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

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Abstract. Lido, the leading Liquid Staking Derivative (LSD) provider on Ethereum, allows users to stake an arbitrary amount of `ETH` to receive `stETH`, which can be integrated with Decentralized Finance (DeFi) protocols such as Aave. The composability between Lido and Aave enables a novel strategy called "leverage staking", where users stake `ETH` on Lido to acquire `stETH`, utilize `stETH` as collateral on Aave to borrow `ETH`, and then restake the borrowed `ETH` on Lido. Users can iteratively execute this process to optimize potential returns based on their risk profile.
This paper systematically studies the opportunities and risks associated with leverage staking. We are the first to formalize the leverage staking strategy within the Lido–Aave ecosystem. Our empirical study identifies 262 leverage staking positions on Ethereum, with an aggregated staking amount of 295,243 `ETH` (482M `USD`). We discover that 90.13% of leverage staking positions have achieved higher returns than conventional staking. Furthermore, we perform stress tests to evaluate the risk introduced by leverage staking under extreme conditions. We find that leverage staking significantly amplifies the risk of cascading liquidations. We hope this paper can inform and encourage the development of robust risk management approaches to protect the Lido–Aave LSD ecosystem.

1 Introduction

The Ethereum blockchain recently underwent the transition from Proof-of-Work (PoW) [25] to Proof-of-Stake (PoS) [12,20,4,21] to achieve a more sustainable consensus mechanism. In the PoS-based Ethereum, a validator stakes `ETH` to secure the system [6,18] and receives staking rewards. Nonetheless, solo staking poses significant entry barriers, demanding capital commitment of 32 `ETH` and technical expertise for maintaining a validator node. Additionally, staked `ETH` becomes illiquid during the staking period, restricting its availability for trading.

To address these challenges, Liquid Staking Derivatives (LSDs) emerged. Retail users can stake an arbitrary amount of `ETH` on liquid staking platforms, receiving LSDs in return [19,22]. LSDs are fungible and tradable representations of the staked `ETH` and the associated rewards. At present, Lido stands as the leading LSD provider in terms of Total Value Locked (TVL) (13.8B `USD`)[3].

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[3] `https://defillama.com/`, accessed on August 23rd, 2023.

Users can stake `ETH` on Lido to receive `stETH`, earning a staking Annual Percentage Rate (APR) of 3.8%[4]. `stETH` can be integrated with DeFi lending platforms such as Aave, or Decentralized Exchanges (DEXs) such as Curve. The Aave–Lido LSD ecosystem allows users to earn rewards on their staked `ETH` while still being utilized as collateral on Aave[5]. The composability between Lido and Aave enables a novel strategy known as "leverage staking", where users stake `ETH` on Lido to receive `stETH`, which is then used as collateral on Aave to borrow `ETH`, subsequently restaked on Lido. A financially rational user can iteratively execute this process to optimize potential returns based on their risk profile.

While yielding higher returns, leverage staking also introduces potential risks. Under adverse market conditions that result in a significant `stETH` price decline, the Aave–Lido LSD ecosystem becomes vulnerable to "cascading liquidations", a phenomenon where multiple liquidations occur successively, causing a downward spiral in the `stETH` price. Yet the opportunities and risks associated with leverage staking remain relatively unexplored in academic research. To close this gap, this paper provides a systematic study of the leverage staking strategy with LSDs, shedding light on its mechanics, potential benefits for users, and inherent risks for stakeholders, while investigating its implications for the broader DeFi ecosystem. We summarize the main contributions of this paper as follows.

- **Strategy Formalization.** We establish a formal framework for leverage staking with `stETH`, deriving the leverage multiplier and leverage staking APR. To our knowledge, we are the first to model leverage staking strategy with LSDs.
- **Empirical Measurement.** We perform an empirical analysis of leverage staking spanning 963 days, from December 17th, 2020 to August 7th, 2023. We detect 262 leverage staking positions, with an aggregated staking amount of 295,243 `ETH` (482M `USD`). Our results show that 90.13% of leverage staking positions have achieved 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 with leverage staking positions behave when faced with potential liquidations. We discover that users actively deleveraged their positions and collectively repaid a substantial debt amounting to 74,983.6 `ETH`, further intensifying the selling pressure on `stETH`.
- **Stress Testing.** We perform stress tests on the Lido–Aave LSD ecosystem to evaluate the risk of cascading liquidations under extreme conditions. We first simulate the liquidation cascades among leverage staking positions. We find that 93.13% of these positions are liquidated. Subsequently, we extend our simulations to include both leverage staking and ordinary positions, showing that leverage staking significantly amplifies the liquidation risk. We find that the `stETH` selling pressure from both liquidations and the deleverage action create a ripple effect within the system, exacerbating price decline and triggering more liquidations.

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[4] `https://lido.fi/ethereum`, accessed on August 23rd, 2023.

[5] `https://github.com/lidofinance/aave-asteth-deployment`

2 Background

2.1 Blockchain and DeFi

Permissionless blockchains are decentralized distributed ledgers that allow any participant to join and engage without requiring authorization. Within this landscape, Ethereum [25] emerges as a pioneering platform. It facilitates the execution of smart contracts, enabling developers to build decentralized applications.

DeFi [24] has recently emerged as a groundbreaking financial segment. DeFi refers to a set of blockchain-based financial services and products that operate without traditional intermediaries, using smart contracts to build an open financial environment. DeFi innovations ranging from lending to DEXs are reshaping the financial system. The TVL in DeFi reached an all-time high of 178B `USD` in November, 2021, with Ethereum dominating DeFi activities (109B `USD`, 61%).

