The Decentralization Spectrum: Design Tradeoffs In Digital Assets

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Table Of Contents

Introduction

Decentralization and centralization are architectures at two ends of digital asset network design. While “decentralized” and “centralized” networks seem to be binary alternatives, the reality is more nuanced. Blockchain design choices fall along a spectrum.

This paper explores digital asset blockchain design with a focus on auditability, security, governance, and ownership. It also examines their tradeoffs. For perspective, the paper considers three blockchain networks—Bitcoin, Solana, and Ethereum—in the context of the decentralization-centralization spectrum, focusing on an additional five variables.

- Node Participation and Accessibility
- Decentralization of Validator and Issuer
- Geographic Concentration
- Governance Participation and Control
- Distribution of Ownership

Four Design Features That Structure The Decentralized-Centralized Spectrum

Decentralized and centralized networks attribute varying degrees of importance to auditability, security, governance, and ownership, as discussed below.

Auditability is the degree to which any independent, external participant can verify the network's transaction history and consensus rules. In a fully auditable network, participants can independently verify that transactions follow the protocol rules and that the ledger is accurate, without relying on trust in a third party. The primary mechanism that achieves auditability is the “full node,” which downloads the blockchain’s history, validates every transaction against its protocol rules, and maintains an independent copy of the current state. Any discrepancy between a node's local validation and an incoming block causes the node to reject the block.

Even a dominant mining pool or validator cannot introduce invalid transactions without being detected.

Security involves the distribution of power and influence among the miners or validators of blocks on the network. The more dispersed the control is among miners and validators, the more difficult it is for a single entity or coordinated group of entities to rewrite history, censor transactions, or double-spend funds. Decentralization raises the real-world cost of coordination that an adversary must bear to subvert the chain. Evaluating security goes beyond raw node counts to the actual concentration of block-producing power, the diversity of participants, and the degree to which any single point of failure could undermine the ledger's integrity.

Governance refers to the processes that can change a blockchain's rule. Centralized systems set rules and enforce them top-down. In a decentralized governance system, participants can propose changes, debate their merits, and signal support or opposition. As a result, decentralized systems preclude unilateral upgrades: no single actor can impose a rule change on the rest of the network without a consensus among the other participants. While the decision-making process might be slower and more contentious than that of centralized systems, decentralized governance ensures that no entity will dominate the decision making.

Ownership and Distribution involve tokens. With decentralized ownership and distribution, no single wallet, foundation, or insider group controls a disproportionate share of the supply. With centralized ownership and distribution, a small number of entities—such as founding teams, venture capital firms, or early investors—hold a significant percentage of tokens, giving them outsized influence over governance, token price, and network incentives. Many foundations, for example, retain a large percentage of token reserves to fund development and operations, particularly those involved in proof-of-stake networks in which token concentration governs block production and validation. In other words, concentrated ownership is not only an economic concern but also a security concern. Evaluating this dimension requires examining token allocation at launch, vesting schedules, the concentration of holdings across wallets, and the distribution of ownership as the network matures.

CRITERIA	DECENTRALIZED	CENTRALIZED
Auditability	Open (any node)	Permissioned
Security	Distributed consensus	Single point of failure
Governance	Community-driven	Top-down
Ownership and distribution	Widely dispersed	Concentrated

Source: ARK Investment Management LLC, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Bitcoin, Ethereum, And Solana On The Decentralization-Centralization Spectrum

According to our research, Bitcoin, Ethereum, and Solana occupy different positions on the decentralization-centralization spectrum, as shown simplistically on the graph below. The four blockchain network design characteristics discussed above determine the position of each one, as discussed in more detail in the second part of this article focused on measures of decentralization.

Public Blockchain Decentralization Spectrum

(Average of the six refreshed dimension scores, July 2026)

Source: ARK Investment Management LLC and Glassnode 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Auditability

Auditability transforms verification from a problem of trust into a problem of computation. The auditability of a highly decentralized architecture like Bitcoin, for example, is the technical foundation of “trustlessness,” because anyone with sufficient hardware and bandwidth can run a full node and confirm the network's state. Importantly, such a process differs categorically from the audit of a bank's balance sheet, which requires access to proprietary information and reliance on the auditor's

integrity. In the digital asset arena, the same principle obtains: in a network with low auditability, in which a single software client represents more than ninety percent of its nodes, is audited by whoever controls that client's codebase.

From that standpoint, client diversity reinforces auditability, whereas a monolithic client base—or concentration of control in the hands of a few—undermines it. Overall, Solana and Ethereum both fall nearer to the centralized end of the design spectrum relative to Bitcoin, but Ethereum's gradual diversification across execution and consensus clients, and Solana's increasing prioritization of a multi-client ecosystem for node software, will create meaningful improvements in auditability over time.

Security

How many independent parties would need to coordinate, collude, or conspire with an attacker to alter a blockchain's ledger? A measure of security is the cost of a blockchain reorganization—or "reorg." Reorgs occur when an attacker constructs an alternative chain with more cumulative work or stake than the canonical chain, causing nodes to reorganize their view of history.

In proof-of-work systems like Bitcoin, the cost of a reorg is in acquiring and deploying more than half the network's hash rate. In proof-of-stake systems like Ethereum or Solana, the cost of a reorg is in acquiring more than one-third (for liveness "failures," when the chain stops "finalizing"[1]) or two-thirds (for safety failures, when conflicting transaction histories finalize) of the staked capital. Let's explain these reorg issues.

Bitcoin's decentralized proof-of-work security model distributes block production across a global mining network. A successful reorg would require coordinating or coercing multiple competing mining pools that operate across different jurisdictions, different regulatory environments, and different energy sources. While theoretically the economic cost of an attack would total tens of billions of dollars, a "successful" attack would be detectable and reversible by the broader community. Bitcoin's high level of security—and its resilience—is a product of its decentralized mining architecture. At minimum, an attacker would need to compromise or collude with three to four of the largest mining pools—entities that today operate independently across multiple continents and legal jurisdictions—to surpass the 51% attack hash rate threshold.

When Ethereum transitioned from a proof-of-work (PoW) to a proof-of-stake (PoS) system[2], its security architecture transitioned as well. Validator influence is proportional to staked ETH[3], which means that the concentration of stake translates directly into block production power. Causing a structural security concern has been the emergence of large liquid staking protocols, particularly Lido, with influence at

times approaching 30% of all staked ETH. The influence of a single smart contract with a majority stake could threaten the network's safety guarantees. Ethereum's community has been working actively to monitor distribution and mitigate the risk of shared infrastructure staking dependencies. Concentrated in a handful of liquid staking protocols and large institutional operators, as few as two to three major staking entities—Lido's node operator set chief among them—could in theory collude and reach the one-third threshold necessary to halt finality, or the two-thirds threshold necessary to control finality.

Solana's architecture leverages a variation of proof-of-stake called delegated-proof-of-stake. Solana's validator set is smaller as stake is “pooled” among validators and SOL holders can delegate their SOL to a chosen validator. While the hardware and stake requirements to run a Solana validator are substantially higher than those for Ethereum, delegation lowers the barriers to entry for acquiring stakes, leaving hardware as the main bottleneck and raising questions about the trade-offs between throughput and decentralization. By far the most performant of the Big Three blockchain protocols, Solana’s impressive transaction speeds can concentrate block production among fewer, better-resourced validators.

Governance

In contrast, governance—not just code—enforces Bitcoin's fixed supply of 21 million. More precisely, no centralized authority has the power to change it. Altering the supply cap would require modifying Bitcoin's consensus rules, which would mean convincing a supermajority of node operators, miners, developers, and users to adopt the change. Because these independent stakeholders are distributed globally and incentivized overwhelmingly to preserve scarcity, achieving such consensus is practically impossible. Previous attempts to alter far less fundamental features, such as the block size wars (“SegWit”), resulted in years of contentious debate and ultimately a chain split rather than a unilateral change. Bitcoin's monetary policy is credible precisely because no single entity or coordinated group can rewrite it, making its governance model the most underappreciated pillar of its value propositions.

Ownership and Distribution

In principle, 10 wallets in proof-of-stake networks like Ethereum and Solana could control 50% of the supply and dominate governance. As a result, the concentration of ownership is both a governance and market risk.

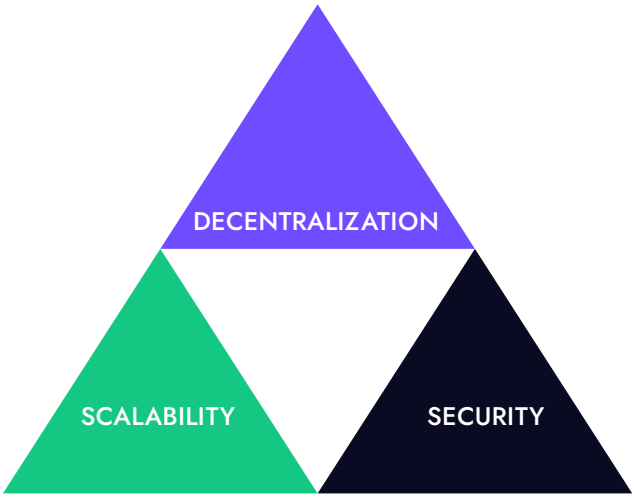
In contrast, the widely distributed token supply characteristic of decentralized systems reduces concentration risk, diversifying voting power in on-chain governance systems and reducing the systemic risk of large holder decisions to sell. Decentralized

systems also broaden the base of economically aligned participants who have economic incentives to support the network's operation and reduce the risk of market manipulation, as no participant can transact in a way that moves the token's price meaningfully.

