Leverage Staking with Liquid Staking Derivatives (LSDs): Opportunities and Risks

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Abstract

In the Proof of Stake (PoS) Ethereum ecosystem, users can stake `ETH` on Lido to receive `stETH`, a Liquid Staking Derivative (LSD) that represents staked `ETH` and accrues staking rewards. LSDs improve the liquidity of staked assets by facilitating their use in secondary markets, such as for collateralized borrowing on Aave or asset exchanges on Curve. The composability of Lido, Aave, and Curve enables an emerging strategy known as leverage staking, where users supply `stETH` as collateral on Aave to borrow `ETH` and then acquire more `stETH`. This can be done directly by initially staking `ETH` on Lido or indirectly by swapping `ETH` for `stETH` on Curve. While this iterative process enhances financial returns, it also introduces potential risks.

This paper explores the opportunities and risks of leverage staking. We establish a formal framework for leverage staking with `stETH` and identify 442 such positions on Ethereum over 963 days. These positions represent a total volume of 537,123 `ETH` (877m USD). Our data reveal that the majority (81.7%) of leverage staking positions achieved an Annual Percentage Rate (APR) higher than that of conventional staking on Lido. Despite the high returns, we also recognize the risks of leverage staking. From the Terra crash incident, we understand that token devaluation can greatly impact the market. Therefore, we conduct stress tests under extreme conditions, particularly during `stETH` devaluations, to thoroughly evaluate the associated risks. Our simulations indicate that leverage staking can exacerbate the risk of cascading liquidations by introducing additional selling pressures from liquidation and deleveraging activities. Moreover, this strategy poses broader systemic risks as it undermines the stability of ordinary positions by intensifying their liquidations.

1 Introduction

The Ethereum blockchain's transition from Proof-of-Work (PoW) [1] to Proof-of-Stake (PoS) [2, 3, 4, 5] is a remarkable shift towards a more sustainable consensus mechanism. This change, while crucial for energy efficiency, introduces new challenges in staking `ETH`. In PoS-based Ethereum, validators must stake `ETH` to secure the network [6, 7] and earn staking rewards. However, solo staking demands a substantial capital commitment of 32 `ETH` and technical expertise in maintaining a validator node. Additionally, staked `ETH` becomes illiquid during the staking period, limiting its usability for other financial activities.

To mitigate these challenges, Liquid Staking Derivatives (LSDs), also referred to as Liquid Staking Tokens (LSTs), have emerged as transformative solutions. These derivatives enhance the liquidity of staked assets while preserving their earning potential. Retail users can flexibly stake any amount of `ETH` on a liquid staking platform (e.g., Lido) to receive the corresponding LSDs. These LSDs are fungible and tradable representations of the staked ETH and its associated rewards. At the time of writing, Lido stands as a leading LSD provider on Ethereum, marked by its top position with a Total Value Locked (TVL) of 40b USD[1].

In the LSD primary market, platforms such as Lido allow users to convert their ETH into stETH, which can then be used in various ways within the Decentralized Finance (DeFi) ecosystem. Specifically, users might choose to simply hold stETH to accrue a staking Annual Percentage Rate (APR) of around 3.6%[2] or utilize stETH in the secondary market for further financial activities. Notably, stETH can serve as collateral on DeFi lending platforms such as Aave to borrow ETH. This allows users to earn rewards on their staked ETH while utilizing stETH as active investment capital[3]. Additionally, stETH can be traded for ETH in the stETH–ETH pool of a Decentralized Exchange (DEX), such as the Curve protocol.

The composability between Lido, Aave, and Curve facilitates two novel strategies of leverage staking (see Figure 2 and 3). The first, known as "direct leverage staking", involves users staking ETH on Lido in the primary market to receive stETH, which is then used as collateral on Aave to borrow ETH, subsequently restaked on Lido. Users can iteratively execute this process to increase financial returns based on their risk profile. The second strategy, "indirect leverage staking", involves initially swapping ETH for stETH within the Curve pool at secondary market prices, then using the acquired stETH as collateral on Aave to borrow more ETH, which is again swapped for stETH in the Curve pool. This allows users to participate in staking and earn rewards without directly staking their ETH on Lido. Together, these strategies demonstrate the flexibility and depth of the LSD ecosystem, offering varied approaches to increasing returns with leveraged positions.

While leverage staking offers high return opportunities, it also presents potential risks. Under adverse market conditions that lead to a substantial decline in stETH prices, leverage staking can act as a catalyst for market instability by increasing the risk of "cascading liquidations", a phenomenon characterized by successive liquidations that trigger a downward spiral in the stETH price. This paper aims to understand the opportunities and risks of leverage staking. We investigate its mechanisms, evaluate its financial benefits and inherent risks, and assess its broader market impact. We outline our main contributions as follows.

Strategy Formalization. We develop a formal framework for leverage staking with stETH that captures both direct and indirect strategies. We conduct an analytical study to derive key metrics such as leverage staking multiplier, Health Factor (HF), and APR for each position. To our knowledge, we are the first to model leverage staking strategy with LSDs.

Empirical Measurement. We empirically analyze leverage staking spanning 963 days, from Dec 17, 2020 to Aug 7, 2023. We detect 262 direct leverage staking positions with a total staked amount of 295,243 ETH (482m USD), and 180 indirect leverage staking positions, with a total swapped amount of 241,880 ETH (395m USD). We observe that a majority (81.7%) of leverage staking positions yielded an APR higher than that of conventional staking.

User Behavior Analysis. We explore the stETH price deviation in relation to the Terra crash incident. We analyze how users behave when faced with potential liquidations. We discover that users actively deleveraged their leverage staking positions and collectively repaid a substantial debt amounting to 136,069 ETH, further intensifying the stETH selling pressure.

Stress Testing. We perform stress tests on the Lido–Aave–Curve LSD ecosystem to evaluate the impact of leverage staking under extreme conditions where the value of stETH

[1] `https://defillama.com/protocol/lido`, last accessed on Mar 11, 2024.
[2] `https://lido.fi/ethereum`, last accessed on Mar 11, 2024.
[3] `https://github.com/lidofinance/aave-asteth-deployment`

dropped significantly. We find that leverage staking can heighten the risk of cascading liquidations by introducing additional selling pressures into the market. Additionally, we observe that leverage staking contributes to broader systemic risks by exacerbating the liquidation of ordinary positions. Furthermore, our simulations suggest that the deleveraging action taken by leveraged positions can intensify liquidation cascades among system participants.

2 Related Work

We provide an overview of the literature related to PoS staking, LSDs, and DeFi lending.

PoS Staking. The economics of PoS staking has been studied by several scholars. For example, Cong *et al.* [8] developed a continuous-time model to explore the economic impact of staking in token-based digital economies. They found that higher staking rewards lead to increased staking ratios, which in turn predict higher token price appreciation and generate profitable carry trade opportunities with significant Sharpe ratios. Additionally, attention has been given to the security of PoS staking. For instance, Chitra [9] investigated how on-chain lending affects the security of a PoS blockchain. They found that when the yield from lending contracts is higher than the inflation rate from staking, stakers are incentivized to remove their staked tokens and lend them out, thus reducing network security.

LSDs. Tzinas *et al.* [10] studied the Principal-Agent problem in the liquid staking setting. They discussed the dilemma between the choice of proportional representation and fair punishment and proposed a concrete attack to illustrate their incompatibility. Scharnowski *et al.* [11] analyzed the liquid staking basis (e.g., the discrepancy) between the prices of LSDs in the primary and secondary market. They observed that the liquid staking basis widens when cryptocurrency volatility increases and liquidity decreases in the secondary market. Cintra *et al.* [12] utilized the Bayesian Online Changepoint Detection (BOCD) algorithm to identify potential depeg incidents using price data from the curve `stETH–ETH` pool. This research shows that the proposed approach can assist users in managing potential risks.

DeFi Lending. Heimbach *et al.* [13] studied the impact of the Ethereum merge on two DeFi lending platforms, Compound and Aave. They investigated the actions taken by Aave to mitigate the liquidation risk of collateralized `stETH` positions. Wang *et al.* [14] formalized a model for under-collateralized DeFi lending platforms and empirically evaluated the risks associated with leveraging, such as impermanent loss, arbitrage, and liquidation.

3 Background

3.1 Blockchain and DeFi

Blockchain is a decentralized digital ledger that records transactions across multiple nodes to ensure security, transparency, and immutability. It is the foundational technology behind cryptocurrencies such as Bitcoin [15] and Ethereum [1], enabling peer-to-peer (P2P) transactions without the need for a trusted third party. The structure of the blockchain as a series of blocks chained together through cryptographic hashes helps prevent alterations to the data once it has been confirmed on-chain. A permissionless blockchain allows any participant to join and engage without requiring authorization. In this context, the Ethereum blockchain [16] emerges as a pioneering platform, supporting the execution of smart contracts and empowering developers to create various decentralized applications.

DeFi [17] represents an innovative application of blockchain technology, focusing on building open financial systems. DeFi refers to a set of blockchain-based financial services and products that operate without intermediaries, using smart contracts to build an open environment. DeFi innovations ranging from collateralized lending to DEXs are reshaping the financial system. The TVL in DeFi hit a record high of 178b `USD` in Nov 2021, with the Ethereum blockchain driving these DeFi activities.

3.2 Ethereum PoS

The PoS consensus mechanism, first proposed in online forums and later examined by academia [18, 6, 19, 20, 21], has emerged as an energy-efficient alternative to PoW.

Beacon Chain. On Dec 1, 2020, Ethereum marked a significant milestone by introducing its PoS-based Beacon Chain that runs in parallel with Ethereum's PoW Mainnet. In the Beacon Chain, "staking" is introduced through a deposit mechanism, allowing participants to become validators by locking up 32 `ETH` in a designated smart contract. Staking enables validators to contribute to the integrity of the network by participating in the consensus process, including proposing and validating blocks. This not only helps maintain the security of the blockchain, but also allows stakeholders to earn rewards proportional to their contributions, incentivizing more participants to engage in the network's operation.

The Merge. On Sep 15, 2022, the Merge enables Beacon Chain to evolve as the consensus mechanism for the entire Ethereum network [22]. Ethereum now runs on the execution layer and the consensus layer. The execution layer is responsible for executing transactions, defining how the state of the Ethereum network changes over time. The role of the consensus layer entails establishing agreement among validators regarding the state of the execution layer. The Ethereum staking system offers various incentives to validators. Rewards from the consensus layer include block proposal, attestation, and sync committee rewards [2]. The execution layer introduces additional rewards, including priority tips and Maximal Extractable Value tips [23, 24]. Penalties also apply for dishonest behaviors.