2.2 Ethereum PoS

PoS, originally proposed in online forums [1] and later explored by the academic community [8,6,11,14,5], has emerged as an energy-efficient alternative to PoW.

Beacon Chain. On December 1st, 2020, Ethereum introduced 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, where participants lock up 32 `ETH` into the designated contract to become validators.

The Merge. On September 15th, 2022, the Merge enables Beacon Chain to evolve as the consensus mechanism for the entire network [3]. 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 [12]. The execution layer introduces additional rewards, including priority tips and Miner Extractable Value tips [9,17]. Penalties also apply for dishonest behavior.

The Shapella Upgrade. On April 12th, 2023, Ethereum underwent the "Shapella upgrade". The Shapella upgrade combines the "Shanghai upgrade" and the "Capella upgrade", which took place on the Ethereum consensus layer and execution layer simultaneously [10]. The Shapella upgrade primarily introduces the capability to unstake `ETH` secured within the Ethereum network.

2.3 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`, thereby maintaining full control over their staking rewards. However, solo staking necessitates technical expertise to run and maintain a validator node. Furthermore, it demands a significant capital commitment, which might be financially unfeasible for retail users.

- Staking as a Service (SaaS). For users with 32 `ETH` but limited technical expertise, SaaS offers a solution to manage the validator's hardware and software for the users, utilizing their signing keys to undertake on-chain tasks[6].
- 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. 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. However, this exposes users to potential risks due to the centralized nature of CEX staking.

2.4 LSD

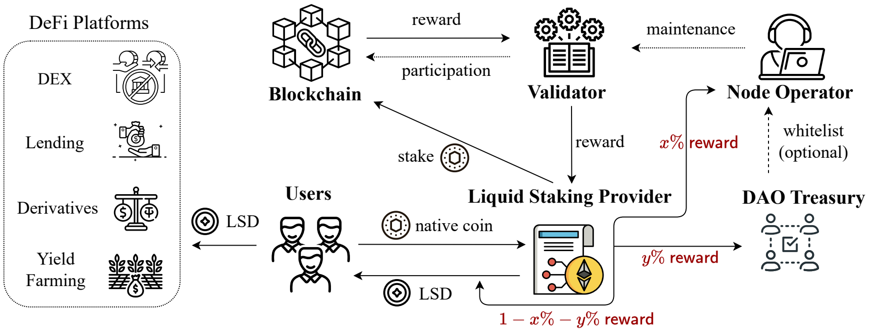

Fig. 1: Overview of the LSD Ecosystem.

Staking offers several advantages, from earning rewards to enhancing network security. However, once `ETH` is locked for staking, it becomes illiquid for a duration, making it inaccessible for trading. Given this challenge, the concept of LSD emerged, representing 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., liquid staking pools), they receive LSDs in return.

Liquid Staking Providers. At the time of writing, liquid staking protocols accumulate a TVL of more than 18.94B `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 (cf. Table 1). Pooled staking protocols

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

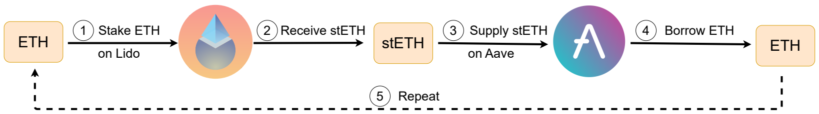

Fig. 2: Overview of Leverage Staking Strategy.

such as Lido, Rocket Pool, Frax, Stakewise, and Swell Network issue 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 (13.8B `USD`). Users stake `ETH` on Lido to receive `stETH` in return. With over 285M stakers, the total amount of `ETH` staked on Lido reached 8.34M in August 2023, accounting for 74.6% of the total `ETH` staked on Ethereum. `stETH` implements the *rebasing mechanism*, where `stETH` holders' account balances get adjusted daily to reflect the accumulated rewards [2]. The rebase can be positive or negative, depending on the validators' performance.

2.5 DeFi Lending Protocols

DeFi lending protocols are decentralized platforms operating on blockchains that facilitate peer-to-peer 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 4.5B `USD`[7]. Notably, Aave follows an over-collateralization model, meaning that users are required to 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 Health Factor (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 $HF_{(\mathsf{U_i})} < 1$ (cf. Equation 1).

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

3 System Model

3.1 System Participants

We consider an LSD ecosystem with the following participants.

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[7] `https://defillama.com/protocol/aave`, accessed on August 23rd, 2023.

- Users: A user ($\mathsf{U_i}$) is a rational participant capable of engaging with diverse DeFi platforms, employing various strategies to optimize its financial gains.
- 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`) that can be used for trading, collateralized borrowing, providing liquidity to DEX pools, etc.
- Lending and Borrowing Providers: $\mathsf{U_i}$ can supply one asset on DeFi lending platforms, such as Aave, as collateral to borrow another asset.

3.2 Leverage Staking with LSDs

- Leverage Staking Strategy: LSDs can be integrated into DeFi in various ways. For instance, DEXs such as Curve allow `stETH` holders to provide liquidity to the pool, at the risk of potential impermanent loss. Alternatively, users can implement a so-called "leverage staking strategy" which brings higher yield and higher risks. Specifically, $\mathsf{U_i}$ first stakes a principal amount of S `ETH` on Lido at time t_0, acquiring S amount of `stETH`. Next, $\mathsf{U_i}$ utilizes the `stETH` as collateral within Aave to borrow $S \cdot l \cdot P^{\mathtt{st}}_{t_0}$ amount of `ETH`, where l denotes the LTV ratio and $P^{\mathtt{st}}_{t_0}$ denotes the `stETH` to `ETH` price at time t_0. $\mathsf{U_i}$ performs this *loop* for n times (cf. Figure 2) and ends in a leverage staking position of `stETH`.