A Note On The Blockchain Trilemma

A blockchain's degree of decentralization determines whether it can serve as neutral global infrastructure, with durable property rights and rules that can overwhelm the power of individual actors—including its own founders. Those design attributes are important because they determine whether investors can trust the blockchain network to guarantee stake ownership, to maintain transactions history, to preserve preset issuance over time, and—in the case of Ethereum and Solana—to honor the ruleset of their smart contracts.

That said, Ethereum Co-Founder, Vitalik Buterin, has observed the Blockchain Trilemma: decentralization, security, and scalability are in tension, as optimization for two of the three requires costs to the third, as illustrated in the image below.



Source: ARK Investment Management LLC and Glassnode 2026,. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

The scalability trade-off manifests most directly in block production. A blockchain's capacity to process transactions is bound by the size of its blocks and the speed at which they are produced. Increasing either parameter expands throughput but raises the hardware requirements for full node operation. As node requirements increase, the population of participants who can afford to run full nodes decreases. As a result,

the network becomes less distributed, weakening the guarantees of auditability and security that come with decentralization.

Bitcoin's block size limit, which was set at one megabyte before the SegWit upgrade and expanded conservatively thereafter, is a deliberate design choice that prioritizes decentralization over throughput. Anyone can operate a full Bitcoin node on commodity hardware, a Raspberry Pi with an external hard drive, which means that the barrier to independent verification is zero for anyone with a modest computing budget. The compromise is low throughput: with a block production period of 10 minutes, Bitcoin processes approximately seven transactions per second on its base layer.

Ethereum has raised its gas limit progressively, effectively shifting the data processing burden to validators. That expansion has supported higher transaction throughput but has increased the hardware cost of running a full node. Ethereum's shift to a proof-of-stake validator-based consensus also raises the economic cost of participation, requiring 32 ETH[4]—or $51,200, according to its price on June 30—to operate a solo validator, a threshold that excludes most retail participants from direct consensus participation. Liquid staking protocols address the retail access problem but introduce new concentration risks.

Solana grapples explicitly with the performance-over-decentralization trade-off. The network’s throughput is tens of thousands of transactions per second through architectural innovations like parallel transaction processing. But those innovations require that validators and nodes operate enterprise-grade server hardware, effectively limiting the validator set to well-capitalized professional operators. Solana intentionally chose that design and, instead of minimizing hardware requirements, has scaled the network with hardware improvements, betting that Moore's Law[5] will expand capacity over time. The result is a network highly performant but less decentralized than Bitcoin or Ethereum, as measured by the number of independently operated validators and the hardware cost per participant.

Investors should remember that different use cases can tolerate different risk profiles. A payment network processing high volumes of small transactions might prioritize throughput. A settlement layer for high-value institutional assets should prioritize decentralization, accepting lower throughput as the cost of stronger store-of-value properties. The blockchain trilemma should cast doubt on claims of unlimited scalability in the absence of centralization.

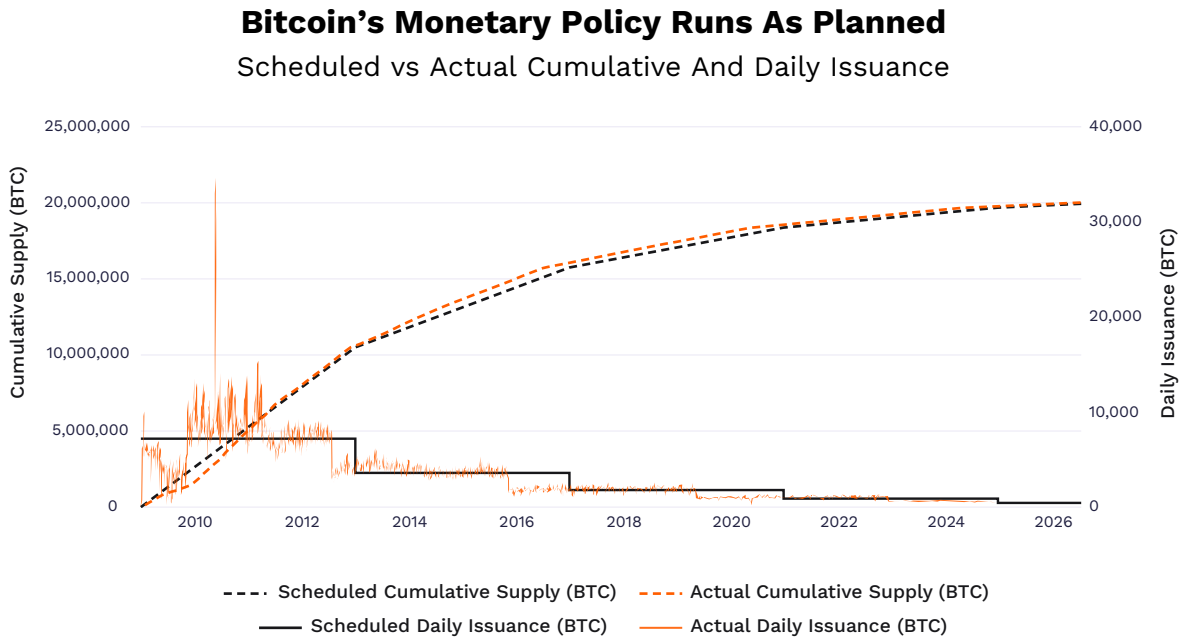
A Note On Decentralization, Property Rights, And Wealth Sovereignty

A network that provides tamper-proof, global, portable property rights competes with central banks, land registries, and sovereign debt—not payment companies. A blockchain controlled by a small consortium of validators, a founding team with upgrade authority, or a treasury with the power to alter supply rules does not provide sovereign property rights. Only sufficiently decentralized networks are built to compete with central banks, land registries, and sovereign debt.

True decentralization enforces three specific guarantees not possible in centralized systems:

1. Decentralization protects against asset seizure
2. Decentralization protects against transaction censorship
3. Decentralization protects against unauthorized changes to the protocol

A network that satisfies all three guarantees ensures the preservation of property rights that, importantly, are enforced by the network's protocol, its mathematical design. As example of the third guarantee, the chart below demonstrates how closely bitcoin's monetary policy has adhered to its initial mathematical design. The black lines assume bitcoin's supply over time, had the design of block time design equaled clock time, or what happened. The two have not deviated measurably from one another beyond market dynamics impacting block demand.



Source: ARK Investment Management LLC, 2026, based on data from Glassnode as of June 30, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Quantitative Measures Of Decentralization

The following sections use quantitative analysis to assess decentralization across Bitcoin, Ethereum, and Solana. This part of the paper is data intensive. We believe that lay readers will find the discussion understandable and enlightening, though the complex data presented may be most meaningful to readers with a background in blockchain analysis. Readers interested in the conceptual-methodological framework of our metrics can reference the summary scoring chart in the Conclusion of this paper.

The following sections address five topics:

- **Node Participation and Accessibility** examines the cost and feasibility of running a full node, the primary mechanism through which any participant can audit the network independently.
- **Decentralization of Validator and Issuer** presents data measuring how block-production power is distributed, who controls it, and how accessible it is to participants—a feature bearing directly on network security.

- **Geographic Concentration** maps the physical footprint of each network, surfacing dependencies that could undermine both auditability and security.
- **Governance Participation and Control** evaluates the processes by which protocol rules are changed and who has the power to influence those changes.
- **Distribution of Ownership** presents data quantifying how token supply is concentrated, with implications for governance power, market stability, and long-term decentralization.

Node Participation And Accessibility

Node accessibility is an important determinant of decentralization, because it governs who can verify the network instead of trusting an intermediary. In practice, the relevant question is not how many nodes exist but how difficult it is for an ordinary operator to run a node. That barrier shapes node count, geographic distribution, infrastructure diversity, and even the dependence of wallets and applications on a small set of providers for network access. Nodes play a key role in validating and relaying blockchain data, enforcing protocol rules, enhancing the robustness of a peer-to-peer network when more people can perform those operations on their own hardware. Ethereum's own documentation makes the same point explicitly, warning that heavy reliance on cloud-hosted nodes can become a single point of failure.[6]

While there are different types of nodes, the key role in this stack is the Full Node, which enables a user to check independently the chain's rules. Full Nodes download chain data, verify blocks and transactions, enforce consensus rules, and relay valid data. Full nodes are present in both Bitcoin and Ethereum. Solana technically does not use a full node, instead relying on non-voting Remote Procedure Call (RPC)[7] nodes to fill a similar role. Pruned Nodes are like full nodes but retain only recent blockchain data to reduce storage costs. Light Nodes are less expensive but conduct independent verification, while Archive Nodes are too heavy for most use cases. The table below compares the four types of nodes and their attributes—Full Node, Light Node, Archive Node, and Pruned Node.

