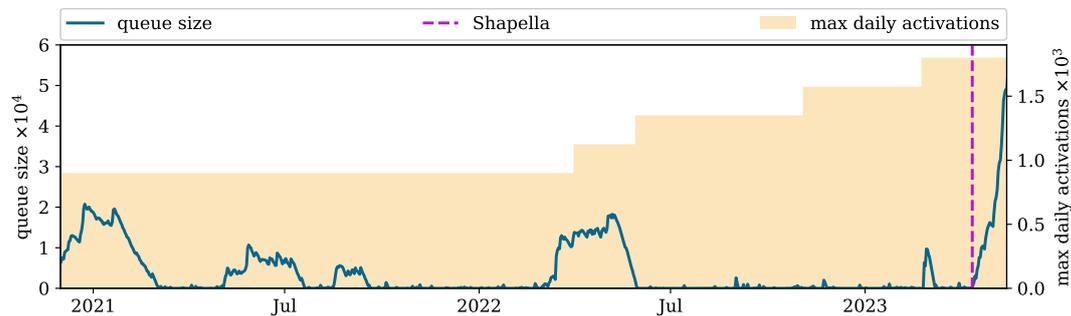
Fee recipient addresses. A fee recipient address is an Ethereum address specified by the validator to collect the execution layer rewards for their block proposals. Validators sharing the same fee recipient address likely represent the same entity. To identify these addresses, we extract the fee recipient field for each block from our Erigon client. If a block is not created through *proposer-builder separation (PBS)* [17], this address corresponds to the validator’s fee recipient address. Otherwise, it belongs to the block builder. Since a significant number of blocks are constructed via PBS, we also inspect the last transaction in each block. If the block was built through PBS, the builder transfers the fees to the validator in this transaction [11]. Hence, if no such transaction exists, we record the block’s fee recipient address as the validator’s fee recipient address. If such a transaction is present, we record the receiver of the ETH in the last transaction as the validator’s fee recipient address. Our dataset identifies 11,515 unique fee recipient addresses.

Validator labels. A validator label is a name that associates a validator with an entity, e.g., staking pools, staking-as-a-service providers, centralized exchanges, or institutional validators. Not all validators have an associated label, as some operators may choose not to disclose their identity or affiliation. We obtain and combine validator labels from the Rated Network API [18], through scraping data from `beaconcha.in` [13] and through manual identification of deposit patterns for Coinbase (cf. Appendix A.1).

Address labels. We further obtain address labels for deposit addresses through data scraping from Etherscan [6]. Specifically, we collect *Ethereum Name Service (ENS)* domain names, i.e., web3 usernames [5]. We will utilize address labels in addition to validator labels



■ **Figure 2** Number of validators over time. Observe the persistent growth of validators on Ethereum. We mark the Shapella upgrade by the purple dashed line.



■ **Figure 3** Number of validators in the queue waiting to join the network along with the maximum number of validators that can be activated, i.e., join the network, each day. The size of the queue increases dramatically after the Shapella upgrade which enabled withdrawals. We mark the Shapella upgrade by the purple dashed line.

to identify and label entities.

Etherclust data set. We cluster Ethereum addresses through the reused centralized exchange deposit addresses method introduced by Victor [49]. To be precise, we cluster together addresses that utilize the same exchange deposit address. The clustering compresses 6,788,215 addresses into 1,410,523 entities with more than one address – representing approximately 2.93% of the 231,625,425 unique Ethereum addresses as of 15 Mai 2023 [8].

3.3 Ethereum Proof-of-Work Miners

We amend our analysis of the Ethereum PoS consensus (de)centralization by comparing it to the former PoW consensus. Thus, we collect the miners for each block from the first block of the Ethereum blockchain on 30 July 2015 to block 15,537,392 (i.e., the last block before the merge on 15 September 2022) from our Erigon client. Additionally, we obtain labels for the miner addresses from Etherscan [3].

4 Beacon Chain Participation

We commence the analysis by providing an overview of the size of the network as well as the participation level of the validators in the consensus.

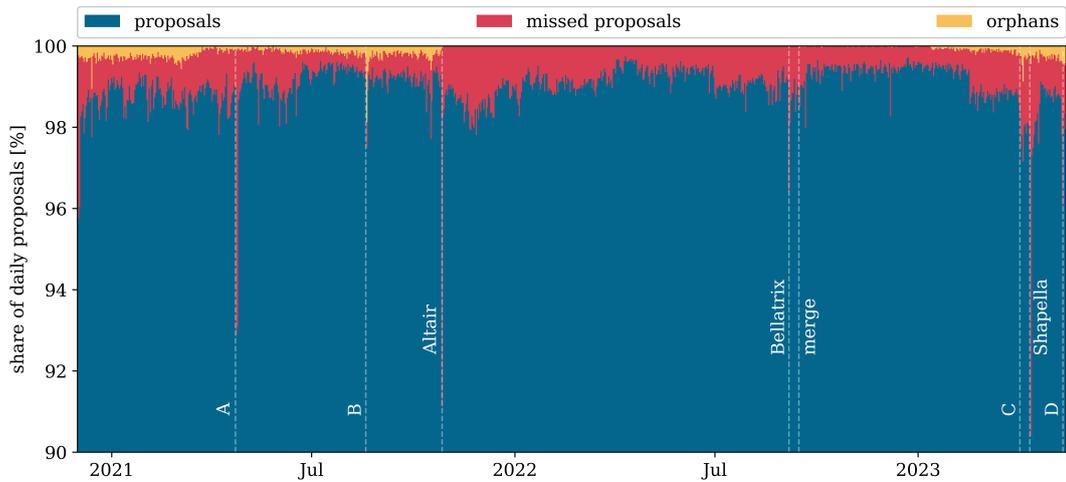


Figure 4 Daily share of successful (shown in blue), missed (shown in red), and orphaned proposals (shown in yellow). We indicate major upgrades/events that had a noticeable impact on the network participation by white dashed lines. The Altair upgrade heavily reduced the number of orphaned blocks. Also highlighted are incidents A, B and D, in all three cases bugs in the Prysm and Teku consensus clients resulted in increased number of missed/orphaned proposals. Further, incident C marks an attack on MEV-Boost.

4.1 Number of Validators

Figure 2 displays the total number of validators on the beacon chain. Notice the consistent increase in the number of validators over time. In part, this growth is due to withdrawals only becoming possible after the Shapella upgrade [9] on 12 April 2023. After the Shapella upgrade, the number of validators remained constant, as both the activation queue (i.e., the queue for validators joining the network) and the exit queue (i.e., the queue for validators exiting the network) were filled. Note that the number of validators that can enter/leave the network is limited and dependent on the network size. Therefore, the in- and out-flow to the network was constant. Then, almost a month later, on 8 May 2023, the in-flow overtakes the out-flow again, and the number of validators starts to increase again. As of 15 May 2023, there are 572,497 active validators. Each has staked at least 32 ETH on the beacon chain, equivalent to 15.23% of all Ether in circulation.

We further plot the size of the activation queue in Figure 3 along with the maximum number of daily activations. Post beacon chain launch, an initial rise in the queue size is observable. Subsequent significant increases are noted in mid-2021 and March 2022, which coincide with periods of high Ethereum prices. We observe the most significant and still persistent queue size increase after the Shapella upgrade. As of 15 May 2023, there are 48,903 validators in the queue waiting to join the network, while only 1,800 can join the network each day (yellow area in Figure 3). Thus, given these limits imposed on the number of validators joining the network, validators entering a queue of this size will have to wait more than 26 days to become activated.

4.2 Proposals

We commence our analysis of the level of network participation of Ethereum with a longitudinal study of the daily share of successful, missed, and orphaned proposals. In Figure 4, we visualize the daily share of successful proposals in blue, while we show missed proposals in red and orphaned ones in yellow. The daily number of successful proposals is high throughout

the entire history of the beacon chain, with an average success rate of 98.95%. Some days stand out with significantly lower success rates. Incidents A [28] and B [29] indicate two bugs in the dominant consensus layer (Prysm) that led to an increased missed and orphaned proposals. In particular, incident B was primarily triggered by a service degradation issue with a Lido operator who controlled roughly 2% of validators. An existing Prysm bug then exacerbated the situation.