- Leverage Multiplier. Assume $\mathsf{U_i}$ acquires a total asset (staked `ETH` on Lido) of $A_{(S,n)}$ `ETH` through leverage staking with an initial principal amount of S `ETH`, the leverage multiplier $LevM_{(S,n)}$ is defined as the ratio between $A_{(S,n)}$ and S.

4 Analytical Study

This section conducts an analytical study of the leverage staking strategy. We begin by examining the standardized case and subsequently offer a generalized formalization encompassing other potential scenarios.

We assume that $\mathsf{U_i}$ is capable of completing n loops within a short time interval such that the `stETH` price remains unchanged. As a rational and risk-averse participant, $\mathsf{U_i}$ determines the value of n according to its risk profile. By applying the leverage staking strategy, $\mathsf{U_i}$ acquires a total investment of $A_{(S,n)}$ `ETH`, collateral of $C_{(S,n)}$ `stETH`, and debt of $B_{(S,n)}$ `ETH` (cf. Equation 2).

$$\begin{aligned}
A_{(S,n)} &= S \times [1 + l \cdot P^{\mathtt{st}}_{t_0} + ... + (l \cdot P^{\mathtt{st}}_{t_0})^n] = S \times \frac{1-(l \cdot P^{\mathtt{st}}_{t_0})^{n+1}}{1 - l \cdot P^{\mathtt{st}}_{t_0}} \\
C_{(S,n)} &= S \times [1 + l \cdot P^{\mathtt{st}}_{t_0} + ... + (l \cdot P^{\mathtt{st}}_{t_0})^{n-1}] = S \times \frac{1-(l \cdot P^{\mathtt{st}}_{t_0})^{n}}{1 - l \cdot P^{\mathtt{st}}_{t_0}} \\
B_{(S,n)} &= S \times [l \cdot P^{\mathtt{st}}_{t_0} + ... + (l \cdot P^{\mathtt{st}}_{t_0})^n] = S \times \frac{l \cdot P^{\mathtt{st}}_{t_0} - (l \cdot P^{\mathtt{st}}_{t_0})^{n+1}}{1 - l \cdot P^{\mathtt{st}}_{t_0}}
\end{aligned} \tag{2}$$

Leverage Multiplier. Equation 3 derives the leverage multiplier ($LevM_{(S,n)}$). Figures 3 and 4 show how $LevM_{(S,n)}$ changes in response to variations in $P^{\mathtt{st}}_{t_0}$ and LTV ratio respectively. It is evident that $LevM_{(S,n)}$ increases with the increase of

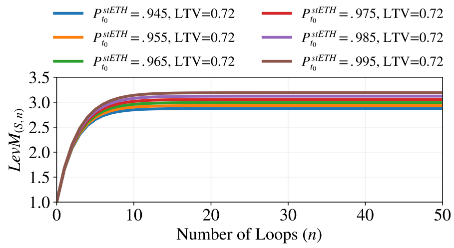

Fig. 3: $LevM_{(S,n)}$with varying $P^{\mathtt{st}}_{t_0}$.

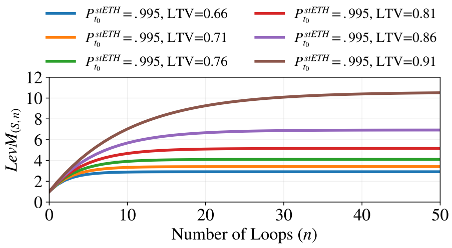

Fig. 4: $LevM_{(S,n)}$with varying LTV.

either `stETH` price or LTV. In addition, we can observe that $LevM_{(S,n)}$ gradually converges to $\frac{1}{1-l\cdot P^{\mathtt{st}}_{t_0}}$ when the number of leverage staking loops (n) increases.

$$LevM_{(S,n)} = \frac{A_{(S,n)}}{S} = \frac{1-(l\cdot P^{\mathtt{st}}_{t_0})^{n+1}}{1-l\cdot P^{\mathtt{st}}_{t_0}}; \quad \lim_{n\to\infty} LevM_{(S,n)} = \frac{1}{1-l\cdot P^{\mathtt{st}}_{t_0}} \tag{3}$$

Health Factor. The leverage staking strategy, although capable of generating substantial returns, concurrently magnifies the risk of liquidation. $\mathsf{U_i}$'s position may be susceptible to liquidation should the value of collateralized `stETH` decrease due to the decline of the `stETH` price (i.e., $P^{\mathtt{st}}_{t_c}<P^{\mathtt{st}}_{t_0}$). As discussed in Section 2.5, Aave uses HF to track the status of each position. $\mathsf{U_i}$'s can be liquidated if HF is less than 1 (cf. Equation 4). In our leverage staking example, the LTV and LT are 69% and 81% respectively (see Table 2 for the historical changes of Aave parameter configurations). Equation 5 suggests that, to uphold a secure position, the largest acceptable percentage decrease in `stETH` price is $\frac{l}{\mathrm{LT}}-1=\frac{12}{81}\approx 14.8\%$. In the event of liquidation, the user's entire collateralized `stETH` amount of $C_{(S,n)}$ will be liquidated, and this effect becomes more pronounced as the number of loops (n) increases, as indicated by $LevM_{(S,n)}$.

