Analysis of Cardano's incentive mechanism

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October 20, 2025

Contents

Acknowledgements

The author wishes to express sincere gratitude to the individuals whose invaluable insights and detailed feedback were instrumental to this work: **Samuel Leathers, Alejandro Garcia, Arturo Mora, Evangelos Markakis, Ryan Wiley, Matthew Capps, and Rich Manderino**.

Special thanks are extended to **Kevin Hammond, Neil Davies, Alexander Moser, Markus Gufler, Vijayanath Bhuvanagiri and Adam Rusch** from the Intersect Protocol Parameters Sub-Committee for their support and technical discussions; and to **Taichi Yokoyama**, who played a critical role in facilitating and translating workshops with the Japanese SPO community.

To the **SPO community** that registered and took part in the focus groups, your candid feedback and operational experiences were vital to grounding this analysis in real-world conditions and to better understanding the motivations and challenges faced by operators: **Atlas, banC, Bastian - SHARE, Baudouin Muvunga, Bernard Sibanda, BTBF, Cassandra de Vries, Chad - BBHMM, Chris - STR8, David Airebamen, Delon Wenyeve, ERTÜRK GÜRBOGA, Fergie Miller, Jeremy, Jesse Smith, Lauri, Leon - HAPPY, Markus Gufler, MUEN, Nekota - NAP, Nils Codes, Rodrigo - CHIL, Shane Lazar, Shawn McMurdo, shiodome47, Star Forge, Stef - RABIT, Rich Manderino, Tatsuro Kyoden, GAIN, NAP, AICHI, ATRMN, ADA1, BTBF, AIRX, CTEC, d-san, Daikon, Daisuke, Genhen, RX78, kpcn, MUEN, MUGEN, n_oyaji, NNSP, Rakuda, Shiodome, TGEM, STARO, Taro, USAGI, YYZ, z-dev.ai, ASY, Taireru, SASA, Tammy, KAP, ISPF**. Their perspectives enriched the qualitative dimension of this report. Best wishes to all for continued success in your stake pool endeavors.

Finally, a special acknowledgment is due to the original designers of the incentive scheme: **Philipp Kant, Lars Brünjes, and Duncan Coutts**. Time has proven their design to be fundamentally sound and robust, successfully guiding rational actors so that their self-interested behavior results in optimal outcomes for the security and efficiency of the protocol.

Executive Summary

This report provides a comprehensive analysis of Cardano's incentive mechanism, five years after its launch in the Shelley era. The primary objective is to evaluate the system's real-world performance against its original game-theoretic design goals, assessing its overall health, identifying systemic risks, and determining the need for protocol adjustments. The methodology compares the theoretical goals codified in the design specification (Section 2) with a deep empirical analysis of on-chain data and qualitative findings from Stake Pool Operator (SPO) focus groups (Section 3).

This document aims to inform the community and governance bodies about the current state of the incentive mechanism it's successes and challenges, and to be a conversation starter for potential refinements and improvements to the system. We encourage the community to review this report, provide feedback, and engage in discussions about the future of Cardano's incentives and sustainability.

Key Findings

The analysis reveals a system of dual outcomes: the incentive mechanism is a resounding technical success in securing the network, while simultaneously creating significant socio-economic challenges for its operator community.

- **A secure and performant network:** The core goals of incentivizing participation and performance have been unequivocally met. The network is robustly decentralized and secure, supported by 741 "Healthy" pools and 246 "Viable" pools, and consistently achieves over 98% of its theoretical maximum block production.
- **Flawless protocol mechanics:** The automated rewards distribution system has functioned flawlessly since inception, validating its design. Furthermore, the pledge mechanism is proven to be a highly effective Sybil deterrent, creating a powerful economic incentive to consolidate capital, just as it was designed to do.
- **The "Paradox of Pledge":** While an effective Sybil deterrent, the pledge mechanism fails as a meaningful "skin-in-the-gam" signal for the vast majority of operators. On-chain analysis confirms the reward bonus is "functionally irrelevan" for pledges under 10M ADA a finding echoed by SPOs. This creates a competitive imbalance that primarily benefits well-capitalized actors.
- **The "Viability gap":** The system has not converged on the theoretical $k = 500$ pools, but has instead found a stable, stratified equilibrium of 1,614 active pools. A direct consequence is the "viability gap": 873 active operators (54% of the total) remain below the 3M ADA threshold required for consistent block production.
- **A Capital-constrained environment:** The viability gap is cemented by two real-world factors not accounted for in a simplified rational-actor model. First, approximately 16B ADA (42%) remains outside the consensus mechanism, creating a capital-constrained, zero-sum environment. Second, delegator behavior is complex, dominated by inertia ("sticky stake") rather than pure yield optimization.
- **Current delegated stake can only saturate 289 pools:** With 21.7B ADA currently delegated, only 289 pools can reach the saturation point of 75M ADA. This means that even in an ideal scenario where all stake is perfectly distributed, only 289 pools can be fully saturated,

leaving the remaining pools undersaturated and less competitive. The stake distribution is highly uneven. At the time of writing this report there are only 77 saturated pools.

Risks and Conclusions

The report identifies two primary risks to the network:

1. **High social risk:** The most immediate threat is operator disillusionment. The “viability gap” and the pledge paradox have created a large segment of the operator community that feels the system is inequitable.
2. **Long-term economic risk:** The network’s sustainability model is contingent on a successful transition from the current reward system, which is overwhelmingly subsidized by the ADA reserves, to one funded by transaction fees. This places immense importance on the system’s ability to increase fee revenue for which Leios update is critical, as the current system would not be able to support the required transaction volume, not even at it’s current maximum capacity. Obviously, this hinges on the ecosystem’s ability to generate projects and utility that drive sustainable on-chain activity.

The findings indicate that the system requires **fine-tuning and targeted revisions, not a complete overhaul**. The fundamental game-theoretic model is sound for its primary purpose of securing the network. The system is decentralized enough to be resilient and censorship-resistant.

Recommendations

The report proposes a multi-pronged approach for consideration by governance and protocol developers:

- **Address the viability gap:** Explore new on-chain mechanisms, such as “pool alliances” or “virtual pools,” to allow the 873 struggling operators to combine resources and compete effectively without compromising decentralization.
- **Re-evaluate parameters:** Formally analyze and debate adjustments to economic parameters, including a Minimum Pool Margin a (minPoolCost) and a reduction and potentially to eliminate minPoolCost.
- **Consider minPoolMargin:** This proposal seems to have the support from pools of all sizes. Should be paired with a reduction of minPoolCost to 0. Researchers think minPoolCost favors Sybil attacks.
- **Prune inactive pools:** Initiate a formal research effort to define an on-chain mechanism for pruning “Inactive” pools, addressing the “stale stake” problem foreseen in the original design.
- **Activate latent stake:** Launch a formal research initiative to understand the barriers preventing 16 billion ADA from participating in consensus.
- **Focus on enabling a healthy economic transition:** Prioritize protocol enhancements and ecosystem development that ensure a smooth transition to a fee-based reward system.
  - **At the protocol level:** This requires two parallel tracks. The first is growing network capacity via Leios to handle higher transaction volumes. The second is enhancing economic competitivity. This involves moving beyond the current, single-price fee model

to implement a more sophisticated, dynamic fee market. A tiered pricing mechanism, for example, would allow the network to better manage resources, improve user experience by offering differentiated service levels, and compete more effectively. The academic paper *Tiered Mechanisms for Blockchain Transaction Fees* [1] should serve as the logical starting point for this conversation.

– **At the ecosystem level:** These protocol upgrades must be met by a focused effort to foster high-value applications. The long-term sustainability of the network will be secured by "killer apps" that drive the meaningful on-chain transaction volume required to fund rewards through fees.

[1]Kiayias, A., Koutsoupias, E., Lazos, P., & Panagiotakos, G. (2023). *Tiered Mechanisms for Blockchain Transaction Fees*. Available at: https://arxiv.org/pdf/2304.06014.pdf

1 Introduction

1.1 Background and motivation

Five years have passed since the Cardano blockchain's transition to the Shelley era, a shift from a federated network to a decentralized Proof-of-Stake (PoS) model. Central to this model is delegation, which allows any holder of the network's native asset, ada, to participate in the protocol's consensus mechanism by delegating their stake to Stake Pools. This is essential for network security and performance.

The success of this decentralized ecosystem depends on its incentive mechanism. This mechanism is the economic engine designed to align the financial self-interest of rational actors—both delegators and SPOs—with the long-term health, security, and decentralization of the network. The design, as detailed in the ***Shelley-era Delegation and Incentives Design Specification (SL-D1)***, is built on game-theoretic principles that predict how participants will behave under a specific set of economic rules. Now, after five years of operation, a body of on-chain data and operational experience exists. This allows for an empirical analysis of the scheme's real-world effectiveness. The question is no longer whether the incentives *will* function as predicted, but whether they *have*. This report provides a review to bridge the gap between the intended design and the observed on-chain outcomes, assessing its performance and identifying areas for potential refinement.

1.2 Scope and primary objectives

This report assesses the economic health and performance of Cardano's stake pool incentive scheme. The analysis is grounded in the goals and mechanisms outlined in the design specifications, primarily the *Shelley-era Delegation and Incentives Design Specification (SL-D1)*. The scope of this report is defined by three objectives:

- To determine if the current incentives scheme has been successful in achieving its stated goals, with these goals being derived directly from the design specification.
- To determine, based on the findings of the initial analysis, whether the system requires minor parameter adjustments (fine-tuning), a more significant revision of its mechanisms (overhaul), or if the current configuration is performing optimally.
- To determine if the current scheme presents systemic risks to the long-term health and security of the network. This includes an assessment of whether stake pool operators have sufficient incentive to continue securing the protocol into the future.

1.3 Methodology and report structure

To achieve these objectives, this report follows a three-phase analytical approach that moves from theory to practice and finally to synthesis.

- **Phase 1: Foundational analysis.** The first phase involves a review of the design specification (SL-D1) to codify the system's intended goals, its predictions out actor behavior, and the mechanics of the rewards system. This creates a theoretical benchmark against which the live network can be measured.
- **Phase 2: Empirical analysis.** The second phase tests the theoretical model against reality. This involves analyzing quantitative on-chain data to measure network outcomes such as decentralization, stake distribution, and delegator behavior. This data is supplemented with

qualitative findings from focus groups with Stake Pool Operators to understand the motivations behind the observed trends.

- **Phase 3: Synthesis and evaluation.** The final phase compares the theoretical design from Phase 1 with the empirical results from Phase 2. This is used to draw conclusions, directly address the three objectives, identify systemic risks, and formulate final recommendations.

The report is structured to follow this methodology. Section 2 summarizes the design of the incentive mechanism. Section 3 presents the empirical analysis of on-chain data. Section 4 synthesizes these findings to evaluate the system's performance, followed by final conclusions and recommendations in Section 5.

2 Foundational analysis: goals of the incentives design

The design of the Cardano incentives scheme intends to align the financial self-interest of individual actors with the overall health, security, and decentralization of the network. An analysis of the *Shelley-era Delegation and Incentives Design Specification* reveals a set of core goals and behavioral predictions that form the theoretical foundation of the economic model.

2.1 Design goals

The delegation design is intended to produce a specific set of behaviors and system properties:

- **System equilibrium:** The mechanism is designed to guide the ecosystem toward a stable state where a majority of stake is delegated to a target number of pools, k, preventing the centralization that could arise from a few dominant pools.
- **Performance and participation:** Rewards are structured to incentivize operators to fulfill their protocol responsibilities, namely consistent block production and providing reliable network infrastructure.
- **Automatic and efficient rewards:** Reward sharing is an automatic protocol function that does not require manual intervention from operators or members. The process is designed to avoid excessive growth of the UTXO set or transaction bursts that could compromise network performance.
- **Sybil resistance:** The mechanism is designed to discourage **Sybil attacks**, where an adversary creates many pools to gain disproportionate influence. This is primarily addressed through the **pledge** mechanism, which rewards owners for committing their own capital ("skin in the game"), making it uneconomical to create numerous low-quality pools.
- **Cooperative behavior:** The monetary expansion formula is dependent on the total number of blocks produced in an epoch, which is designed to incentivize cooperative behavior and discourage pools from sabotaging each other's blocks.

2.2 The rewards calculation mechanism

The rewards calculation is the mechanism through which the incentive structure is materialized. A stake pool's ability to earn rewards depends on structural and operational factors. Structurally, its total stake (σ) and owner's pledge (s) determine its theoretical reward cap, with both values constrained by the saturation point (z_0). The system rewards operators who commit more personal stake through the pledge influence factor (a_0), while capping benefits for oversaturated pools to promote decentralization. Operationally, actual rewards are gated by performance ($\bar{p}$); only pools that produce blocks receive rewards. Additionally, pools must meet their declared pledge to qualify for any rewards. The distribution mechanism ensures operator costs and margins are prioritized before delegators are paid. Together, these parameters align incentives around decentralization, reliability, and operator commitment.

1. **The epoch reward pot (R) is determined.** Before individual pool rewards are calculated, a total amount of rewards available for the epoch is established. This pot is sourced from transaction fees collected during the epoch (`fees`) and a percentage (ρ) of the remaining ADA in the reserves (`reserves`). The calculation proceeds as follows:

(a) Calculate monetary expansion:

$$\text{Monetary Expansion} = \rho \cdot \text{reserves}$$

(b) Calculate total potential rewards:

$$\text{Total Potential Pot} = \text{fees} + (\rho \cdot \text{reserves})$$

(c) Calculate the final reward pot (R):

$$R = (1 - \tau) \cdot (\text{fees} + \rho \cdot \text{reserves})$$

This value R is the total ADA available to be shared among all stake pools in a given epoch, τ is the treasury cut and ρ is the monetary expansion rate.

2. **A pool's optimal reward is calculated.** The protocol calculates the maximum potential reward a pool is entitled to, assuming perfect performance. The formula is:

$$f(s, \sigma) := \frac{R}{1 + a_0} \cdot \left(\sigma' + s' \cdot a_0 \cdot \frac{\sigma' - s' \frac{z_0 - \sigma'}{z_0}}{z_0} \right)$$

The formula uses $\sigma' = \min(\sigma, z_0)$ and $s' = \min(s, z_0)$. This is the mechanism that enforces the saturation point. Any stake a pool controls beyond the saturation point (z_0) is ignored for the reward calculation.