NODE TYPE	WHAT IT DOES	SIGNIFICANCE	COMPARATIVE NUANCES
Full Archive Node [Subset of Full Node]	Stores the blockchain's full historical record. Necessary for full chain reconstruction.	Useful for analytics, explorers, and historical data access.	More storage-intensive than standard full nodes. Bitcoin full nodes effectively function as archive nodes due to lower complexity.

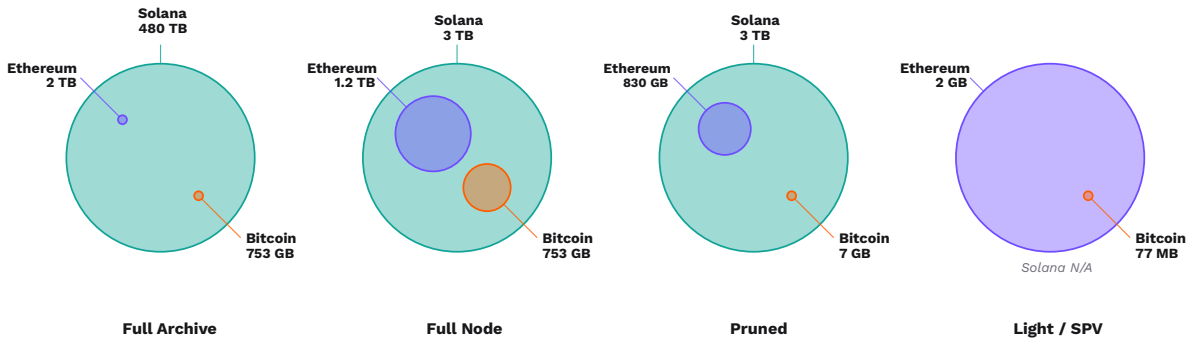
NODE TYPE	WHAT IT DOES	SIGNIFICANCE	COMPARATIVE NUANCES
Full Node	Downloads and verifies blockchain data while enforcing network rules.	Enables independent verification without relying on third parties.	Common across Bitcoin and Ethereum; Solana uses non-voting RPC nodes in a similar role.
Pruned Node [Subset of Full Node]	Verifies the network while storing only recent blockchain data.	Reduces storage requirements while preserving independent verification.	More common on Ethereum and Solana, where blockchain data increases more quickly.
Light/SPV Node	Stores limited data and relies on full nodes for most information.	Makes blockchain access cheaper and easier for wallets and lightweight apps.	Common on Bitcoin and Ethereum: Solana does not support light nodes natively.

From an auditability perspective, Full Nodes are the most important category, because they independently verify network rules and reject invalid data. By refusing to relay invalid blocks or transactions to exchanges, wallets, and applications, they create economic pressure for block producers to follow consensus rules. Other node types either depend on Full Nodes for verification or are too resource-intensive to serve as the primary verification layer for most operators. As a result, Full Nodes must be accessible and small enough for ordinary operators to run them.

The chart below illustrates the differences in storage requirements by each node type across the three networks.

Chain Size by Node Type — Bubble View

Per node type, smaller circles nest inside the largest, offset so each stays visible; scaled linearly within each type



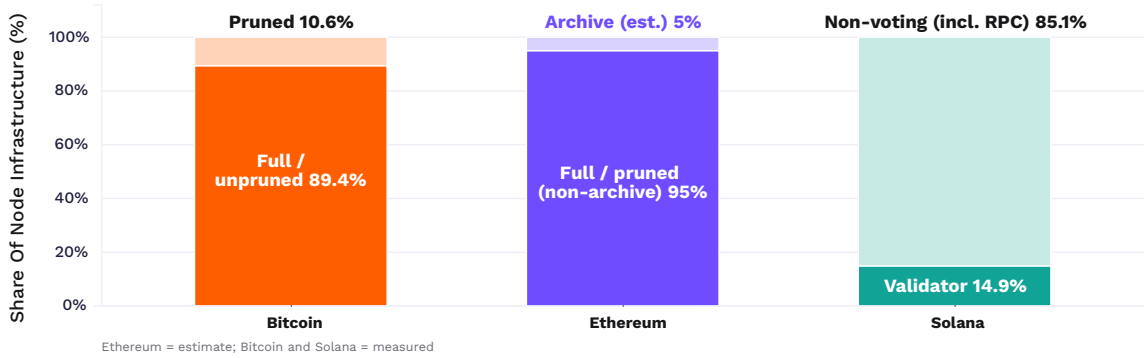
Source: ARK Investment Management LLC, 2026, based on data from ycharts.com, erigon.tech, geth.ethereum.org, cherryservers.com, getblock.io, and rpcfast.com as of July 12, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

While not to scale, a closer look suggests a wide spectrum storage demands across the node types. Archive Nodes are the most storage-intensive, followed by Full Nodes and Pruned Nodes, while Light Nodes require minimal resources. Bitcoin is a notable exception, as the storage demands of its Archive and Full Nodes are almost the same because the network's architecture is simple relative to that for smart contract platforms. These resource requirements ultimately will shape the distribution of node types across each network. Examining this distribution offers additional insight into the accessibility of network verification.

The chart below displays the breakdown of node type across each network

Node-Type Breakdown By Chain

Taxonomies differ by design across chains



Source: ARK Investment Management LLC, 2026, based on data from Bitnodes.io, Ethereum.org, rockertpool.net, ethstaker.org, geth.ethereum.org, solanacompass.com, validators.app. Bitcoin data as of April 27, 2026. Ethereum and Solana data as of July 10, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Traditional Full Nodes dominate both Bitcoin and Ethereum, while Solana relies on RPC Nodes as shown in the chart above. While Bitcoin/Ethereum Full Nodes participate directly in the peer-to-peer validation and block propagation that underpins consensus, Solana RPC nodes operate outside validator consensus and primarily serve read/query functionality. Both nodes verify independently block validity, but traditional Full Nodes shape the canonical chain while RPC nodes cannot.

The cost of running a Full Node is the best benchmark in terms of which to compare node accessibility across networks. The most important variables impacting cost are storage and random-access memory (RAM). While other metrics like central processing units (CPU), bandwidth, and uptime play a role, the combination of storage and RAM offers the estimate that captures both the total chain history and current operational requirements.

The cost of running a Full Node and an Archive Node across each network—direct proxies for the accessibility of independent auditability and for the cost of chain reconstruction—is summarized in the chart below.

Full Node & Archive Node Costs Across Each Network

Full node (operational, current state)

COST LINE	BTC	ETH	SOL
Storage (full node)	$75 (1 TB NVMe)	$165 (2 TB NVMe)	$2,178 (3 TB ent.)
RAM	$124 (8 GB DDR5)	$375 (32 GB DDR5)	$18,300 (512 GB ECC)
Compute + ancillary	$30-90	$170-190	$1,000
Total hardware	$289	$730	$21,478
Class	Consumer PC	Mid-range server	Enterprise server

Full archive chain (entire history)

COST LINE	BTC	ETH	SOL
Upfront hardware	$289	$730	$48,000
Growth cost / yr	~$35	~$260	~$10,600
5-year TCO (NPV @ 5%)	$441	$1,856	$93,887
Note	archive = full node	Geth path-based ~2 TB	history offloaded to providers

Note: TB NVMe: terabytes of NVMe (Non-Volatile Memory Express). TB ent.: terabytes of enterprise-grade storage. GB DDR5: gigabytes of DDR5 system memory. GB ECC: gigabytes of ECC (Error-Correcting Code) memory. 5-yr TCO (NPV @ 5%): total cost of ownership over 5 years, discounted to present value at a 5% annual rate. Note: Solana validators and RPC nodes do not store the full chain history natively; historical data is typically offloaded to external providers, making the archive cost here an estimate for reconstructing that history rather than a standard operational requirement. Source: ARK Investment Management LLC, 2026, based on data from tomshardware.com, counterpointresearch.com, networkworld.com, bacloud.com, trendforce.com, ycharts.com, newegg.com, www.atpinc.com, semiconductor.samsung.com, jito-labs.gitbook.io/firedancer, and jumpcrypto.com as of July 12, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

On that basis, the three networks are on a spectrum. Bitcoin is the least expensive environment for both independent verification and chain reconstruction, as its less

complex design suggests that running a full node is equivalent to a Full Archive Node. Ethereum is more complex, as its Full Nodes require both an execution client and a consensus client, while executing and storing the state associated with smart contract activity. When reconstructing the entire Ethereum blockchain by running an Ethereum Archive Node, the complexity becomes even more apparent. Solana is the most demanding of the three, as it pairs the smart contract capabilities of Ethereum with higher performance: independent verification and chain reconstruction create a much higher cost structure than those for Ethereum and especially Bitcoin.

Both chain reconstruction and network verification follow the same pattern: the cost aligns with the complexity and performance of the network. In practical terms, Bitcoin offers the lowest-cost path to independent verification, Ethereum sits in the middle, and Solana imposes the highest hardware burden. By design, Solana does not optimize for low node costs. The network scales through hardware, based on the premise that hardware performance improves over time.

Even though they run full nodes, miners and validators are evaluated separately. While Bitcoin miners and Ethereum/Solana validators produce blocks or attestations, decentralization is anchored by the independent verification of blocks. If block production is concentrated but verification is broad-based and accessible, the network can be decentralized. If verification becomes expensive and concentrated, however, the auditability of the system will become more dependent on small group of participants and less decentralized.