$$\begin{aligned} HF_{\mathsf{U_i}}(P^{\mathtt{st}}_{t_c}|P^{\mathtt{st}}_{t_0}) &= \frac{\sum_k^n k^{\text{th}} \text{ collateralized } \mathtt{stETH} \text{ value in } \mathtt{ETH}\cdot \text{LT}}{\sum_k^n k^{\text{th}} \text{ borrowed } \mathtt{ETH} \text{ value}} \\ &= \frac{C(S,n)\cdot P^{\mathtt{st}}_{t_c}\cdot \text{LT}}{B(S,n)} = \frac{P^{\mathtt{st}}_{t_c}\cdot \text{LT}}{P^{\mathtt{st}}_{t_0}\cdot l} \end{aligned} \tag{4}$$

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

APR. Equation 6 calculates leverage staking profitability. Let r_s, r_c, r_b represent the staking APR offered by Lido and the supply 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 $R_s(n)$ from Lido, a supply APR of $R_c(n)$ while pays a borrow APR of $R_b(n)$ to Aave. As such, $\mathsf{U_i}$ obtains a net APR of

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

$R_{Net}(n) = R_s(n) + R_c(n) - R_b(n)$. The necessary condition for a rational $\mathsf{U_i}$ to apply leverage staking rather than conventional staking is $R_{Net}(n) > r_s$.

$$\begin{aligned} R_{Net}(n) = R_s(n) + R_c(n) - R_b(n) &= r_s \cdot \frac{A_{(S,n)}}{S} + r_c \cdot \frac{C_{(S,n)}}{S} - r_b \cdot \frac{B_{(S,n)}}{S} \\ &= r_s \cdot LevM_{(S,n)} + r_c \cdot (LevM_{(S,n)} - (l \cdot P^{\mathsf{st}}_{t_0})^n) - r_b \cdot (LevM_{(S,n)} - 1) \end{aligned} \tag{6}$$

In addition to the standardized case discussed above, real-world leverage lending situations can exhibit variation among users. For example, some users may not supply all the received `stETH` as collateral on Aave. We refer interested readers to Appendix B for a generalized formalization of leverage staking.

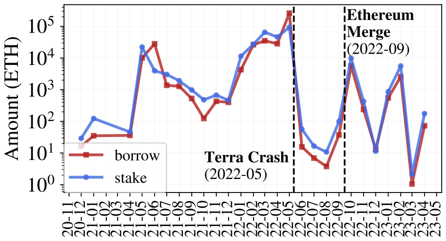

Fig. 5: Leverage staking statistics.

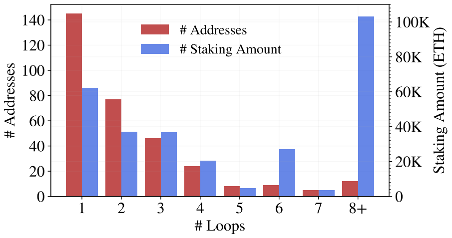

Fig. 6: Leverage staking distribution.

5 Empirical Study

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

Data Colletction. We crawl the historical `submitted` events related to Lido stETH Token when users stake `ETH` on Lido. We crawl the on-chain events involving users' historical actions for adjusting positions on Aave V2 lending pool, including `deposit`, `borrow`, `withdraw`, and `repay` events. 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 (December 17th, 2020) to block 17,866,191 (August 7th, 2023), 963 days in total. We identify 290,984 `submitted` events on Lido, 449,528 `deposit`, 238,388 `borrow`, 336,746 `withdraw` and 173,596 `repay` events on Aave V2 lending pool.

Leverage Staking Detection. We proceed to analyze the users who adopt leverage staking across Lido and Aave. 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 an algorithm (cf. Algorithm 1) to identify the addresses involving leverage staking. Basically, we extract the event sequence (`submitted`, `deposit`, `borrow`, `submitted`) in chronological order, which follows the leverage staking process shown in Figure 2.

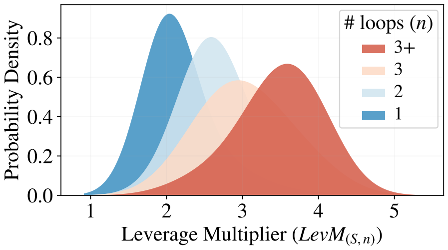

Fig. 7: Leverage multiplier distribution.

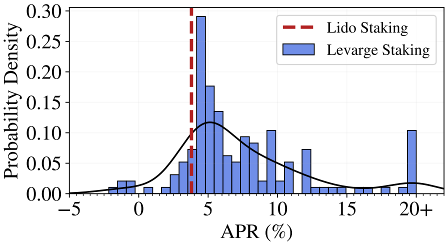

Fig. 8: Staking APR distribution.

Our investigations reveal the existence of 262 addresses that have been engaging in leverage staking activities across Lido and Aave V2 lending pools, spanning the timeframe from December 17th, 2020 to August 7th, 2023. Cumulatively, these addresses have amassed a total staking amount of 295,243 `ETH`. The distribution of leverage borrowing and staking amounts is depicted in Figure 5. Interestingly, we observe that the volume of leverage staking was substantially impacted by the Terra crash in May 2022, leading to a drastic decline from the peak monthly staking amount of 93,661 `ETH` in May 2022 to just 11 `ETH` in August 2022. Moreover, the Ethereum Merge brought about a resurgence in leverage staking, with a staking amount of 9,814 `ETH` in October 2022.