The Shapella Upgrade. On Apr 12, 2023, Ethereum underwent the "Shapella upgrade". The Shapella upgrade combines the "Shanghai upgrade" and the "Capella upgrade", which took place on the consensus and execution layer simultaneously [25]. The Shapella upgrade primarily introduces the capability to unstake `ETH` secured within the network. This newfound ability enhances the operational dynamics for both individual stakers and validators. Validators can initiate withdrawals of their staked `ETH`, either partially or in full, enabling them to reclaim their capital and potentially redeploy it elsewhere. Similarly, if a user has staked `ETH` on Lido (see Section 3.4), they now have the flexibility to partially or fully unstake their assets, allowing for greater liquidity and control over their investments.

3.3 Staking Options

Ethereum participants are presented with four distinct staking options as follows.

Solo Staking. In solo staking, individual participants operate their validator nodes by committing a threshold of 32 `ETH`, thus maintaining full control over the staking rewards. However, solo staking necessitates technical expertise to manage a validator node. Furthermore, its substantial capital requirement may render it financially inaccessible for many retail users.

Staking as a Service (SaaS). For users possessing the requisite 32 `ETH` but lacking in technical expertise, SaaS presents a viable solution. SaaS manages the validator node on behalf of the user, utilizing their signing keys to perform on-chain tasks[4]. This simplifies the staking process for individuals and mitigates the risks associated with node management.

[4] `https://ethereum.org/en/staking/saas/`

Pooled Staking. For retail users with holdings below the 32 ETH threshold, pooled staking emerges as a feasible alternative, enabling them to collectively participate in the network's validation process, earn rewards, and capitalize on the broader Ethereum ecosystem without the need for individual, full-node commitments. Typically, staking pools charge fees, which are further split between Node Operators (NOs) and the protocol Decentralized Autonomous Organization (DAO). NOs run and maintain validator nodes on behalf of the staking pool, while the DAO selects NOs and configures crucial parameters for the protocol.

Centralized Exchange (CEX) Staking. CEXs, such as Coinbase and Binance, provide centralized and custodial staking services to users. These services simplify the staking process by managing technical aspects and providing a user-friendly interface. However, such convenience comes with inherent risks associated with the centralized nature of CEX staking. Users must trust these platforms with their assets, making them vulnerable to security breaches, regulatory changes, or operational failures.

3.4 LSD

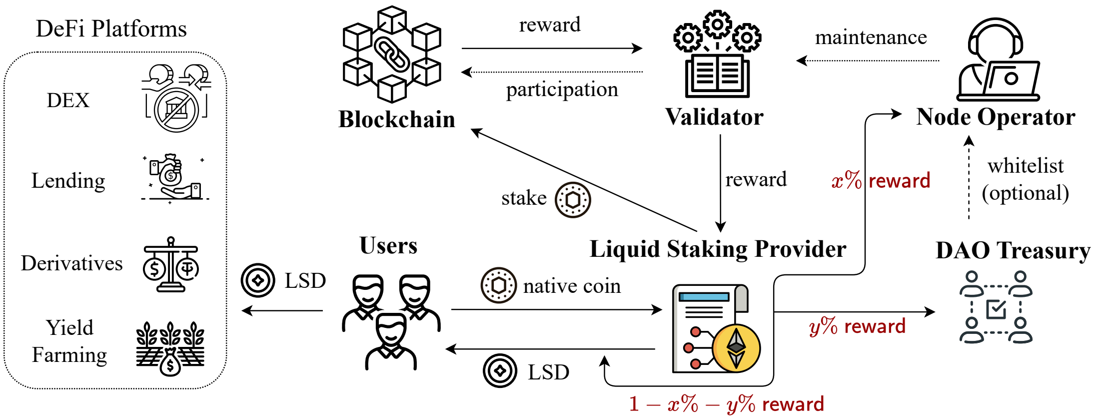

Figure 1: Overview of the LSD Ecosystem.

Staking offers several advantages, from earning rewards to enhancing network security. However, once ETH is locked for staking, it becomes illiquid, making it inaccessible for trading. Given this challenge, the concept of LSD emerged, which represents staked assets and rewards in a tradable form. Figure 1 provides an overview of the LSD ecosystem. When users stake ETH within an LSD provider (e.g., a liquid staking pool), they receive LSDs in return.

At the time of writing, liquid staking protocols accumulate a TVL of more than 53.3b USD, securing the top position in TVL across various DeFi sectors. Users can obtain LSDs through two primary staking methods: pooled staking and CEX staking. Pooled staking protocols such as Lido, Rocket Pool, Frax, Stakewise, and Swell Network provide LSDs to users. CEXs such as Coinbase and Binance also support LSDs.

Lido is currently the leading LSD provider and ranks as the largest DeFi protocol in terms of TVL (40b USD). Users stake ETH on Lido to receive stETH in return. With over 430k stakers, the total amount of ETH staked on Lido reached 9.76m in Mar 2024, accounting for 71% of the total ETH LSDs. stETH implements the *rebasing mechanism*, where stETH holders' account balances get adjusted daily to reflect the accumulated rewards [26]. The rebase can be positive or negative, depending on the validators' performance.

3.5 DeFi Lending Protocols

DeFi lending protocols are decentralized platforms that facilitate P2P lending and borrowing of cryptocurrency assets through the automated execution of smart contracts. At the time of writing, Aave stands as the leading DeFi lending protocol, with a total TVL of 11.6b `USD`[5]. The Aave V2 lending protocol follows an over-collateralization model, meaning that users must supply more collateral value than the borrowed amount. As an illustration, when the collateral value amounts to S `ETH`, the user's borrowing capacity is restricted to no more than $S \cdot l$ `ETH`, where $l \in [0, 1]$ denotes the Loan-to-Value (LTV) ratio. In the event that the collateral value falls below a specified threshold, users may need to add more collateral or risk the liquidation of their asset to repay the borrowed amount and accrued interest. To monitor the collateralization status of each position, Aave utilizes Liquidation Threshold (LT) to establish the threshold percentage that designates a position as under-collateralized, and HF as a key metric to quantify the liquidation status of a position. For example, user $\mathsf{U_i}$'s position can be liquidated if $HF_{(\mathsf{U_i})} < 1$ (see Equation 1).

$$HF_{(\mathsf{U_i})} = \frac{\sum_j \text{collateralized value of asset}_j \text{ in } \texttt{ETH} \cdot \text{LT}_j}{\sum_j \text{borrowed value of asset}_j \text{ in } \texttt{ETH}} \tag{1}$$

4 System Model

We first provide a set of notations to facilitate the understanding of related equations.

Notation	Meaning	Notation	Meaning
S	Initial investment (principal amount) in `ETH`	$p^{1st}_{t_0}$	`stETH` price in the primary market at t_0
l	The Loan-to-Value (LTV) ratio used by Aave	$p^{2nd}_{t_0}$	`stETH` price in the secondary market at t_0
LT	The liquidation threshold used by Aave	$p^{a}_{t_0}$	`stETH` price used by Aave at time t_0
$HF_{\mathsf{U_i}}$	The health factor (HF) of U_i's position	$p^{a}_{t_c}$	`stETH` price used by Aave at time t_c

Table 1: Notations used to formalize the leverage staking strategy.

4.1 System Participants

We consider an LSD ecosystem on the Ethereum blockchain with the following participants.

Users: A user ($\mathsf{U_i}$) is depicted as a rational and strategic entity, proficient in interacting with multiple DeFi platforms. $\mathsf{U_i}$ can adopt diverse strategies to maximize financial returns.

Liquid Staking Providers: $\mathsf{U_i}$ can stake native tokens (e.g., `ETH`) on liquid staking platforms (e.g., Lido) to receive LSDs (e.g., `stETH`). These derivatives can then be used in various financial activities, including trading, collateralized borrowing, and liquidity provision.

Lending and Borrowing Providers: $\mathsf{U_i}$ can supply a single asset on DeFi lending platforms such as Aave, using it as collateral to secure a loan in the form of a different asset.

4.2 Leverage Staking with LSDs

This section introduces and compares three strategies: *(i)* leverage borrowing, *(ii)* direct leverage staking, and *(iii)* indirect leverage staking strategies.

[5] `https://defillama.com/protocol/aave`, last accessed on Mar 11, 2024.

Investment Strategy	Asset Pair	Leverage Pattern	Staking Reward	Deposit-Borrow Revenue
Leverage Staking (Direct)	`ETH`–LSD	Stake→Deposit→Borrow→Stake	✔	✔
Leverage Staking (Indirect)	`ETH`–LSD	Swap→Deposit→Borrow→Swap	✔	✔
Leverage Borrowing	Non-LSD Pair	Swap→Deposit→Borrow→Swap	✖	✔

Table 2: Comparison of leverage staking and leverage borrowing strategies on Ethereum.

4.2.1 Leverage Borrowing

In the context of Etherem, particularly prevalent in its PoW phase, "*leverage borrowing*" emerges as a commonly adopted strategy. This process involves users initially exchanging asset X for Y within a DEX pool. Subsequently, asset Y is supplied as collateral on lending platforms to borrow asset X. This borrowed asset X is then exchanged again for Y in the DEX pool, enabling users to iteratively amplify their leverage borrowing positions.

The financial incentive behind the leverage borrowing strategy lies in the user's ability to expand the deposit-borrow leverage by repeatedly cycling through swapping, depositing, and borrowing. Although the deposit rate offered by the lending platform is lower than the borrowing rate, the larger total amount of asset Y deposited compared to asset X borrowed typically results in net earnings, which can be further amplified through leverage.

4.2.2 Leverage Staking

Following the introduction of PoS staking, a concept analogous to leverage borrowing, termed "*leverage staking*", has emerged. It is a strategy intricately linked with LSDs and involves a recursive cycle of staking/swapping, depositing, and borrowing (see Figure 2 and 3) to increase financial returns. We concentrate our analysis on leverage staking within the Lido–Aave–Curve ecosystem and describe direct and indirect leverage staking as follows.

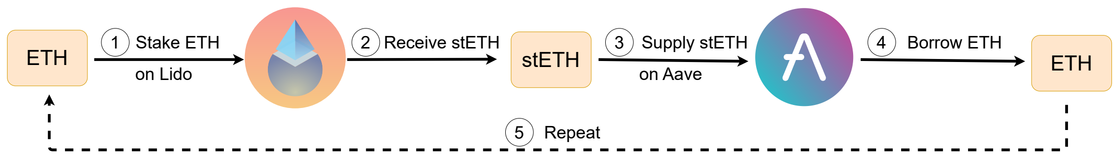

Figure 2: Overview of the direct leverage staking strategy.

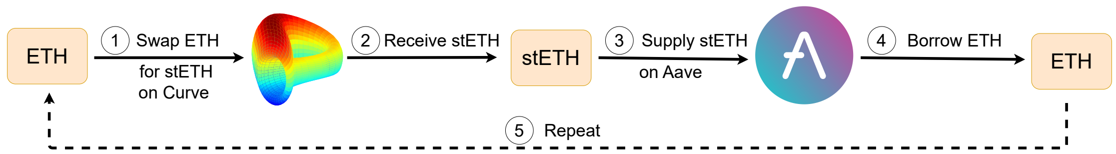

Figure 3: Overview of the indirect leverage staking strategy.