Decentralization Of Validator And Issuer

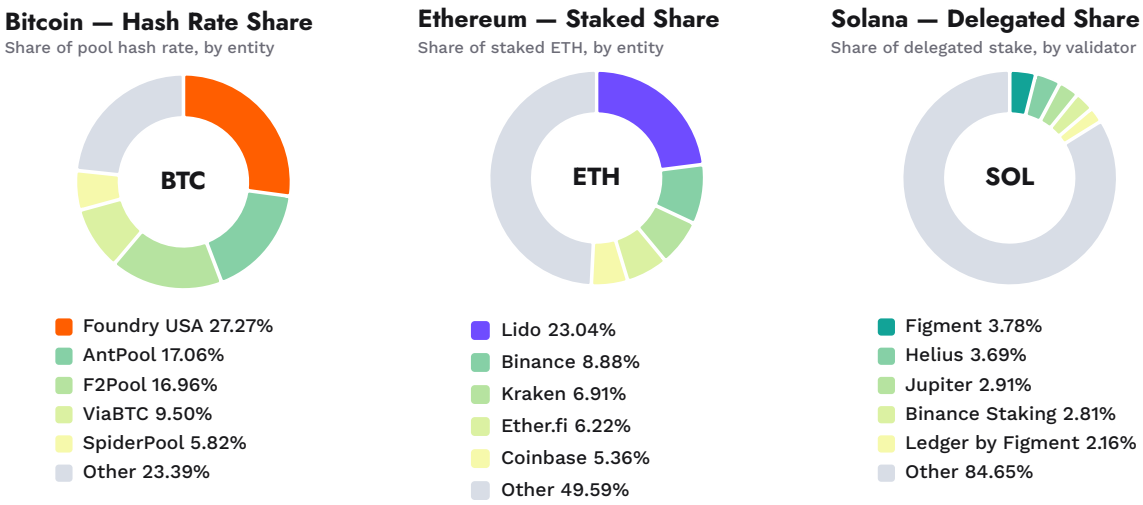
Miners and validators are responsible for producing blocks and ordering transactions. While full nodes enforce the network's rules, miners and validators control the operational layer of block production, making their distribution a core component of both security and decentralization. The more distributed their influence, the harder to corrupt the network. In practice, decentralization at this layer is less about the number of participants than about the distribution of block production power, the aggregation of block production through pools or shared infrastructure, and the entry costs for new participants.

The most useful proxy is the distribution of control over block production. For Bitcoin, that control is hash rate. For Ethereum and Solana, it is stake weight. Reward distribution is downstream, as rewards generally flow to whoever controls the underlying resource. Key is the concentration of block production. This manifests in the share of hash rate, stake held by the largest entities, and the number of entities necessary to reach critical thresholds such as 51% of Bitcoin hash rate or ~33% or

~67% of stake on proof-of-stake systems. A network with many participants can be concentrated operationally if a small number of participants control most of the block production.

To illustrate the concentration of hash rate across Bitcoin and the concentration of staking on Ethereum and Solana, please see the chart below.

Distribution Of Block Production Influence Across Bitcoin, Ethereum, & Solana

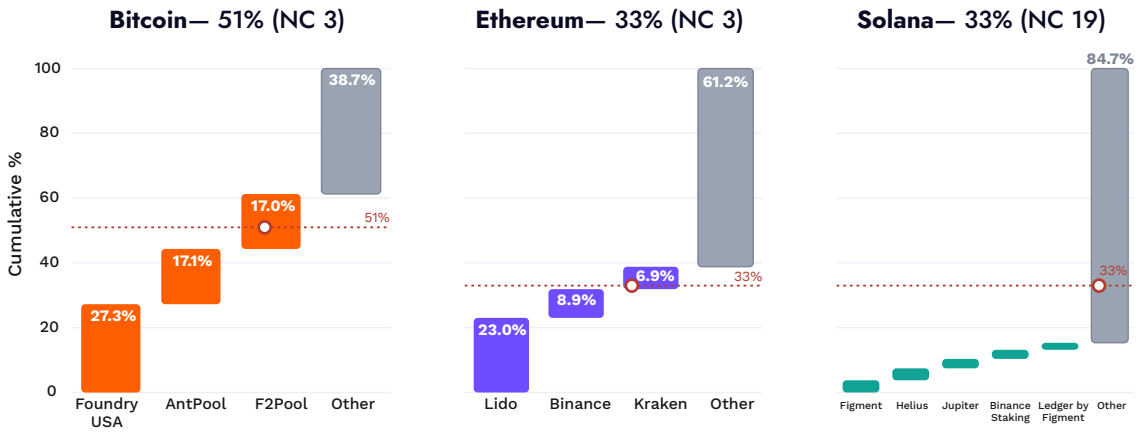


Source: ARK Investment Management LLC, 2026, based on data from hashrateindex.com, explorer.rated.network, validators.app as of July 10, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

The percentage of independent actors necessary to meet the critical thresholds necessary to alter or disrupt the ledger is 51% on the Bitcoin network and 33% on both Ethereum and Solana, as shown below.

Critical Thresholds Across Bitcoin, Ethereum, & Solana

How many entities must collude to cross each chain's control threshold — that minimum count is the Nakamoto Coefficient (NC)



Source: ARK Investment Management LLC, 2026, based on data from mempool.space.com, explorer.rated.network, validators.app as of July 9, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Surprisingly, Bitcoin and Ethereum hit their critical thresholds with only three entities, while Solana requires 20 entities to do the same. That said, an important nuance in the data is that Bitcoin and Ethereum are heavily influenced by pools. Because of its architecture in a delegated-proof-of-stake (DPoS) network, Solana does not have those influences to the same extent.

Because solo block rewards are inconsistent, most Bitcoin miners do not mine independently. Instead, they contribute hash rate to mining pools to smooth earnings. For that reason, the network can look more concentrated than is the underlying hardware ownership, but miners can redirect hash rate to other pools seamlessly. That said, pools matter because typically they specify a template for block construction and therefore influence over transaction inclusion and ordering.

Ethereum's dynamic is similar. Liquid staking pools provide access to staking and preserve a degree of user sovereignty, but they also aggregate economic weight, which can create concentration at the level of governance, operations, or shared infrastructure. Lido, for example, aggregates stakes across node operators instead of acting as a single validator. While running independent infrastructure, the node operators coordinate through Lido's governance and staking framework, creating a layer of shared dependency. In contrast, Solana delegation is native to the network instead of an overlay. Token holders delegate stake directly to validators, so "pooling" is embedded in the design.

Additional Details on Critical Thresholds and Block Production Distribution

METRIC	BTC	ETH	SOL
Threshold	51% Hash rate	33% stake	33% stake
Nakamoto coefficient	3	3	19
Top entity	Foundry 27.27%	Lido 23.04%	Figment 3.78%
Network hash rate / stake	945.03 EH/s (Glassnode 90d SMA)	40.3M ETH (~33%)	~428M SOL (~68% of total supply)
Prior NC (Mar 2026)	2	3	18

Note: EH/s: exahashes per second (10^18 hashes/sec), a measure of network or miner computing power. OPEX: operating expenditure, ongoing costs to run operations. MW: megawatt, a unit of power (energy per unit time). TWh: terawatt-hour, a unit of energy (power sustained over time). APR: annual percentage rate, the yearly rate of return or interest before compounding. PoW: Proof-of-Work, a consensus mechanism where participants expend computational effort to earn the right to add blocks to a blockchain. Source: ARK Investment Management LLC, 2026, based on data from hashrateindex.com, cryptominerbros.com, asicminervalue.com, validatorqueue.com, solanacompass.com, glassnode.com, stakingrewards.com, datawallet.com, helius.dev as of July 15, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Cost is another major consideration in the concentration of a network's block production. Cost determines whether validator or miner participation is truly open, which impacts security since higher costs-of-entry concentrate block production among fewer, better-resourced operators. Bitcoin's operational barriers are the clearest cut: mining requires specialized application-specific integrated circuit (ASIC) hardware, access to cheap power, and the ability to manage hardware at scale, in addition to running a full node to stay synced to the network. These requirements favor industrial operators with energy source advantages.

Ethereum's barrier is different. A solo validator must post 32 ETH and run a full node—both an execution client and a consensus client—which requires meaningful capital but little hardware. The operational burden is real, but lower than Bitcoin's physical mining footprint.