The next sharp increase in the proportion of missed proposals coincides with the Altair upgrade [9], which was the first beacon chain upgrade. While the missed proposals reach about 9% on the day of the upgrade (likely due to operators not updating their clients in time), the proportion of orphaned blocks almost drops to zero after the update. From then on, the proposal success rate remains relatively stable for almost a year. The Bellatrix upgrade [9], which was the second beacon chain upgrade in preparation for the merge, only increased the number of missed proposals on the day of the upgrade. Further, there is no noticeable drop in the proportion of successful proposals during the merge.

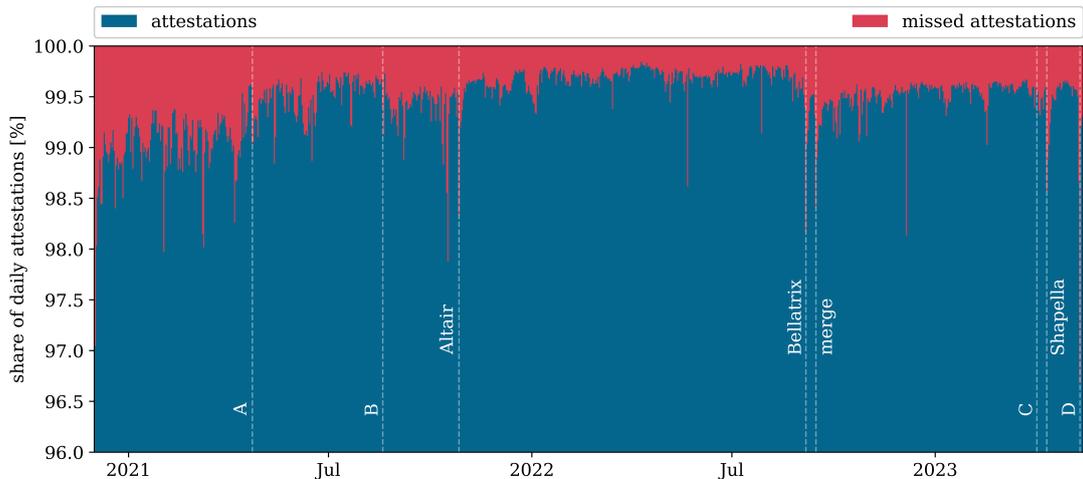
In the aftermath of the merge, we observe a slight increase in the daily share of proposals. Potentially a consequence of the added execution layer rewards received by proposers after the merge — making block proposals significantly more profitable. However, this trend starts to change in early 2023, with both the share of orphans and missed proposals increasing. In particular, the attack by a validator on MEV-Boost [40] (event C) had a lasting impact on the number of missed proposals. After the attack, the timing requirements for validators using MEV-Boost were tightened, which might explain the persistent increase in missed proposals. Shapella [9], the third beacon chain upgrade, again increases the number of missed proposals in its immediate aftermath due to validators not updating their clients in time. The final sharp increase in the number of missed proposals during our data collection coincides with the finality issues experienced by Ethereum on 11 and 12 May 2023 [15] as a result of a bug in the Prysm and Teku consensus clients (event D).

We conclude that throughout the entire beacon chain history, proposal participation was very high. Noticeably, the most significant losses in participation, with the exception of upgrades, are at least in part a consequence of bugs in one or more consensus clients. Thus, a high centralization of the consensus clients can pose significant security concerns.

4.3 Attestations

We continue by analyzing the network’s participation level for attestations. While lower participation in the block proposals reduces the blockchain’s throughput, low participation (less than two-thirds) in attestation can stall the blockchain’s finality indefinitely. Finality indicates that a block is considered irreversible and permanently added to the blockchain, i.e., it cannot be removed or altered without burning one-third of staked Ether. Thus, high network participation for attestations might even be more crucial than for proposals.

In Figure 5, we plot the daily share of successful and missed attestations. First, we note that similar to what we previously saw with proposals, the overall participation for attestations is high. On average, 99.46% attestations are successful each day — even higher than for proposals. Further, we observe an overall increasing trend in the daily share of successful attestations. By looking at Figure 5 in detail, we notice that incidents A, B, and D, which all mark bugs in one or more consensus clients, are not or less noticeable in the attestation participation levels. All three beacon chain upgrades (i.e., Altair, Bellatrix, and Shapella) and the merge led to short-term increases in the number of missed attestations. In the aftermath of Bellatrix and the merge, the daily share of missed attestations further stays higher than the previous level and only decreases slowly. Importantly, the drop in



■ **Figure 5** Daily attestation success rate over time. We indicate major upgrades that had a noticeable impact on the network participation by white dashed lines. Also highlighted are incidents A, B and D, in all three cases bugs in the Prysm and Teku consensus clients resulted in increased number of missed/orphaned proposals. Further incident C marks an attack on MEV-Boost.

participation as a result of incident D led to a non-finalizing state. Incident C, the attack of a validator on MEV-Boost, does not appear to have caused a prolonged increase in missed attestations. This is likely because the tightened timing requirements imposed on MEV-Boost validators do not directly affect the attestation procedure.

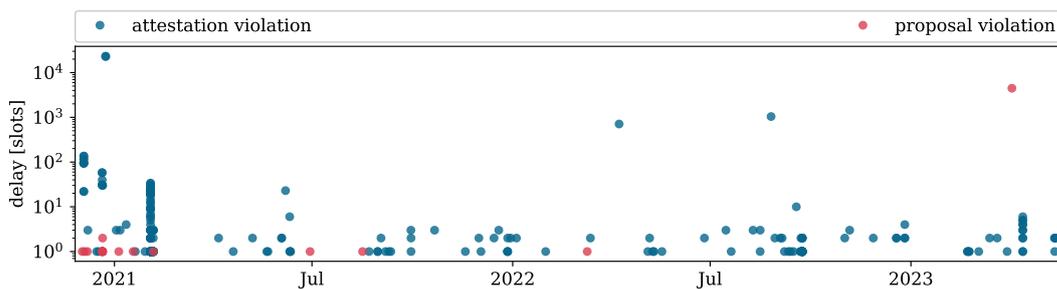
4.4 Slashing

Until now, our analysis was focused on network participation. As mentioned previously, validators that do not fulfill their duties will only face small penalties (cf. Section 2.3). To explore the prevalence of serious misbehavior, we examine all slashings — punishments for serious offenses — in our data collection window.

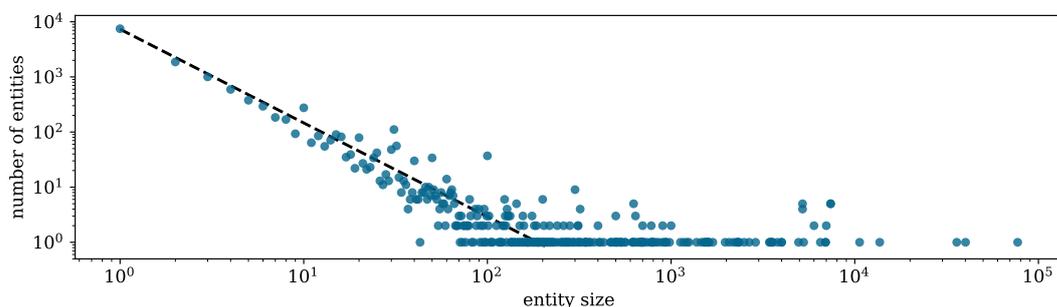
Figure 6 plots all slashings for attestation violations (i.e., attesting to a block that “surrounds” another or engaging in “double voting” by attesting to two candidates for the same block) and for proposal violations (i.e., proposing and signing two different blocks in the same block) from the inception of the beacon chain until 15 May 2023. The Y axis indicates the delay, the number of slots between the slashing and the offense of the slashing. We find that there are a total of 248 slashings that have taken place: 230 for attestation violations and 18 for proposal violations. Thus, there are only very few (identified) violations in the history of the beacon chain. Additionally, we observe that the vast majority of violations (81.45%) are identified within ten slots.

5 Validator Landscape

Although every validator starts with an equal initial stake of 32 ETH, a single entity can control multiple validators, thereby increasing their *staking power*. In the subsequent analysis, we group validators into entities and examine the level of (de)centralization within the validator landscape by assessing the distribution of staking power amongst entities.



■ **Figure 6** Slashings for attestation violations (shown in blue) and proposal violations (shown in red) over time. We observe a total of 230 attestation violations and a total of 18 proposal violations. The Y axis indicates the delay of the slashing in comparison to time of the offense.