Direct Leverage Staking. $\mathsf{U_i}$ first stakes a principal amount of S `ETH` on Lido at time t_0 to acquire $S/p_{t_0}^{1st} = S$ `stETH`, where $p_{t_0}^{1\text{st}} = 1$ denotes the `stETH` to `ETH` price in the primary market. Next, $\mathsf{U_i}$ supplies `stETH` on Aave to borrow $S \cdot l \cdot p_{t_0}^{a}$ amount of `ETH`, where l denotes the LTV ratio and $p_{t_0}^{a}$ denotes the `stETH` to `ETH` price used by Aave V2 lending protocol[6].

[6]The Aave V2 lending protocol uses the Chainlink price oracle. See `https://etherscan.io/address/0xa50ba011c48153de246e5192c8f9258a2ba79ca9#code`

Then $\mathsf{U_i}$ restakes the borrowed ETH on Lido. $\mathsf{U_i}$ performs this *loop* for n times, amplifying both the staking reward from Lido and the deposit-borrow revenue from Aave.

Indirect Leverage Staking. Instead of acquiring stETH from Lido, $\mathsf{U_i}$ can first swap S ETH for $S/p_{t_0}^{\text{2nd}}$ stETH[7] within the Curve pool at time t_0, where $p_{t_0}^{\text{2nd}}$ denotes the stETH to ETH price in the secondary market. Subsequently, $\mathsf{U_i}$ supplies stETH on Aave to borrow $S{\cdot}p_{t_0}^{a}{\cdot}l/p_{t_0}^{\text{2nd}}$ ETH. The borrowed ETH is swapped again for stETH within the Curve pool. Although not engaging in direct staking on Lido, $\mathsf{U_i}$ can still accrue staking rewards, as stETH employs a rebasing mechanism for reward distribution (see Section 3.4).

Leverage Multiplier. Assume $\mathsf{U_i}$ invests a total asset (staked ETH on Lido or swapped ETH within Curve) of $A_{(S,n)}$ ETH through leverage staking with an initial investment of S ETH, the leverage multiplier $LevM_{(S,n)}{=}\frac{A_{(S,n)}}{S}$ is defined as the ratio between $A_{(S,n)}$ and S.

Direct vs Indirect Leverage Staking. Both direct and indirect leverage staking strategies are designed to amplify staking rewards through a recursive methodology. However, direct leverage staking acquires stETH from the LSD primary market, whereas indirect leverage staking obtains stETH from the secondary market. Notably, indirect leverage staking bypasses the staking process, consequently not contributing to the increase in the total staked ETH within the network. Utilizing the same principal amount of ETH, $\mathsf{U_i}$ generally acquires more stETH through the indirect strategy, as the stETH to ETH price in the secondary market is often below 1. However, this approach incurs additional costs associated with swaps and is susceptible to potential price slippage, often exacerbated by front-running activities.

Leverage Staking vs Leverage Borrowing. While leverage staking and leverage borrowing both exhibit recursive patterns, they diverge for several reasons. Firstly, leverage staking primarily targets LSDs, whereas leverage borrowing is focused on non-LSD tokens. Secondly, leverage staking aims to amplify both staking rewards and the deposit-borrow revenue, while leverage borrowing solely seeks to enhance the deposit-borrow revenue (see Table 2). Third, they bear different risk sources. In addition to market risk, leverage staking involves the risk of slashing (see Section 3.2). To summarize, although the traditional leverage borrowing strategy shares some similarities with the leverage staking strategy discussed in this paper, they differ in terms of underlying assets, income sources, and associated risk.

5 Analytical Study

This section conducts an analytical study on the leverage staking strategy. We also offer a generalized formalization encompassing other potential scenarios in Appendix B.

We assume that $\mathsf{U_i}$ can complete n loops (see Figure 4) within a short time interval such that the stETH price remains unchanged. As a rational participant, $\mathsf{U_i}$ determines the value of n according to its risk profile. Let $p_{t_0}^{a}$ denote the Aave lending price of stETH and $p_{t_0}^{m}$ be the stETH to ETH market price, where $p_{t_0}^{m} = p_{t_0}^{1st}$ for direct leverage staking and $p_{t_0}^{m} = p_{t_0}^{2nd}$ for indirect leverage staking. $\mathsf{U_i}$ acquires a total investment amount of $A_{(S,n)}$ ETH, collateral

[7] Ignore swap fees for illustration purposes.

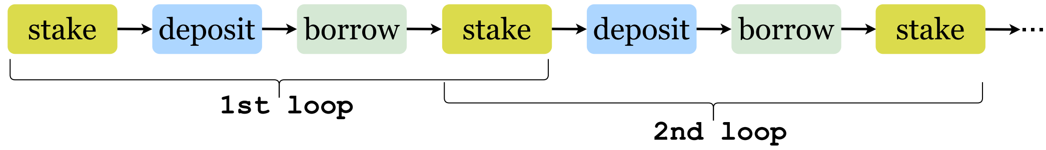

Figure 4: The illustration of direct leverage staking loops. The user completes the k_{th} loop via a sequence of actions: {`stake, deposit, borrow, (re)stake`}. In parallel, an indirect leverage stake loop is characterized by the sequence {`swap, deposit, borrow, (re)swap`}. Within these frameworks, the (re)stake/(re)swap is crucial in completing the respective loops.

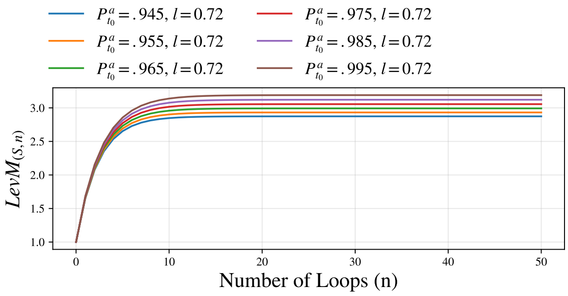

Figure 5: $LevM_{(S,n)}$with varying $p^a_{t_0}$.

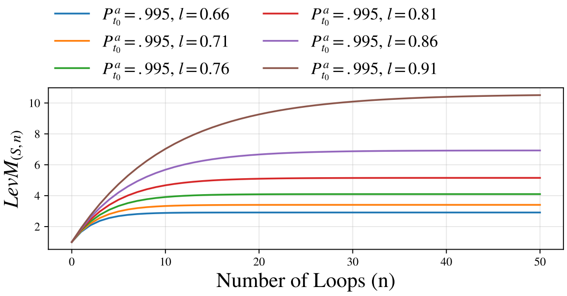

Figure 6: $LevM_{(S,n)}$with varying l.

amount of $C_{(S,n)}$ `stETH` and debt amount of $B_{(S,n)}$ `ETH` (see Equation 2).

$$
\begin{aligned}
A_{(S,n)} &= S \cdot \left[1 + \frac{l \cdot p^a_{t_0}}{p^m_{t_0}} + \ldots + \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^n\right] = S \cdot \frac{1 - \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{n+1}}{1 - \frac{l \cdot p^a_{t_0}}{p^m_{t_0}}} \\
C_{(S,n)} &= \frac{S}{p^m_{t_0}} \cdot \left[1 + \frac{l \cdot p^a_{t_0}}{p^m_{t_0}} + \ldots + \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{n-1}\right] = \frac{S}{p^m_{t_0}} \cdot \frac{1 - \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{n}}{1 - \frac{l \cdot p^a_{t_0}}{p^m_{t_0}}} \\
B_{(S,n)} &= S \cdot \left[\frac{l \cdot p^a_{t_0}}{p^m_{t_0}} + \ldots + \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^n\right] = S \cdot \frac{\frac{l \cdot p^a_{t_0}}{p^m_{t_0}} - \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{n+1}}{1 - \frac{l \cdot p^a_{t_0}}{p^m_{t_0}}}
\end{aligned}
\tag{2}
$$

Leverage Multiplier. In Equation 3, the leverage multiplier is defined as the ratio of $A_{(S,n)}$to S. For direct leverage staking, we use the primary market price ($p^m_{t_0} = p^{1st}_{t_0} = 1$). Consequently, $LevM_{(S,n)}$ simplifies to $(1-(l \cdot p^a_{t_0})^{n+1})/(1-l \cdot p^a_{t_0})$. Figure 5 and 6 show how $LevM_{(S,n)}$ changes in response to variations in the `stETH` price use by Aave ($p^a_{t_0}$) and the LTV ratio (l) respectively. Notably, when looping towards infinity, the value of $LevM_{(S,n)}$ converges to $1/(1 - l \cdot p^a_{t_0})$. For indirect leverage staking where $p^m_{t_0} = p^{2nd}_{t_0}$, when $\frac{l \cdot p^a_{t_0}}{p^m_{t_0}} < 1$, $LevM_{(S,n)}$ coverages towards $1/(1 - \frac{l \cdot p^a_{t_0}}{p^m_{t_0}})$ as the number of loops approaches infinity.

$$
LevM_{(S,n)} = \frac{A_{(S,n)}}{S} = \frac{1 - \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{n+1}}{1 - \frac{l \cdot p^a_{t_0}}{p^m_{t_0}}}
\tag{3}
$$

Health Factor. Leverage staking can yield high returns but also raises the risk of liquidation. $\mathsf{U_i}$'s position may be susceptible to liquidation if the value of the collateralized `stETH` declines following a decrease in the stETH price over time. As discussed in Section 3.5, Aave uses HF to track the status of each position. $\mathsf{U_i}$'s can be liquidated if HF is less than 1 (see Equation 4). In our leverage staking example, the parameters l and LT are 69% and 81% respectively (see Table 3 for the historical changes of Aave configurations). Historically, the Aave v2 lending protocol design always ensures $l <$ LT.