With no fixed staking threshold, Solana's barrier to entry can be lower, but its operating costs are much higher given the hardware, bandwidth, performance

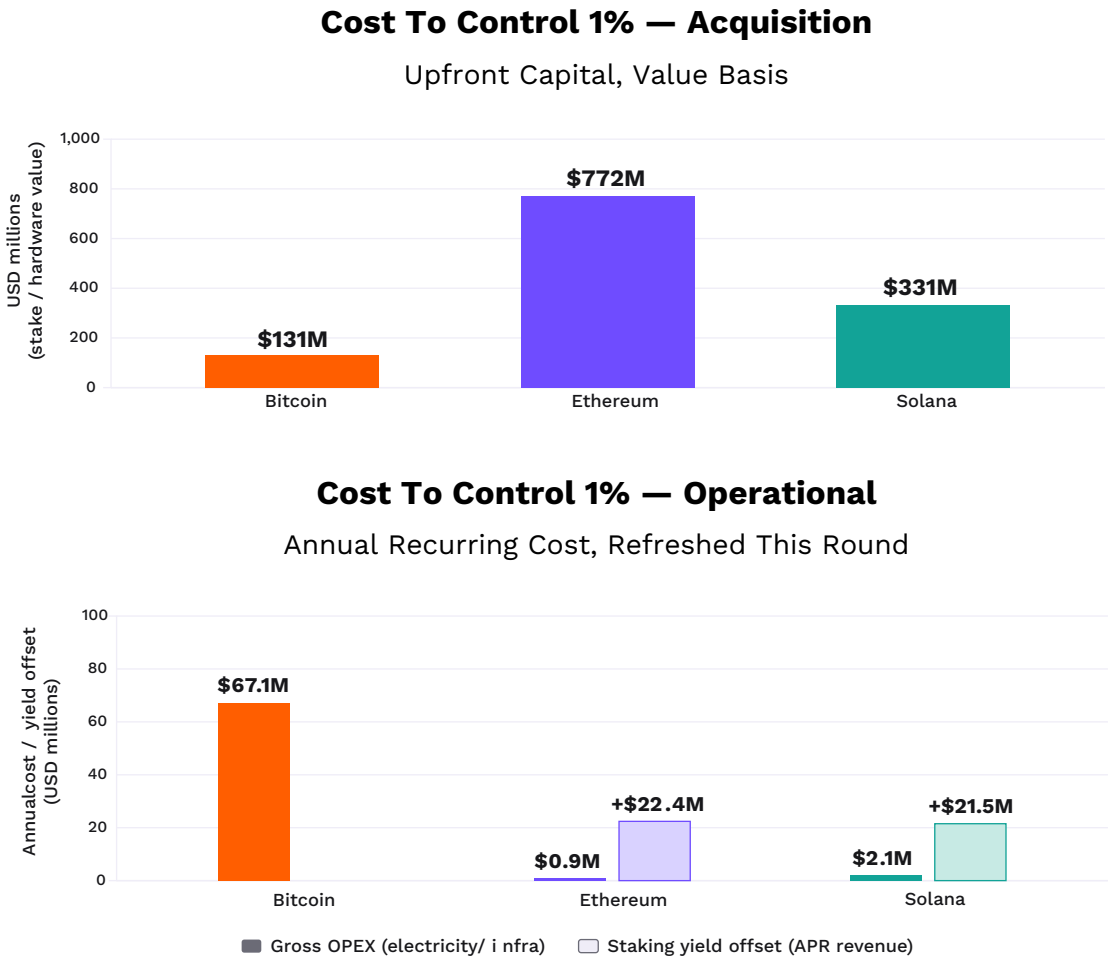
requirements, and vote transaction costs. In practice, its market-driven threshold for economic viability typically requires validators to stake ~50,000-100,000+ SOL to operate sustainably, with competitive validators often managing stakes upwards of 1 million SOL. Typically, the validator does not bear the entire burden of accumulating the stake, as Solana's delegation-based system allows them to attract stake from external delegators. In other words, success depends both on capital and on validator reputation.

A comparison of the upfront and recurring costs of operating a miner/validator controlling 1% of Bitcoin, Ethereum, or Solana, as of June 30, 2026, is shown in the table below.

Cost Associated With Controlling 1% Of Each Network

METRIC	BTC	ETH	SOL
1% of network	9.45 EH/s	403,000 ETH	4.28M SOL
Reference price (Jul 15 close)	n/a	$1,916.33	$77.22
Capital to control 1%	~$131M hardware (35,000 S21 XP @ ~$3,749)	~$772M stake	~$331M stake
Prior basis (draft)	9.49 EH/s	372,000 ETH	3.9M SOL

Depicted graphically below are the upfront costs and operational costs necessary to control 1% of the respective networks as of June 30, 2026.



Source: ARK Investment Management LLC, 2026, based on data from hashrateindex.com, asicminervalue.com, validatorqueue.com, solanacompass.com, glassnode.com, stakingrewards.com, datawallet.com, and helius.dev as of July 15, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Bitcoin's operational and recurring costs are the highest among the three networks, as proof-of-work (PoW) makes mining computationally and energy intensive. The upfront cost involves acquiring enough hardware to generate 1% of the Bitcoin network's hash power.

Although Ethereum enjoys the lowest operational and recurring costs, its upfront costs are the highest, as the proof-of-stake (PoS) consensus mechanism requires an operator to access 1% of the entire supply of staked ETH.

Solana falls in the middle, with the second highest upfront costs based on its stake-based consensus mechanism. Solana operational and recurring costs also are second highest given its high-performance demands.

The high upfront cost associated with operating on Ethereum and Solana are a function of the massive stake necessary to control 1% of the network. That stake

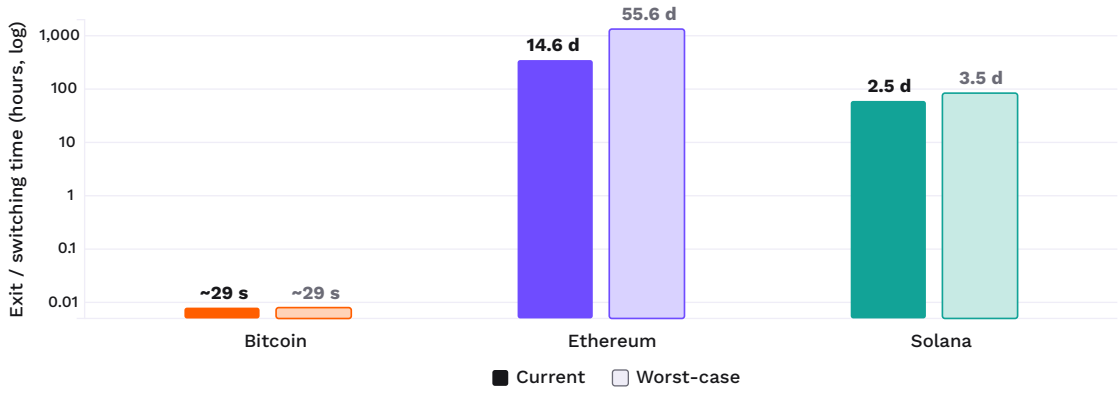
generates a recoverable native yield based on honest validator behavior and sufficient uptime. In contrast, Bitcoin miners rely on bitcoin fees and issuance as rewards while paying the operating costs and experiencing hardware depreciation associated with their mining.

Today, most people cannot become miners or validators on networks like Bitcoin and Solana. Ruthlessly competitive in the face of high operational costs, these networks are geared toward large entities with sophisticated business strategies. While Ethereum's capital hurdle of 32 ETH is not trivial, its operational costs are more manageable after clearing the upfront costs. Decentralization weakens when participation requires either large amounts of capital or highly specialized infrastructure.

Validator and miner mobility is another consideration in the decentralization of a network. The speed at which validators or miners can exit a network impacts the security tradeoff between operator autonomy and network stability. The chart below shows the estimated time to exit a 1% position of either stake or hash rate on each network.

Time To Exit 1% Of Network

Current vs Worst-Case, By Chain



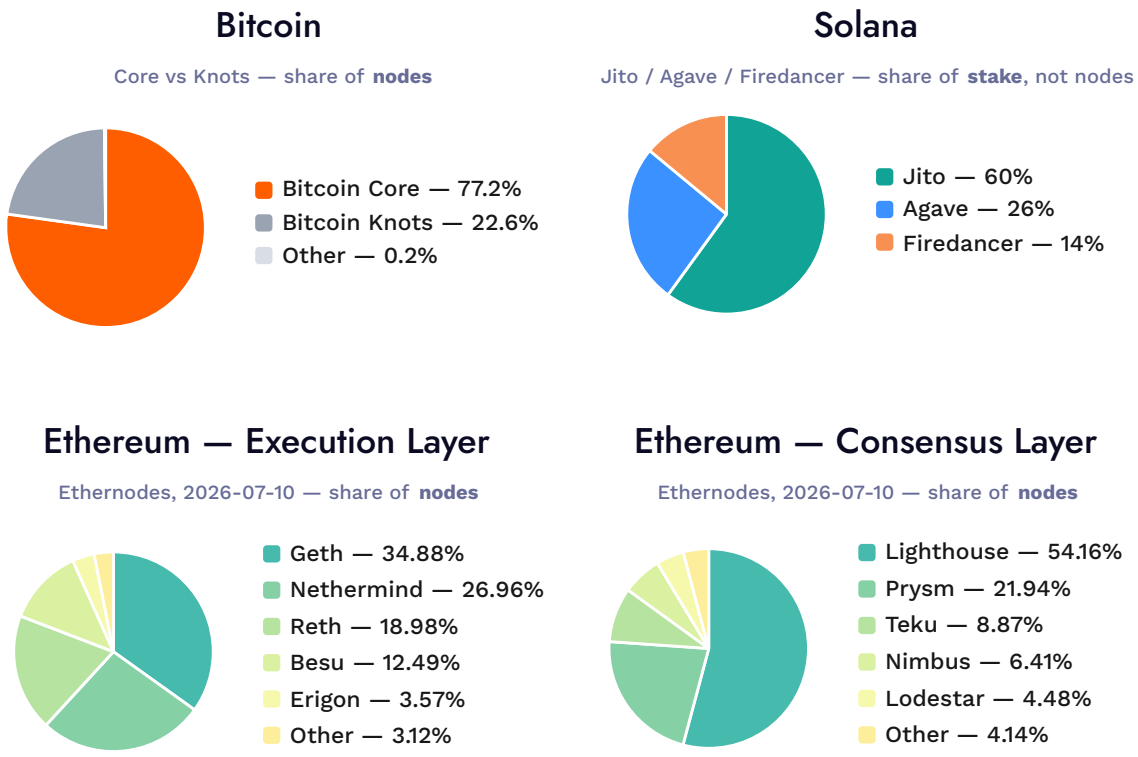
Note: In the chart above, "s" stands for seconds and "d" stands for days. Source: ARK Investment Management LLC, 2026, based on data from hashrateindex.com, validatorqueue.com, and solanacompass.com as of July 10, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Bitcoin's participation is the most fluid, with no entity forced to secure the network: its hash rate can drop 1% in ~30 seconds, as a miner simply turns off hardware. In contrast, Ethereum and Solana impose algorithmically adjusted times necessary to unstake, currently ~17 days and ~2.5 days, respectively. Under stress, Ethereum's exit window can stretch significantly, its worst-case reaching ~63 days. At first glance, faster exits seem better for decentralization: lower switching costs, improved mobility,