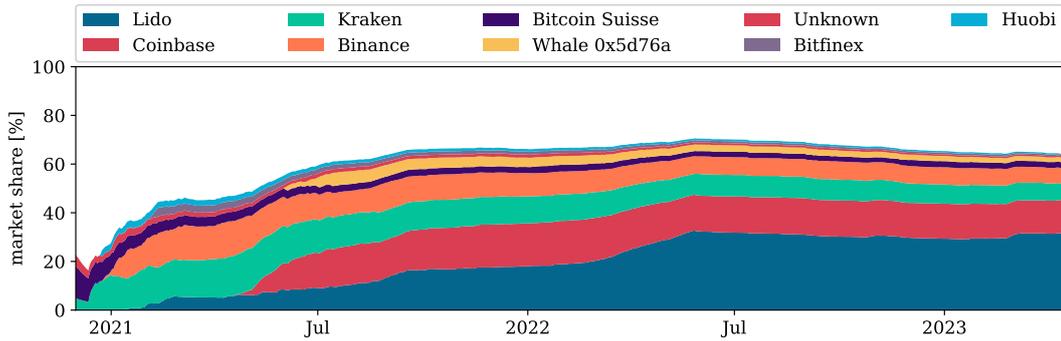
■ **Figure 7** Distribution of the number of validators in an entity. Nearly 7,500 entities are made up by a single validator (top left), while the largest entity consist of 77,108 validators (bottom right). Entity size follows a power-law distribution as demonstrated by the fitted curve.

5.1 Entity Clustering

We commence by describing our entity clustering procedure. Our clustering relies on the data set described in Section 3.2. Barring exceptions, which we detail in Appendix A.2, the clustering process is executed in four steps:

1. Validators sharing the same label (i.e., validator labels obtained from Rated Network API and `beaconcha.in`) are grouped into a single entity.
2. Entities or individual validators with at least one common *deposit address* (i.e., the address(es) used to stake the 32 ETH) are merged into the same entity.
3. Entities or individual validators sharing at least one *fee recipient address* are consolidated into the same entity if at least one of the entities does not have a label yet and has consistently used the same *fee recipient address*. This is a conservative approach that reduces the risk of incorrect clustering.
4. Entities or individual validators whose *deposit address(es)* belong to the same entity, as per the Etherclust data set, are combined.

We note that the inherent complexities and nuances to consider during entity clustering, especially given the variety of strategies and structures present in the Ethereum staking landscape, necessitate some manual adjustments and informed exceptions to our clustering process. Throughout, we always opt for the conservative route to maintain the integrity of our analysis. We provide an overview of and detail the exceptions we make in Appendix A.2.



■ **Figure 8** Staking power distribution of the largest nine entities over time. Notice that the biggest four entities hold more than 50% of the staking power from mid 2021 onwards. In this depiction, Lido is considered as a single entity.

5.2 Staking Power (De)centralization

We proceed by analyzing the validator distribution across entities and assess the level of decentralization in staking power over time. To commence, Figure 7 illustrates the distribution of the entity size — the number of validators belonging to an entity. We observe that there are many small entities, e.g., nearly 7,500 entities only count a single validator and a few very large entities. The largest entity we identify is Coinbase, with 77,108 validators under their control. There are a couple of entities with the exact same size of around 6,000. These entities are all Lido operators, which are capped in size (cf. Appendix B). In short, we find that the entity size follows a power law distribution as demonstrated by the fitted curve (number of entities \propto entity size $^{-\alpha}$).

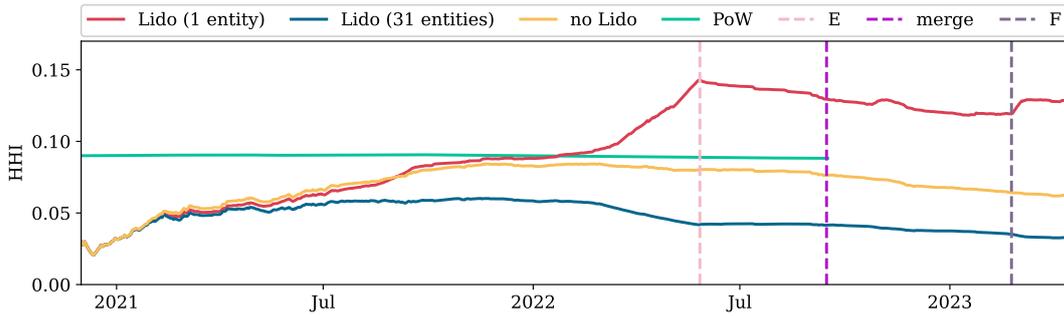
We conclude the analysis of the validator landscape by analyzing the (de)centralization of staking power over time. In Figure 8, we plot the market share of the biggest nine entities. Notice that in this analysis, we represent Lido as a single entity instead of treating each Lido operator as a distinct entity. In the subsequent analysis, we will also explore the implications of considering Lido as separate entities. The classification of Lido as a single entity or multiple distinct entities is ambiguous, as we discuss in Appendix B.

Remarkably, the biggest four entities hold more than 50% of the staking power from mid-2021 onwards. We further point out that the market share of Lido increases throughout the history of the beacon chain and sits at 31.7% on 15 April 2023. This trend is worrying, as Lido almost controls a third of all validators: the fraction of validators required to disrupt the blockchain’s network for Ethereum PoS.

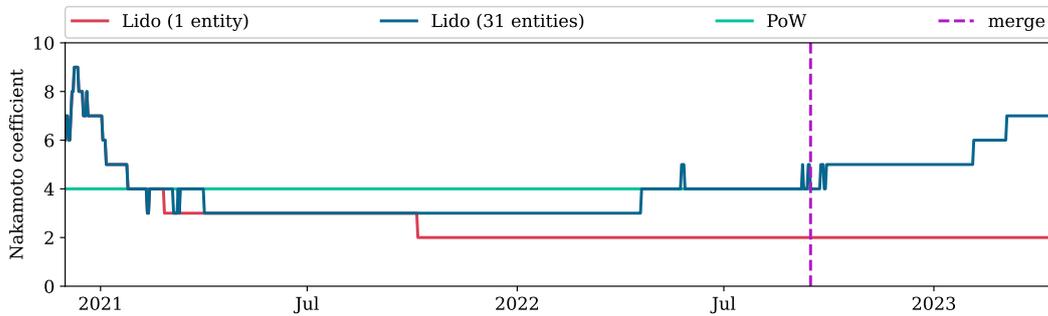
To assess the concentration, i.e., centralization, of the staking power in greater detail, we calculate the *Herfindahl-Hirschman Index (HHI)*. The HHI is used for assessing market concentration and competition in economics. Mathematically, it is expressed as

$$HHI = \sum_{i=1}^n s_i^2,$$

where n is the number of firms in the market, and s_i denotes the market share of firm i as a fraction. Thus, the HHI ranges between 0, indicating a competitive market, and 1, representing a monopolized market with a single dominant firm. We note here that we use the HHI to measure the concentration (i.e., centralization) of the Ethereum staking power instead of the Gini coefficient, as the Gini coefficient measure inequality. To be precise, the Gini coefficient would not distinguish between a validator landscape, where a single entity controls 100% of the staking power, and one with a thousand equal sized entities sized firms.



(a) Comparison between the HHI, i.e., concentration, of Ethereum PoS with Ethereum PoW (green line). For Ethereum PoS, we calculate the HHI for Lido considered as a single entity (red line), Lido as 31 separate entities (blue line) and without Lido (yellow line). Notice that the concentration of the staking power largely depends on whether Lido is viewed as a single entity or not. We further indicate important events by dashed vertical lines. Event E marks the start of forum discussions about potential Lido protocol’s self-limitation [20] and event F indicates the largest ETH deposit into the Lido protocol [10].



(b) Comparison between Ethereum PoS and PoW (green line) Nakamoto coefficient. For Ethereum PoS we calculate the Nakamoto coefficient considering Lido as a single entity (red line) and as 31 separate entities (blue line).

■ **Figure 9** Decentralization, i.e., HHI (cf. Figure 9a) and Nakamoto coefficient (cf. Figure 9a) of Ethereum PoS and PoW. Note that we view Lido as 31 separate entities as opposed to 30 operators as we do not have operator labels for seven Lido validators which we view as a separate entity as to not increase the centralization.

In the context of Ethereum and staking, we apply the HHI to analyze validator concentration and potential centralization risks. For us, n is the number of entities, and s_i is the proportion of staking power controlled by entity i . A low HHI value indicates a more decentralized network with numerous independent validators, while a high HHI value points to a more concentrated network, possibly making the system more vulnerable to attacks.