Let $\Delta\%p^a_{\Delta t}$ denotes the percentage change of Aave stETH price from t_0 to t_c. $\Delta\%p^a_{\Delta t}$ is negative if stETH price declines. When stETH price increases, Equation 5 always holds. When stETH price decreases, Equation 5 suggests that, to uphold a secure position with $HF > 1$, the largest acceptable percentage decrease in stETH price is $\frac{l}{\mathrm{LT}} - 1 = -\frac{12}{81} \approx -14.8\%$. In a liquidation event, the user's entire collateralized stETH will be liquidated, and this effect becomes more pronounced as the number of loops (n) increases, as indicated by $LevM_{(S,n)}$.

$$HF_{\mathsf{U_i}}(p^a_{t_c}|p^a_{t_0}) = \frac{\sum_k^n k^{th} \text{ collateralized } \texttt{stETH} \text{ value in } \texttt{ETH} \cdot \mathrm{LT}}{\sum_k^n k^{th} \text{ borrowed } \texttt{ETH} \text{ value}} = \frac{C(S,n) \cdot p^a_{t_c} \cdot \mathrm{LT}}{B(S,n)} = \frac{p^a_{t_c} \cdot \mathrm{LT}}{p^a_{t_0} \cdot l} \tag{4}$$

$$HF_{\mathsf{U_i}}(p^a_{t_c}|p^a_{t_0}) \geq 1 \implies \frac{p^a_{t_c}}{p^a_{t_0}} > \frac{l}{\mathrm{LT}} \implies \Delta\%p^a_{\Delta t} \geq \frac{l}{\mathrm{LT}} - 1 \tag{5}$$

Profit Breakdown. Equation 6 calculates leverage staking profitability. Let r_s, r_c, r_b represent the staking APR offered by Lido and the deposit and borrow interest rates provided by Aave, respectively. It is worth noting that r_s changes in accordance with the validator performance, while r_c and r_b vary based on Aave's interest rate model[8]. $\mathsf{U_i}$ earns a staking APR of $R_s(n)$ and a deposit APR of $R_c(n)$, while pays a borrow APR of $R_b(n)$. In the case of leverage staking, the factor by which $R_s(n)$ is amplified is the total amount of the investment divided by the initial amount of the investment (i.e., $\frac{A_{(S,n)}}{S} = LevM_{(S,n)}$). Similarly, the factor by which $R_c(n)$ is amplified is the total amount of the collateral divided by the initial amount of the collateral (i.e., $\frac{C_{(S,n)}}{S/p^m_{t_0}}$). The same logic applies to $R_b(n)$. As such, $\mathsf{U_i}$ obtains a net APR of $R_{Net}(n) = R_s(n) + R_c(n) - R_b(n)$. The necessary condition for a rational $\mathsf{U_i}$ to apply leverage staking rather than conventional staking is $R_{Net}(n) > r_s$.

$$R_{Net}(n) = R_s(n) + R_c(n) - R_b(n) = r_s \cdot \frac{A_{(S,n)}}{S} + r_c \cdot \frac{C_{(S,n)} \cdot p^m_{t_0}}{S} - r_b \cdot \frac{B_{(S,n)} \cdot p^m_{t_0}}{S \cdot l \cdot p^a_{t_0}} \tag{6}$$

In addition to the standardized scenario discussed above, real-world applications of leverage staking can vary significantly among users. For instance, a user might choose not to reinvest all of their received stETH on Aave. For a more detailed exploration of this variability, please see the generalized formalization in Appendix B.

6 Empirical Study

We outline the empirical evaluation of leverage staking across Aave, Lido and Curve.

Data Collection. We first crawl the on-chain events involving users' actions on the Aave V2 lending pool, including `deposit`, `borrow`, `withdraw`, and `repay` events. For direct leverage staking, we crawl the historical `stake` (i.e, `submitted`) events related to Lido stETH Token when users stake ETH on Lido. For indirect leverage staking, we crawl the historical `swap` (i.e., `TokenExchange`) events for Curve stETH–ETH pool. We use an Ethereum Geth node on a Linux machine running Ubuntu 22.04 LTS, which is equipped with AMD 48-core CPU, 256 GB of RAM, and 12 × 2 TB SSD. We capture all the targeted events from block 11,473,216 (Dec 17, 2020) to block 17,866,191 (Aug 7, 2023), 963 days in total. We identify 290,984

[8] https://docs.aave.com/risk/liquidity-risk/borrow-interest-rate

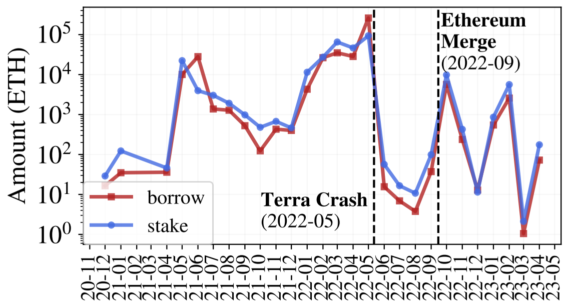

Figure 7: Direct Leverage staking statistics.

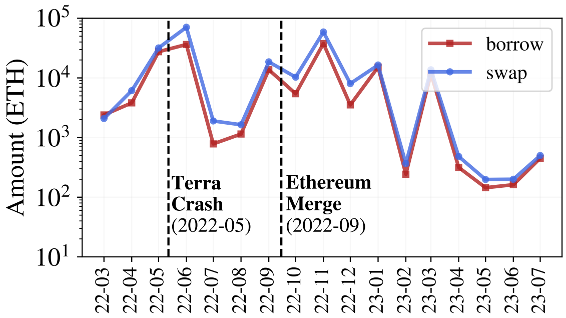

Figure 8: Indirect Leverage staking statistics.

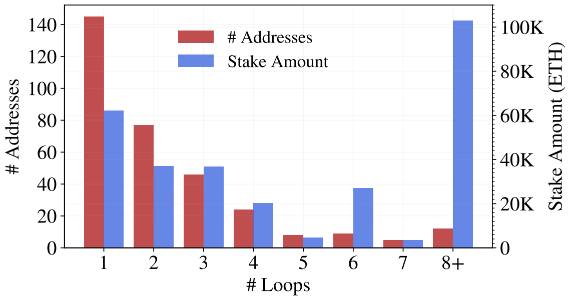

Figure 9: Stake amount and the number of direct leverage staking addresses by loops.

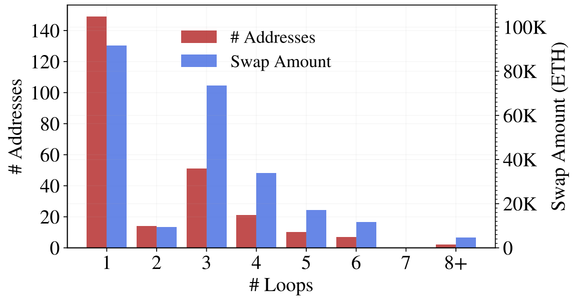

Figure 10: Swap amount and the number of indirect leverage staking addresses by loops.

`stake` events on Lido, 449,528 `deposit`, 238,388 `borrow`, 336,746 `withdraw` and 173,596 `repay` events on Aave V2 lending pool, and 105,310 `swap` events on Curve `stETH–ETH` pool.

Leverage Staking Detection. We proceed to analyze the users who adopt the direct or indirect leverage staking strategy. From the 449,528 `deposit` and 238,388 `borrow` events on Aave V2, we find that 743 addresses are used to deposit `stETH` as collateral and then borrow `ETH`. We then propose Algorithm 1 and 2 (see Appendix C) to identify the addresses involving direct and indirect leverage staking respectively. Specifically, we extract the event sequences of (`stake`, `deposit`, `borrow`, `stake`) and (`swap`, `deposit`, `borrow`, `swap`) in chronological order, which follows the direct and indirect leverage staking process (Figure 4).

We have identified 262 addresses that have been engaging in direct leverage staking activities, with a cumulative stake amount of 295,243 `ETH`. In addition, we observe 180 addresses that have performed the indirect leverage staking strategy, with a cumulative swap amount of 241,880 `ETH`. The distribution of leverage stake and swap amount is depicted in Figure 7 and 8 respectively. Interestingly, we observe that the volume of both direct and indirect leverage staking was substantially impacted by the Terra crash in May 2022. The stake amount of direct leverage staking experienced a drastic decline from the peak monthly stake amount of 93,661 `ETH` in May 2022 to 11 `ETH` in Aug 2022. Similarly, the swap amount of indirect leverage staking declines from 70,655 `ETH` in Jun 2022 to 1,639 `ETH` in Aug 2022. Moreover, the Ethereum Merge brought about a resurgence in leverage staking activities, with a stake amount of 9,814 `ETH` and a swap amount of 10,293 `ETH` in Nov 2022.

Leverage Staking Loops. Among 262 and 180 addresses that have adopted direct and indirect leverage staking, we conduct an analysis focusing on two key elements: the number of loops (denoted as n) and the leverage multiplier (denoted as $LevM_{(S,n)}$), derived from their extracted action sequence $\mathcal{E}_s$ (see Algorithm 1 and 2). To calculate the number of direct

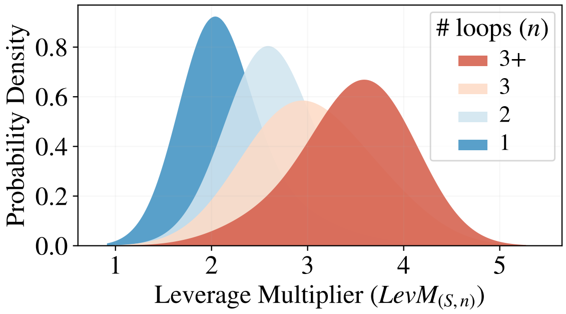

Figure 11: Distribution of direct leverage staking $LevM_{(S,n)}$ by leverage loops.

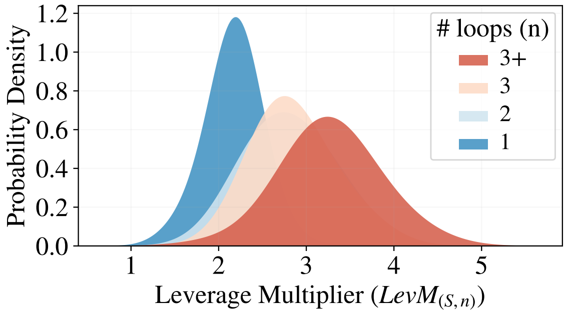

Figure 12: Distribution of indirect leverage staking $LevM_{(S,n)}$ by leverage loops.

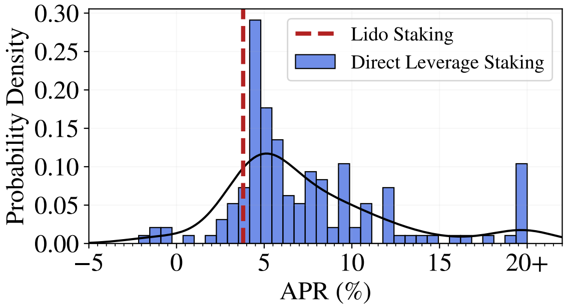

Figure 13: Direct leverage staking APR.

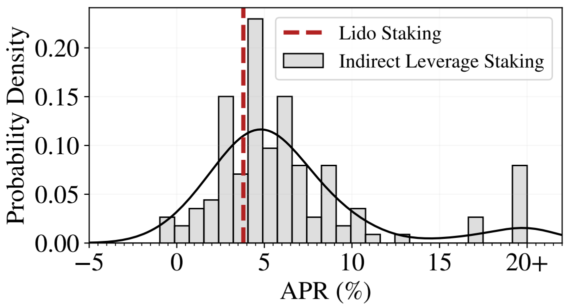

Figure 14: Indirect leverage staking APR.

and indirect leverage staking loops, we identify consecutive sub-sequences in $\mathcal{E}_s$ consisting of (`stake`, `deposit`, `borrow`) and (`swap`, `deposit`, `borrow`) respectively. Figure 9 reveals that 145 addresses (55.35%) performed direct leverage staking with a single loop ($n = 1$), while Figure 10 shows that 149 addresses (82.78%) performed indirect leverage staking with a single loop. Notably, we discover that although only a smaller subset of 12 addresses performs direct leverage staking with more than eight loops, their cumulative staking activities amount to a significant volume of 102,998 `ETH`. This highlights a concentrated yet substantial engagement in direct leverage staking. In contrast, only 2 addresses performed indirect leverage staking with more than eight loops, with a total swap amount of 4,669 `ETH`. The difference in the number of participants and the total amount staked suggests distinct participant profiles and strategies between direct and indirect leverage staking. The comparison indicates that direct leverage staking is more likely to attract sophisticated market participants who are willing to perform more loops with substantial capital commitments.