3. **Rewards are adjusted for performance.** The optimal reward is a theoretical maximum. This value is multiplied by the pool's apparent performance ($\bar{p}$). The actual reward $\hat{f}$ being:

$$\hat{f}(s, \sigma, \bar{p}) := \bar{p} \cdot f(s, \sigma)$$

4. **The final reward is distributed to stakeholders.** Once a pool's final, performance-adjusted reward ($\hat{f}$) is calculated, it is split according to its declared parameters. If a pool's owners fail to meet their declared pledge in an epoch, the pool earns zero rewards for that epoch. If the pledge is met, the reward is distributed as follows:

   - First, the fixed cost (c) is subtracted and given to the operator.
   - Second, the percentage margin (m) is calculated from the remainder and also given to the operator.
   - Finally, all remaining rewards are distributed proportionally among all delegators (including the pool owner's pledge) based on their stake contribution.

3 Empirical analysis: on-chain outcomes vs design goals

This section tests the theoretical design goals from Section 2 against real-world outcomes by analyzing on-chain data and various aspects of the stake pool ecosystem.

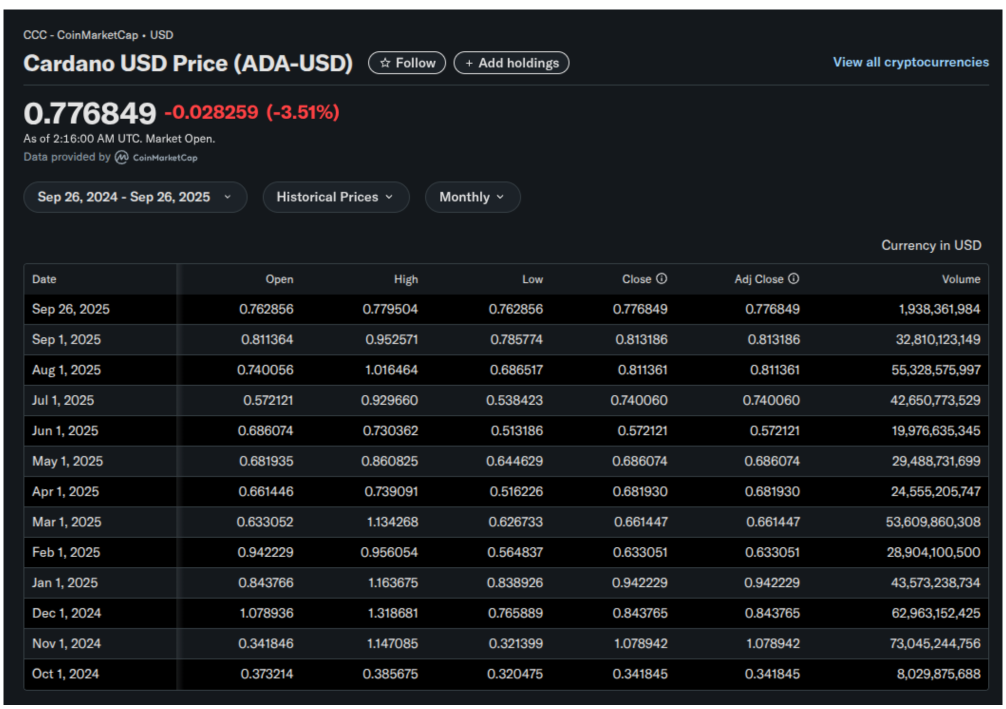
3.1 Determining the economic viability threshold

A sustainable, decentralized network requires that stake pool operations are economically viable. This means operators should not be forced to subsidize infrastructure with external capital, which is an unstable long-term condition.

Establishing a definitive viability threshold is a primary analytical challenge. Operational costs vary significantly with infrastructure, geography, and scale. Volatility between fiat-denominated costs and ADA-denominated rewards adds to this complexity. Our methodology addresses these variables by establishing a baseline cost profile derived from empirical data.

This cost model is derived from an analysis of on-demand pricing from major cloud service providers (AWS, Google Cloud, Digital Ocean) for a standard three-node topology (**one block producer, two relays**). The analysis establishes a baseline operational expenditure of approximately **$667 USD per month**, accounting for compute, network, and storage costs. This baseline was validated by cross-referencing against cost data reported by a sample of stake pool operators, who reported expenditures ranging from $150 to $1200 USD per month. Therefore, the $667 figure seems like a reasonable estimate for the median cost of a professionally managed operation.

To denominate this fiat cost in ADA, we employ the average ADA/USD exchange rate from the preceding six-month period (April 2025 – September 2025), which stands at $0.71. This timeframe was selected to provide a contemporary valuation while mitigating the effects of short-term market volatility.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Cardano USD Price (ADA-USD) ☆ Follow + Add holdings View all cryptocurrencies

0.776849 -0.028259 (-3.51%)

As of 2:16:00 AM UTC. Market Open.

Data provided by CoinMarketCap

Sep 26, 2024 - Sep 26, 2025 Historical Prices Monthly

Currency in USD

Date	Open	High	Low	Close	Adj Close	Volume
Sep 26, 2025	0.762856	0.779504	0.762856	0.776849	0.776849	1,938,361,984
Sep 1, 2025	0.811364	0.952571	0.785774	0.813186	0.813186	32,810,123,149
Aug 1, 2025	0.740056	1.016464	0.686517	0.811361	0.811361	55,328,575,997
Jul 1, 2025	0.572121	0.929660	0.538423	0.740060	0.740060	42,650,773,529
Jun 1, 2025	0.686074	0.730362	0.513186	0.572121	0.572121	19,976,635,345
May 1, 2025	0.681935	0.860825	0.644629	0.686074	0.686074	29,488,731,699
Apr 1, 2025	0.661446	0.739091	0.516226	0.681930	0.681930	24,555,205,747
Mar 1, 2025	0.633052	1.134268	0.626733	0.661447	0.661447	53,609,860,308
Feb 1, 2025	0.942229	0.956054	0.564837	0.633051	0.633051	28,904,100,500
Jan 1, 2025	0.843766	1.163675	0.838926	0.942229	0.942229	43,573,238,734
Dec 1, 2024	1.078936	1.318681	0.765889	0.843765	0.843765	62,963,152,425
Nov 1, 2024	0.341846	1.147085	0.321399	1.078942	1.078942	73,045,244,756
Oct 1, 2024	0.373214	0.385675	0.320475	0.341845	0.341845	8,029,875,688

Figure 1: ADA/USD price, April 2025–September 2025. Source: CoinMarketCap.

This gives an equivalent operational cost in ADA, calculated per epoch (5 days):

$$\text{Cost per Epoch (ADA)} = \frac{\text{Monthly Cost (USD)}/(\frac{30 \text{ days}}{5 \text{ days/epoch}})}{\text{Average ADA Price (USD)}} = \frac{\$667/6}{\$0.71} \approx 156 \text{ ADA}$$

This figure of **156 ADA per epoch** serves as the benchmark for evaluating stake pool viability.

It must be noted that this fiat-denominated cost basis subjects all operators to exchange rate volatility. A sustained depression of the ADA/USD exchange rate represents a systemic risk, as it could render pools operating near the viability threshold unprofitable. While this analysis acknowledges this market exposure, its scope does not include exchange rate forecasting. The benchmark of 156 ADA is therefore established as a point-in-time metric, intended to provide a stable baseline for evaluating the current economic state of the pool ecosystem.

A pool's economic viability is contingent upon its ability to generate rewards by consistently producing blocks. This analysis defines "consistency" as a 95% probability of producing at least one block per epoch. The corresponding stake required to meet this threshold is derived from a binomial probability model.

1. **Inputs**
    - $S = 432,000$ (slots per epoch)
    - $f = 0.05$ (active slot coefficient)
    - $\alpha = 0.95$ (target probability per epoch)
    - $A = 21,700,000,000$ ADA (active delegated stake)
2. **Leader selection math** A node is eligible to lead if its certified VRF value p for that slot satisfies
   $$p < 1 - (1 - f)^{\sigma}$$
   The probability of at least one leadership slot in an epoch is:
   $$P(\geq 1) = 1 - (1 - p_{\text{slot}})^S = 1 - ((1 - f)^{\sigma})^S$$
   We solve for σ, the minimum relative stake proportion, that achieves $P(\geq 1) = \alpha$:
   $$(1 - f)^{\sigma S} = 1 - \alpha \Rightarrow \sigma = \frac{\ln(1 - \alpha)}{S \cdot \ln(1 - f)}$$
3. **Computation**
   $$\sigma = \frac{\ln(0.05)}{432,000 \cdot \ln(0.95)} \approx 0.0001351943861$$
   This gives a required stake in ADA:
   $$\text{Required ADA} = A \cdot \sigma = 21,700,000,000 \times 0.0001351943861 \approx 2,933,718 \text{ ADA}$$

The calculation yields a required stake of approximately 2.93M ADA. For clarity and standardization, this report henceforth refers to this as the **3M ADA viability line**.

Individual pools may achieve profitability below this threshold by using low-cost infrastructure or cost-sharing alliances. Nevertheless, the 3M ADA threshold serves as a standardized benchmark for the rest of this analysis.

3.2 Stake distribution

Having established the 3M ADA viability line, we can now use it as a lens to analyze the on-chain distribution of stake pools. This allows us to assess what proportion of the network's operators are positioned for economic sustainability versus those that fall below this critical threshold.

3.2.1 Stake distribution across pools

A primary design goal of the incentive mechanism is to encourage decentralization by guiding the majority of delegated stake toward the top 'k' most desirable pools. We can assess this by analyzing how the total active stake is distributed across pools of different sizes.

Figure 2 illustrates the distribution of pool sizes. The first noticeable aspect of this chart is the large number of small pools. We removed from the analyzis all pools deemed as Inactive (1,305) to focus on the competitive landscape. The number of small pools (less than 3M ADA delegated) has been consistently decreasing over the last 260 epochs.

In the other hand, the number of pools close to saturation (>70M ADA) has been steadily increasing, reaching 77 in epoch 583. This indicates that while the market has not yet fully stabilized around 'k' pools, it is slowly trending in that direction.

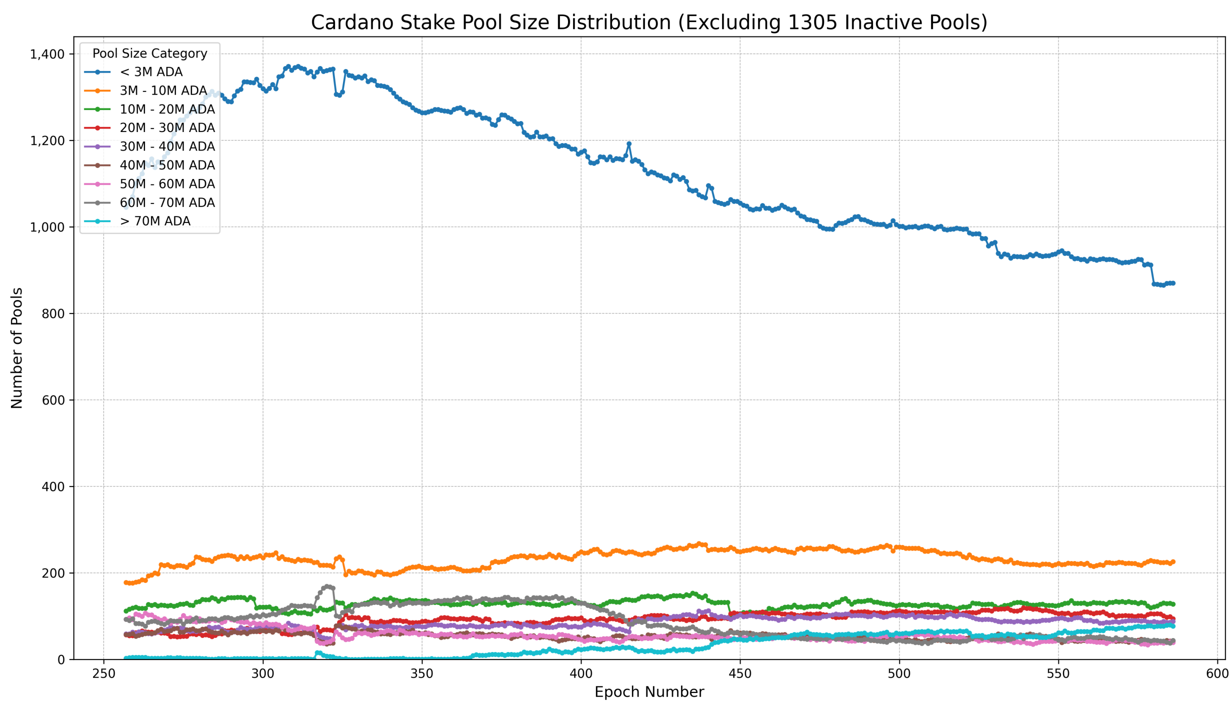


Figure 2: Pool size distribution. This chart shows the number of active pools within each size category

Figure 3 provides a historical lens on stake allocation by pool size categories over epochs, excluding the 1,305 abandoned pools. This time-series data shows steady growth in the upper tiers amid active stake fluctuations. These patterns are consistent with the game-theoretic design, which predicted delegators would favor larger pools, leading to a concentrated core of operators. This clustering results in 741 healthy pools securing the majority of stake.

Key insights from this data include:

- **Robust supply and targeted demand**: The number of smaller pools signals community interest in operating Stake Pools, while the concentration of delegation reflects market behavior consistent with the incentive model's predictions. As the model predicted, this dynamic directs stake toward high-return pools. This enhances network stability without compromising diversity.