Figure 9a plots the HHI of the Ethereum staking power over time and compares it to that of the Ethereum mining power during the PoW era. The green line indicates the HHI of the mining power, which is consistently around 0.09 from the launch of the beacon chain until the merge. We plot the HHI of the Ethereum staking power with Lido considered as a single entity and as 31 separate entities, i.e., the various operators. Notice that the HHI, regardless of how Lido is viewed, increases initially. Then, from early 2022 on, the HHI with Lido as a single entity continues to increase and overtake the HHI of Ethereum PoW, while the HHI with Lido as 31 separate entities even drops slightly. The HHI with Lido as a single entity reaches its maximum of 0.14 in mid-2022 just as discussion regarding a potential self-limitation of Lido commences in the governance forum (marked by event E). We note the significant rise in the HHI in early 2023 (marked by event F) after the largest ETH deposit into the Lido protocol. Finally, we plot the HHI of the Ethereum staking power after removing Lido (yellow line) to cement the impact of how Lido is viewed on the

decentralization of the Ethereum network. Without Lido, the network is more decentralized when viewing Lido as one entity, the opposite holds when viewing it as 31 separate entities.

Regardless of the view of Lido, the HHI for the Ethereum staking power never exceeds 0.15, and industries with a HHI below 0.15 are generally regarded as unconcentrated. Yet, when we consider the Lido as a single entity, the HHI is increasing with time.

In the following, we calculate the *Nakamoto coefficient* to further assess the degree of decentralization of Ethereum PoS. The Nakamoto coefficient determines the number of entities that need to be compromised for an adversary to disrupt the blockchain’s network [45] (i.e., $> 50\%$ in Ethereum PoW and $> 33.3\%$ in Ethereum PoS [48]) of the system. A high Nakamoto coefficient signifies greater decentralization, as it requires a larger number of nodes to be compromised to control the network.

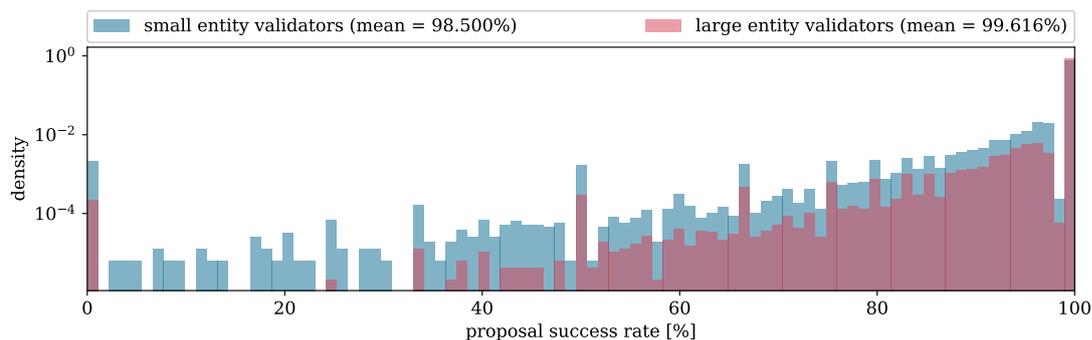
In Figure 9b, we visualize the Nakamoto coefficient of Ethereum over time. Again, for Ethereum PoS, we differentiate between viewing Lido as one entity (red line) and 31 entities (blue line). We further show the Nakamoto coefficient for Ethereum PoW for comparison. For Ethereum PoW the Nakamoto coefficient is always four from the beginning to the beacon chain to the merge. Notice that during the initial phase of the beacon chain, the Nakamoto coefficient is at its highest and reached ten before it starts to decrease to three for Ethereum PoS by mid-2022, i.e., drops below the Nakamoto coefficient of Ethereum PoW. From then on, the Nakamoto coefficient of Ethereum PoS, depending on how one views Lido starts to drift apart. While the Nakamoto coefficient with Lido as 31 entities increases to six, that with Lido as a single entity drops to two. A Nakamoto coefficient of two indicates that it only takes two entities to shut down the blockchain.

Thus, the decentralization of the staking power of Ethereum, whether measured with the HHI or Nakamoto coefficient, is not optimal. Still, the level of decentralization is comparable to that during the PoW times but still exhibits significantly more volatility. However, especially when viewing Lido as a single entity, the increase in centralization in both measures is worrying, while the opposite hold when considering Lido 31 separate entities. Whether it is appropriate to view Lido as a single entity or not is inconclusive. For example, a bug in Lido’s smart contracts could allow a single entity to potentially overtake the entire Lido staking power. However, assuming that the audited smart contracts do not allow for such attacks, the staking power is better distributed. For one, 30 separate operators run the validators. Further, the protocol is governed by a *decentralized autonomous organization (DAO)* that is controlled by the Lido (LDO) token holders. Finally, the Ether staked through Lido originates from many different individuals. We provide a detailed discussion of the centralization within Lido in Appendix B.2.

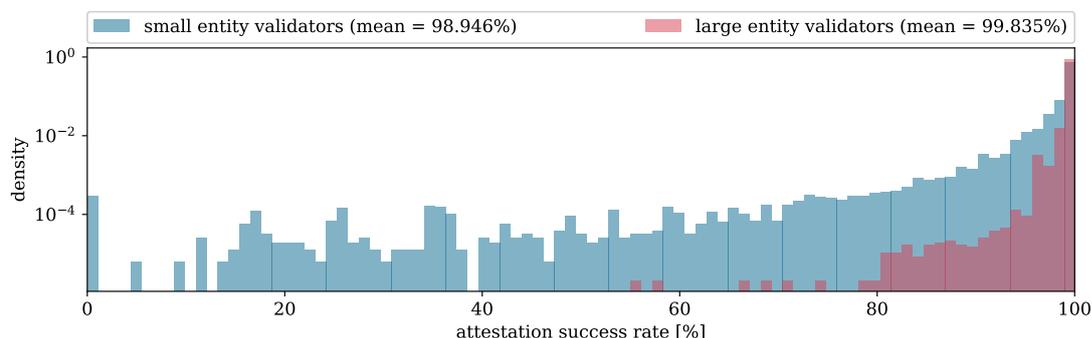
We conclude the analysis of the decentralization of staking power by discussing the impacts of high centralization. The assignment of proposals and attestations is known at least one epoch in advance. Thus, an entity controlling a continuous sequence of blocks will know this ahead of time. This peculiarity of Ethereum PoS opens the door to what is known as *multi-block MEV*: value extraction through transaction order manipulation across multiple consecutive blocks. One example of multi-block MEV is oracle manipulation, which becomes cheaper when one is certain to be in control of at least two consecutive blocks [39].

sequence length	1	2	3	4	5	6	7	8
number of occurrences	5,681,309	227,480	26,024	3,558	493	77	13	1

■ **Table 1** Number of occurrences of block proposal sequences by the same entity. Generally, an entity only controls a single consecutive block, but we observe numerous instances where an entity controlled more than one block in a row.



(a) Attestation success rate across all validators. Validators affiliated with large entities exhibit a superior attestation success rate. On average, their success rate is elevated by 1.1%.



(b) Successful proposal rate for all validators. On average, their success rate is 0.9% higher.

■ **Figure 10** Proposal (cf. Figure 10a) and attestation (cf. Figure 10b) success rate of all validators split by entity size. We consider all entities with less than 1,000 validators as small entities (shown in blue), and all entities with at least 1,000 validators as large entities (shown in red). Notice the logarithmic scale on the Y axis.

To better understand the threat of such attacks under the current staking power distribution, we study the occurrences of uninterrupted block proposal sequences in Table 1. Note that we consider Lido operators individually in this analysis. In the vast majority of cases, an entity only controls a single block in a row. However, we observe more than 220,000 sequences of length two and more than 25,000 sequences of length three. Thus, these occur multiple times a day. Startlingly, there are even 13 sequences of length seven and one of length eight — all either for Coinbase or Kraken. The certainty for entities to control long sequences opens up additional security concerns for Ethereum PoS that were not present in the same form in Ethereum PoW and exemplifies the threats posed by a lack of decentralization in the consensus layer.

5.3 Entity Performance Analysis

In the following, we investigate whether we observe the performance (i.e., the proportion of successful attestations and proposals) between small and large entities. We start by analyzing both the proposal and attestation success rate of validators depending on the size of the entity they belong to. To be precise, we consider a validator to belong to a small entity if the entity size is smaller than 1,000, else we consider the validator to be part of a large entity. Figure 10 visualizes the proposal (cf. Figure 10a) and attestation (cf. Figure 10b) success rates of validators as a histogram. We show the small entity validators in blue and the large entity validators in red.