Leverage Staking Multipliers. Furthermore, we compute $LevM_{(S,n)}$ for each address by taking into account the initial and the cumulative sum of `stake` or `swap` amount (See Equation 3). Figure 11 and 12 illustrate the distribution of $LevM_{(S,n)}$ across various n. The trend indicates that an increasing loop count n is associated with a higher $LevM_{(S,n)}$ in practical scenarios. Additionally, it is noteworthy that the majority (more than 90%) of the direct and indirect leverage staking addresses exhibit a $LevM_{(S,n)}$ smaller than 4.

Leverage Staking APR. We focus on a subset of 152 and 137 direct and indirect leverage staking addresses that have successfully repaid their debts and withdrawn their collateral from Aave `stETH–ETH` positions. To calculate their *actual* APR, as outlined in Equation 7, we consider the net earnings from `deposit` and `withdraw` actions, balanced against the `ETH`

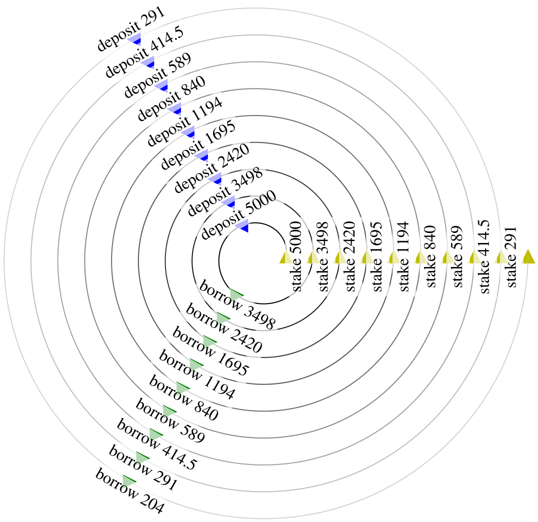

Figure 15: 0xD2...701: Direct leverage staking from block 14,617,906 to 14,627,202.

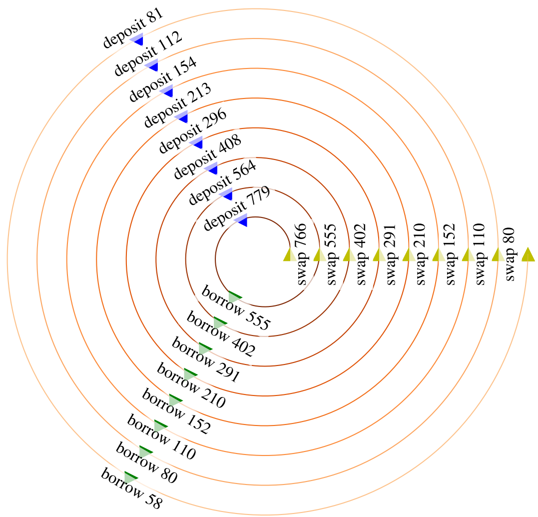

Figure 16: 0xA1...882: Indirect leverage staking from block 16,031,087 to 16,031,208.

accrued through `borrow` and `repay` actions. Additionally, we account for the conversion of accrued `ETH` to `stETH`, factoring in the `stETH` price at the time of the last `withdraw` action.

$$\begin{aligned}
&\mathsf{actualAPR} = \frac{\left(\mathsf{accruedstETH} - \frac{\mathsf{accuredETH}}{p_{\mathrm{stETH}}}\right) \cdot \frac{3600 \cdot 24 \cdot 365}{12}}{\mathsf{totalDepositstETH} \cdot (\mathsf{lastWithdrawBlock} - \mathsf{firstDepositBlock})} \\
&\mathsf{accruedstETH} = \mathsf{totalWithdrawstETH} - \mathsf{totalDepositstETH} \\
&\mathsf{accruedETH} = \mathsf{totalRepayETH} - \mathsf{totalBorrowETH}
\end{aligned} \tag{7}$$

The distributions of direct and indirect leverage staking APR are visually depicted in Figure 13 and 14 respectively. Notably, our findings reveal that a significant majority (81.7%), precisely 137 (90.13%) direct and 99 (73.33%) indirect leverage staking addresses, have realized an APR higher than the APR of conventional staking on Lido.

Leverage Staking Examples. We present two examples to enhance the understanding of leverage staking. From block 14,617,906 to 14,627,202, a whale wallet address 0xD2...701 executed the direct leverage staking strategy with 9 loops. The recursive action sequences of (`stake, deposit, borrow, stake`) are shown in Figure 15. 0xD2...701 invested a principal amount of 5,000 `ETH`. The direct leverage staking results in a total investment amount of 16,145.5 `ETH`. This led to a leverage multiplier of 3.23, demonstrating the amplification effect of the leverage strategy. In another instance, from block 16,031,087 to 16,031,208, 0xA1...882 performed the indirect leverage staking strategy. This was accomplished by recursively executing the action sequence of (`swap, deposit, borrow, swap`). 0xA1...882 started with a principal investment amount of 766 `ETH`. Through 8 leverage loops, 0xA1...882 achieved a total investment of 2,624 `ETH`, resulting in a leverage multiplier of 3.43. This illustrates the effectiveness of the indirect leverage staking strategy in increasing the total investment.

7 Cascading Liquidation

In this section, we offer an overview of the `stETH` price deviation in relation to the Terra crash incident. We illustrate how the `stETH` price can potentially lead to liquidation cascades within the LSD ecosystem, especially in the context of leverage staking.

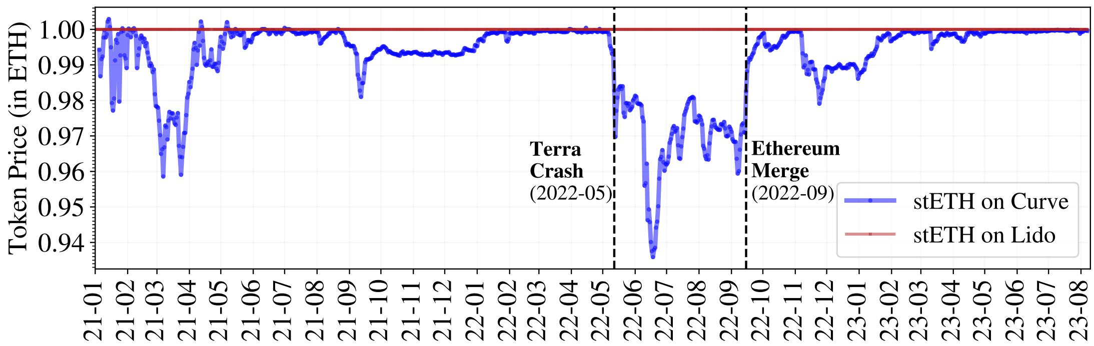

Figure 17: `stETH` price in the primary (Lido) and secondary (Curve) markets.

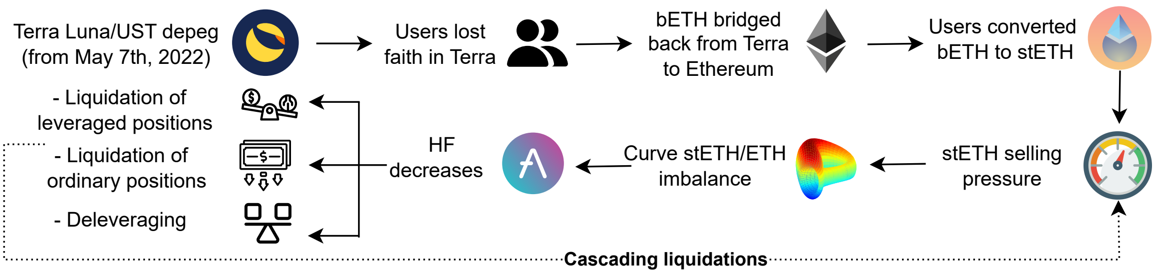

Figure 18: Illustration of liquidation cascades.

7.1 `stETH` Price Deviation and Terra Crash

As a rebasing LSD, `stETH` changes its token supply to distribute rewards to stakers (see Section 3.4). As such, the `stETH` to `ETH` price in the primary market (i.e., Lido) is 1. While `stETH` is not required to trade on par with `ETH` in the secondary market (e.g., Curve), the price is anticipated to converge to 1. Our empirical data show that `stETH` did maintain a loose peg to `ETH` for most of its history. However, the `stETH` price began to drop from May 12, 2022, reaching its lowest point of 0.931 on May 18, 2022 (see Figure 17).

The `stETH` price decline can date back to the `UST`/`LUNA` depeg. The Terra collapse instilled fear and triggered selling pressure throughout the market [27, 28]. Specifically, following the `UST`/`LUNA` depeg incident between May 7 to 16, investors grew concerned about the security and stability of the Terra network. Given the prevailing bearish sentiment, investors moved to bridge back `bETH` (a wrapped version of `stETH` on Terra) from Terra to Ethereum via the Wormhole contract. Our data show that 614k `bETH` was bridged to Ethereum, with a remarkable 98% of these `bETH` converted back to `stETH`. This mass conversion reflects the widespread desire to exit Terra-based staking assets. Subsequently, the secondary market experienced significant selling pressure, primarily from institutions such as Celsius. This imbalance in the Curve `stETH`–`ETH` pool contributed to the price decline of `stETH`.

7.2 Cascading Liquidation and User Behaviors

The decline in `stETH` price may trigger liquidation cascades within the LSD ecosystem, especially in the context of leverage staking (see Figure 18). Specifically, the decline in `stETH` price reduces the HFs of `stETH` collateralized borrowing positions on Aave, potentially leading to liquidations. In response to liquidations, users with leverage staking positions can either take no action and undergo liquidation, or choose to deleverage their positions.

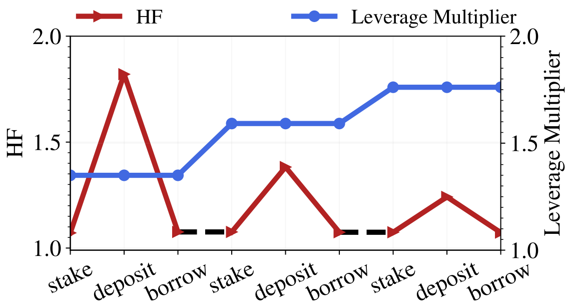

Figure 19: Example of the leverage action.