and voluntary validator participation. That said, longer exit periods can stabilize the network, preventing sudden, cascading withdrawals during market shocks or coordinated attacks and giving infrastructure operators, developers, and other ecosystem participants time to adapt and respond. The tradeoff is between accessibility and resilience: frictionless exit maximizes autonomy, while delayed exit protects collective security.

Client diversity another consideration in gauging the security of a network. Diversity determines the resilience of a network in the face of software failure, which is relevant to both auditability and security: independent codebases verifying the same rules reduce the probability of a single point of software failure impacting all network infrastructure operators.

Capturing diversity, the charts below delineate the share of each client implementation across the three networks.



Source: ARK Investment Management LLC, 2026, based on data from coin.dance, Ethernodes.org, wenfiredancer.com as of July 10, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

By design, Bitcoin is the most ossified network, so concentrated client usage is a risk, though manageable, as a lower frequency of upgrades means that the network

typically is using the same provenly reliable software. Ethereum's complexity makes client diversity more important, especially because its execution and consensus clients are changing constantly. When upgrading software, a bug in a dominant client can impact a large part of the network: diversity of different clients among infrastructure operators reduces the chance that a single software failure will become systemic. Historically, Solana has faced greater correlated failure risk, given closely related client implementations like Jito and Agave. Efforts to introduce additional clients, like Firedancer, are improving its resilience by reducing dependence on closely correlated implementations. Client diversity is an important complement to economic decentralization, not a substitute for it.

Taken together, these metrics provide a clearer view of validator and miner decentralization than any single variable. The distribution of hash rate or stake captures block production power, while pooling and delegation reveal power aggregation. Costs determine access to participation; exit delays impact operator mobility; and client diversity reflects the network's ability to withstand failures. Measures like the number of entities required to reach control thresholds are useful but require interpretation, as staking pools and shared infrastructure can mask underlying coordination. An additional nuance, particularly for Ethereum and Solana, is the growing role of maximal extractable value (MEV), or the equivalent of pay-for-order-flow, and block-building like Flashbots, Titan Builder, Jito, and Harmonic, which can introduce shared infrastructure dependencies and centralization that concentrate influence beyond visible validator ownership.

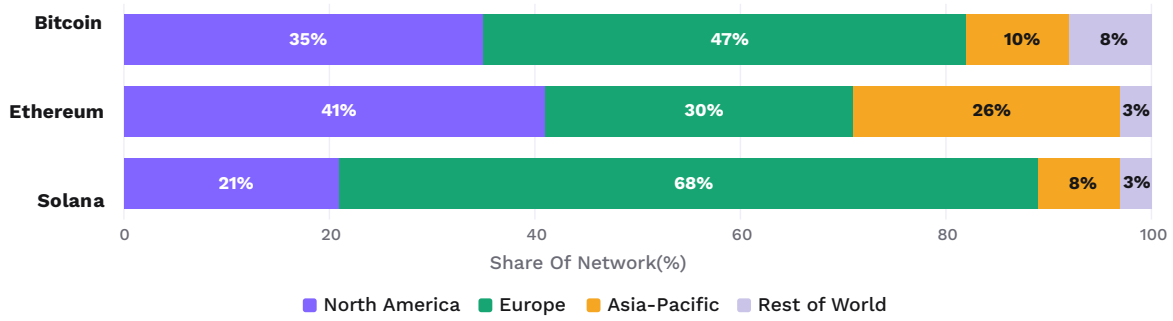
Also important to note is the role of economic incentives in maintaining network integrity, such as slashing in PoS and energy expenditure in PoW. Notably, Solana does not enforce native slashing, relying on offchain social coordination instead. That said, several Solana improvement proposals like SIMD-0204 and SIMD-0212 are progressing toward programmatic, onchain slashing. Ultimately, decentralization at the block production layer cannot be measured just by the number of participants. Understanding the vectors of operational control, as well as the aggregation, fluidity, and resilience of those vectors is essential.

Geographic And Infrastructure Concentration

The geographic distribution of network infrastructure adds another dimension to decentralization, impacting security (jurisdictional resilience against coordinated coercion) and auditability (geographic latency impacting the competitiveness of a verifying node). The chart below shows the regional concentration of infrastructure across each of the three networks.

Regional Concentration

Regional split of network infrastructure, aligned to the project's D6 dataset, as of 2026-07-12.



Source: ARK Investment Management LLC, 2026. Solana data based on data from helius.dev as of November 18, 2024. All other data based on data from bitnodes.io, ethernodes.org, etherscan.io, as of July 12, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

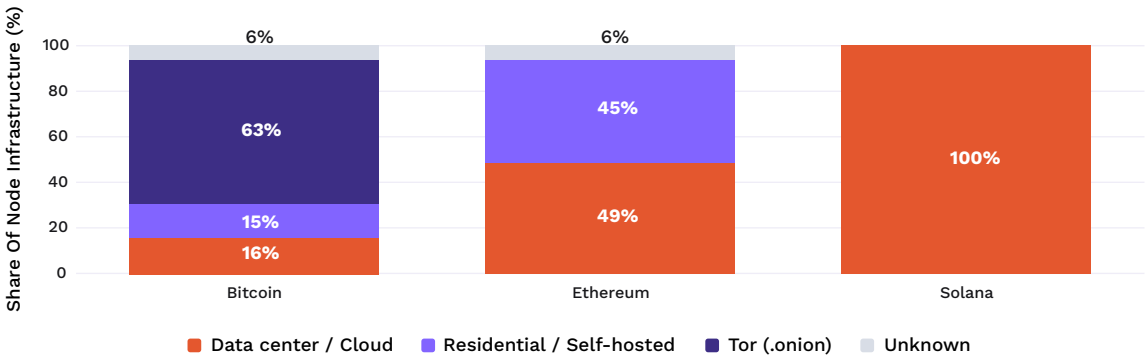
Bitcoin's node footprint is the most evenly spread, split 35% North America and 47% Europe with meaningful representation in Asia-Pacific and the rest of the world. Ethereum follows a similar pattern, with a slight tilt toward North America at 41% and Europe at 30%. Solana is the clear outlier, with 68% of its infrastructure concentrated in Europe and only 21% in North America. The skew is largely a product of early network economics: Solana's high-performance architecture complemented the cheap bare-metal data centers available in central Europe. Solana’s clustering has created tradeoffs, particularly marginal latency disadvantages in execution for participants outside of Europe. Efforts are underway to address the situation, notably DoubleZero's initiative to incentivize validator expansion into Asia and other underserved regions.[8]

Hosting environments also impact decentralization. Nodes hosted in residential environments or routed through Tor[9] are more difficult to coordinate, censor, or disrupt physically, because of their geographic and operational distribution across independent operators. In contrast, infrastructure concentrated in commercial data centers or cloud providers might offer superior performance and reliability, but they risk greater platform concentration and identifiable points of failure.

The chart below displays the distribution of infrastructure by hosting environment across the three networks.

Hosting Environment

Data center vs. residential vs. Tor share of node infrastructure.



Source: ARK Investment Management LLC, 2026, based on data from bitnodes.io as of April 27, 2026. Al other data from ethernodes.org, validators.app as of July 11, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Bitcoin is the least dependent on centralized hosting providers, with 16% of its infrastructure running in data centers and 63% of its nodes operating behind Tor. As a result, its network is the most resistant to disruptions from the host. Ethereum is more exposed, with ~49% of its nodes hosted by cloud providers and 45% self-hosted. That said, Amazon Web Services (AWS) hosts 20% of its nodes, introducing moderate concentration risk.

Solana operates at the opposite end of the spectrum, with ~100% of its infrastructure running in data center environments, by design. The hardware, bandwidth, and performance requirements needed to run a Solana validator or RPC node make residential or self-hosted operations impractical, pushing the network toward professional hosting. While enabling Solana's throughput, the network's physical infrastructure is dependent on a more privileged group of hosting providers. Solana considers its reliance on data centers a feature, not a bug, as moving data at the speed and volume its clients demand requires dedicated hardware in hundreds of data centers globally.