Notice that overall validators, regardless of their entity size, exhibit very high proposal and attestation success rates with 99.34% on average for proposals and 99.61% on average for attestations. Thus, participation is very high regardless of the size of the entity. Still, we observe noticeably higher participation from validators belonging to large entities for both proposals and attestations. We believe that this difference in success rate likely stems from the fact that entities with more validators can afford to use better hardware, have better connectivity to the network, and have faster emergency response times.

We also want to point out that very few validators have a 0% success rate in their proposals and attestations (cf. Figure 10). In total, 442 validators have a 0% proposal success rate, while only 43 validators have a 0% attestation rate. This discrepancy might be due to the possibility that a validator who, due to unfortunate circumstances, misses their first proposal or generates an orphaned block will subsequently plummet to a 0% success rate. This could potentially persist for months until the next proposal opportunity arises. For attestations, on the other hand, the validator has a new chance every couple of minutes. Hence, we estimate the number of nodes entirely abandoned by their operators to be 43.

	attestation success rate [%]	proposal success rate [%]
Lido	99.866	99.792
Coinbase	99.908	99.494
Binance	99.877	99.454
Kraken	99.819	99.609
Bitcoin Suisse	99.805	99.528

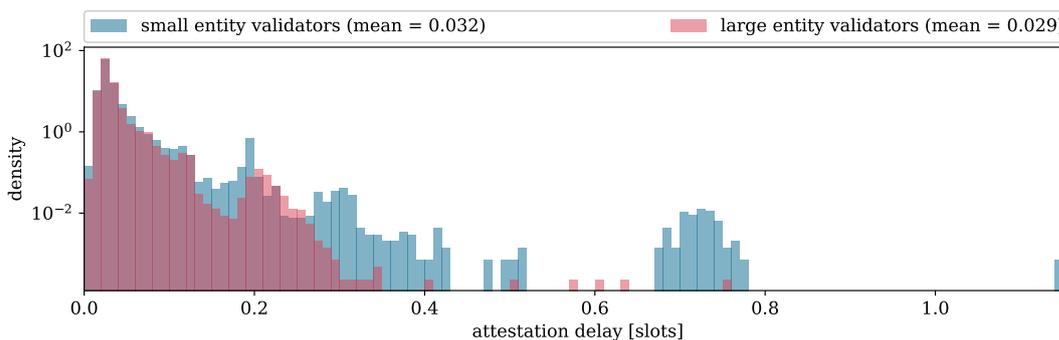
■ **Table 2** Attestation and proposal success rate for the five biggest entities.

We further take an in-depth look at the participation rate of the five biggest entities (Lido, Coinbase, Kraken, Binance, and Bitcoin Suisse) in Table 2. Note that, here, we consider Lido as one entity but provide an overview of the performance of the 30 individual operators in Appendix B.1. From Table 2, we can see that all big operators have very high and similar participation rates for attestations (higher than 99.80% for all) and proposals (higher than 99.45% for all). Further, it is not clear which of the five biggest entities has the highest participation rate. While Coinbase has the highest attestation success rate, Lido has the highest proposal success rate.

Another takeaway from this analysis is that the success for attestations is significantly higher than that for proposals, both in general, but also for each of the five biggest entities. Possibly, this is due to attestations being counted as successful even if they are delayed by a couple of slots, while proposals to be successful need to arrive within the slot's twelve seconds. Thus, we also analyze the average delay of attestations for each validator, grouped by the size of the entity the validator belongs to, in Figure 11. We find that even though the distribution of attestation delays for validators in small and large entities exhibit differences, these differences are small. The mean delay is only 0.031 slots for small entities and 0.028 for large entities. Note that we consider an attestation for slot x to be without delay if it arrives in slot $x + 1$.

6 Consensus Client Landscape

Our previous analysis demonstrates a significant degree of centralization in Ethereum's staking power. While this centralization can be a security risk, our analysis in Section 4 demonstrated that the biggest drops in participation and finality issues were related to



■ **Figure 11** Attestation delay of all validators split by entity size. We consider all entities with less than 1,000 validators as small entities (shown in blue), and all entities with at least 1,000 validators as large entities (shown in red). Notice the logarithmic scale on the Y axis.

problems with consensus clients. Thus, we also analyze the consensus client landscape of Ethereum in the following.

6.1 Beacon Chain Block Fingerprinting

Ethereum consensus layer clients possess unique methods for packing attestations into blocks, providing the basis for block fingerprinting. By coupling these distinct patterns with block graffiti, we can utilize the Blockprint classifier developed by Sigma Prime [21] to predict the consensus layer client used by a validator for each of their proposals.

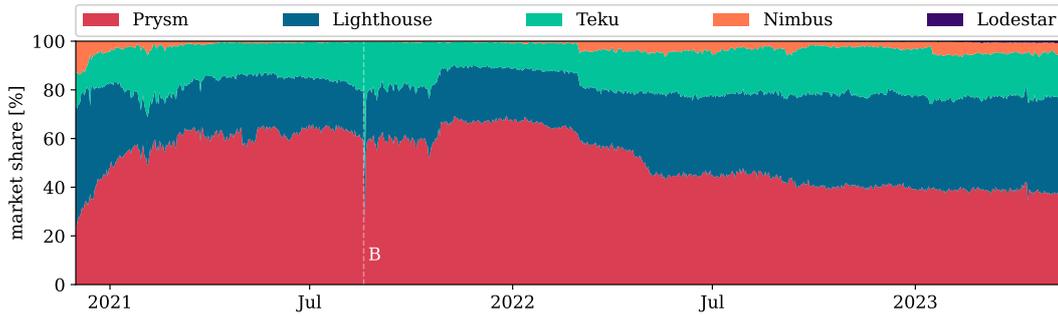
Blockprint uses a *k-nearest neighbors* (*k-NN*) classifier to identify the consensus client utilized to build a beacon chain block. The classifier is trained on a feature matrix constructed from the block’s reward batches, i.e., the attestations included in the block. Labels for the training data are obtained from the block’s graffiti — a customizable identifier. For around 17% of validators, the client software and version are indicated in the graffiti. While it is possible that validators manually change their graffiti to indicate false client information, we believe this to be unlikely and take the graffiti as ground truth.

We perform a single modification to the Blockprint script and create a separate test data set, i.e., we remove the graffiti for 20% of all validators before training on them. This allows us to measure the accuracy of the classifier. Our analysis finds that the overall accuracy of the classifier is 96.75%.

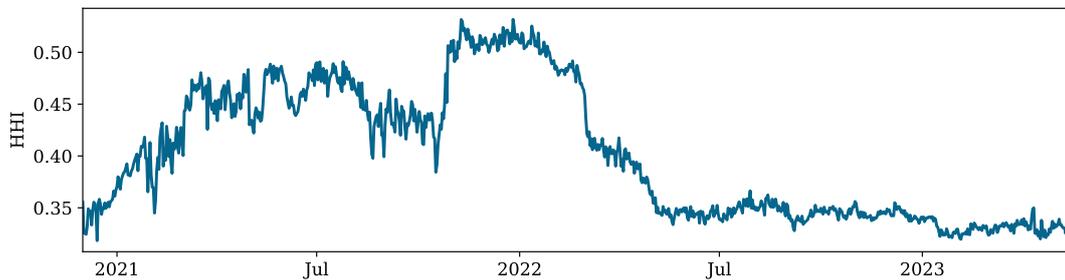
Finally, we note that our consensus client analysis focuses on block proposals. Thus, it is not directly comparable to the consensus client distribution in the network as recorded by Miga Labs [12], for instance. Whereas our focus is on the consensus client distribution amongst validators, they record the consensus client distribution in the P2P network. That means if a large entity runs on a single node, we will give it more weight, whereas nodes that are not validators are not counted in our analysis.

6.2 Consensus Client (De)centralization

We commence our analysis of the consensus level of decentralization in the consensus client landscape by plotting the daily market share of each of the five clients over time. More than 70% of validators run Prysm or Lighthouse on all but one day (event B). From the start of the beacon chain, Prysm quickly becomes the largest consensus client and generally has a market share of more than 50% throughout 2021. There is one significant drop in the share of Prysm consensus clients on a day when the Prsym client experienced problems (event



■ **Figure 12** Staking power distribution of the five established consensus clients over time. Notice that at least 70% of validators consistently run Prysm or Lighthouse. Incident B marks issues with the Prysm client.