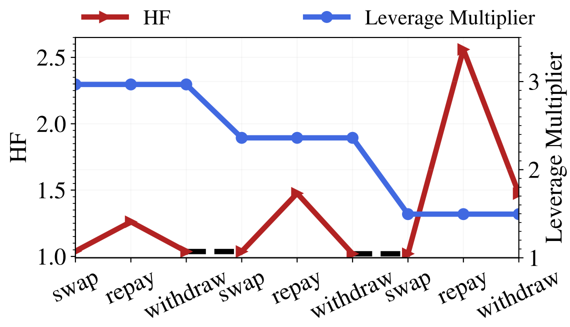

Figure 20: Example of the deleverage action.

On the one hand, users with leverage staking positions may take no action when their HFs approach the critical threshold of 1. In this case, their collateralized `stETH` might be liquidated. The liquidators repay `ETH` to acquire `stETH`, with the liquidation amount being amplified by $LevM_{(S,n)}$. Subsequently, a significant amount of `stETH` is sold in the Curve pool, contributing to additional selling pressure on `stETH` (see Figure 18). This extensive selling further imbalances the Curve `stETH`–`ETH` pool, resulting in a further decline in `stETH` price. Consequently, an increasing number of positions, including both leverage staking and ordinary positions, are vulnerable to liquidation as a result of declining HFs.

On the other hand, users can choose to deleverage their positions on Aave to restore HFs. Assuming $\mathsf{U_i}$ has executed a direct or indirect leverage staking strategy with n loops, $\mathsf{U_i}$ can initiate a deleveraging process with the following steps. *(i)* $\mathsf{U_i}$ executes a `swap` to convert `stETH` into `ETH` within the Curve `stETH`–`ETH` pool. *(ii)* The received `ETH` is then used to repay the `ETH` borrowed in the n^{th} loop. *(iii)* $\mathsf{U_i}$ then `withdraws` the `stETH` that was supplied in the n^{th} loop from Aave and continues converting it into `ETH` using the Curve pool. This "`swap-repay-withdraw`" process is repeated as necessary to deleverage the position and restore HF until it remains above 1.

Taking address 0xD2...701 as an example, the overall trend of HF and $LevM_{(S,n)}$ during the deleveraging process (see Figure 20) exhibit a remarkable degree of symmetry when compared to those observed in the leveraging process (Figure 19). With each `repay` action, the HF of the address increases, as indicated by the red line, while the leverage multiplier decreases, as shown by the blue line. This symmetrical trend illustrates the correlation between repaying debt and improving HF, which consequently reduces $LevM_{(S,n)}$.

During the period from May 8, 2022 to May 18, 2022, i.e., the first ten days after the Terra crash (Figure 17), we observed 13 users actively deleveraging their direct leverage staking positions and 5 users deleveraging their indirect leverage staking positions. This activity resulted in a total debt repayment of 74,983.6 `ETH` and 61,085.5 `ETH` respectively. However, it is important to note that even if a user manages to avoid liquidation by deleveraging, the additional selling pressure generated by the `swap` transactions on Curve can still intensify the decline in `stETH` price. This decline may potentially make other leverage staking and ordinary positions more susceptible to liquidation. Such ripple effect may increase market instability and affect a broader range of participants beyond those directly engaged in deleveraging.

To summarize, users with leverage staking positions can take various actions to respond to potential liquidations. Regardless of their choices, these actions may contribute to additional selling pressure on `stETH`, further exacerbating price declines and liquidation cascades. This dynamic underscores the interconnection of leverage staking and the broader market ecosystem. In the following section, we will conduct stress tests to evaluate such risks.

8 Stress Testing

8.1 Motivation

By crawling the `liquidationcall` events on Aave V2 lending pool from Dec 17, 2020 to Aug 7, 2023, we identify 18 liquidations for the positions where users supplied `stETH` to borrow `ETH`, 7 liquidations for direct leverage staking positions, and 2 liquidations for indirect leverage staking positions. This relatively low number of liquidations can be attributed to the fact that `stETH` has historically only experienced a modest price decline (reaching a low of 0.931). However, drawing from the `LUNA`–`UST` incident, we recognize that a token may become entirely devalued. Should `stETH` undergo a devaluation similar to that of `LUNA`, it could trigger a surge in liquidations. Therefore, it is crucial to conduct stress tests to assess the risk of cascading liquidations under the worst-case scenario.

8.2 Simulation

Motivated by these concerns, we perform stress tests on the Lido-Aave-Curve LSD ecosystem under extreme conditions, simulating potential liquidation events, selling pressures, and subsequent liquidation cascades triggered by a significant drop in `stETH` value. Our objective is to address the following simulation questions (SQs):

SQ1 How are leverage staking positions affected by `stETH` devaluation?

SQ2 How does the liquidation of leverage staking positions affect the price of `stETH`?

SQ3 How do leverage staking positions affect ordinary positions during `stETH` devaluation?

SQ4 What are the effects of deleveraging actions on `stETH` price and market participants?

We first categorize Aave collateralized `stETH` borrowing positions into two groups: the leverage staking group (G_L) and the ordinary group (G_O). We then simulate four distinct scenarios to investigate the answers to the corresponding SQs.

8.2.1 SQ1

SQ1 aims to simulate the experience of leverage staking positions during the steep drop of the `stETH` price. Our analysis centers on the fluctuations in HFs and examines how leverage staking intensifies the risk of cascading liquidations.

Simulation Setup. We initialize the Curve `stETH`–`ETH` pool by forking its state at block 17,500,000 (Jun 17, 2023), with reserve of 265,972 `ETH` and 266,966 `stETH`. Subsequently, we mimic the institutional selling pressure (e.g., Celsius, see Figure 18) after Terra crash by simulating a sale of 170,000 `stETH` on Curve. This sizable transaction leads to the decline in the `stETH` price, resulting in a new exchange rate of 100 `stETH` = 90.52 `ETH`, denoted as $p_0 = 0.9052$. In addition, we initialize G_L with 262 direct and 180 indirect leverage staking positions, each with an `address` that we have detected in Section 6. For each position, the values of `totalDebtETH`, `totalCollateralETH`, and `HF` are set to the corresponding values recorded in the transaction logs of that position's most recent borrowing transaction. Furthermore, the `stETHPrice` for all positions is initialized as p_0.

Simulation Process. The simulation consists of a series of sequential rounds. In each round, the `stETHPrice` for all positions is updated as the current `stETH` price in the Curve `stETH`–`ETH` pool. Subsequently, the HF for each position is recalculated, using the updated stETHPrice. If, at any point, a position's HF drops below the threshold of $HF = 1$, a simulated liquidation event is triggered. In this scenario, a designated liquidator steps in to settle the debt by repaying it in ETH. In return, the liquidator receives the collateral in stETH. All received stETH is converted to ETH in the Curve stETH–ETH pool, as shown in Figure 18. This process continues until no more liquidatable positions remain.

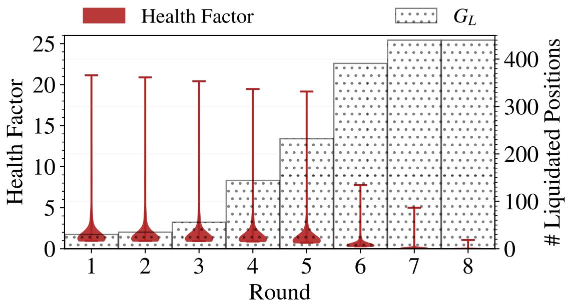

Figure 21: Number of liquidated leverage staking positions and the change of HFs.

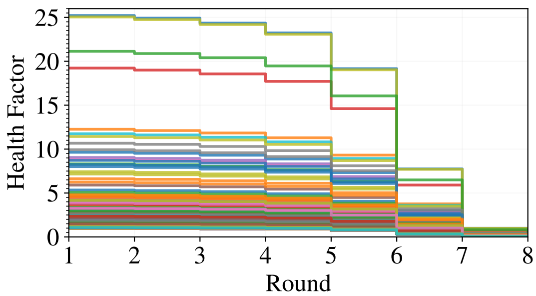

Figure 22: Simualted change in HFs for leverage staking positions in G_L.

> **Finding 1** Leverage staking positions are vulnerable to liquidation during stETH devaluation due to significant declines in their HFs.

Simulation Result. We examine the liquidation dynamics of G_L's leverage staking positions and the fluctuations in their HFs throughout simulations. Figure 21 shows the number of liquidated users in group G_L and the variations in HFs across different simulation rounds. The simulation terminates after 8 rounds, where 440 (99.55%) positions are liquidated. A noteworthy observation is that HFs of all positions exhibit a steep decrease, as depicted in Figure 22. The liquidation cascades experienced by leverage staking positions result in a total liquidated amount 497,375 ETH, ultimately driving the stETH price down to 0.01 ETH.

8.2.2 SQ2

SQ2 aims to explore how the liquidation of leverage staking positions can impact the price of stETH. We first simulate a scenario to evaluate the effects of leverage staking strategies (G_L), followed by a contrasting scenario where users do not adopt these strategies. The selling pressure originates from the liquidation of the corresponding positions.

> **Finding 2** Leverage staking can amplify the risks of cascading liquidations. The liquidation of leverage staking positions introduces additional selling pressure to the market, thereby exacerbating the decline in stETH prices and triggering further liquidations.

In our simulation, we first simulate a scenario to assess the impact of leverage staking on stETH price and the liquidation volume. Next, we simulate an alternative scenario in which users within group G_L, which includes 262 direct and 180 indirect leverage staking positions, do not adopt leverage staking strategies. This involves setting the initial values for totalCollateralETHs, totalDebtETHs, and HFs as the values recorded in the transaction logs when the *first* borrowing action for the position occurred.

Figure 23 illustrates the comparative simulation results for scenarios in which users either adopt or do not adopt the leverage staking strategy. In the absence of leverage staking, the stETH price stabilized at 0.84 ETH in the last rounds, leading to a comparatively modest liquidation amount of 28,201 ETH. However, with the application of leverage staking,

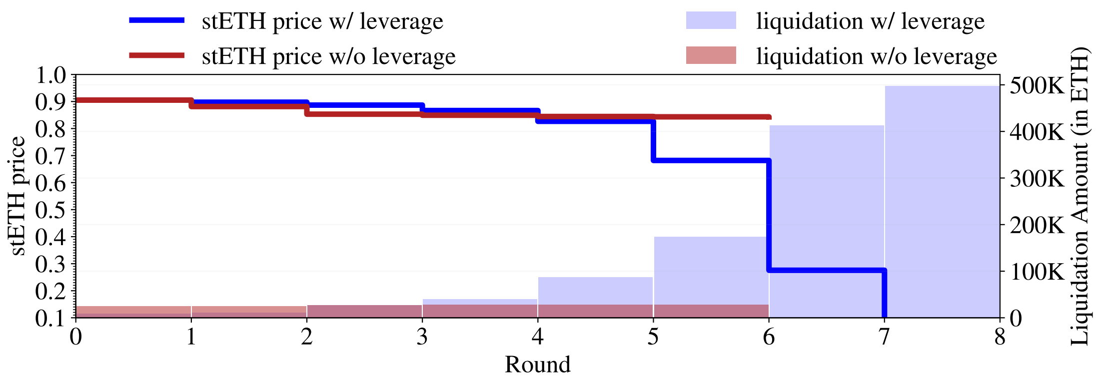

Figure 23: Comparision of `stETH` price and liquidation amount with and without leverage staking. The blue and red lines (bars) show the change of the `stETH` price (the change of liquidation amount) when users in G_L adopt or do not adopt the leverage staking strategy.

the `stETH` price plummeted to 0.01 `ETH` at the end of the simulation, and the liquidation amount (497,375 `ETH`) escalated to 16 times that of the scenario where such strategies were not applied. Our simulation findings indicate that the adoption of leverage staking strategies significantly exacerbates the risk of cascading liquidation in response to market downturns. This underscores the importance of prudent risk management within the LSD system. Implementing such strategies without careful consideration of their potential impact on market stability can lead to adverse outcomes that affect a wide range of stakeholders.