The table below provides a snapshot of both geographic and infrastructure concentration, highlighting key risks—particularly for auditability and security, since a compromised or shuttered hosting provider can reduce verification capacity and disrupt block production simultaneously.

Hosting Environment Snapshot Across Bitcoin, Ethereum, and Solana

RISK DIMENSION	BTC	ETH	SOL
Top country share	US 31.25%	US 38.96%	Germany 23.55% (stake)

RISK DIMENSION	BTC	ETH	SOL
Top 3 countries	49.6%	67.5%	55.3% (stake)
Top hosting provider	Hetzner 3.8%	AWS ~20%	TeraSwitch 30.23% (stake)
Top 2 providers	~5.3%	~27%	~35.7% (stake, OVH now #2)
Data center ratio	~16%	~49% (EL)	~100%
Tor / anonymous	62.99%	Negligible	Negligible
Hosting Nakamoto coeff.	residential-dominant	moderate	data-center-dominant

Source: ARK Investment Management LLC, 2026, based on data from bitnodes.io as of April 27, 2026. All other data from ethernodes.org, validators.app, etherscan.io, as of July 11, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

These metrics reinforce the broader pattern: Bitcoin's low-cost, lightweight design produces the most distributed and host-resilient infrastructure; Ethereum's geographic diversification is reasonable, with moderate cloud dependency; and Solana's performance-first architecture has necessitated concentration in both geography and hosting that raises the risk of points of failure.

Governance Participation And Control

The decentralization of a network's governance is measured not by developer activity but both by the processes through which protocol rules are changed and by the number of independent entities that can influence those changes. For that reason, metrics like "ecosystem wide commits" become a poor proxy for decentralization. The cleaner lens is how core network development is coordinated and network-level signaling, which refers to changes that govern node behavior or show miner/validator preference when implementing changes.

Bitcoin is the most straightforward case of decentralized governance but also the most disordered. Bitcoin has no ecosystem leader responsible for network development. The protocol has a formal proposal mechanism, Bitcoin improvement proposals (BIPs), but the process itself can be disjointed, as it requires disparate authors to build community consensus and document dissent. That process impacts certain features of the network like block production, as illustrated by the SegWit

upgrade (BIP 141).[10] After the change, even though miners could continue to produce blocks however they saw fit, because the majority of nodes coordinated around an agreed-upon change to the network's software, the network rejects blocks produced that do not comply. The reaction to BIP141, for example, resulted in Bitcoin Cash, as the minority of nodes that refused to adopt the network's changes saw their blocks split from the canonical Bitcoin blockchain to form a separate SegWit-free fork of the chain with increased block size limits. Due to Bitcoin's inactive upgrade cadence and thus lack of client diversity, the most relevant Bitcoin upgrades are to Bitcoin's main node software, Bitcoin Core, typically initiated through BIPs. Additionally, specific governance issues can leverage network-level signaling, allowing node operators to express their preferences by implementing different client software selectively. This was most recently exhibited in the Bitcoin Core versus Knots controversy surrounding Bitcoin Core v30[11]—an indication of network sentiment toward changes and ecosystem direction. As a result, important decisions and direction changes can take years to materialize, as no central entity coordinates the process.

Ethereum's governance is coordinated through All Core Devs (ACD) calls that bring together contributors from many organizations across Ethereum's execution, consensus, and application layers. Ethereum is explicitly multi-client: a node runs separate execution and consensus clients, with client diversity a core part of network resilience. These factors make vital to the network's trajectory the recurring opportunity for organization and alignment across disparate ecosystem participants, which ACD provides. Since its inception, Ethereum's governance process has somewhat followed a central coordinator, particularly the Ethereum Foundation. Ethereum Foundation prefers to take a backseat role, however, making Ethereum's governance deliberative and distributed, in exchange for a slow and unwieldy process. In terms of network-signaling, validators do not usually cast a formal on-chain vote on upgrades. Instead, they shape outcomes by choosing which software to run (client to use). In some cases, they signal directly in blocks, as with gas-limit adjustments during block production.

Solana runs a more top-down, organized coordination process that allows it to pivot faster. The Solana Foundation leads the process with a hands-on approach to growing and supporting the network. Guided by a concentrated set of infrastructure providers and a venture-capital-inspired culture, Solana's execution is highly effective. Solana's validator-client landscape is one reason, as historically a small group dominated by Agave/Jito has enabled swift network fluidity. Only recently has the diversity brought by Firedancer emerged as an alternative implementation.

On May 2, 2025, the Solana Foundation announced that it had rallied key ecosystem leaders to patch a zero-day bug in the network quietly, reflecting both the effectiveness and the concentration of Solana's leadership. This episode offered an

example of Solana's historically fluid governance. As for network-signaling, some of Solana's most revealing governance data have come from validators signaling for Solana improvement proposals (SIMDs), the formal path for core changes. In the case of SIMD-228—a proposal to lower the Solana inflation rate—910 validators representing 74% of staked SOL participated,[12] and, despite major ecosystem players pushing for the proposal, it failed to clear the required threshold of two-thirds of the participating staked SOL. These two examples highlight both sides of Solana's governance design: fewer major implementation centers than Ethereum, but enough ecosystem input and validator independence to block a public, high-profile change.

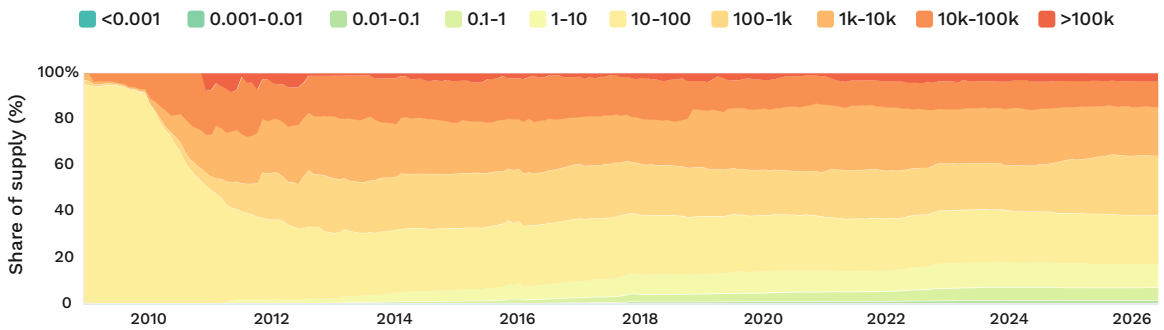
Distribution Of Ownership

The distribution of token ownership is one of the clearest indicators of a network's decentralization, revealing who holds structural power over the network. In proof-of-stake (PoS) systems, validators are selected based on the amount of tokens they stake, so token ownership translates directly into validator power—suggesting that ownership can reinforce concentrated control over time. Shaping the degree of control is a network's consensus mechanism and its initial token distribution.

Proof-of-work (PoW) networks like Bitcoin distribute ownership naturally and more broadly over time. Miners face ongoing operational costs for hardware and electricity, forcing them to sell portions of their rewards into the market and creating continuous token distribution that prevents long-term accumulation. In its early years, Bitcoin's distribution was organic, as anyone with a CPU could mine. Bitcoin's distribution is the most dispersed among the big three, with ~20-30% of supply held in each of three medium sized bands, as shown below.

Bitcoin Supply Distribution

Monthly share of supply by wallet-size cohort, 2009-2026



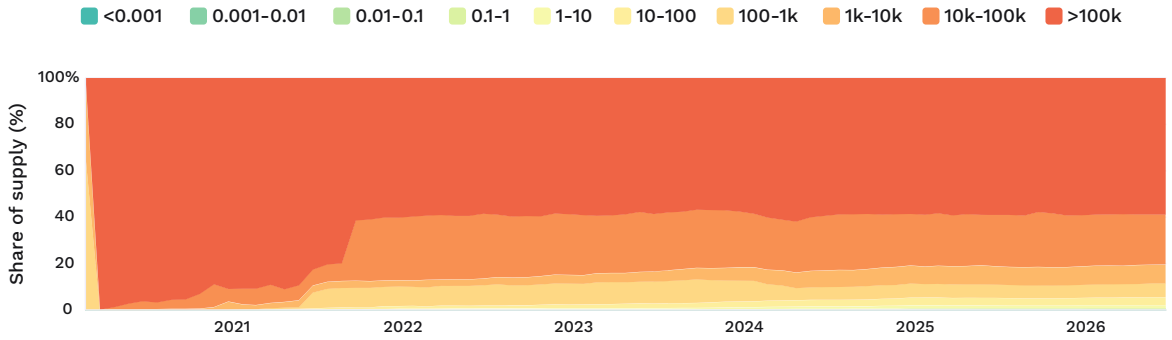
Source: ARK Investment Management LLC, 2026, based on data from glassnode.com as of July 1, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

PoS networks operate differently. Staking rewards flow primarily to existing holders, and because validators face few external costs, ownership tends to compound rather than redistribute. As a result, the network's initial token allocation is quite important, as early concentrations can strengthen over time. Solana's supply distribution is a case in point: its initial distribution was heavily venture-backed, and its delegated proof-of-stake model reinforced that concentration through staking rewards that compounded. While some large validator wallets can represent delegated stakes from a number of entities, ownership remains structurally more concentrated than in PoW systems.