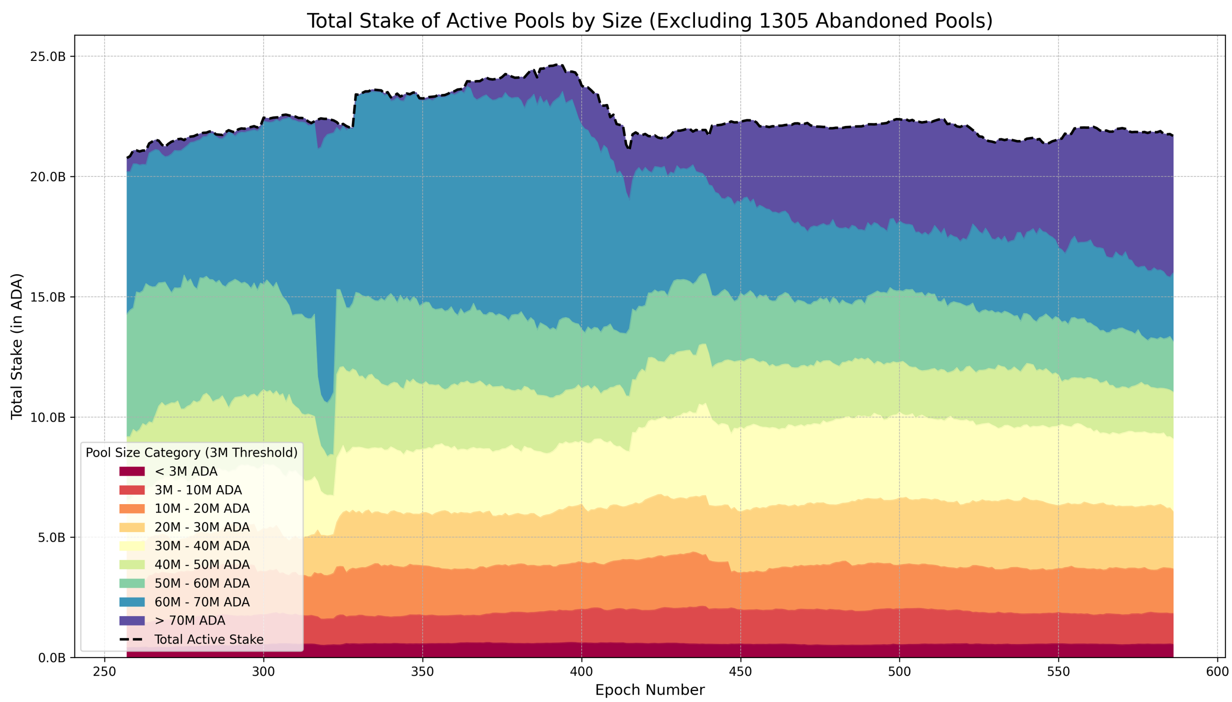


Figure 3: Total Stake of Active Pools by Size. This stacked area chart depicts the evolution of stake (in billions of ADA) across size categories over epochs, alongside the cumulative total active stake (black line).

3.2.2 Wallet distribution and stake control

The on-chain distribution of delegated ADA, illustrated in Figure 4, is highly concentrated. While over one million wallets hold less than 1,000 ADA, their collective stake is negligible at 0.03%. Conversely, a cohort of approximately 4,500 wallets, each holding over 500,000 ADA, controls a significant majority (68.5%) of the total delegated stake.

This Pareto-like distribution of capital primarily determines the delegation market's dynamics. The concentration of stake among a small number of large holders creates a significant barrier to growth for new and smaller pools, as these large-stake entities are rationally incentivized to delegate to established, high-performance operators or to operate their own private pools. It must be noted that this analysis is limited to on-chain data and does not account for holdings on exchanges or in custodial services, suggesting the true concentration of capital may be even more pronounced.

This distribution provides the necessary context for understanding the competitive environment in which stake pools operate and the structural challenges they face in attracting delegation.

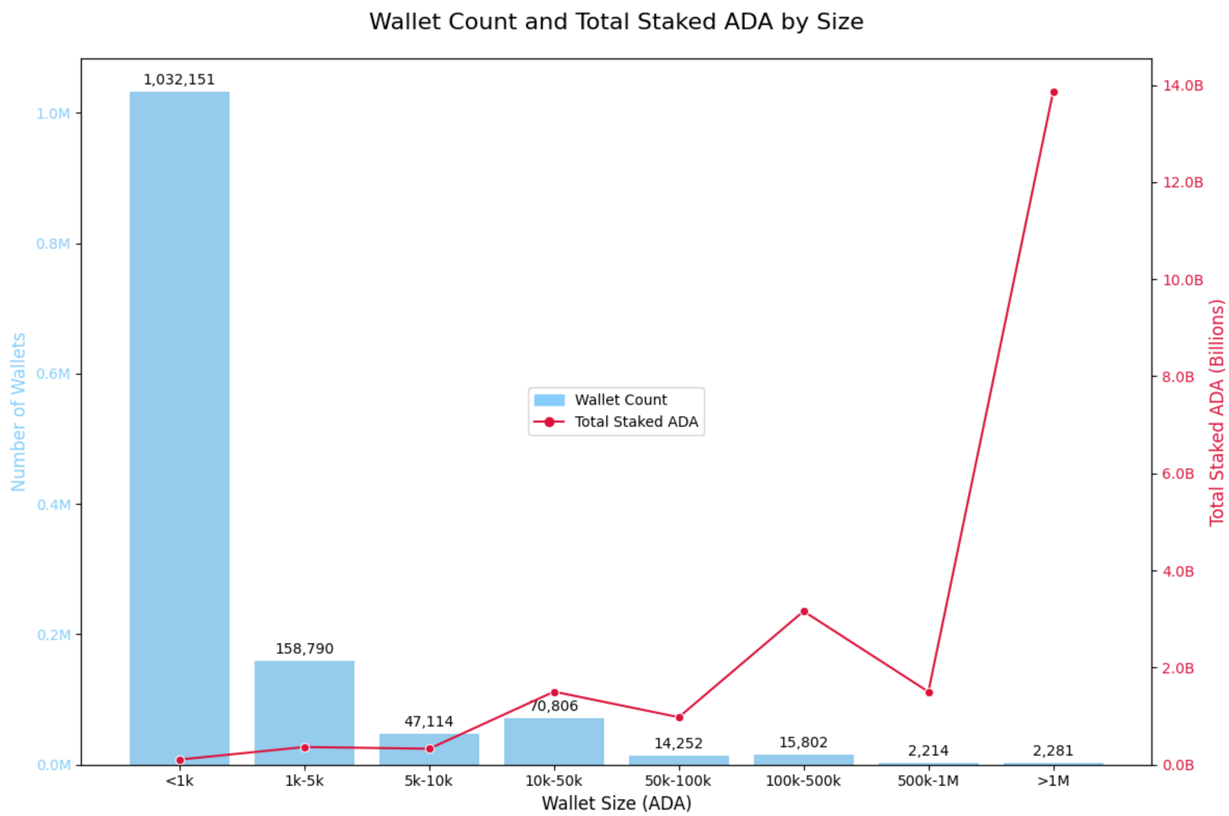


Figure 4: Wallet count and total staked ADA by size. This chart illustrates the skewed distribution of ADA holdings across network wallets.

3.3 The four tiers of stake pool viability

We developed a classification system based on an analysis of all active pools over the last 36-epoch period (Epochs 548 to 583). The methodology evaluates each pool's performance against two benchmarks derived from the previous analysis:

- **Stake threshold of 3 million ADA**, which ensures a 95% probability of producing at least one block per epoch.
- **Rewards threshold of 5,500 ADA** over the analysis window, which roughly corresponds to the break-even point for covering operational costs of 156 ADA * 36 epochs.

In addition to these quantitative measures, pools were assessed for qualitative signals of inactivity, such as:

- Unmet pledge at the end of the analysis period.
- No pool updates during the analysis period.
- Zero block production during the analysis period.
- No participation in governance (Delegation or Direct voting) during the analysis period.

By combining these financial and operational indicators, each pool was assigned to one of the four viability tiers.

Status	**Description**	**Number of Pools**	**Controlled Stake (ADA)**
Inactive	Unmet Pledge plus another sign of neglect and no blocks	1305	46.87 M
Active & Struggling	< 3M Stake & < 5500 ADA in cumulative rewards	627	190.83 M
Active & Viable	Viable but small (< 3M ADA stake, > 5500 ADA rewards)	246	368.07 M
Healthy	Healthy (>= 3M ADA stake)	741	21.14 B
Total Active		**1614**	**21.70 B**
Grand Total	All Non-Retired Pools	**2919**	**21.74 B**

Table 1: Summary of all registered pools by viability status for epochs 548–583. *[Appendix A (appendixA.txt) contains a comprehensive report on all non-retired pools by viability status.]*

The inactive layer: The largest group, comprising 1,305 pools (44%), is classified as `Inactive`. These operators have failed to meet viability thresholds and show multiple signs of inactivity or abandonment While this is a large number of pools, their economic impact is negligible. Together, they control only ~47 million ADA, less than 0.22% of the delegated stake. This "long tail" of inactive pools does not pose a systemic risk to the network's security.

The active ecosystem: healthy, viable, and struggling pools: The competitive landscape is made up of 1,614 pools classified as `Active`. These operators are actively maintaining their infrastructure and competing for delegation. This active group is not monolithic and can be broken down into three sub-categories.

- **Healthy - 741 Pools (~26%):** This is the core of the Cardano network. These operators have surpassed the 3M ADA viability line, ensuring consistent block production and financial sustainability. They control the majority of the network's stake (21.14 billion ADA) and are responsible for most of its security and block production. The existence of a large and diverse set of healthy operators is an indicator of the incentive scheme's success.

- **Viable but small - 246 Pools (~8%):** This is a group of operators who have not yet reached the 3M ADA stake threshold but have demonstrated strong performance by earning enough rewards to cover their costs. They control approximately 368 million ADA. These pools represent a combination of operational skill, community support, and statistical luck.
- **Struggling - 627 Pools (~22%):** This large group of operators is actively participating but failing to achieve financial viability. They have neither the stake for consistent block production nor the cumulative rewards over the analysis period to cover their costs. Collectively control about 191 million ADA. Their long-term sustainability is uncertain.

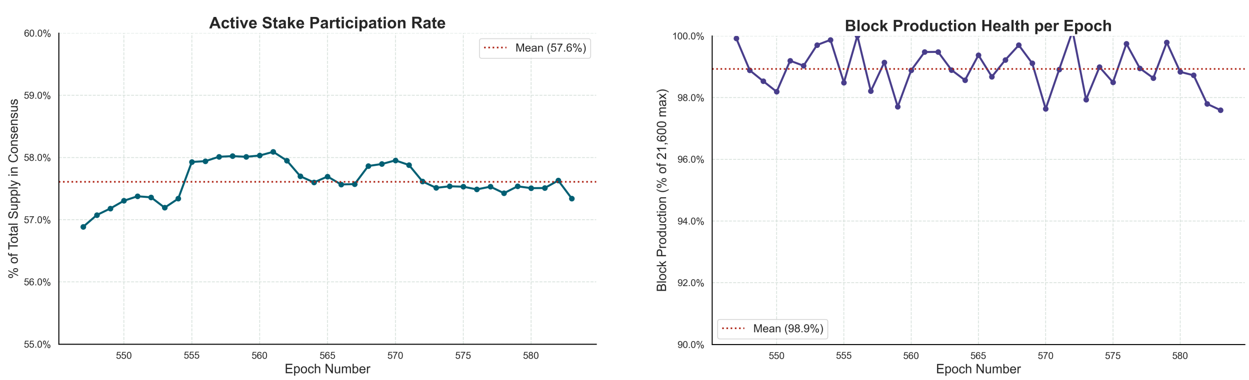
The large number of pools in the `Viable but Small` and `Struggling` categories (873 total) points to a large portion of the operator community facing challenges with scale.

This suggests the potential benefit of an on-chain mechanism that would allow them to form alliances. Such a mechanism could enable thesegroups to combine resources and operational duties, creating a larger, more reliable, and cost-efficient 'virtual stake pool'[2] This capability is, of course, very common in the traditional markets, companies form consortia, joint ventures, and strategic alliances to pool resources and share risks. We think this is an interesting avenue for future research for Cardano.

3.4 System in equilibrium

3.4.1 Network's state over a 36-epoch period

An empirical analysis of the network's state over the last 36-epoch period (Epoch 548 to 583) reveals a system that has settled into a multi-faceted and stable equilibrium. The core indicators of network health, overall stake participation and block production efficiency, demonstrate a consistent operational state, as shown in Figure 5.



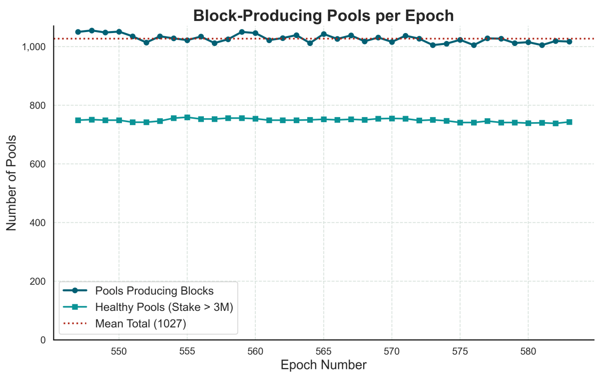
(a) The percentage of the total circulating supply participating in consensus has remained stable, holding consistently around a mean of 57.4%.

(b) Network block production has been highly efficient and reliable, consistently achieving over 95% of the theoretical maximum of 21,600blocks per epoch.

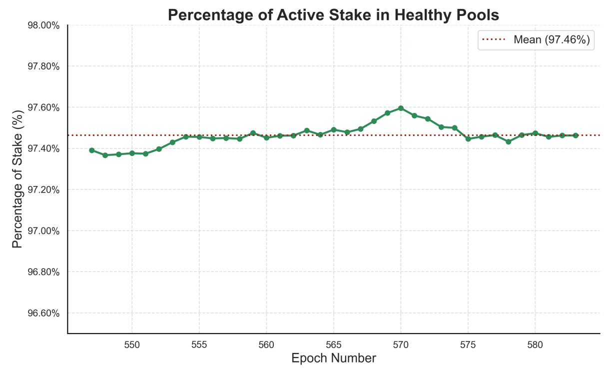
Figure 5: Macro-level indicators of network stability from Epoch 548 to 583.

[2] The term 'virtual stake pool' and core insight from the telecommunications industry were provided by Dr. Neil Davies of the Intersect Parameters sub-committee. In a conversation with the author on October 2, 2025, Dr. Davies described how practices like network sharing agreements and Mobile Virtual Network Operators (MVNOs) allow smaller operators to compete in an industry dominated by larger incumbents. In discussing this parallelism, we noted an important distinction: whereas MVNOs typically lease network capacity from a larger provider, virtual stake pools would instead pool their collective resources to form a new, larger entity, sharing both operational responsibilities and rewards among its members.

This high-level stability is underpinned by a predictable and decentralized structure of network operators. As illustrated in Figure 6, the system consistently supports over 1,000 unique pools producing blocks each epoch. Of these, a core group of approximately 741 “Healthy Pools” (those with active stake exceeding 3M ADA) forms the reliable foundation of the network. The incentive mechanism has proven highly effective at concentrating the majority of delegated stake within this group, which consistently secures over 97% of all active stake.



(a) The number of pools producing blocks per epoch is highly stable, anchored by a consistent core of Healthy Pools.



(b) The percentage of active stake controlled by the Healthy Pools remains constant at over 97%, confirming a stable delegation equilibrium.

Figure 6: Distribution and stake control of network operators.