Leverage Staking Loops and Multipliers. Among the 262 addresses that have adopted 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 $\mathcal{E}_s$ (cf. Algorithm 1). To calculate the number of leverage staking loops, we identify consecutive subsequences in $\mathcal{E}_s$ consisting of (`submitted`, `deposit`, `borrow`). The results, as depicted in Figure 6, reveal that 145 addresses (55.35%) performed leverage staking with a single loop ($n = 1$). Notably, a smaller subset of 12 addresses have engaged in leverage staking with more than eight loops, and their cumulative staking activity amounts to an impressive amount of 102,998 `ETH`.

Furthermore, we compute $LevM_{(S,n)}$ for each address, taking into account their initial `stake` amount and the cumulative sum of `stake` amounts (cf. Equation 3). Figure 7 illustrates the distribution of $LevM_{(S,n)}$ across various n. The trend indicates that an increasing loop count n is associated with a higher leverage multiplier in practical scenarios. Additionally, it is noteworthy that the majority (87.57%) of addresses exhibit a $LevM_{(S,n)}$ smaller than 3.5.

Leverage Staking APR. We proceed to analyze the practical implications of leverage staking APR. Our analysis centers on a subset of 152 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 8, we consider the net earnings from `deposit` and `withdraw` actions, balanced against the `ETH` 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

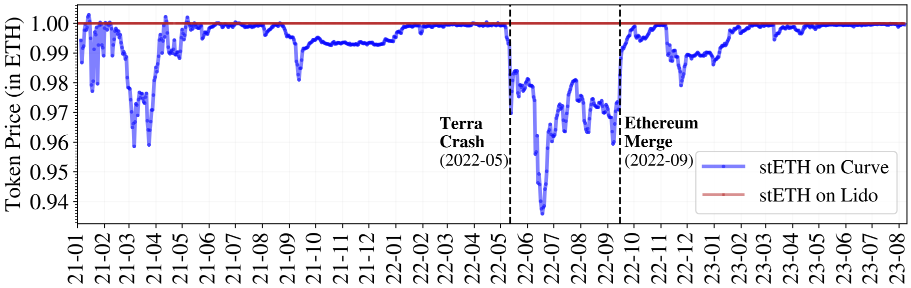

Fig. 9: `stETH` price on the primary and secondary market.

of the last `withdraw` action. The distribution of APR for these 152 addresses is visually depicted in Figure 8. Notably, our findings reveal that a significant majority, precisely 137 leverage staking addresses (90.13%), have realized APR higher than the APR of conventional staking on Lido.

6 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 Lido–Aave LSD ecosystem, especially in the context of leverage staking. Furthermore, we conduct stress tests to evaluate the risk of cascading liquidations under extreme conditions.

6.1 `stETH` Price Deviation and Terra Crash

As a rebasing LSD, `stETH` changes its token supply to distribute rewards to stakers (cf. Section 2.4). 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 12th, 2022, reaching its lowest point of 0.931 on May 18th, 2022 (cf. Figure 9).

In fact, the `stETH` price decline can date back to the `UST`/`LUNA` depeg. The Terra collapse undoubtedly instilled fear and triggered selling pressure throughout the market [16,15]. Specifically, following the `UST`/`LUNA` depeg incident between May 7th and 16th, 2022, investors grew concerned about the security and stability of the Terra network. Amidst prevailing bearish sentiment, investors swiftly 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

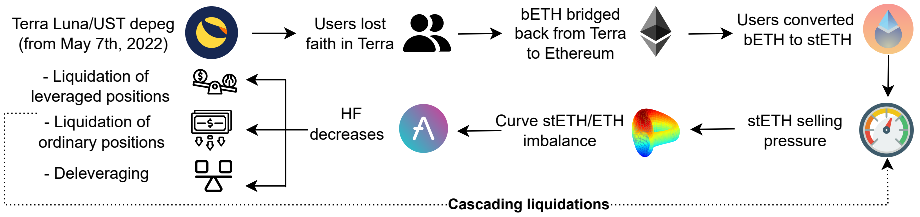

Fig. 10: Illustration of the cascading liquidation risk.

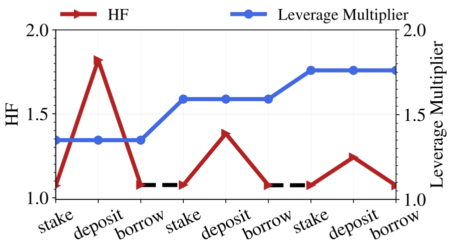

Fig. 11: Example of leveraging.

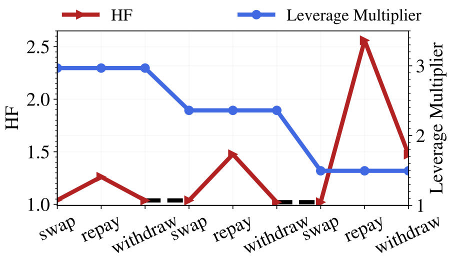

Fig. 12: Example of deleveraging.

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`.

6.2 Cascading Liquidation and User Behaviors

The decline in `stETH` price may trigger liquidation cascades within the Lido–Aave LSD ecosystem, especially in the context of leverage staking (cf. Figure 10). 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.