■ **Figure 13** Concentration (HHI) of Ethereum PoS consensus clients. The consensus client landscape is highly concentrated, i.e., centralized.

B). Then from early 2022 onwards, the Lighthouse client starts to gain a more significant market share. By mid-2023, both clients each have approximately a third of the market share. The remaining three clients have a smaller market dominance while Teku’s market share is 16.51% on average that of Nimbus sits at 2.52% while that of Lodestar is 0.10%.

To further analyze the decentralization of the consensus client landscape we again plot the HHI index in Figure 13. The HHI index for the consensus client initially increases until it reaches more than 0.5 at the end of 2022. Then, as the Lighthouse client gains market share and the Prysm client loses market share, the HHI starts to drop at the beginning of 2022. From mid-2023 onwards, the HHI is generally stable and sits at around 0.35. However, typically even industries with an HHI larger than 0.25 are regarded as highly concentrated. Their centralization of the consensus client landscape is further exemplified by the fact that a single client controls $33.\bar{3}\%$ of all proposers on each day. Thus, the consensus client Nakamoto coefficient sits at one throughout the entire history of the beacon chain.

Finally, we study the consensus client distribution of the largest five entities and consider Lido as a single entity. Table 3 shows the proportion of consensus clients used to make proposals by each of the five biggest entities over time. Binance, Coinbase, and Kraken all proposed more than 50% of their blocks with Prysm — the dominant consensus client throughout the beacon chain history. Further, all three have a significant share of block proposals with Lighthouse and Teku, while little to none with Nimbus and Lodestar. Bitcoin Suisse exhibits a starkly different consensus client distribution. Nearly 90% of its blocks were proposed with Teku with the only other consensus client with a significant share being Nimbus. Interestingly, even though the consensus client centralization for Bitcoin Suisse as an entity is very high, it might help the broader ecosystem as Teku is one of the smaller consensus clients. In analyzing Lido’s consensus client distribution, we observe a balanced

split among the five clients, though the majority of blocks are proposed using the two largest clients: Lighthouse and Prysm.

	Lighthouse [%]	Prysm [%]	Teku [%]	Nimbus [%]	Lodestar [%]
Lido	49.149	35.911	12.965	1.754	0.222
Coinbase	22.893	62.980	11.611	2.516	0.000
Binance	12.994	82.035	4.747	0.224	0.000
Kraken	11.398	76.101	11.225	1.276	0.000
Bitcoin Suisse	0.199	0.961	89.366	9.474	0.000

■ **Table 3** Client distribution of the five biggest entities.

Table 3 offers an overall picture of the consensus client distribution for the five biggest entities but does not offer details regarding changes over time. Thus, we offer a longitudinal analysis of the consensus client distribution for the five biggest entities in Appendix D and find that for all but Bitcoin Suisse, the consensus client distribution is becoming more balanced in recent months. Thus, it appears that these big entities are making an effort to decentralize the consensus client landscape.

We conclude our analysis of the consensus client landscape by re-iterating the immense centralization. As exemplified by all major participation drops outside of upgrades being related to issues with at least one of the consensus clients, decentralization in the consensus client landscape is also essential but is currently lacking.

7 Related Work

Decentralization. One of the fundamental design principles and objectives of a permissionless blockchain is decentralization. Gencer et al. [31] were the first to investigate the decentralization of the blockchain consensus layer. Their research revealed that the mining processes of Bitcoin and Ethereum exhibit a significant level of centralization. Subsequent studies by Kiffer et al. [36] and Lin et al. [38] for Ethereum PoW also reach the same conclusion. In contrast to these works, we are, to the best of our knowledge, the first to study the decentralization of the staking power in Ethereum PoS.

Kim et al. [37] present a measurement study of the client heterogeneity for Ethereum PoW to find that the majority client makes up more than 75% of the P2P network. Our work studies the consensus client heterogeneity of Ethereum PoS and further focuses on the client diversity amongst validators as opposed to amongst nodes in the P2P network.

A recent body of work has examined the concentration, or lack of decentralization, in Ethereum transactions. Zhang et al. [54] proposed a taxonomy for measuring blockchain decentralization and demonstrated an increasing trend in the centralization of transactions within the decentralized finance (DeFi) space. Similarly, Ao et al. [24] and Heimbach et al. [34] observed the same trend when analyzing peer-to-peer transactions. In this paper we focus on the consensus layer as opposed to the transaction layer. Thus, these works are orthogonal to ours.

Censorship. In light of the recent imposition of cryptocurrency mixer sanctions by the U.S. Office of Foreign Assets Control (OFAC), the censorship resilience of Ethereum has come under scrutiny. Wahrstätter et al. [50] conducted a study on the security impact of blockchain censorship. Their findings indicate an 85% increase in the inclusion delay of sanctioned transactions and highlights the associated security concerns. Wang et al. [52] specifically focused on the security implications of censoring for validators. Their research reveals that

validators engaging in censorship are susceptible to Denial of Service (DoS) attacks. While these works focus on the security implications of censorship on the Ethereum blockchain, we measure the consensus layer decentralization of Ethereum. Higher decentralization in the consensus layer is expected to improve censorship resistance.

Maximal extractable value. MEV presents a further security concern to the Ethereum consensus [42]. Daian et al. [26] and Eskandari et al. [30] provide an early description of MEV. Measurement studies of MEV presented by Torres et al. [47] and Qin et al. [42] reveal the immense presence and value of MEV. Further, they outline resulting the security risks presented to the consensus layer of a permissionless blockchain. In comparison to these previous studies in the Ethereum PoW era, we analyze Ethereum PoS and highlight the heightened security risk posed by MEV in PoS.

Proposer-builder separation. PBS was designed to decentralize the the consensus layer [17] and its adoption dramatically rose to more than 90% [33, 51, 53] since the merge. Recently, multiple works have emerged that study the PBS landscape [32, 33, 43, 51, 53]. These works highlight both theoretically and empirically the increasing trends to centralization of block building under PBS. In this work, we focus on the decentralization of the consensus layer and not block building.

8 Concluding Discussion

Active participation in and high decentralization of the Ethereum consensus layer are key to the health and security of Ethereum. Thus, it is essential to understand both the network participation levels in consensus as well as the decentralization of the consensus layer.

Network participation levels. Our longitudinal analysis of the consensus participation levels demonstrates the incredibly high participation rates of validators. On average, 99.00% of blocks are proposed successfully, and 99.53% of attestations are received. Most dips in participation are during network upgrades or due to problems with consensus clients or large entities. While the vast majority of these temporary drops had no bigger impact on network consensus, the dips in participation level in mid-May, due to bugs in the Prsym and Teku consensus clients, prevented the network from reaching finality for a couple of epochs.

Decentralization. In our work, we analyze the decentralization of the Ethereum PoS consensus layer by studying both the staking power and consensus client distribution. For both, we find evidence of undesirable centralization. However, while observing recent significant improvements in the consensus client diversity, we do not discover the same pattern concerning staking power. Lido's staking power market share is ever-growing and approaching one-third. If this were to happen, Lido alone could hinder Ethereum from reaching agreement. The Ethereum community is aware of this problem but is not yet able to work against this trend. Even though the community ensures that the hardware requirements for running a validator are low [41], too many people choose the easier route by utilizing staking services instead of running their own validators, i.e., solo staking. A further challenge faced is the congestion in the activation queue, as it might be too big of a sacrifice for solo-stakers to wait weeks for activation. Finally, the better performance we observe for large entities, compared to small entities, is likely to cause a disproportionate growth of large entities as opposed to small ones. Thus, incentivizing more solo staking is an open problem.

Security implications. Finally, we wish to comment on the security implications of a lack of decentralization in the consensus layer — these go beyond requiring one-third of validators to stall the blockchain or the potential for censorship. Given the prevalence

of MEV on the Ethereum blockchain, which is a known risk to the consensus layer, the possibility of multi-block MEV in Ethereum PoS only adds to this. The larger an entity, the higher the chance that it will control multiple consecutive blocks. These additional MEV opportunities reserved for larger entities could even lead to their market share increasing as their execution layer rewards are expected to be higher.

To conclude, our study provides an overview of the Ethereum PoS consensus layer and underwrites the need and desire for increased decentralization — especially in light of the security concerns posed by heightened centralization in the consensus layer.