This stability extends beyond the total stake to the underlying structure of its distribution. Over the 36-epoch window, the allocation of capital across pools of different sizes has remained structurally consistent, characterized by a core of large, healthy pools and a persistent periphery of smaller operators. For instance, in epoch 548, pools with less than 3M ADA controlled 2.63% of the total active stake. By epoch 583, this figure remained nearly unchanged at 2.53%. In contrast, the largest pools (controlling `>70M ADA`) saw their share of stake grow steadily from 19.30% to 26.26% over the same period, indicating a slow but predictable consolidation of capital at the top. This consistent structure, with its stable periphery and slowly consolidating core, confirms that the network is not in a state of flux but has reached a mature equilibrium.

3.4.2 The impact of stake not participating in consensus

This observed equilibrium is mathematically constrained. Approximately 16B ADA in circulating supply remains outside the delegation system, creating a capital-constrained environment that has shaped the competitive landscape into its current form. See Figure 7.

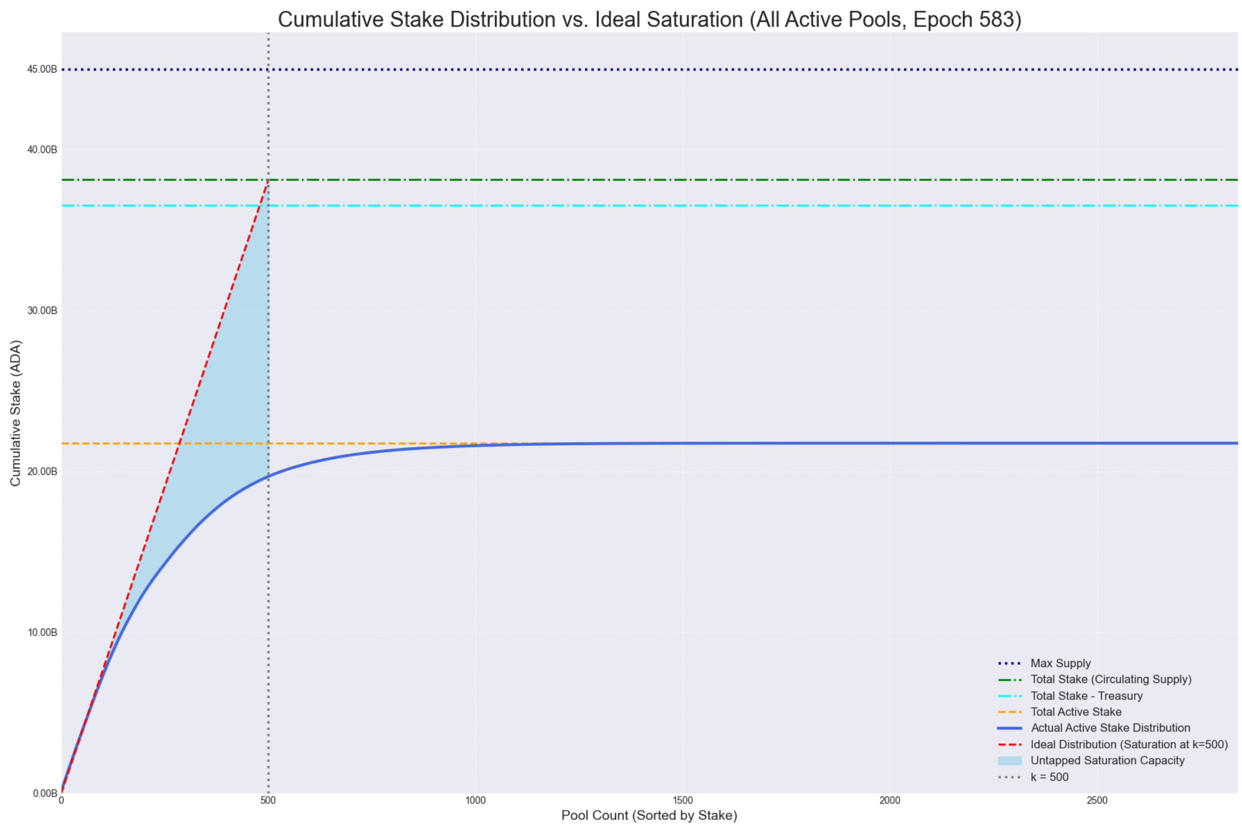


Figure 7: Cumulative Stake Distribution vs. Ideal Saturation (Epoch 583). The chart highlights the significant gap between the total circulating supply (less treasury) and the total active stake. This 16B ADA in non-participating capital is the primary constraint for more saturated pools and makes it harder for smaller pools to grow.

The chart above clearly visualizes the primary constraint on the incentive system. The gap between the “Total Stake - Treasury” line (approximately 38B ADA) and the “Total Active Stake” line (approximately 22B ADA) represents **16 billion ADA** that is not delegated.

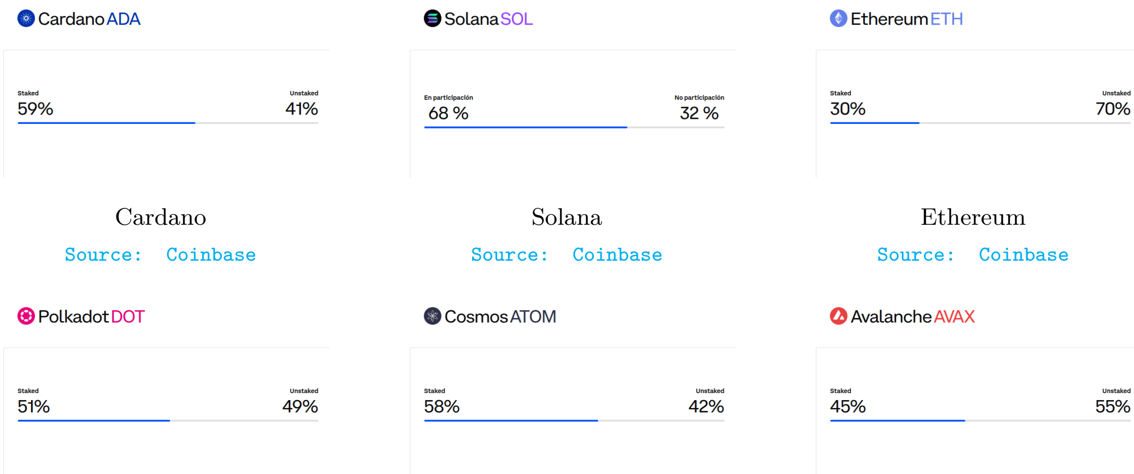
With a circulating supply of approximately 38B ADA, the saturation point for a pool at $k = 500$ is approximately 76M ADA. Saturating 500 such pools would require all 38B ADA to be actively delegated. With only approximately 22B ADA actively staked, the maximum number of pools that could theoretically be saturated is:

$$\text{Max Saturated Pools} = \frac{\text{Total Active Stake}}{\text{Saturation Point}} = \frac{22,000,000,000}{76,000,000} \approx 289 \tag{1}$$

The more direct consequence is a capital-constrained environment for the active delegation market. With a finite 22B active ADA, a small or new pool can only grow by persuading delegators to re-delegate from established, healthy pools.

This is a challenging proposition due to significant incumbent advantages and delegator inertia. Larger pools offer a proven history of consistent block production and reliable rewards, making them the rational choice for financially-motivated, risk-averse or passive delegators. This dynamic creates a constant tension within the ecosystem: a community of smaller stake pool operators, many driven by ideological alignment and a desire to contribute, finds itself in direct competition for a limited resource against the network's most successful incumbents. Thus, the 16B ADA's absence from consensus does not merely limit the theoretical number of saturated pools; it fundamentally defines the competitive landscape, creating a high barrier to growth for new entrants and sustaining the "viability gap" observed in the on-chain data.

Cardano is not unique in having a significant portion of its circulating supply outside of consensus. In fact, it appears to be a consistent characteristic across major Proof-of-Stake (PoS) blockchains. A comparative analysis of staking data from a major exchange reveals that Cardano's participation rate is among the highest in the industry.



Cardano — Source: Coinbase | Solana — Source: Coinbase | Ethereum — Source: Coinbase

Polkadot — Source: Coinbase | Cosmos — Source: Coinbase | Avalanche — Source: Coinbase

Figure 8: Comparative analysis of staking participation rates across major Proof-of-Stake networks as of October 2025. Cardano's participation rate is notably high relative to its peers.

A thought experiment: Impact of full stake delegation

To understand the impact of this capital constraint, it is useful to conduct a thought experiment and consider what would happen if the 16B undelegated ADA were suddenly to enter the system.

1. **Initial shock and saturation cascade:** The influx of stake would rapidly flow to the most desirable pools, quickly saturating and then oversaturating the largest operators.
2. **The k parameter at play:** As the top pools become oversaturated, their ROA would begin to decline for all members. The saturation parameter (z_0), which is currently a soft ceiling for most, would become a hard economic wall.
3. **Capital flows downhill:** Rational delegators from these oversaturated pools would be financially incentivized to move their stake to the next-best-performing unsaturated pools. This would create a cascade of delegation flowing down the ranks.
4. **The "Long Tail" shrinks:** Many pools in the lower tiers would find themselves suddenly viable as they attract new and re-delegated stake, rapidly growing towards mid-level sizes.

Characterizing the 16B in undelegated stake is relevant for future protocol enhancements. This includes identifying its composition (e.g., exchanges, institutional custodians, or individuals) and the barriers to its participation.

This large pool of dormant capital shapes the competitive landscape for stake pool operators. While the prevailing strategy involves competing for existing delegators in a near zero-sum environment, a more productive paradigm would focus on activating this latent stake. Activating even a fraction of this capital would represent a positive-sum gain for the entire ecosystem, simultaneously increasing network security and the viability of smaller pools.

3.4.3 Registrations and retirements over time

A historical view of pool registrations versus retirements highlights the competitive pressures and maturation of the ecosystem.

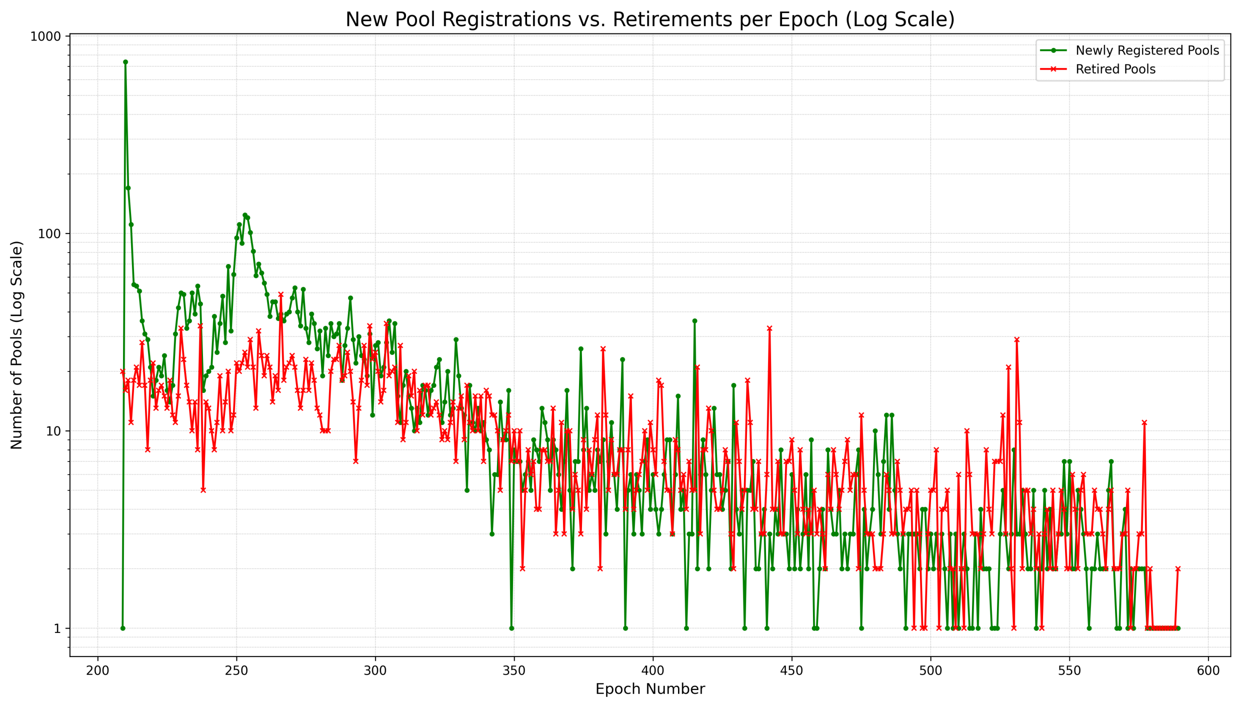


Figure 9: This chart shows the number of new pool registrations (green) versus retirements (red) over time, indicating the ecosystem has reached a mature equilibrium.

The chart shows three phases:

- An initial "boom" phase (epochs ~210-280): New pool registrations outpaced retirements.
- A consolidation phase (epochs ~280-400): The gap between entries and exits narrowed as the market matured.
- A mature equilibrium phase (epochs ~400-present): The number of retiring pools consistently matches or exceeds new registrations.

This trend suggests the ecosystem has moved from rapid growth to consolidation, reinforcing that the primary challenge for SPOs today is achieving long-term sustainability in a competitive environment.

3.5 Analysis of pool parameters

3.5.1 Pool cost

On October 27th, 2023 (epoch 445), the protocol's minimum fixed cost for stake pools was lowered from 340 ADA to 170 ADA to increase the competitiveness of smaller pools. An analysis of active pools shows a varied operator response.