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`. 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 leverage staking strategy with n loops,

$\mathsf{U_i}$ can initiate the 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 until HF remains above 1. Taking address `0xD27...701` as an example, the overall trends of HF and leverage multiplier during the deleveraging process (cf. Figure 12) exhibit a remarkable degree of symmetry when compared to those observed in the leveraging process (cf. Figure 11). 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. During the period from May 8th, 2022 to May 18th, 2022, i.e., the first ten days after the Terra crash (cf. Figure 9), we observed 13 users actively deleveraging their leverage staking positions, resulting in a total debt repayment of 74,983.6 `ETH`. However, 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 and make other leverage staking and ordinary positions susceptible to liquidation.

To summarize, users with leverage staking positions can take different actions in response to potential liquidations. However, regardless of their choice, these actions may contribute to additional selling pressure on `stETH`, further exacerbating the price decline and potentially triggering liquidation cascades.

6.3 Stress Testing

Motivation. By crawling the `liquidationcall` events on Aave V2 lending pool from December 17th, 2020 to August 7th, 2023, we identify 18 liquidations for the positions where users supplied `stETH` to borrow `ETH` and 7 liquidations for leverage lending positions. However, drawing from the `LUNA`–`UST` incident, we recognize that a token may become entirely devalued. In the event that `stETH` faces a fate similar to `LUNA`'s devaluation, it could lead to a surge in liquidations. Considering that `stETH` has historically only experienced a relatively modest price decline (reaching a low of 0.931), it is imperative to conduct stress tests to assess the risk of cascading liquidations under a worst-case scenario.

Therefore, we perform stress tests on the Lido–Aave LSD ecosystem under extreme conditions, simulating potential selling pressure and subsequent liquidation cascades if the `stETH` experiences a dramatic decline. Specifically, we divide the Aave collateralized `stETH` borrowing positions into the leverage staking group (G_L) and ordinary group (G_O). We simulate the following cases:

Case 1: We simulate liquidation cascades within G_L, with selling pressure originating from the liquidation of leverage staking positions. We analyze the changes in HFs and how leverage staking amplifies the risk of cascading liquidations.
Case 2: We simulate liquidation cascades across both G_L and G_O to explore their mutual impact. The selling pressure is generated by liquidations.

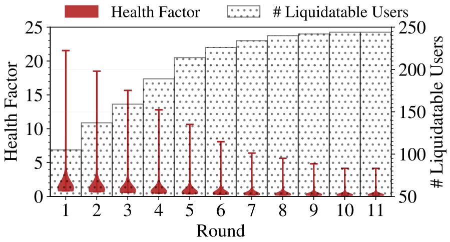

Fig. 13: Simualted HF distribution.

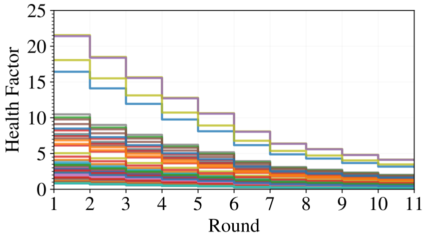

Fig. 14: Simualted HF results.

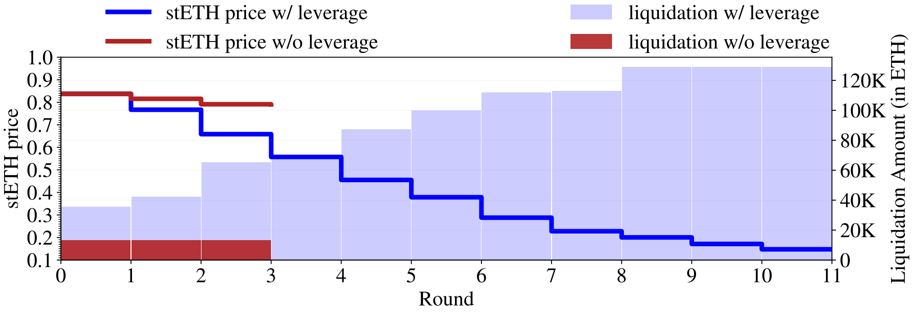

Fig. 15: `stETH` price and liquidation amount during the liquidation cascades.

Case 3: We simulate liquidation cascades across G_L and G_O, assuming that users in G_L choose to deleverage their positions when HFs approach a threshold of 1.1. The selling pressure arises from deleveraging and potential liquidations.

Simulation Setup. We initialize the Curve `stETH`–`ETH` pool by forking its state at block 17,500,000 (June 17th, 2023), with reserve of 265,972 `ETH` and 266,966 `stETH`. Subsequently, we mimic the institutional selling pressure (e.g., Celsius, see Figure 10) after Terra crash by simulating a sale of 200,000 `stETH` on Curve. This sizable transaction leads to the decline in the `stETH` price, resulting in a new exchange rate of 100 `stETH` = 83.76 `ETH`, denoted as $p_0 = 0.8376$.

- **Simulation of Case 1.** We initialize 262 leverage staking positions, each with an `address` that we have detected in Section 5. 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 unfolds through 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 critical threshold of 1, a simulated liquidation event is triggered.

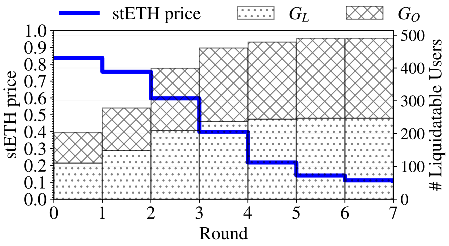

Fig. 16: Case 2 simulation results.