8.2.3 SQ3

SQ3 aims to explore the impact of leverage staking positions on ordinary positions during the steep decline of `stETH` value. This simulation constructs two scenarios: a control scenario, which involves only the ordinary group (G_O) consisting of 442 users, and an experimental scenario, where G_L (442 users) and G_O (442 users) coexist on the Aave platform. Both scenarios are subjected to identical simulation processes to record the number of liquidated positions within G_O and the fluctuations in the `stETH` price, allowing for a direct comparison of outcomes with and without the influence of leverage staking.

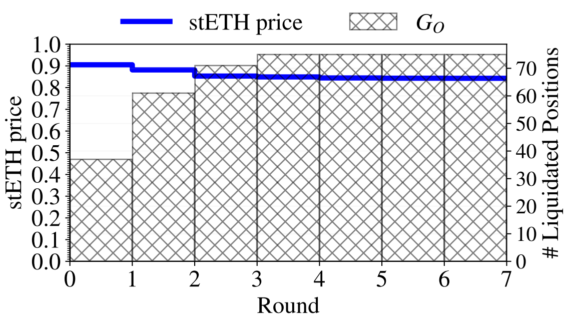

Figure 24: The change of `stETH` price and # liquidated positions in G_O without the presence of the leverage staking group (G_L).

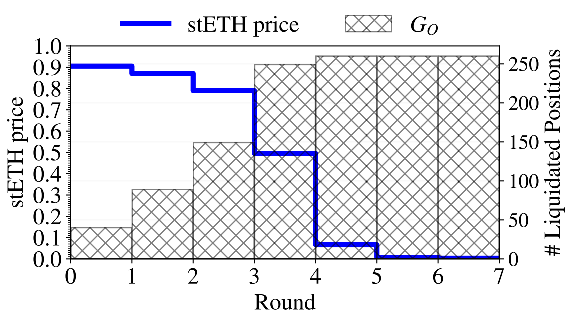

Figure 25: The change of `stETH` price and # liquidated positions in G_O in the presence of the leverage staking group (G_L).

Finding 3 Leverage staking introduces broader systemic risks because it significantly exacerbates the liquidation of ordinary positions during the devaluation of `stETH`.

The simulation results for the control scenario (see Figure 24) indicate that 75 ordinary positions are liquidated in the absence of G_L. In contrast, the results for the experimental scenario (see Figure 25) reveal that 260 ordinary positions are liquidated, suggesting a significant increase in liquidations when G_L is present. Our simulation results suggest that leverage staking not only intensifies the risk profile of individual portfolios but also contributes to broader systemic risks, particularly during periods of sharp declines in LSD prices. The comparative analysis of liquidation rates between the two scenarios underscores the influence that leverage staking positions can exert on the stability of ordinary positions. The increased liquidations in the presence of G_L point to a contagion effect, where vulnerabilities in leveraged positions can cascade to affect even traditionally less risky, ordinary positions. This suggests that systems designed to stabilize market dynamics need to account not only for individual positions but also for their interdependencies. Therefore, our simulation results highlight the necessity for regulatory frameworks and platform governance structures to consider these interconnections.

8.2.4 SQ4

As discussed in Section 7.2, users holding leverage staking positions might choose to deleverage during a decline in `stETH` value. SQ4 is designed to examine the effects of such deleveraging actions on the `stETH` price and LSD market participants. We simulate two scenarios: the control scenarios where G_L does not deleverage and the experimental scenarios where G_L chooses to deleverage at the beginning of the simulation (round 0).

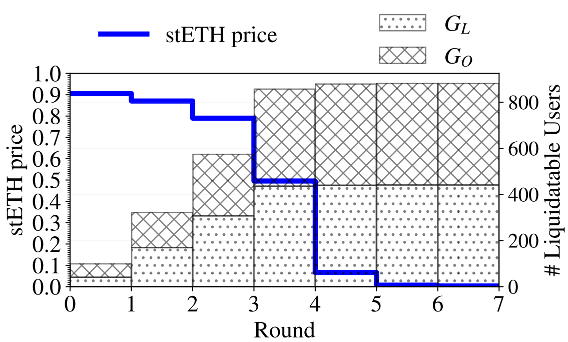

Figure 26: The change of `stETH` price and # liquidated positions without deleveraging.

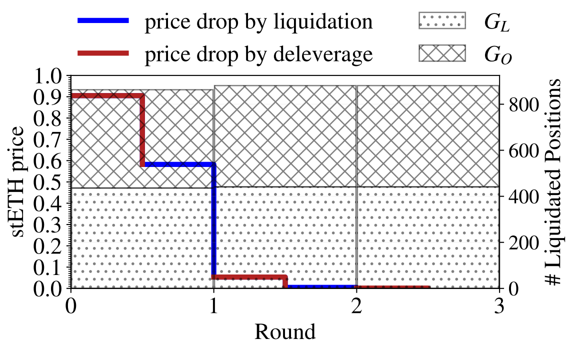

Figure 27: The change of `stETH` price and # liquidated positions with deleveraging.

Finding 4 The deleveraging actions taken by G_L can introduce additional selling pressure, thereby intensifying the liquidation cascades among system participants.

When users in G_L do not choose to deleverage, our simulation result (see Figure 26) shows that the liquidation ends in 7 round, with 441 users in G_L and 440 users in G_O being liquidated. Conversely, when G_L decides to deleverage at round 0, the liquidation process is significantly shortened, ending in just 3 rounds. This pronounced difference underscores the critical role that deleveraging actions play in market dynamics. Not only do they shorten the duration of liquidations, but they also potentially amplify market volatility by introducing additional selling pressure. This indicates that deleveraging action can exacerbate systemic risk by accelerating the liquidation cascade, affecting a broader range of system participants.

9 Discussion and Future Research Directions

Our comprehensive stress tests on the Lido-Aave-Curve LSD ecosystem reveal critical vulnerabilities and dynamic interplays under extreme conditions of significant `stETH` devaluation. These simulations illustrate that leverage staking strategies, while innovative, expose the market to heightened risks. The presence of leverage staking significantly escalates the risk of cascading liquidations within the LSD ecosystem. This finding underlines a crucial concern: systemic risk is exacerbated not only through direct liquidations but also via the market pressures these actions generate. The selling pressure on `stETH`, driven by both liquidations and deleveraging actions, can trigger a ripple effect across the system, further depressing `stETH` prices and adversely impacting the financial stability of broader market participants (such as ordinary users). Therefore, it is crucial to strike a balance between leveraging opportunities for higher returns and the potential for destabilization in LSD ecosystems.

Building upon these insights, future research can pursue several avenues. A crucial direction is the development of refined models that simulate a broader range of conditions, incorporating more granular behaviors of market participants and liquidity variations. This could lead to more robust parameterization of platforms such as Aave, similar to the 'safe parameterization' design used in traditional finance, which aims to mitigate risks without stifling innovation. Additionally, exploring new regulatory frameworks tailored to LSDs could help prevent the systemic shocks observed in our simulations. By integrating advanced risk management strategies and regulatory innovations, future research can contribute to creating a more resilient LSD ecosystem. This involves a holistic approach to understanding the interdependencies and collective behaviors that define these platforms.

10 Conclusion

This paper systematically studies the leverage staking strategy with LSDs. In the analytical section, we propose a formal model to capture the direct and indirect leverage staking strategy within the Lido–Aave–Curve LSD ecosystem. In the empirical section, we introduce heuristics to identify historical leverage staking positions and assess factors such as leverage amounts, loops, multipliers, and APRs. Our findings indicate that the majority of leverage staking positions yield an APR higher than the APR of conventional staking, underscoring their high-return nature. However, recognizing the associated risks, we also conduct stress tests to simulate various extreme scenarios. These tests reveal that leverage staking significantly increases the risk of cascading liquidations within the LSD ecosystem because it triggers additional selling pressures during liquidations and deleveraging. Furthermore, our simulation suggests that leverage staking not only intensifies the risk profile of individual portfolios but also contributes to broader systemic risks as it exacerbates the liquidation of ordinary positions. We hope our research inspires academic researchers and protocol developers to create robust risk assessment methods and safe parameterizations that safeguard all stakeholders within the LSD ecosystem.

References

[1] G. Wood, "Ethereum: A secure decentralised generalised transaction ledger," *Ethereum project yellow paper*, vol. 151, pp. 1–32, 2014.

[2] D. Grandjean, L. Heimbach, and R. Wattenhofer, "Ethereum proof-of-stake consensus layer: Participation and decentralization," *arXiv preprint arXiv:2306.10777*, 2023.

[3] C. Schwarz-Schilling, J. Neu, B. Monnot, A. Asgaonkar, E. N. Tas, and D. Tse, "Three attacks on proof-of-stake ethereum," in *International Conference on Financial Cryptography and Data Security*, pp. 560–576, Springer, 2022.

[4] S. Agrawal, J. Neu, E. N. Tas, and D. Zindros, "Proofs of proof-of-stake with sublinear complexity," *arXiv preprint arXiv:2209.08673*, 2022.

[5] W. Tang and D. D. Yao, "Transaction fee mechanism for proof-of-stake protocol," *arXiv preprint arXiv:2308.13881*, 2023.

[6] V. Buterin, D. Hernandez, T. Kamphefner, K. Pham, Z. Qiao, D. Ryan, J. Sin, Y. Wang, and Y. X. Zhang, "Combining ghost and casper," *arXiv preprint arXiv:2003.03052*, 2020.

[7] J. Neu, E. N. Tas, and D. Tse, "Ebb-and-flow protocols: A resolution of the availability-finality dilemma," in *2021 IEEE Symposium on Security and Privacy (SP)*, pp. 446–465, IEEE, 2021.

[8] L. W. Cong, Z. He, and K. Tang, "Staking, token pricing, and crypto carry," *Available at SSRN 4059460*, 2022.