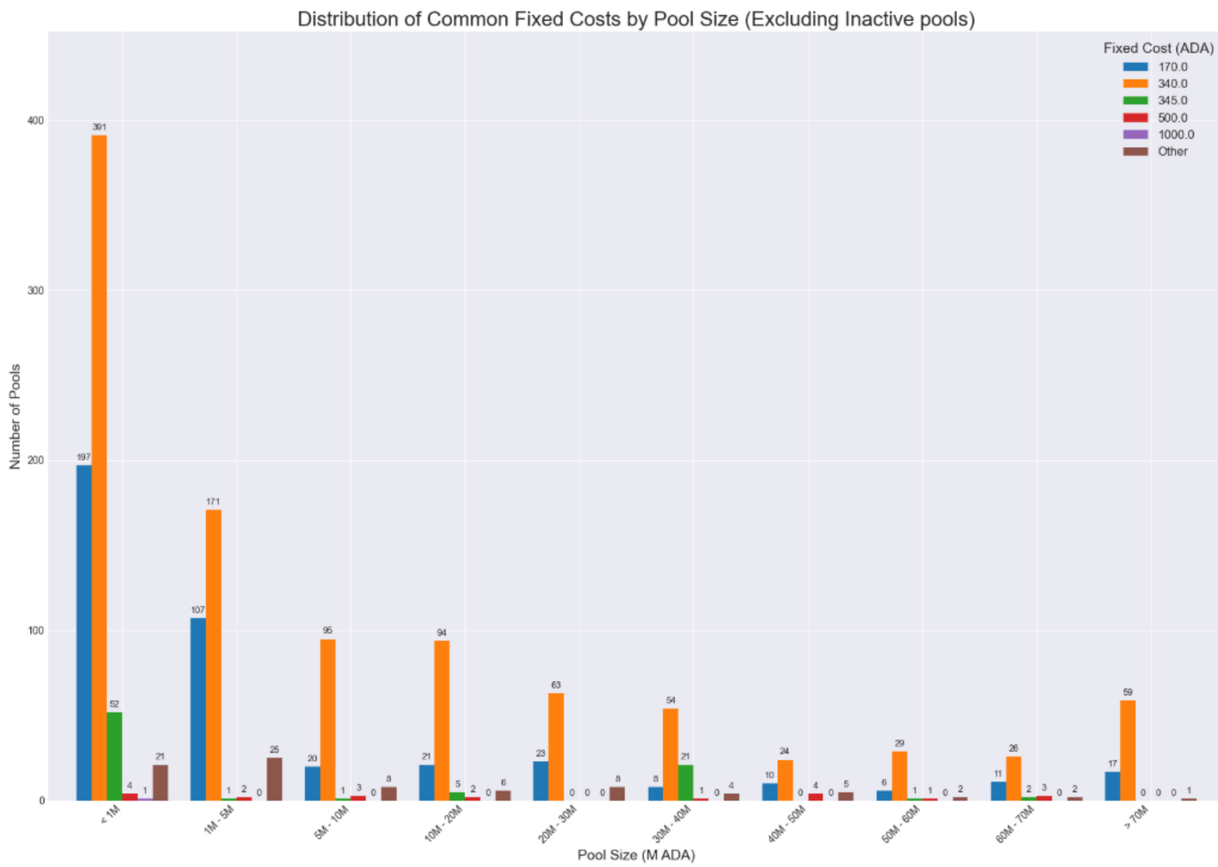


Figure 10: Current distribution of common fixed costs by pool size. The chart shows that 340 ADA remains the most common fixed cost setting across all active pool sizes.

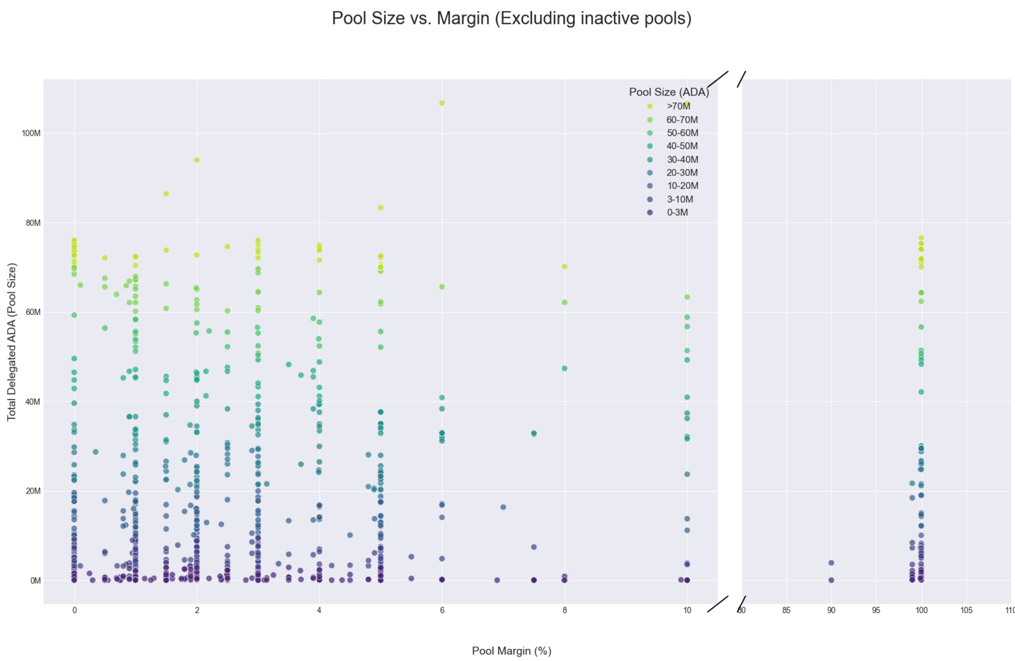
Data shows that 340 ADA remains the dominant fixed cost setting for every pool size despite the availability of the lower 170 ADA minimum. This suggests that 340 ADA is treated as the standard fee. The 170 ADA fee is the second most popular choice. The data indicates that the reduction in the minimum pool cost did not cause a market-wide fee reduction. Instead, it bifurcated the market into two main tiers:

1. **The incumbents (340 ADA):** Established pools that compete on factors like performance and reputation.
2. **The challengers (170 ADA):** Smaller pools using the new minimum as a strategic tool to attract delegation.

IO Research team believe that Min Pool Cost favors Sybil attacks and should be lowered to 0 or removed. Which could be paired with the introduction of Min Margin as a new protocol parameter to prevent a race to the bottom on fees.

3.5.2 Pool margin

The pool margin, the percentage of rewards taken by the operator, is a key strategic choice for pool operators. The plot reveals two fundamentally different groups of pools: a large, competitive market of public pools and relatively small set of private pools.



The public market (0-10% Margin) Within the competitive public market, the most significant finding is that **pool size does not dictate margin strategy**. Operators of all sizes can be found at every major strategic fee point.

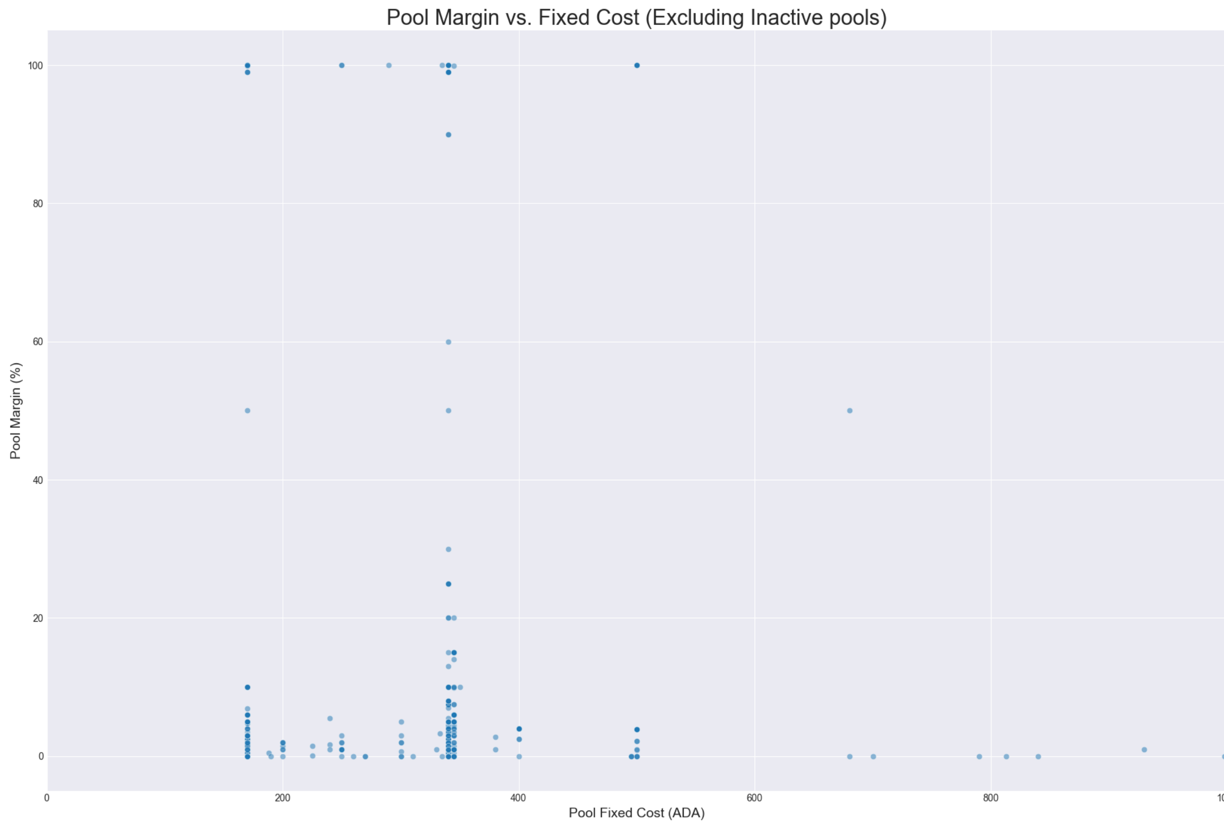
The 0% margin strategy A dense cluster of pools is visible at the 0% margin line. Crucially, these pools span **every size category**, from the smallest pools to some of the largest, fully saturated pools on the network. This demonstrates that 0% margin is not merely a growth tactic for new pools but a deliberate, competitive choice used by operators of all sizes to maximize their attractiveness to delegates.

The "Sweet Spot" (1-5%) The 1-5% margin range is the most densely populated part of the public market. It also features pools from **every size category**. This range appears to be the market's stable "sweet spot," representing a standard, sustainable fee. Operators here, whether large or small, are competing on factors beyond just the margin, such as reputation, performance, and community engagement.

The uncompetitive high-margin zone (5-10%) The area *between* 5% and 10% is almost entirely empty. This strongly suggests that margins in this range are uncompetitive and fail to attract significant delegation, regardless of pool size. The very small, scattered cluster of pools *exactly at* 10% (which also contains pools of various sizes) reinforces this. These are likely niche outliers, do not seem to be part of a viable public strategy, and are probably sustained by a small, ideologically-aligned group of delegators or are friends & family pools.

3.5.3 Pool margin vs fixed cost

The relationship between a pool's margin and fixed cost reveals that operators adopt one of a few distinct fee strategies, creating clusters of behavior.



- **The standard public pool (340 ADA, 0-5% Margin):** The largest cluster is centered at a 340 ADA fixed cost and a low margin, representing the ecosystem's standard.
- **The competitive challenger (170 ADA, 0-3% Margin):** A second cluster is located at the minimum 170 ADA fixed cost, used by smaller pools to attract initial delegators.
- **The private pool (100% Margin):** Pool cost is irrelevant for private pools, they will collect all rewards from the pool anyway.

Outside of these three strategies, the chart is sparse, indicating that operators see little incentive to deviate from these established fee packages.

3.5.4 Pledge

The incentive design's primary defense against **Sybil attacks** is the pledge mechanism, which is intended to make it economically unattractive for an adversary to create a large number of low-quality pools. By rewarding operators for committing their own capital "skin in the game", the system is designed to encourage the consolidation of stake into a smaller number of high-quality, high-commitment pools. To move from this theoretical understanding to a quantitative one, a simulation was conducted based on the rewards formula detailed in Section 2.

The simulation calculates the optimal rewards for pools of varying sizes (3M, 10M, 20M, and 76M ADA) across a range of pledge amounts (100k, 1M, 10M, 20M, and 76M ADA). The results, summarized in Table 2, show the reward bonus (as a percentage increase over a zero-pledge baseline) that each pledge level provides for each pool size.

Pool Size (ADA)	Pledge 100k ADA	Pledge 1M ADA	Pledge 10M ADA	Pledge 20M ADA	Pledge 76M ADA (Saturated)
3M	3,923 ADA (Δ +0.039%)	3,934 ADA (Δ +0.31%)	-	-	-
10M	13,037 ADA (Δ +0.039%)	13,149 ADA (Δ +0.31%)	14,354 ADA (Δ +3.13%)	-	-
20M	26,036 ADA (Δ +0.039%)	26,147 ADA (Δ +0.31%)	27,352 ADA (Δ +3.13%)	28,634 ADA (Δ +6.21%)	-
76M (Saturated)	98,168 ADA (Δ +0.039%)	99,280 ADA (Δ +0.31%)	111,332 ADA (Δ +3.92%)	124,158 ADA (Δ +7.79%)	233,634 ADA (Δ +30.00%)

Table 2: Simulated pledge reward bonus (ΔRewards %) by pool size and pledge amount. The table shows the calculated optimal rewards and the percentage increase over a zero-pledge baseline.

The simulation confirms that the economic impact of pledge is non-linear and varies with a pool's size.

- **Marginal impact of small pledges:** For smaller pools and for pledges under 1M ADA, the reward bonus is marginal (e.g., +0.039% for a 100k pledge), an amount unlikely to be a deciding factor for delegators.
- **Exponential scaling at saturation:** As pools grow and the pledge amount increases, the bonus scales significantly. For a nearly saturated pool (76M ADA), a 10M ADA pledge yields a +3.92% reward bonus. Pledging the entire pool's stake results in a +30.00% bonus.

This dynamic confirms that the pledge mechanism discourages sybil attacks by creating a greater return for consolidating stake into one large, highly-pledged pool. However, it also introduces a competitive advantage for well-capitalized operators, contributing to the "viability gap" for smaller operators.

It's worth noting that the pledge bonus does not bring more rewards from the Reserves to the Rewards Pot, but rather allocates a larger share of the Rewards pot to the high-pledge pools.

3.5.5 Pledge in practice

To empirically validate the simulation's findings, we analyzed on-chain performance data from all active pools over a 36-epoch period. The methodology for this analysis, detailed in Appendix C, was designed to isolate the economic impact of pledge from other variables. For each epoch, we grouped pools of similar size into performance-matched cohorts that had produced the **exact same number of blocks**, allowing for a direct comparison of how pledge affects the rewards of otherwise equally performing pools.

The on-chain data provides a confirmation of the simulation's core prediction: the reward bonus from pledge scales **non-linearly** with pool saturation and pledge size. The following case studies illustrate this dynamic, showing that while the impact is functionally irrelevant for the vast majority of operators, it becomes a dominant economic factor at the high end of the spectrum.