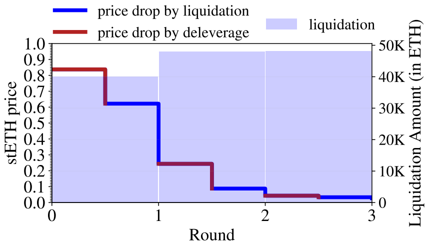

Fig. 17: Case 3 simulation results.

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 10. This process continues until no more liquidatable positions remain.

Simulation Results. We analyze the liquidation amount, HFs, and `stETH` price during the simulation process. As shown in Figure 13, the simulation terminates after 11 rounds, and 244 (93.13%) positions are liquidated. A noteworthy observation is that HFs of all positions exhibit a gradual decrease, as depicted in Figure 14. This is directly attributed to the successive price drops of `stETH`, as visualized in Figure 15. The cascading liquidations result in a total liquidation amount of 128,998 `ETH`, ultimately driving the `stETH` price down to 0.15.

As a comparison, we simulate the scenario where the above-mentioned 262 positions do not utilize the leverage staking strategy. This involves setting the initial values for `totalCollateralETH`s, `totalDebtETH`s, and `HF`s as the values recorded in the transaction logs when the *first* borrowing action for the position occurred. As illustrated in Figure 15, the red bars and lines represent the outcome of these simulations. Notably, the cascading liquidation triggered by positions without leverage staking ceases after only three rounds. Merely 13,329 `ETH` ($\frac{1}{9.68}\times$ of the case with leverage staking) will be liquidated, and the `stETH` price remains more than 0.79 `ETH`. Our simulation findings indicate that leverage staking significantly amplifies the risk of cascading liquidation.

- **Simulation of Case 2.** We simulate the scenario where G_L and G_O co-exist on Aave. We initialize a total of 524 positions, equally divided into two groups. We then execute an identical simulation process as in Case 1, recording the number of liquidated addresses and the `stETH` price throughout the simulation.

Simulation Results. As depicted in Figure 16, the simulation terminates after just 7 rounds, resulting in an aggregate liquidation amount of 146,330 `ETH` and a significant drop in the `stETH` price to 0.11. Clearly, the situation in Case 2 is more severe than in Case 1. This is due to the liquidation of both leverage staking and ordinary positions, further intensifying the decline in the `stETH` price.

- **Simulation of Case 3.** We proceed to simulate the scenario where G_L and G_O co-exist on Aave, with users in G_L opting to deleverage their positions.

We initiate 256 leverage staking addresses and 256 ordinary positions. At the beginning of each round, users in G_L monitor their positions' HFs and initiate the deleveraging if $HF < 1.1$. The deleveraged `stETH` is then swapped for `ETH` in the Curve `stETH`–`ETH` pool, causing a subsequent drop in the `stETH` price. Subsequently, the HF for each position is recalculated based on the updated `stETH` price. The remainder of the simulation process mirrors that of Case 1.

Simulation Results. In this case, the `stETH` price declines due to deleveraging and liquidation, as depicted in Figure 17. Notably, the price swiftly declines to 0.03 within just three rounds. In this case, although users in G_L avoid liquidation by closing positions before reaching $HF < 1$, their deleveraging actions exacerbate the `stETH` price drop, heightening liquidation risks for users in G_O.

Limitation. A notable limitation of our simulation is the omission of arbitrage activities. Should sizable arbitrage transactions be executed, they could act as stabilizing forces to restore the price equilibrium and prevent continuous declines.

6.4 Discussion

Our simulation results reveal important insights. If `stETH` faces extreme conditions and undergoes a significant price decline, the Aave–Lido LSD ecosystem is at risk of cascading liquidation, especially with the presence of leverage staking. The `stETH` selling pressure, arising from both liquidations and deleveraging, can initiate a ripple effect within the system, resulting in a further decline in the `stETH` price and more liquidations. As such, it is imperative for Lido and Aave to develop robust approaches to mitigate the risk of cascading liquidations, particularly during periods of significant market volatility. Proactive risk management is essential for building a stable staking and lending environment.

7 Related Work

There is currently limited academic literature on liquid staking. Scharnowski *et al.* [19] analyze the liquid staking basis (e.g., the discrepancy) between the prices of LSDs in the primary and secondary market. They observe that the liquid staking basis widens during times of increased cryptocurrency volatility and decreased liquidity in the secondary market. Cintra *et al.* [7] utilize 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.

There are also several studies on DeFi lending platforms. For example, Heimbach *et al.* [13] conduct a study on the impact of the Ethereum merge on two DeFi lending platforms, Compound and Aave. They investigate the actions taken by Aave to mitigate the liquidation risk of collateralized `stETH` positions. Wang *et al.* [23] present a formal model for evaluating under-collateralized DeFi lending platforms and conduct a risk assessment for leverage lending positions.

8 Conclusion

This paper systematically studies leverage staking with LSDs. We propose a formal model to capture the leverage staking strategy within the Lido–Aave ecosystem. We empirically detect and analyze leverage staking positions, assessing the leverage staking amount, leverage multiplier, and APR. We analyze the volatility of `stETH` price and its impact on liquidations. We analyze the deleveraging actions undertaken by users and the selling pressure arising from the liquidation, recognizing their potential to exacerbate declines in the `stETH` price, thereby possibly triggering cascading liquidations. We conduct stress tests to evaluate the risk introduced by leverage staking under extreme conditions. Our simulation results indicate that leverage staking can amplify the risks of cascading liquidations. We hope that our work will inform and encourage DeFi lending and staking protocols to develop robust risk assessment approaches for effectively monitoring and mitigating the risks associated with leverage staking, as well as enhancing the protection of stakeholders within the LSD ecosystem.