Solana's distribution is the most concentrated among the big three, with ~59% of supply held in the largest band and ~80% held between the top two.

Solana Supply Distribution

Monthly share of supply by wallet-size cohort, 2020-2026

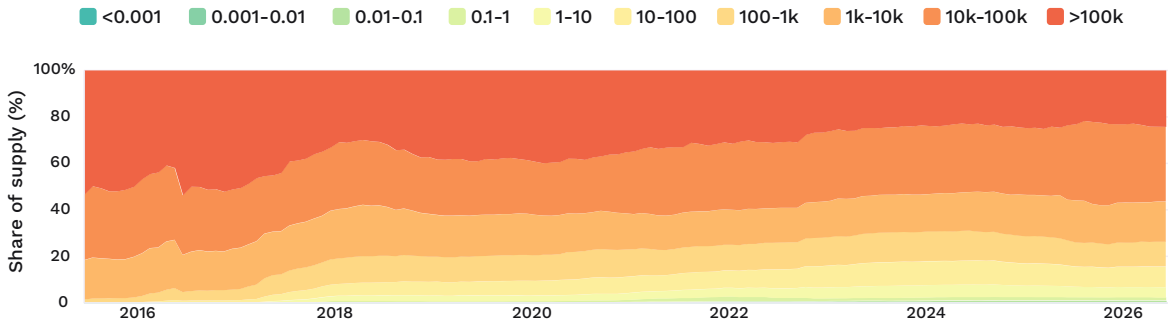


Source: ARK Investment Management LLC, 2026, based on data from glassnode.com as of July 1, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Once again, Ethereum is positioned between the two. Although now operating under PoS, Ethereum spent roughly seven years under PoW before transitioning with the Merge in 2022. During that period, mining-driven distribution helped spread ETH ownership more broadly before staking dynamics took hold. As a result, Ethereum's ownership structure is more concentrated than Bitcoin's but more distributed than networks that launched directly into PoS. With ~23% and ~33% of supply held in each of the top two bands and 10-20% of supply held in each of the two medium sized bands, Ethereum's distribution is moderately decentralized, as shown below.

Ethereum Supply Distribution

Monthly share of supply by wallet-size cohort, 2015-2026



Source: ARK Investment Management LLC, 2026, based on data from glassnode.com as of July 1, 2026. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

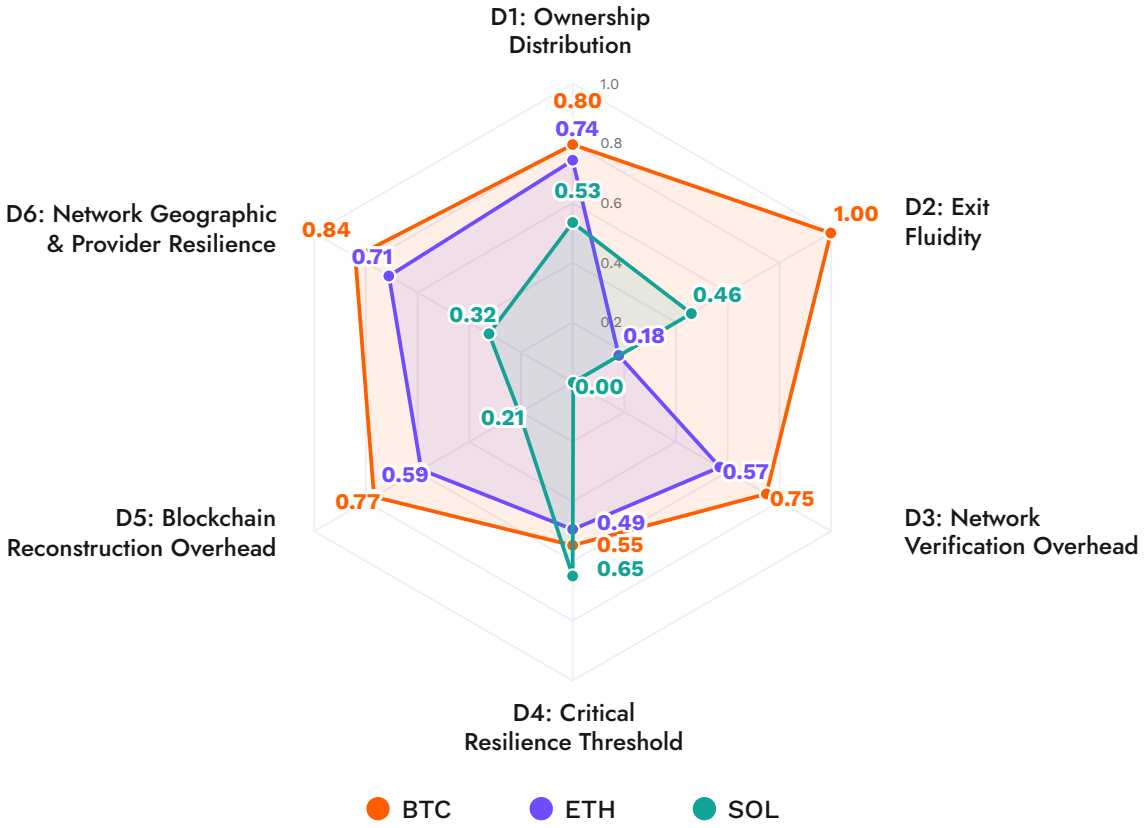
4.0 Conclusion

No blockchain optimizes on every dimension of decentralization. Bitcoin scores strongest in auditability, ownership distribution, and geographic resilience, reflecting the long-term effects of proof-of-work and low-cost network verification. Ethereum occupies a middle ground across most categories, balancing broader distribution and client diversity with greater operational complexity. Solana prioritizes performance and coordination speed, resulting in higher infrastructure requirements and greater ownership concentration, while still demonstrating meaningful validator participation and governance independence. Taken together, the metrics make clear that no network leads across every design dimension but instead embodies tradeoffs that serve each community.

The chart below reflects each network's score across the four design dimensions introduced in the qualitative section—auditability, security, governance, and ownership and distribution—using the findings in the quantitative section above to calculate the values.

Decentralization Scores — All Six Dimensions

D1-D6, current as of July 2026



Source: ARK Investment Management LLC, 2026, based on data from a range of external sources as of July 27, 2026.[13] For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security or cryptocurrency.

Note to the technical reader: for a full description of the math and methodology behind the scoring above, please see our Appendix.

Endnotes

1. “Finality” is the point at which a transaction or block is considered irreversible absent a major consensus failure.

2. Proof-of-Work (PoW): a consensus mechanism in which participants (miners) expend verifiable computational effort to earn the right to add a block, making block production costly to fake but cheap to verify. Proof-of-Stake (PoS): a consensus mechanism in which validators lock up the native token as collateral that can be slashed for misbehavior, with staked amount determining participation in block proposal and validation.

3. ETH is the native cryptocurrency and utility token of the Ethereum network, also known as “ether”. Staked ETH: ETH locked up by a participant to run a validator and take part in Ethereum's proof-of-stake consensus. This includes proposing blocks and attesting to them. Activating a validator requires 32 ETH.

4. https://www.coingecko.com/en/coins/ethereum

5. Moore's Law is the observation that the number of transistors packed onto a microchip doubles roughly every two years, while the cost of computers drops.

6. https://ethereum.org/developers/docs/nodes-and-clients/run-a-node

7. “Remote Produce Call (RPC) Node” refers to a server that lets wallets and apps query a blockchain and submit transactions to it. It is an access point, not necessarily a validator.

8. https://www.coindesk.com/tech/2026/02/25/a-former-solana-exec-is-taking-a-page-out-of-wall-street-playbook-to-make-global-crypto-trades-faster

9. Tor (“The Onion Router”) is a privacy network that routes internet traffic through multiple relays to obscure a user’s location and activity.

10. “Segregated Witness (SegWit) upgrade” refers to a Bitcoin Improvement Proposal (BIP 141), activated in August 2017, that increased Bitcoin’s block capacity by restructuring how transaction data are stored by separating witness (signature) data from the rest of each transaction.

11. “Bitcoin Core v30”: Released in October 2025, Bitcoin Core v30 increased the amount of arbitrary data that could be stored on the Bitcoin blockchain by raising the default OP_RETURN data limit. The change sparked a divide over whether Bitcoin should facilitate greater non-transaction data, prompting many node operators to adopt the alternative Bitcoin Knots client, which retained more restrictive policies.

12. Jain, T. 2025. “SIMD-228 was a historic milestone for crypto…” X.

13. Source: ARK Investment Management LLC, 2026, based on data from a range of external sources as of July 27, 2026. mempool.space, hashrateindex.com, explorer.rated.network, datawallet.com, dune.com, validators.app, nakaflow.io, solanacompass.com, streamflow.finance, validatorqueue.com, beaconcha.in, newegg.com, tomshardware.com, datacenterdisk.com, docs.anza.xyz, geth.ethereum.org, bitnodes.io, ethernodes.org, etherscan.io as of July 27, 2026.