The analysis of cohorts with lower block production shows that the economic impact of pledge is negligible. For instance, a case study from Epoch 581 found 11 different pools that each produced exactly two blocks. Despite a wide range of pledge amounts—from 794k ADA down to just 187 ADA—the highest-pledge pool earned only **0.07 ADA** more than the lowest.

```
--- Case Study: 11 pools produced 2 blocks in Epoch 581 ---
                                               pool_id  total_stake_ada  pledge_ada  rewards_ada
22  pool10n23qyec2zcetv0e3x7fdjydscsrlet5sph2hgtfc7x5ze56jqn      1043074.99   794100.55       679.36
19  pool1v5g4rmkk0394q6swgfusgzjjzrv9ajy8qntgpuumegka5xhpgam       991267.68   251888.56       679.80
23  pool1tjr4zpndkvwkw3du3fvt59f5men6jhuevt7rpx6xw0wcct5kl04      1060966.75   148926.49       679.45
20  pool16cdtqyk0fvxzfkhjg3esjcuty4tnlpds5lj0lkmqmwdjyzaj7p8      1014793.27   104190.05       679.48
16  pool1qaxrj6n50naglqmzj5puq5sd0awgy9wnqmykpwmcah4vzhndpve       899147.25    67806.80       679.42
15  pool1gf8a46j6hvhad8e48hez4084x34snpua8k7t3kzy9w42q6w60z8       882172.09    42264.68       679.37
18  pool1gvnkmpfu26vncrmhj6hr792kwu32hw553upadcphjwu4qewj7jz       983848.10    42148.81       679.30
14  pool1w9yeaaadjz9563tf2h7katrlujvxnywda8el8z66h02ckccx95x       865607.69    34586.19       679.38
17  pool1p42f6kw9lkgw5tn77kqyrc22zrs4uq298p468gacwzw6gq0ckq2       908598.17     6194.68       679.31
13  pool1lugxr82p89qm35spzwccle405t5dfdznhrasyrtr2cyv2vyfud6       861126.09      785.44       679.30
21  pool1sffl322qgsrsmkcedzzwk05396dkmj56pcepqvj6px3n2re3qu4      1041945.65      187.75       679.30
  -> Analysis: The highest pledge pool earned 0.07 ADA more than the lowest pledge pool.
---------------------------------------
```

Figure 11: Case Study: 11 pools producing 2 blocks each in Epoch 581. The reward delta is negligible.

This pattern holds even as performance increases. In a cohort from Epoch 561 where 11 pools produced 13 blocks each, the reward delta attributable to pledge was still a mere **1.40 ADA**. These amounts are too small to influence delegator choice, confirming that for small-to-medium-sized pools, pledge does not function as a meaningful differentiator.

```
--- Case Study: 11 pools produced 13 blocks in Epoch 561 ---
                                               pool_id  total_stake_ada   pledge_ada  rewards_ada
9   pool18xu4fh88v4naq5u3x9ya5aevfkrfd7a8a4gw6sejdvjnsrpud2a     12532571.95  12532571.95      4639.98
14  pool1ld9hkah2dkzh73pvh9tf6xr0x28us34msv3zcv2sase5vhvq962     14691163.11    466911.97      4644.06
10  pool1yr0cv3dtmhcfgqa6yetvmf769ngk89e6tepecmjrmjl2jzcw2lm     12899291.41    210730.95      4643.61
12  pool1fs2m5rmlx66crcwwrrsf2pcxjhvk7kzdurcqusd3v5gm65cufnj     13508561.88    102979.77      4631.04
15  pool1uzla0r73fvpnvxr07m98nfzlxcv3q26mkjz00cqjfh7uqsyjkju     14820191.15     68400.51      4640.90
7   pool1zpdxs9nsrfrl9l2rywdfxsrqveqfzvqjsy2g24pmkpvkslky3v5     12180437.07     35147.98      4639.98
8   pool1kprt6l4quz03dhqx8jw22spdjvp5dkshdnn567vlexqkj35hd8a     12464247.01     32067.82      4604.24
13  pool10pd44d65586rldtdzuu88e7mn4sxjctvdksmt05nnqfzqu7g7hd     13684854.44      4795.16      4639.98
11  pool18jqumjfevywycjj54m62g74ghds4mmuyqynpwfkaem0xktazlqw     13250964.95      2726.35      4640.00
6   pool1chtam5czevzk2ttctvltpsc8twlwf6zzyh7kj3jkz72gks975sn     12059799.62      1008.47      4640.00
5   pool1ea568m9q882n0tx5d4vxff2dmz2n7rq5h62hx5ystq625m4tcfu     11836662.18      1002.83      4638.58
  -> Analysis: The highest pledge pool earned 1.40 ADA more than the lowest pledge pool.
---------------------------------------
```

Figure 12: Case Study: 11 pools producing 13 blocks each in Epoch 561. The reward delta remains insignificant.

Even for pools producing a significant number of blocks, the pledge bonus remains marginal unless the pool is also approaching saturation. Two separate cohorts where pools produced 20 blocks each—one from Epoch 574 and another from Epoch 575—show reward deltas of only **26.53 ADA** and **0.90 ADA**, respectively. These amounts are insignificant compared to the total rewards of nearly 7,000 ADA per pool.

```
--- Case Study: 3 pools produced 20 blocks in Epoch 574 ---
                                                   pool_id  total_stake_ada  pledge_ada  rewards_ada
5  pool1vdh6kxcqt9mxavyv80ggnec6jjwms44ms30rhle3lt266aj8jgh      26605861.74  1005161.19      6918.45
4  pool1smy2r8jdvgna5ykhe8rrch7h4qalyfafyzyh0rmanmq0jxptww7      24377455.46    61237.22      6893.28
6  pool12udshcl3ycj4qpxes28n0ugsye23h89rj8z2a5ast4482m08xe7      26925519.62    49757.14      6891.92
 -> Analysis: The highest pledge pool earned 26.53 ADA more than the lowest pledge pool.
----------------------------------------
```

Figure 13: Case Study 1: 3 pools producing 20 blocks each in Epoch 574.

```
--- Case Study: 4 pools produced 20 blocks in Epoch 575 ---
                                                   pool_id  total_stake_ada  pledge_ada  rewards_ada
6  pool1fg42yz0qpu5jd0gd3g5xty4mm6jdxkje8szag8h798nyyxw6zd3      20889475.24   100543.82      6879.72
5  pool1p9sjhjx0v3k76wvgdqu7jcks2ra48wqlhc6g0mkewd25k3zcymy      20271687.01    59706.74      6880.17
8  pool126mkma8nv5axltmz7mmg8qz9e70nmhnf58hwx5772fhwgkhk6ag      24074142.16    28957.46      6879.34
7  pool130c3kgpkjctag540j7sxqfrlhsmpc6d8u0n7j6crm9ayy75mkpt      21187511.86    14078.32      6878.82
 -> Analysis: The highest pledge pool earned 0.90 ADA more than the lowest pledge pool.
----------------------------------------
```

Figure 14: Case Study 2: 4 pools producing 20 blocks each in Epoch 575.

The effect of pledge only becomes a dominant economic force at the extreme end of the spectrum, precisely as the simulation predicted. A powerful case study from Epoch 583 provides the clearest evidence: two nearly saturated pools both produced exactly **87 blocks**. The only significant variable was their pledge. One pool was fully self-pledged with **~74M ADA**, while the other had a pledge of **~203k ADA**. The result was a staggering reward delta of **8,850.36 ADA** directly attributable to the larger pledge.

```
--- Case Study: 2 pools produced 87 blocks in Epoch 583 ---
                                                   pool_id  total_stake_ada   pledge_ada  rewards_ada
2  pool1yyar66t9fw9dscj8huhredgwplcnf22zq7q7vugur0t5c9nzt97      74027432.74  74027432.74     37520.55
1  pool1vx9tzlkgafernd9vpjpxkenutx2gncj4yn88fpq69823qlwcqrt      72005340.36    203160.44     28670.20
 -> Analysis: The highest pledge pool earned 8,850.36 ADA more than the lowest pledge pool.
----------------------------------------
```

Figure 15: Case Study: 2 saturated pools producing 87 blocks each in Epoch 583, showing a dramatic reward delta.

These results empirically demonstrate the pledge mechanism is working as designed: it creates a powerful incentive to consolidate capital into a single, highly-pledged pool while offering a negligible reward bonus for low-pledge pools, thereby resisting Sybil attacks. However, this also confirms that for the vast majority of operators who cannot pledge millions of ADA, the mechanism fails to provide a meaningful "skin in the game" signal and creates a significant competitive advantage for the most well-capitalized actors.

3.5.6 The influence of apparent performance

While the analysis shows high-pledge pools earning more, there are isolated instances where a pool with a higher pledge earns less than a competitor in the same performance cohort. This highlights the importance of apparent performance ($\bar{p}$)—a measure of blocks produced versus blocks *expected*. A high-pledge pool that underperforms its statistical expectation can receive a performance penalty that outweighs its pledge bonus, resulting in a lower final reward than a low-pledge pool that overperforms. These cases demonstrate that the incentive structure balances two operator virtues: **long-term commitment (pledge)** and **epoch-to-epoch reliability (performance)**.

3.6 Analysis of Multi-Pool Operators (MPOs)

The primary objective of this section is to analyze the influence of large-scale, professionalized staking entities, commonly known as Multi-Pool Operators (MPOs), on the decentralization of the Cardano network. This is critical for evaluating the incentive scheme's effectiveness in mitigating Sybil-like centralization risks.

To focus the analysis on entities with a significant potential for market influence, this report defines an MPO as any entity operating **more than five pools**. This scale indicates a professionalized operation with a strategic approach to market share, distinct from the organic growth of a single successful pool into a few additional ones. The identification of these MPO groups was conducted via a heuristic analysis of on-chain data, correlating pools that share common identifiers in their registration metadata, such as pool tickers, reward addresses, and DNS domain names.

It is important to contextualize the nature of these MPOs. The term is a broad descriptor that encompasses entities with different motivations. In many cases, these operators have a legitimate right and even a responsibility to manage a large number of pools. This includes large exchanges providing custodial staking, which are mandated to maximize returns for their customers (who are, themselves, ADA holders). It also includes large private funds or individuals staking their own substantial capital. Therefore, while the concentration of stake under a single MPO is a factor in decentralization metrics, it does not in itself signify a malicious Sybil attack. The analysis that follows focuses on the observable on-chain impact of these groups, regardless of their underlying motivation.

3.6.1 MPO stake evolution (Epoch 208-584)

The two charts tracking Multi-Pool Operator (MPO) stake show the distribution of stake among all operators running more than five pools.

% of circulating supply: The total stake controlled by all MPOs (as defined above) remains in a stable range, ending the period at approximately 22% of the total circulating supply (defined as 45B ADA - Reserves, the basis for calculating the pools saturation point).

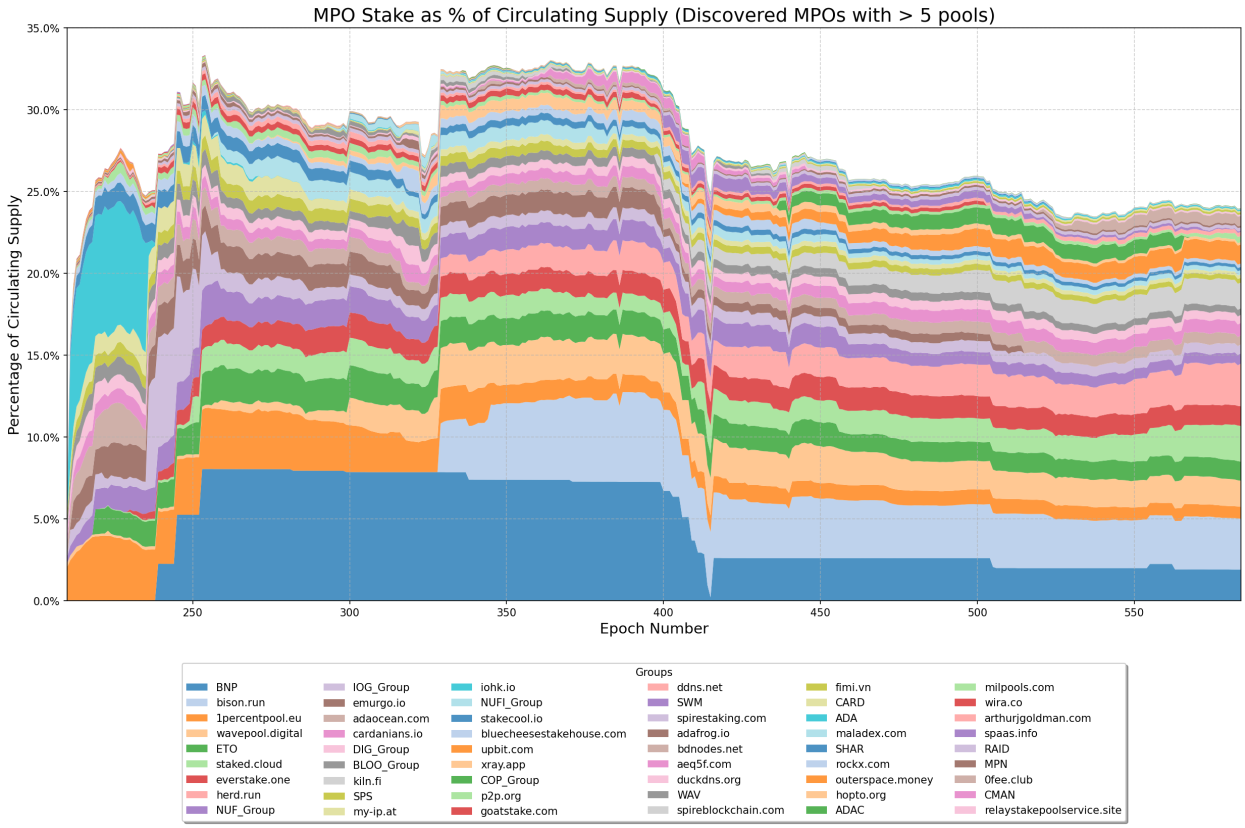


Figure 16: MPO Stake as a Percentage of Circulating Supply (Epochs 208-584). This chart shows the stability of stake held by large MPOs relative to the total stake (circulating supply).

This level of stake concentration does not pose a risk to network security, as the Nakamoto Coefficient remains high (see next section). However, it is worth noting that Section 2.1.5 of the *Shelley-era Delegation and Incentives Design Specification (SL-D1)*, in its discussion of Neutral addresses, states: ***"We should provide addresses that can hold value, but do not contribute to the PoS protocol. Those might be appropriate for use by exchanges, which will hold large amounts of value, without legally owning it."*** This suggests the specification's authors may not have anticipated that exchanges would eventually offer custodial staking services (as many now do) or that they would come to hold such large proprietary amounts of ADA..