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A Label and Clustering Exceptions

In the following we detail our Coinbase validator identification process (cf. Section A.1) and all clustering exceptions (cf. Section A.2).

A.1 Coinbase Validator Labels

We undertake an additional identification process for Coinbase validators, as especially recent ones have not been labeled by our data sources, i.e., Rated Network API [18] and `beaconcha.in` [13]. Coinbase adheres to a unique and easily identifiable pattern when rolling out new validators, allowing a straightforward detection of their validators. In particular, the following properties hold for any Coinbase validator:

1. Each validator employs a unique deposit address.
2. The Ether sent to the deposit address originates from a Coinbase address.
3. Post-deployment, the surplus Ether is redirected back to a Coinbase address.
4. A small nominal amount of Ether, typically around 0.0006 ETH, is left in the deposit address.

Thus, we run through all unlabeled validators and label those for which all of the above properties hold as Coinbase. In doing so, we label an additional 3,222 validators as Coinbase. Note that we obtain a list of all Coinbase addresses from Etherscan [2].

A.2 Entity Clustering Exceptions

In the following, we detail the primary challenges and the corresponding adjustments we make during entity clustering. These exceptions allow us to mitigate any unnecessary over-clustering.

Validator label exclusion. Our data set includes labels for companies providing only the hardware and software for staking, with the staker controlling the deposit and fee recipient addresses — *non-custodial staking*. In such cases, we aim to sidestep clustering a validator with the company providing the underlying resources.

Instead, we strive to cluster it with other validators controlled by the same staker. The distinction between custodial and non-custodial staking services is not always apparent and some providers even changed over time. We do not cluster an entity by its validator label, if all three of the following criteria are met: (1) the service permits non-custodial staking, (2) the staker knows their exact validator ID, and (3) upon clustering all labels of this entity together, the entity exhibits numerous used deposit addresses and at least one of these deposit addresses is associated with an unrelated address label (ENS name), suggesting user control over this address.

We remove these validator labels for non-custodial staking services that meet all our previously outlined criteria. Namely, these non-custodial staking services are *Staked.us*, *Stakefish*, and *Bloxstaking*.

Validator label-only clustering. Liquid staking protocols such as *Lido* and *StakeWise*, multiple different operators run the protocol's validators. The validator labels we obtain from the Rated Network API allow us to identify which validators are run by which operator. Given all validators belonging to these protocols, regardless of the operator running them, they typically share the same deposit addresses. Our standard clustering method would cluster all validators belonging to such a liquid staking protocol as one entity.

	fee recipient address
Stakefish	0xffee087852cb4898e6c3532e776e68bc68b1143b 0x54cd0e6771b6487c721ec620c4de1240d3b07696 0x5caf7c1b096cf684b09ece3d3a142db0d46fc58e 0xe94f1fa4f27d9d288ffea234bb62e1fbc086ca0c
Rocket Pool Smoothing Pool	0xd4e96ef8eee8678dbff4d535e033ed1a4f7605b7
Ethpool	0xb364e75b1189dcbbf7f0c856456c1ba8e4d6481b
Ankr	0x3bef77233e52d23969958587127d99ec2367c2bd 0x90b0c836a19a74195d45fad2d2d3895a7a3eab08 0x6a0db4cef1ce2a5f81c8e6322862439f71aca29d

■ **Table 4** Fee recipient addresses which we exclude during clustering and which entity they are associated with. These addresses would lead to unwanted linking of entities.

To retain the higher resolution provided by the validator labels obtained from the Rated Network API, we modify our approach for validators from *Lido* and *StakeWise* and only focus on their validator labels during the clustering process. Throughout our analysis we will, at times, analyze the impact of viewing all validators belonging to a liquid staking service as one entity as opposed to multiple entities depending on the operators in control of the validators.

Fee recipient address exclusion. Node operators participating in non-custodial staking services (e.g., Rocket Pool), have the option to designate a communal smoothing pool address as their fee recipient address. This shared pool is designed to even out the potentially fluctuating MEV rewards, which can be particularly beneficial for smaller node operators. However, this setup causes all Rocket Pool nodes that join the smoothing pool to be clustered as a single entity, even though they are controlled by multiple different operators.

To counteract this, we exclude certain fee recipient addresses from our clustering process. These include fee recipient addresses associated with *Stakefish*, *Staked.us*, *Ethpool Staking*, *Ankr*, and the *Rocket Pool smoothing pool*. A complete list of these excluded addresses can be found in Table 4.

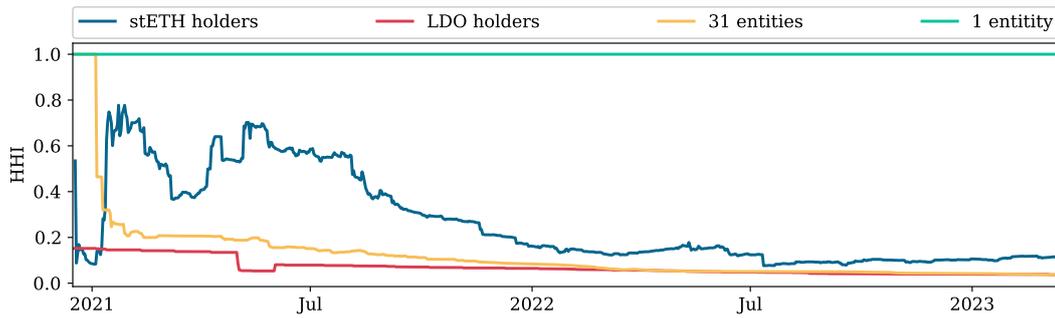
Etherclust exceptions. In step four of our clustering procedure (cf. Section 5.1), we further manually ensure that entities unlikely to belong to the same entity are not further merged. To be precise, we refrain from clustering well-known entities with any other entity. We make this exception on five separate occasions: (1) multiple LIDO operators, (2) multiple Rocket Pool operators, (2) Bitfinex, Binance, and Whale 0xEAB8, (3) Coinbase and zachrellim.eth, and (4) Stakely.io and StaFi.

B Lido

As the dominant liquid staking protocol with a significant influence on the network’s health, Lido merits a closer look.

B.1 Lido Operator Participation Comparison

We analyze the participation metrics across all 30 Lido staking operators in Table 5. A pattern of consistently high performance emerges throughout their operational history. However, RockLogic GmbH and Chorus One stand out with a comparatively lower performance. The



■ **Figure 14** Concentration (HHI) of Lido’s stETH tokens, LDO tokens, and the 31 Lido staking operator entities included in our data set. An on going trend towards dispersion is observable.

dip in performance for RockLogic GmbH might be attributed to a slashing incident that occurred on 13 April 2023. The incident was triggered by the inadvertent duplication of validator keys across two active clusters, which resulted in a double vote and consequent slashing of eleven validators [14]. As for Chorus One, an extended downtime event in October 2021 might be the origin of this reduced performance. The downtime was accidental and was the result of complications during node migrations [19].

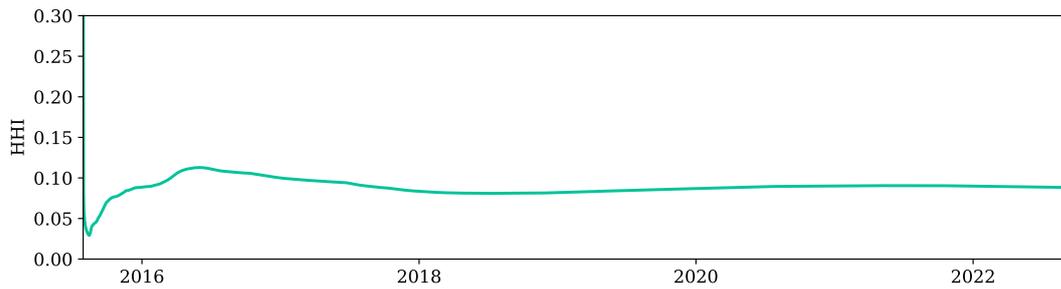
B.2 Lido (De)centralization

In the following, we provide an in-depth analysis into the distribution of power within Lido. As of the time of writing, Lido operates through 30 permissioned node operator companies tasked with performing the staking. However, those operators alone do not have the power to arbitrarily change the protocol. Currently, Lido’s operations on Ethereum are governed by LDO token holders through an Aragon DAO. This governance encompasses a wide range of aspects, including the Lido treasury, staking withdrawal keys, the registry of node and oracle operators, DAO Access Control List permissions, and the execution of EVM scripts. In effect, LDO holders have root access to the Lido protocol. Proposals are being considered to circumscribe the DAO’s authority by enabling stETH holders having the power to veto certain decisions. However, a wide and diverse distribution of the LDO and stETH tokens is indispensable for a healthy protocol.