[9] T. Chitra, "Competitive equilibria between staking and on-chain lending," 2021.

[10] A. Tzinas and D. Zindros, "The principal–agent problem in liquid staking," *Cryptology ePrint Archive*, 2023.

[11] S. Scharnowski and H. Jahanshahloo, "The economics of liquid staking derivatives: Basis determinants and price discovery," *Available at SSRN 4180341*, 2023.

[12] T. N. Cintra and M. P. Holloway, "Detecting depegs: Towards safer passive liquidity provision on curve finance," *arXiv preprint arXiv:2306.10612*, 2023.

[13] L. Heimbach, E. Schertenleib, and R. Wattenhofer, "Defi lending during the merge," in *5th Conference on Advances in Financial Technologies*, 2023.

[14] Z. Wang, K. Qin, D. V. Minh, and A. Gervais, "Speculative multipliers on defi: Quantifying on-chain leverage risks," *Financial Cryptography and Data Security*, 2022.

[15] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," 2008. Available at: `https://bitcoin.org/bitcoin.pdf`.

[16] V. Buterin *et al.*, "Ethereum white paper," *GitHub repository*, vol. 1, pp. 22–23, 2013.

[17] S. Werner, D. Perez, L. Gudgeon, A. Klages-Mundt, D. Harz, and W. Knottenbelt, "Sok: Decentralized finance (defi)," in *Proceedings of the 4th ACM Conference on Advances in Financial Technologies*, pp. 30–46, 2022.

[18] P. Daian, R. Pass, and E. Shi, "Snow white: Robustly reconfigurable consensus and applications to provably secure proof of stake," in *International Conference on Financial Cryptography and Data Security*, pp. 23–41, Springer, 2019.

[19] P. Gaži, A. Kiayias, and D. Zindros, "Proof-of-stake sidechains," in *2019 IEEE Symposium on Security and Privacy (SP)*, pp. 139–156, IEEE, 2019.

[20] A. Kiayias, A. Russell, B. David, and R. Oliynykov, "Ouroboros: A provably secure proof-of-stake blockchain protocol," in *Annual International Cryptology Conference*, pp. 357–388, Springer, 2017.

[21] S. Bano, A. Sonnino, M. Al-Bassam, S. Azouvi, P. McCorry, S. Meiklejohn, and G. Danezis, "Sok: Consensus in the age of blockchains," in *Proceedings of the 1st ACM Conference on Advances in Financial Technologies*, pp. 183–198, 2019.

[22] "The Merge," 2023. Available at: `https://ethereum.org/en/roadmap/merge/`.

[23] P. Daian, S. Goldfeder, T. Kell, Y. Li, X. Zhao, I. Bentov, L. Breidenbach, and A. Juels, "Flash boys 2.0: Frontrunning in decentralized exchanges, miner extractable value, and consensus instability," in *2020 IEEE Symposium on Security and Privacy (SP)*, pp. 910–927, IEEE, 2020.

[24] Y. Liu, Y. Lu, K. Nayak, F. Zhang, L. Zhang, and Y. Zhao, "Empirical analysis of eip-1559: Transaction fees, waiting times, and consensus security," in *Proceedings of the 2022 ACM SIGSAC Conference on Computer and Communications Security*, pp. 2099–2113, 2022.

[25] Ethereum.org, "The history of ethereum," 2023. Available at: `https://ethereum.org/en/history/`.

[26] "Lido tokens integration guide," 2023. Available at: `https://docs.lido.fi/guides/lido-tokens-integration-guide`.

[27] J. Liu, I. Makarov, and A. Schoar, "Anatomy of a run: The terra luna crash," tech. rep., National Bureau of Economic Research, 2023.

[28] S. Lee, J. Lee, and Y. Lee, "Dissecting the terra-luna crash: Evidence from the spillover effect and information flow," *Finance Research Letters*, vol. 53, p. 103590, 2023.

A Aave Parameter Configuration

Table 3 depicts the historical changes of Aave parameter configurations. We crawl the `collateralConfigurationChanged` events for Aave V2 lending pool.

Block Number	Transaction Hash	LTV(l)	LT
14289297	0x94780dc1914af5aec3b6d303e2d974669074bbceb6d1baac7d93ad0400593db0	0.70	0.75
14693506	0x993926559f17a579c3b0c0b5fc83fd3c9d5772e9b314f7f0e78e704c6b984726	0.73	0.75
14804760	0xbc40546b65ada9f5d4f8346f405a5f9c0da6d8f66bb27b7c64c0efa70eeae080	0.69	0.81
14837221	0x5206c144845ac63f982125f51c31b0fc474655281e2d433f8270505d87f8bbf4	0.70	0.75
14999895	0x25e33e04d2e5d92acd91f542a2677045e59b2d6b385e4fa0315a404396bc5c99	0.69	0.81
15759644	0x48653014a79433bf5f21781424b306a697f4476077a8b92e17b2ae6eda58706e	0.72	0.83
16392718	0xdcaa33ddef0700a2a625e0b7a0c2da14499901e42c073064390f11dd83cefd19	0.69	0.81

Table 3: Historical changes of Aave V2 parameter configurations.

B Generalized Formalization For Leverage Staking

B.1 Generalized Formalization

In addition to the standardized cases discussed in Section 5, real-world leverage lending situations can exhibit substantial variation among users. Specifically, we delineate the following variations using the direct leverage staking strategy as an example.

(i) Within each leverage staking loop, $\mathsf{U_i}$ may choose not to supply all the `stETH` acquired from Lido as collateral on Aave. Instead, in the $k^{\mathbf{th}}$ loop, $\mathsf{U_i}$ may opt to supply only c_k ($c_k \in [0,1]$) percent of the `stETH`. *(ii)* In the k^{th} loop, $\mathsf{U_i}$ has the option to borrow an amount of `ETH` that is less than the maximum borrowing capacity. In this scenario, $\mathsf{U_i}$'s effective borrowing capacity becomes $b_k \cdot l$, where $b_k \in [0,1]$. *(iii)* In the k^{th} loop, $\mathsf{U_i}$ has the flexibility to restake (reswap) part of the borrowed `ETH` on Lido (Cruve). $\mathsf{U_i}$ may choose to restake (reswap) only s_k ($s_k \in [0,1]$) percent of the `ETH` borrowed in the the $k-1^{\text{th}}$ loop (or the principal amount of $k=1$) at the start of the k^{th} loop. After borrowing `stETH` from Aave, $\mathsf{U_i}$ may restake only s_{k+1} ($s_{k+1} \in [0,1]$) percent of the borrowed `ETH` at the end of the k^{th} loop (equals to the beginning of $k+1^{\text{th}}$ loop). Note that as illustrated by Figure 4, the stake and restake parameters (s_k and s_{k+1}) together establish the the k^{th} loop. Equation 8 introduces a generalized formalization to accommodate these variations.

$$
\begin{aligned}
A_{(S,n)} &= S \cdot \sum_{k=1}^{n+1} \left(\prod_{i=1}^{k} s_i\right) \cdot \left(\prod_{i=1}^{i-1} c_i\right) \cdot \left(\prod_{i=1}^{k-1} b_i\right) \cdot \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{k-1} \\
C_{(S,n)} &= S \cdot \sum_{k=1}^{n} \left(\prod_{i=1}^{k} s_i\right) \cdot \left(\prod_{i=1}^{k} c_i\right) \cdot \left(\prod_{i=1}^{k-1} b_i\right) \cdot \frac{(l \cdot p^a_{t_0})^{k-1}}{(p^m_{t_0})^k} \\
B_{(S,n)} &= S \cdot \sum_{k=1}^{n} \left(\prod_{i=1}^{k} s_i\right) \cdot \left(\prod_{i=1}^{k} c_i\right) \cdot \left(\prod_{i=1}^{k} b_i\right) \cdot \left(\frac{l \cdot p^a_{t_0}}{p^m_{t_0}}\right)^{k} \\
HF_{\mathsf{U_i}}(p^a_{t_c} | p^a_{t_0}) &= \frac{C_{(S,n)} \cdot p^a_{t_c} \cdot \text{LT}}{B_{(S,n)}}
\end{aligned}
\tag{8}
$$

C Leverage Staking Detection Algorithm

Algorithms 1 and 2 depict the heuristics used to detect addresses that have performed direct and indirect leverage staking respectively.

Algorithm 1: Direct Leverage Staking Detection.

Input: An address `addr`
Output: `addr`'s leverage staking actions.

Extract `addr`'s `deposit` events $\{w_i\}_i$ and `borrow` events $\{b_j\}_j$ on Aave, and `stake` events $\{s_k\}_k$ on Lido;
Let $\mathcal{E} = \{w_i\}_i \bigcup \{b_j\}_j \bigcup \{s_k\}_k$;
Convert $\mathcal{E}$ to a sequence $\mathcal{E}_s$ by sorting $\mathcal{E}$ in chronological order;
if $\mathcal{E}_s$ *contains a sub-sequence with a order of* (`stake`, `deposit`, `borrow`, `stake`) **then**
    if *For the sub-sequence* (`stake`$_0$, `deposit`, `borrow`, `stake`$_1$)*:* (i) *The* `stETH` *amount received in* `stake`$_0$ *event* $\approx$ *the* `stETH` *amount in* `deposit` *event;* (ii) *The* `stETH` *amount in* `deposit` *event* $>$ *the* `ETH` *amount in* `borrow` *event;* (iii) *The* `ETH` *amount in* `borrow` *event* $\approx$ *the* `ETH` *amount in* `stake`$_1$ *event* **then**
        return $\mathcal{E}_s$;
    return $\emptyset$;
else
    return $\emptyset$;

Algorithm 2: Indirect Leverage Staking Detection.

Input: An address `addr`
Output: `addr`'s indirect leverage staking actions.

Extract `addr`'s `deposit` events $\{w_i\}_i$ and `borrow` events $\{b_j\}_j$ on Aave, and `swap` events $\{s_k\}_k$ on Curve;
Let $\mathcal{E} = \{w_i\}_i \bigcup \{b_j\}_j \bigcup \{s_k\}_k$;
Convert $\mathcal{E}$ to a sequence $\mathcal{E}_s$ by sorting $\mathcal{E}$ in chronological order;
if $\mathcal{E}_s$ *contains a sub-sequence with a order of* (`swap`, `deposit`, `borrow`, `swap`) **then**
    if *For the sub-sequence* (`swap`$_0$, `deposit`, `borrow`, `swap`$_1$)*:* (i) *The* `stETH` *amount received in* `swap`$_0$ *event* $\approx$ *the* `stETH` *amount in* `deposit` *event;* (ii) *The* `stETH` *amount in* `deposit` *event* $>$ *the* `ETH` *amount in* `borrow` *event;* (iii) *The* `ETH` *amount in* `borrow` *event* $\approx$ *the* `ETH` *amount in* `swap`$_1$ *event* **then**
        return $\mathcal{E}_s$;
    return $\emptyset$;
else
    return $\emptyset$;