Internal Composition: The internal dynamics of the MPO category show a noticeable shift around epoch 400. Prior to this, *Binance* and *bison.run* held a significant 13% of the stake. However, a substantial drop in their controlled stake at epoch 400 caused a corresponding decrease in the

MPO group's total share. In the period since, the landscape has stabilized. While these prominent MPOs remain large, the relative market shares among all major operators have held steady. Notably, no new major multi-pool operators have emerged, suggesting a mature and potentially consolidated market.

3.6.2 From the Edinburgh Decentralization Index

The Edinburgh Decentralization Index shows that Cardano is among the most decentralized blockchains in the industry. Two key metrics from the index directly relate to our MPO analysis: the Nakamoto Coefficient and the 1-concentration ratio.

Nakamoto Coefficient The Nakamoto Coefficient, representing the minimum number of independent entities (pools) required to control 51% of the stake, shows a consistent and significant upward trend. It begins the period at a value of approximately 20 and rises to a value approaching 80 by epoch 584.

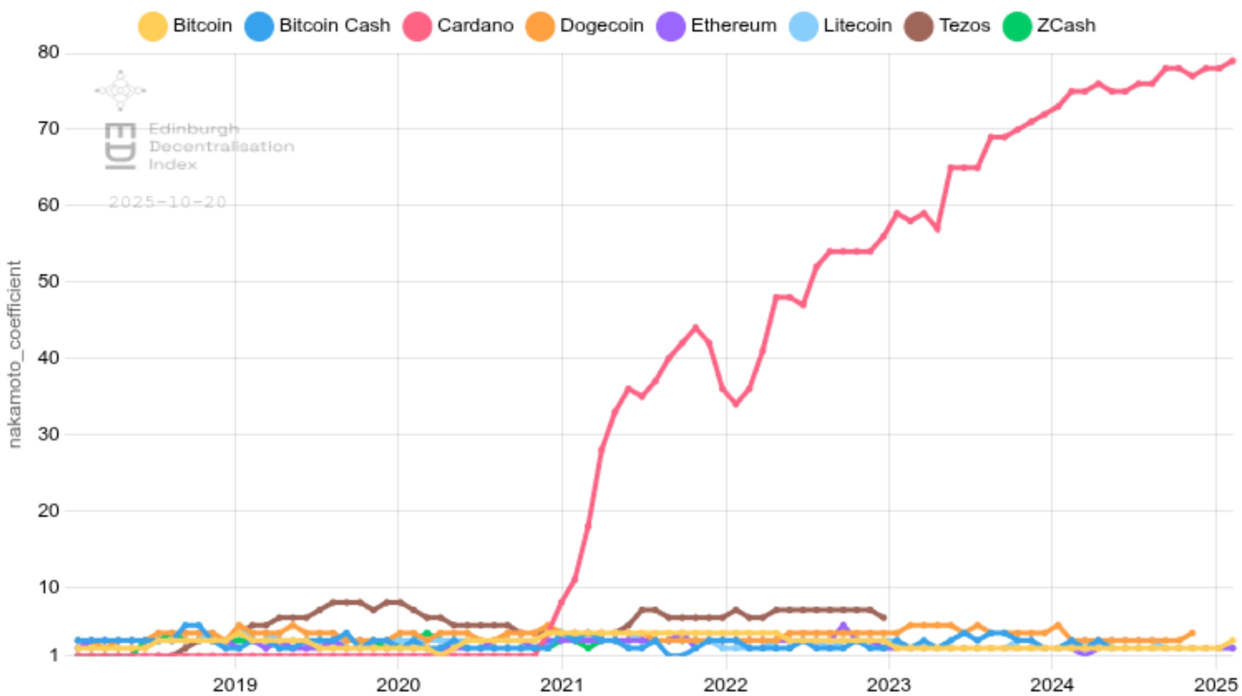


Figure 17: Nakamoto Coefficient. The steady increase demonstrates a consistent improvement in the network's decentralization and security against collusion.

1-Concentration Ratio This chart plots the share of blocks produced by the single most powerful entity. The on-chain data shows a clear and steady downward trend, starting from approximately 25% at the beginning of the period and decreasing to just over 10% by epoch 584. This downward slope is a strong indicator of increasing decentralization, as it demonstrates that the influence of the single largest block producer has consistently diminished over time. This metric, complementary to the Nakamoto Coefficient, confirms that the network's consensus power has become progressively more distributed.

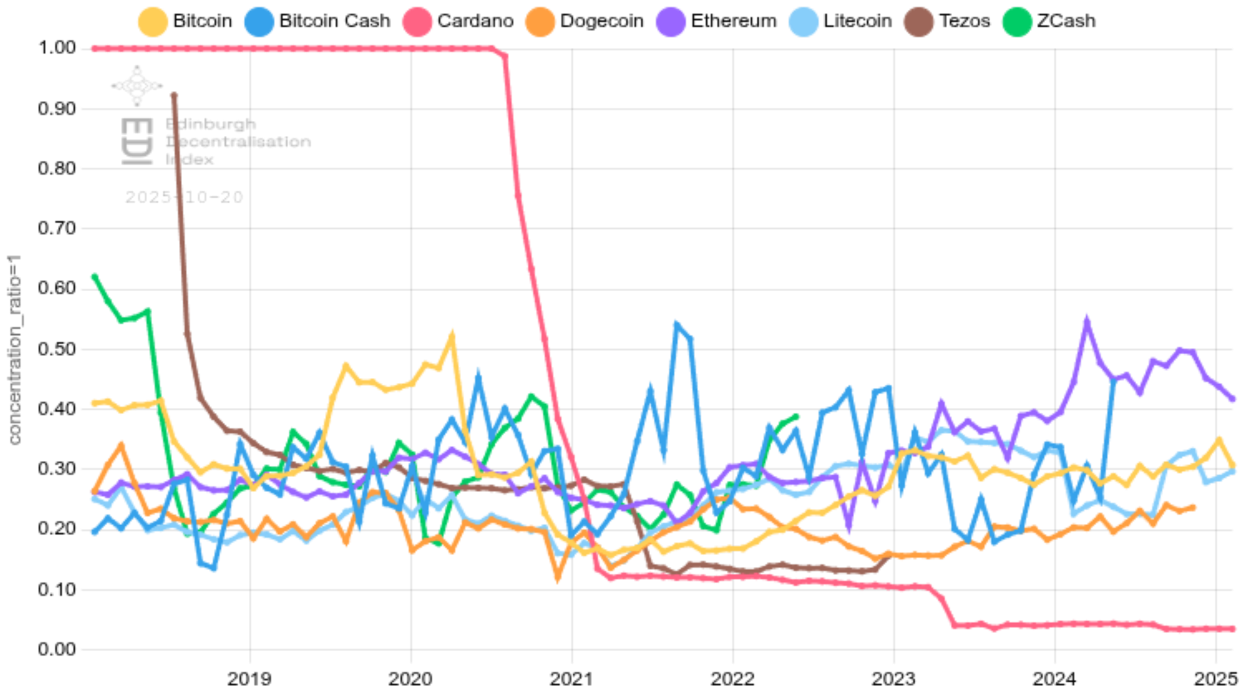


Figure 18: 1-Concentration Ratio. The sustained downward trend indicates a decreasing concentration of block production and a corresponding increase in network decentralization over time.

3.7 Automatic rewards distribution

The design goal of an automatic and efficient rewards system is one of the most verifiably successful aspects of the incentive mechanism. Distribution of rewards is a deterministic protocol function,requiring no manual intervention from either stake pool operators or delegators. As designed, earned rewards are automatically calculated by the ledger and credited to the appropriate reward accounts two epochs after the epoch in which they were generated. This automated process has proven to be both reliable and efficient, seamlessly distributing rewards each epoch without causing the transaction bursts or UTXO bloat that the design specification explicitly sought to avoid. The mechanism's flawless execution in the live environment serves as direct empirical validation of this core design principle.

3.8 Network sustainability trends

The chart below illustrates key trends related to the sustainability of Cardano's staking reward mechanism, plotting historical data from epoch 208 to 583 and projecting future trends.

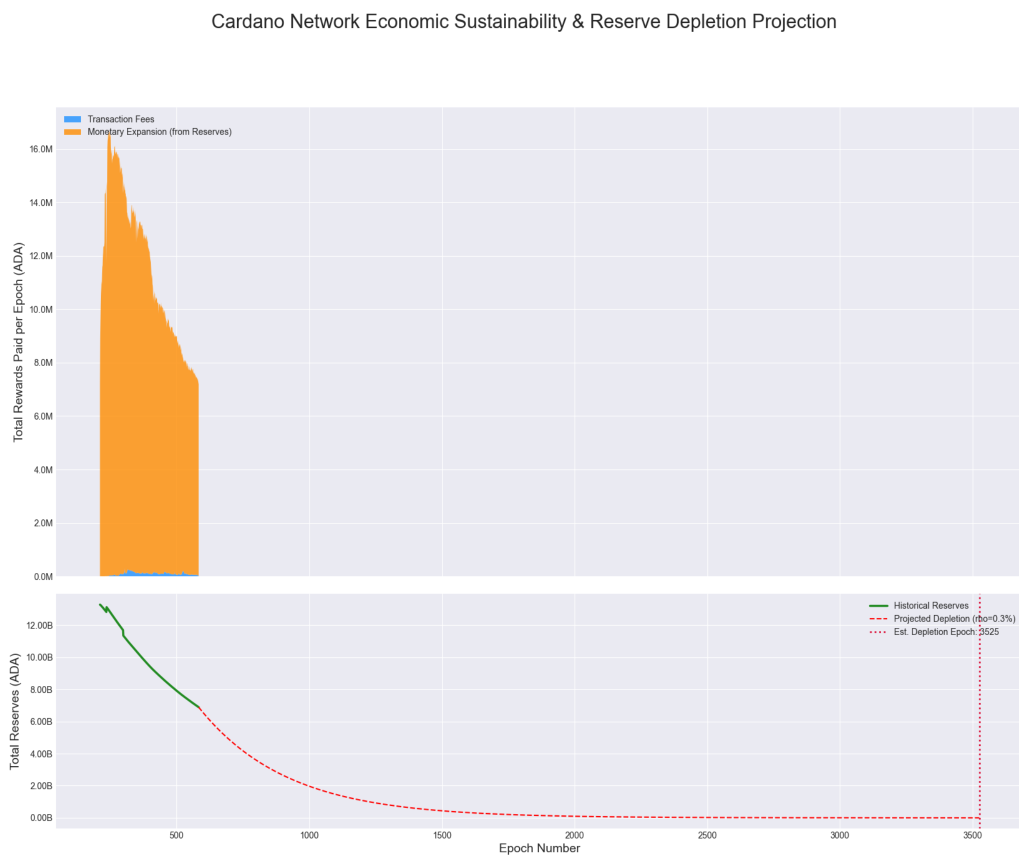


Figure 19: Cardano reward funding sources and Reserves projection

The top panel clearly shows that the vast majority of staking rewards distributed are currently funded by monetary expansion drawn from the ADA reserves (parameter ρ). Transaction fees contribute only a minor fraction to the total rewards paid. The bottom panel depicts the historical decline of the ADA reserves due to this monetary expansion and projects its depletion, estimating reserves will run out around epoch 3500.

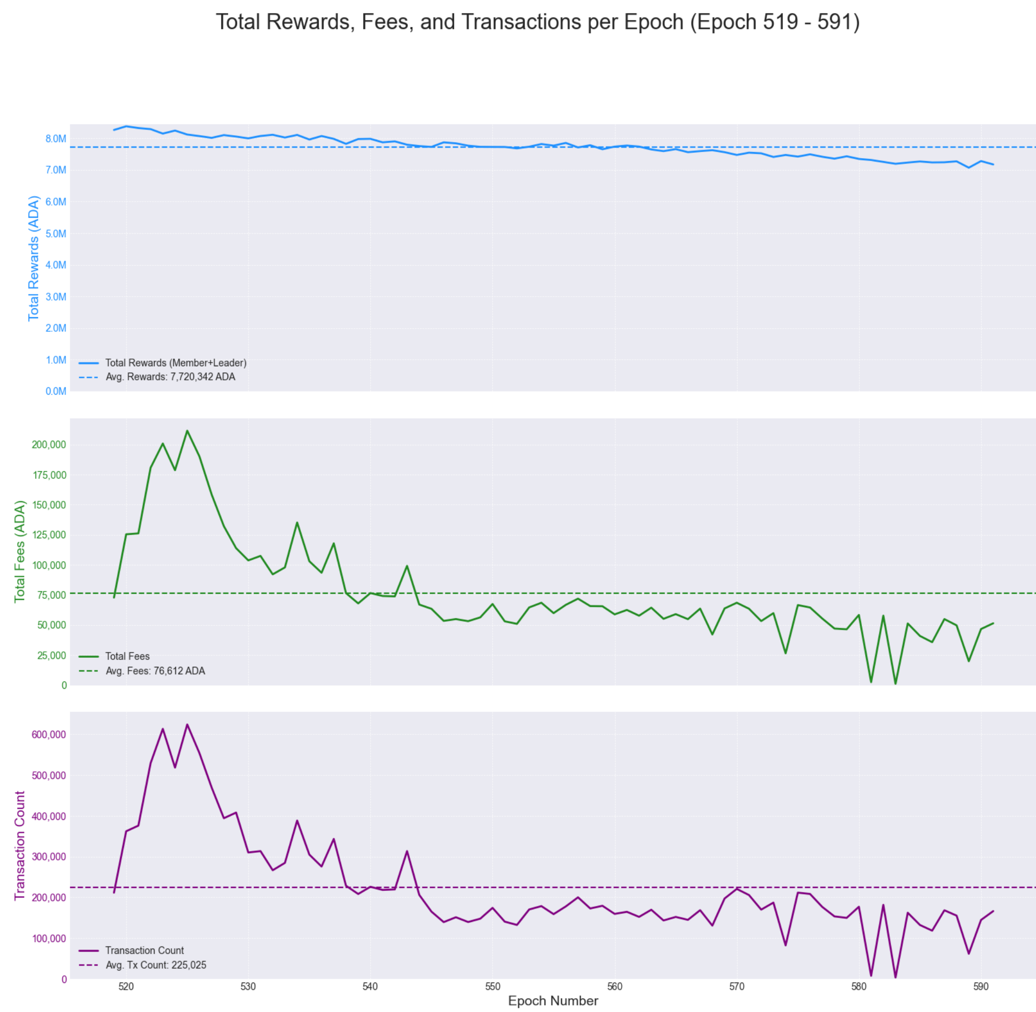


Figure 20

An analysis of the last 73 epochs (1 year) shows that Cardano processed an average of 233,909 transactions per epoch. At an average fee of 0.32 ADA, these transactions generated 76,902 ADA in fees per epoch.