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A Supplementary Figures and Tables

Protocol	Type	Mechanism	LSD	TVL(USD)	Staked `ETH`	Fee	APR
Lido	Pooled	Rebasing	`stETH`	13.8B	8.34M	10%	3.8%
Coinbase	CEX	Reward-bearing	`cbETH`	2.09B	1.21M	25%	3.74%
Rocket	Pooled	Reward-bearing	`rETH`	1.47B	892K	14%	4.32%
Binance	CEX	Reward-bearing	`wBETH`	730M	709K	10%	3.85%
Frax	Pooled	Dual-token	`frxETH-sfrxETH`	417M	253K	10%	4.78%
Stakewise	Pooled	Dual-token	`sETH2-rETH2`	157M	96K	10%	3.83%
Swell	Pooled	Reward-bearing	`swETH`	76M	46K	10%	3.37%

Table 1: Statistics of top LSD providers on Ethereum, as of August 23rd, 2023.

Block Number	Transaction Hash	LTV	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 2: Historical changes of Aave V2 parameter configurations.

A.1 Liquid Staking Providers

Table 1 provides the statistics of top LSD providers on Ethereum.

A.2 Aave Parameter Configuration

Table 2 depicts the historical changes of Aave parameter configurations. We crawl the `collateralConfigurationChanged` events for Aave V2 lending pool.

B Generalized Formalization For Leverage Staking

In addition to the standardized cases discussed in Section 4, real-world leverage lending situations can exhibit substantial variation among users. Specifically, we consider the following variations. *(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^{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 part of the borrowed `ETH` on Lido. In this scenario, $\mathsf{U_i}$ may choose to restake only s_k ($s_k \in [0,1]$) percent of the borrowed `ETH`.

Let $LevM_{(S,n)}$, $ColM_{(S,n)}$, and $BorM_{(S,n)}$be the leverage multiplier, collateral multiplier, and borrowing multiplier respectively. We know that $LevM_{(S,n)} = \frac{A_{(S,n)}}{S}$, $ColM_{(S,n)} = \frac{C_{(S,n)}}{S}$ and $BorM_{(S,n)} = \frac{B_{(S,n)}}{S}$. Equation 7 introduces a more generalized formalization to accommodate these variations.

$$
\begin{aligned}
LevM_{(S,n)} &= \sum_{k=1}^{n+1}[\prod_{i=1}^{k} s_i \cdot \prod_{j=1}^{k-1} c_j \cdot \prod_{m=1}^{k-1} b_m \cdot (l \cdot P^{\mathsf{st}}_{t_0})^{k-1}] \\
ColM_{(S,n)} &= \sum_{k=1}^{n}[\prod_{i=1}^{k} s_i \cdot \prod_{j=1}^{k} c_j \cdot \prod_{m=1}^{k-1} b_m \cdot (l \cdot P^{\mathsf{st}}_{t_0})^{k-1}] \\
BorM_{(S,n)} &= \sum_{k=1}^{n}[\prod_{i=1}^{k} s_i \cdot \prod_{j=1}^{k} c_j \cdot \prod_{m=1}^{k} b_m \cdot (l \cdot P^{\mathsf{st}}_{t_0})^{k}] \\
HF_{\mathsf{U_i}}(P^{\mathsf{st}}_{t_c} | P^{\mathsf{st}}_{t_0}) &= \frac{ColM_{(S,n)} \cdot P^{\mathsf{st}}_{t_c} \cdot \mathrm{LT}}{BorM_{(S,n)}}
\end{aligned}
\tag{7}
$$

Algorithm 1: 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
  submitted 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 (submitted, deposit, borrow,
  submitted) then
    if For the sub-sequence (submitted$_0$, deposit, borrow, submitted$_1$): (i)
      The stETH amount received in submitted$_0$ 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 submitted$_1$ event then
        return $\mathcal{E}_s$;
    return $\emptyset$;
else
    return $\emptyset$;
```

C Leverage Staking Detection Algorithm

Algorithm 1 depicts our approach to detect leverage staking addresses.

D Additional Leverage Staking Measurement Results

D.1 Actual APR Computation

Equation 8 represents our proposed method for calculating the *actual* APR in the context of leverage staking. This approach involves the net earnings yielded from `deposit` and `withdraw` actions, which are then offset against the `ETH` consumed during `borrow` and `repay` actions. Furthermore, our calculation takes into consideration the conversion of consumed `ETH` to `stETH`, factoring in the `stETH` price at the moment of the last recorded deposit action.

$$
\begin{aligned}
\mathsf{actualAPR} &= \frac{\left(\mathsf{earnedstETH} - \frac{\mathsf{accuredETH}}{p_{\mathtt{stETH}}}\right) \cdot \frac{3600 \cdot 24 \cdot 365}{12}}{\mathsf{totalDepositstETH} \cdot (\mathsf{lastWithdrawBlock} - \mathsf{firstDepositBlock})} \\
\mathsf{accruedstETH} &= \mathsf{totalWithdrawstETH} - \mathsf{totalDepositstETH} \\
\mathsf{accruedETH} &= \mathsf{totalRepayETH} - \mathsf{totalBorrowETH}
\end{aligned}
\tag{8}
$$