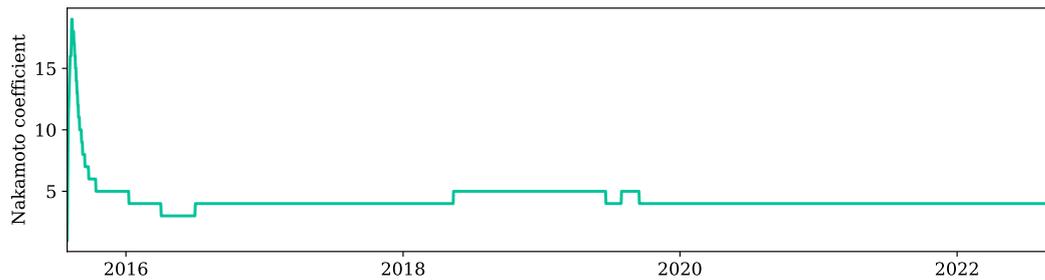
Figure 14 visually represents the concentration trends among LDO and stETH holders over time, as measured by the HHI. It is encouraging to observe a progressive decentralization, with stETH holders’ HHI approximating 0.1 and LDO holders’ HHI around 0.034 towards the end of the observed period. Similarly, Lido’s staking operators exhibit an ongoing dispersion trend with a current HHI of 0.036. Overall, the concentration has been on a decline for the past two years. Nonetheless, it is imperative to recognize and address risks the current Lido dominance poses to the Ethereum network, as for instance the Lido smart contracts could be a single point of failure.

C Ethereum Proof-of-Work (De)centralization

In the following we provide some additional insight regarding the network (de)centralization fluctuations during Ethereum’s PoW era. Figures 15a and 15b illustrate an early surge in network decentralization immediately following Ethereum’s launch. However, according to the HHI and Nakamoto coefficient, this level of decentralization quickly diminished and



(a) HHI, i.e., concentration, of Ethereum PoW consensus from Ethereum genesis until the merge.



(b) Nakamoto coefficient of Ethereum PoW consensus from Ethereum genesis until the merge.

■ **Figure 15** Decentralization, i.e., HHI (cf. Figure 15a) and Nakamoto coefficient (cf. Figure 15b) of Ethereum PoW.

largely maintained steady levels until the end of PoW.

D Consensus Client Distribution of Large Entities

In this section, we present the distribution of the five consensus layer clients — Prysm, Lighthouse, Teku, Nimbus, and Lodestar — over time, focusing on the five largest entities as of May 15 2023. We plot the consensus client distribution for each of the five largest entities in Figure 16. Note that the time frames vary as not all entities have participated on the beacon chain since its inception. A trend towards consensus client diversification is visible for four of the five large entities, with Bitcoin Suisse being the exception. However, at the time of writing Teku is a minority client and Bitcoin Suisse is therefore helping the overall client diversity with their choice. Incident B indicates the time when the Prysm client faced issues and we thus observe a drop in Prysm market share on this day. Further, it appears that Binance slowly started to rely more on the Lighthouse client after this incident.

	attestation success rate [%]	proposal success rate [%]
Attestant	99.997	99.940
Allnodes	99.990	99.960
Prismatic Labs	99.974	100.000
Kukis Global	99.972	99.971
RockX	99.969	99.932
Blockdaemon	99.968	99.900
Sigma Prime	99.968	99.896
Everstake	99.967	99.889
CryptoManufaktur	99.967	99.986
HashQuark	99.964	99.938
InfStones	99.961	99.795
ChainLayer	99.961	99.937
P2P.ORG - P2P Validator	99.952	99.756
Stakely	99.945	99.909
Blockscape	99.938	99.903
Staking Facilities	99.925	99.873
Anyblock Analytics	99.921	99.918
Nethermind	99.907	99.869
Kiln	99.890	99.726
Simply Staking	99.858	99.806
Stakin	99.829	99.851
Figment	99.824	99.836
ConsenSys Codefi	99.806	99.800
Stakefish	99.794	99.841
DSRV	99.778	99.947
Certus One	99.758	99.441
ChainSafe	99.743	99.697
BridgeTower	99.734	99.818
RockLogic GmbH	99.477	99.290
Chorus One	99.458	99.086

■ **Table 5** The 30 Lido staking operators exhibit consistently high performances in both attestation and proposal success rates.

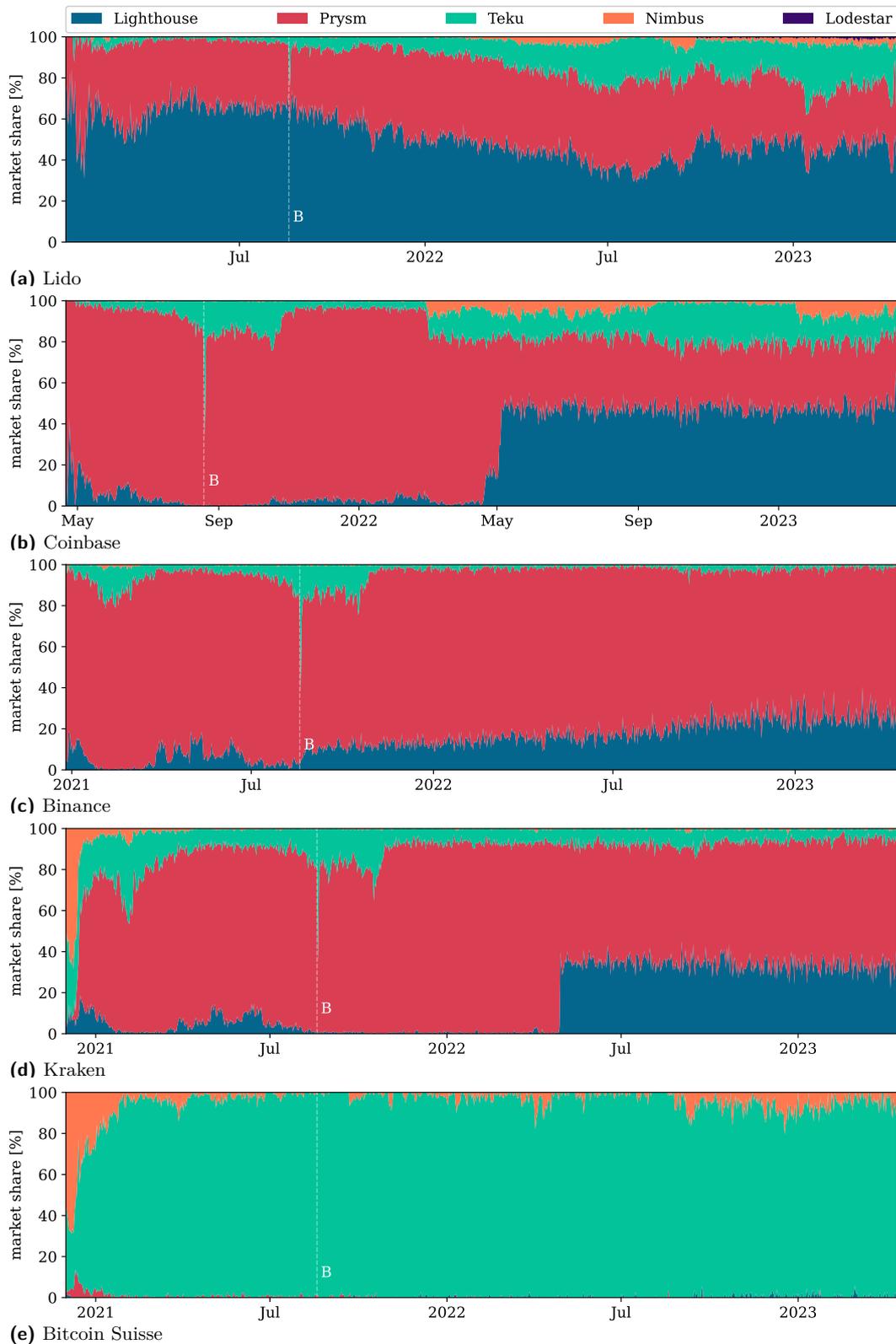


Figure 16 Staking power distribution of the five established consensus clients over time for the five largest entities.