This revenue contrasts with the approximately 7.7 million ADA per epoch in rewards paid out to stake pools and their delegators during the same period. Consequently, current transaction fees cover only 0.9% of distributed rewards. As rewards from reserves diminish, the gap between fee revenue and rewards paid will continue to grow.

To understand the path to a fully fee-driven model, it is crucial to differentiate between the network's theoretical and realistic capacity. While the 90,112-byte block size allows for an absolute theoretical maximum of 22.5 TPS (based on a minimal 200-byte transaction), the current average transaction size of 1,436 bytes defines a more realistic throughput. At this average size, a block can fit 62 transactions, capping realistic network throughput at 3.1 TPS. This realistic throughput equates to a maximum of 1,339,200 transactions per epoch, yielding a potential fee revenue of approximately

428,000 ADA per epoch—a figure still far from the current rewards level.

This analysis highlights two distinct needs. First, increased utilization is required, as the current yearly average of 233,909 transactions per epoch represents only 13% of the network's realistic capacity. Second, and more importantly, a substantial increase in raw network capacity is essential. To cover current rewards solely through fees, the network would need to process approximately 12-16 times more transactions than its current realistic maximum allows.

The heavy reliance on reserves to fund rewards was designed to bootstrap the network and incentivize participation during its growth phase. The network must now mature toward a fee-driven model as reserves deplete.

If transaction levels remain at present levels, significant pressure on the reward system may emerge between epochs 1000 and 1200, roughly to the point when the reserves decline to 2 billion ADA. This underscores the criticality of increasing fee revenue for the system. The upcoming Leios upgrade, which aims to substantially increase network capacity, is very important to achieve a fee-driven model, but that is only half of the equation: Leios provides the necessary infrastructure for higher throughput, long-term sustainability hinges on the growth of the Cardano ecosystem to create the applications and utility to drive the transaction volume needed to adequately fund staking rewards through fees alone.

In addition to network capacity and increasing utilization, other strategies to enhance fee revenue and Cardano competitiveness should be explored. These include Tiered Pricing Models like the one proposed in *Tiered Mechanisms for Blockchain Transaction Fees* [3]. This research proposes a mechanism that separates available space in each block into a maximum of k different tiers. Each tier has its own delay and price parameters, with delays increasing and prices decreasing in successive tiers. The delay of the first tier is always set to 1, i.e., it is minimal, while all other delays and prices change dynamically.

3.9 SPO focus group findings

Between September 11 and 17, 2025, five focus groups were held with Stake Pool Operators (SPOs) from around the world, representing a variety of pool sizes and experiences. These sessions were designed to gather qualitative insights into the current SPO landscape.

3.9.1 What motivates stake pool operators

Across the discussions, a consistent set of motivations emerged:

- **Ideological alignment:** A primary driver is a belief in Cardano's core principles of decentralization and its research-based approach.
- **Technical interest:** Many operators are passionate about technology and view running a pool as a hands-on way to learn and contribute to network infrastructure.
- **Financial incentives:** The potential for revenue is a driver, whether as passive income or a strategic way to acquire ada to cover operational costs.
- **Community engagement:** A desire to engage with the Cardano community, support the ecosystem, and fund real-world projects is a recurring theme.

[3] Kiayias, A., Koutsoupias, E., Lazos, P., & Panagiotakos, G. (2023). *Tiered Mechanisms for Blockchain Transaction Fees*. Available at: https://arxiv.org/pdf/2304.06014.pdf

3.9.2 Key challenges and frustrations

Despite their motivations, SPOs consistently face a significant set of challenges:

- **Attracting and retaining delegators:** This was identified as the most common problem. Delegator stake is often “sticky,” rarely moving from large or even retired pools, making it difficult for smaller pools to gain visibility and grow.
- **Economic viability and rising costs:** The rising cost of hardware and server maintenance, coupled with declining Return on ADA (ROA), makes it increasingly difficult for SPOs to remain profitable.
- **Centralization and competition:** A concern is the concentration of stake in a few large entities and centralized exchanges, which operate many pools and make it difficult for smaller, community-focused SPOs to compete.

3.9.3 Ineffective protocol parameters

- **Pledge:** There is widespread frustration that the pledge parameter has little impact on rewards unless the amount is exceptionally large, failing to function as the intended “skin in the game” mechanism for most operators.
- **Minimum pool fee:** This is a point of contention. While smaller pools rely on the fixed fee to cover costs, it can also deter delegators who see their rewards consumed.
- **Slow pace of protocol changes:** Operators expressed frustration with the slow progress on implementing improvements to incentive parameters that have been discussed within the community for years.

3.9.4 Discussion of existing proposals

SPOs provided feedback on several proposals aimed at addressing these challenges:

- **Minimum margin proposal:** The general sentiment was that a minimum margin could create a fairer environment, but there were concerns that large pools could set their margin to the minimum while smaller pools would need a higher margin to be sustainable.
- **CIP-50 (pledge leverage):** This proposal was generally viewed positively as a way to make pledge more effective, though some worried it could put more pressure on SPOs in a growth phase.
- **Raising the k value:** Increasing the k parameter was contentious. Some saw it as a way to encourage decentralization, while larger pools felt like they would be penalized for their hard work and success.

4 Synthesis and evaluation

This section synthesizes the findings from the preceding analysis to evaluate the performance of Cardano's stake pool incentive mechanism. By comparing the theoretical design goals from section 2 with the empirical on-chain outcomes from section 3, we can directly address the project's primary objectives and offer an informed conclusion on the system's health and effectiveness.

4.1 Evaluating the achievement of design goals

The incentive mechanism has been a resounding success in achieving its core **technical and security goals**, while simultaneously highlighting the **divergences between a simplified economic model and the complex, human-driven reality** of a live ecosystem.

4.1.1 Observed successes

- **A highly performant and secure network:** The goal of incentivizing performance and participation has been unequivocally met. The network is reliably secured by 741“Healthy” 246“Viable” stake pools,and 627 pools that are struggling but are ready to produce blocks when called upon. The system consistently achieves an efficiency of over 98% of block production. The high Nakamoto Coefficient and decreasing concentration ratio further confirm the network is robustly decentralized.
- **Flawless automatic rewards:** The goal of an automatic and efficient rewards system is fully realized. The protocol has functioned flawlessly since inception, distributing rewards every epoch without manual intervention or the negative network effects (like UTXO bloat or transaction bursts) the design specification sought to avoid.
- **Effective Sybil resistance:** The pledge mechanism, as the primary tool for Sybil resistance, works exactly as designed in its primary function. Both simulation and on-chain case studies prove it creates a powerful, non-linear economic incentive to consolidate capital, making the creation of many low-quality pools uneconomical.

4.1.2 Divergences between model and reality

- **The paradox of pledge:** While an effective Sybil deterrent, the pledge mechanism **fails as a meaningful “skin-in-the-game” signal** for the vast majority of operators. As shown in the analysis, the reward bonus is “functionally irrelevant” fo‘r pledges under 10M ADA (e.g., deltas as low as 0.07 ADA) , a finding echoed by frustrated SPOs. This creates a severe competitive imbalance, where the mechanism only benefits well-capitalized actors, directly contributing to the “viability gap”.
- **Equilibrium reality vs. The k expectation:** The expectation of the ecosystem converging on k desirable pools (currently 500) was a theoretical outcome based on a model of perfectly rational economic actors. This is not a design failure, but a clear illustration of the gap between a simplified model and a human-driven ecosystem. The on-chain reality is a more complex, stratified system with 1,614 active pools. While not the $k = 500$ prediction, the system *has* achieved a **substantial and stable equilibrium**, characterized by a consistent operator structure and a predictable rate of registrations and retirements. The core issue is that within this stable equilibrium, 873 active operators remain below the 3M ADA viability

line. **16B ADA remaining outside the consensus mechanism** is a major real-world factor creating a capital-constrained environment that cements this viability gap.

- **The Complexity of actor behavior:** The assumption of a purely "rational delegator" is a necessary simplification used in game theory to allow for formal reasoning about a model. It is not a prediction of individual behavior, as reality is always far more complex. The empirical analysis highlights these complexities.

4.2 Determining the need for protocol changes

The findings indicate that the system requires **fine-tuning and targeted revisions, not a complete overhaul**. The fundamental game-theoretic model is sound for its primary purpose: securing the network.

However, the system is not optimal. The significant divergences—particularly the ineffectiveness of pledge for most operators and the persistent "viability gap", necessitate adjustments. The operator frustration with the slow pace of change on these known issues underscores this need.

The analysis points toward three avenues for improvement:

1. **Parameter adjustment:** The pledge mechanism fails to provide a meaningful signal for most operators , and fee structures are a point of contention. This suggests a re-evaluation of these parameters is warranted.
2. **New on-chain mechanisms:** The "viability gap" affecting 873 active but struggling operators points to a structural problem that parameter-tuning alone may not solve. This suggests a need to explore new protocol-level mechanisms, such as the "virtual pool" or pool alliance concept, to allow smaller operators to combine resources and compete effectively.
3. **Discuss minPoolMargin**: The widespread support among operators for a minimum margin parameter indicates that this change could address some economic viability concerns. Given that a formal proposal already exists, it is recommended that this proposal be formally analyzed and validated against the findings in this report and the changes to be included in the upcoming Dijkstra era hardfork.

5 Conclusions and recommendations

We conclude that the **most significant *immediate* risk to the network is social, not technical**, while a significant *long-term* risk is economic.

- **Technical risk is low:** The network is robustly decentralized and secure. The existence of 741 "Healthy" pools far exceeds original design requirements. The analysis of MPOs shows their stake is stable and does not pose a systemic threat to consensus.
- **Social risk is high:** The primary immediate risk is **operator disillusionment**. This is a direct consequence of the divergences identified above. The large number of active but unprofitable operators (873 pools below the 3M ADA viability line) has created a disenfranchised segment of the community. These operators feel the system is inequitable, citing the pledge paradox (which only benefits whales), the high barrier to consistent rewards, and the struggle against delegator inertia. This social friction is fundamentally rooted in the network's underlying wealth distribution: a small number of wallets control a majority of the delegated stake, and a substantial portion (16B ADA) remains unstaked.
- **Long-Term economic risk:** Beyond the social risk, the analysis confirms a critical long-term **economic risk: network sustainability**. As detailed in Section 3.8, the current reward model is overwhelmingly subsidized by the ADA reserves, which are on a finite depletion schedule. The network's long-term survival is contingent on a successful transition to a fee-market model, where transaction fees alone are sufficient to incentivize stake pool operators.

This places immense importance on the forthcoming **Leios upgrade**. While Leios is designed to provide the necessary network capacity for high throughput, it only creates the "highway" and does not guarantee the "traffic". The primary long-term risk is a failure to generate the ecosystem growth required to produce sustainable transaction volume.

This suggests a strategic imperative for the community. Ecosystem funds, particularly the **Treasury and Project Catalyst**, should consider prioritizing and directing resources toward identifying and nurturing "killer apps" with the potential for mass adoption that can drive significant on-chain activity in the Leios era. To accelerate this growth, projects should also be encouraged to seek traditional **VC funding** and not rely solely on community-governed treasuries.

Finally, the economic model itself requires active governance. The monetary expansion parameter, ρ **(rho)**, is a key component of the current reward subsidy. Should the fiat value of ADA rise to new, sustained levels, the real-world value of these rewards could become misaligned with security needs. This, and all other core economic parameters, must be considered dynamic and subject to being **revisited and updated via governance** to ensure the long-term economic health and stability of the network.

5.1 Recommendations

The findings indicate that the system requires targeted revisions and the exploration of new mechanisms rather than a fundamental overhaul. The following actions are recommended:

1. **For governance consideration:**
    - **On the k parameter:** This report demonstrates that the network is securely decentralized with its current number of healthy pools. Determining the *desired* number of pools,

and therefore whether k should be adjusted, is a policy decision that transcends technical analysis. These findings should serve as a key input for a formal, on-chain debate on this matter.

- **On fee parameters:** There is broad operator consensus for introducing a minimum margin protocol parameter. Given that a formal proposal already exists for this, it is recommended that this proposal be formally analyzed and validated against the findings in this report. This exploration should also consider a corresponding reduction or elimination of the minimum fixed cost and be brought forward for debate through the governance framework.

2. **For protocol development:**

   - **Introduce a mechanism for pool alliances:** To directly address the viability gap faced by smaller operators, it is recommended that a research and development track be initiated to create an on-chain mechanism for “joint ventures” or “virtual pools”. This would allow smaller pools to combine their resources to compete more effectively. Such a mechanism could enable these groups to combine resources and operational duties, creating a larger, more reliable, and cost-efficient ‘virtual stake pool’. This capability is, of course, very common in the traditional markets, where companies form consortia, joint ventures, and strategic alliances to pool resources and share risks. We think this is an interesting avenue for future research for Cardano.
   - **Adopt a two-stage process for new economic parameters:** To de-risk future upgrades, any new economic parameters should be introduced via a hardfork with a null or non-active value. The final, active value should then be set by a subsequent on-chain governance action. This separates technical upgrades from economic policy decisions.
   - **Formalize the pruning of inactive pools:** The 1,305 Inactive pools identified in this report are empirical evidence of the ‘stale stake’ problem. This problem was anticipated but deferred in the Shelley-era Delegation and Incentives Design Specification (SL-D1).This report moves beyond confirmation by proposing a more nuanced approach to identifying these pools. Given that the problem predicted in the SL-D1 document is now materialized, we recommend initiating a formal research effort to determine the optimal on-chain mechanism for identifying and pruning abandoned pools. This research should evaluate both the original performance-based criteria and the commitment-based signals introduced here, with the goal of defining a robust, automated system to ensure the long-term health of the active stake pool set.

3. **For future research:**

   - **Investigate unstaked ada:** A market research initiative should be launched to understand the factors driving the ˜16 billion ada that remains unstaked. Understanding this cohort is critical to improving network participation.
   - **Analyze the impact of custodial stake:** A study should be conducted to quantify the impact of custodial stake on governance participation and explore potential solutions to ensure broad and legitimate representation in the decision-making process.
   - **Systematic review of existing proposals:** A comprehensive analysis should be undertaken of all active community proposals related to the incentive scheme. Each proposal, such as those discussed by SPOs, should be evaluated against the diagnostics in

this report to determine its potential as a viable solution for the core problems identified, including the "viability gap" and the ineffectiveness of pledge for most operators.

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