# Exploring the Market Dynamics of Liquid Staking Derivatives (LSDs)

***Abstract*—Staking has emerged as a crucial concept following Ethereum's transition to Proof-of-Stake consensus. The introduction of Liquid Staking Derivatives (LSD) effectively addresses the illiquidity issue associated with solo staking, gaining significant market attention. In this paper, we analyze LSD market dynamics from the perspectives of both liquidity takers (LTs) and liquidity providers (LPs). We first quantify the price discrepancy between the LSD primary and secondary markets. Then we investigate and empirically measure how LTs can leverage such discrepancy to exploit arbitrage opportunities, unveiling the potential barriers to LSD arbitrages. In addition, we evaluate the financial profit and losses experienced by LPs who participate in supplying LSDs for liquidity provision. Our findings reveal that 66% LSD liquidity provision positions yield an Annual Percentage Rate (APR) lower than simply holding the corresponding LSDs.**

## I. Introduction

Bitcoin uses the Proof-of-Work (PoW) consensus (also referred to as Nakamoto consensus [1]) to achieve agreement among nodes in a decentralized setting. This consensus model was also adopted by smart contract-enabled blockchains such as Ethereum [2]. While successful in maintaining network security, PoW raised environmental concerns due to its substantial energy consumption. Consequently, the Ethereum community has been actively striving to propose more sustainable alternatives. Among these, Proof-of-Stake (PoS) [3–6] has risen as one of the most preferred options. Ethereum initiated its transition to a PoS consensus on December 1st, 2020, with the introduction of Beacon Chain. On September 15th, 2022, the Merge completes Ethereum's transition to PoS consensus.

Subsequently, PoS staking [7] replaces PoW mining on the Ethereum blockchain. Instead of relying on the computational power of PoW mining to secure the network, PoS depends on validators who are chosen to create new blocks based on the amount of `ETH` they are willing to stake as collateral. Specifically, participants can lock up 32 `ETH` into the designated deposit contract to become validators. However, solo staking requires substantial capital commitment and technical expertise to maintain the validator node. Moreover, the staked `ETH` becomes illiquid during the lock-up period, thus restricting users from capitalizing on broader market opportunities.

To address these challenges, the concept of Liquid Staking Derivative (LSD) emerged [8–10]. Liquid staking providers enable retail users, particularly those with limited capital and technical expertise, to collectively engage in the network's validation process and earn staking rewards. Various LSDs adopt diverse token mechanisms for staking reward distribution. Rebasing LSDs adjust token supply to distribute staking rewards, whereas reward-bearing LSDs increase token values to represent accumulated staking rewards. These token mechanisms not only determine reward distribution but also hold the potential to impact the dynamics of the LSD market.

In the LSD primary market, users can stake any desired amount of `ETH` on liquid staking platforms to receive the corresponding LSD, which represents both the underlying `ETH` and the staking reward. Following this, users can utilize their LSDs to integrate with existing Decentralized Finance (DeFi) protocols in the secondary market. For instance, they can leverage LSDs as collateral on lending platforms to borrow assets, contribute both `ETH` and LSDs to add liquidity to Decentralized Exchange (DEX) pools, and engage in asset trading by swapping LSDs for other assets through DEX pools.

Despite the considerable market attention that LSDs have attracted, the dynamics of the LSD market remain inadequately explored in the existing literature. This paper aims to comprehensively analyze LSD market dynamics, focusing on the perspectives of both Liquidity Takers (LTs) and Liquidity Providers (LPs). Our objectives are twofold. Firstly, we seek to investigate the price discrepancy between the LSD primary and secondary market and understand how LTs leverage this discrepancy for arbitrage opportunities. Secondly, we aim to evaluate the financial profit and losses experienced by LPs who engage in supplying LSDs for liquidity provision. We outline the main contribution of this paper as follows.

- ◇ **Token Mechanisms Systematization.** We systematically categorize the token mechanisms implemented by LSD protocols, including the rebasing, reward-bearing, and dual-token models. We further formalize token mechanisms of rebasing LSD (e.g., `stETH`) and reward-bearing LSD (e.g., `rETH`), as well as illustrate their functionality in the distribution of staking rewards.
- ◇ **Price Discrepancy and Arbitrage Analysis.** For rebasing and reward-bearing LSDs, we quantify their price discrepancies between primary and secondary markets. Furthermore, we identify 325.6K `ETH` (683.8M `USD`) arbitrage amount caused by the price discrepancies since the inception of LSDs. We provide empirical insights into the strategies adopted by arbitrageurs, revealing potential entry barriers in the context of arbitrages with LSDs.
- ◇ **LSDs Liquidity Provision Measurement.** We empirically measure and compare the Annual Percentage Rate (APR) experienced by 1,002 LPs supplying LSDs (e.g., `stETH` and `rETH`) to DEX liquidity pools such as Curve, Uniswap V3, and Balancer. We find that 66% of LSD liquidity provision positions yield a net APR lower than the APR of simply holding the corresponding LSDs.

## II. Backgroud

### A. Blockchain and DeFi

Permissionless blockchains are decentralized distributed ledgers overlaying a global peer-to-peer network infrastructure, allowing any entity to join and participate freely. Within this context, especially in systems such as Ethereum [2], participants can create many decentralized applications using smart contracts. Built upon permissionless blockchains, DeFi [11, 12] empowers users to participate in decentralized financial activities such as lending, borrowing, and trading.

### B. From Pow Mining to PoS Staking

PoW consensus has also been adopted by Ethereum since its inception. Nevertheless, a notable drawback of PoW lies in its substantial computational demands and energy consumption. Motivated by the need for a more sustainable consensus mechanism, Ethereum embarked on a transition from PoW [2] to PoS [13–17]. This transition started in December 2020 by introducing the Beacon Chain system with a "staking" mechanism. Participants can deposit 32 `ETH` into the designated contract, thereby taking on the validator role for block proposal, block attestation, and synchronizing committee [13]. On September 15th, 2022, the Ethereum "Merge" formally adopted the Beacon Chain as the new consensus layer to the original Mainnet execution layer. After the Merge, staking on the PoS system replaces PoW mining, reducing energy consumption by an estimated 99.95% [18]. On April 12th, 2023, Ethereum underwent the "Shapella upgrade", facilitating the withdrawal of the staked `ETH` for validators [19].

### C. Staking Options on Ethereum

Ethereum participants are presented with four staking options: solo staking, Staking as a Service (SaaS), Centralized Exchange (CEX) staking, and pooled staking.

In *solo staking*, participants manage their validator nodes by staking at least 32 `ETH`, ensuring complete control over staking rewards. This staking strategy can enhance blockchain security. However, it requires technical expertise in operating a validator node and a significant capital commitment of a full 32 `ETH`, presenting a significant barrier to user participation.

Compared with solo staking, *SaaS staking* substantially reduces the operational burden for users who possess 32 `ETH` but lack technical expertise. The SaaS provider manages the validator node on behalf of the user, receiving operational fees proportional to the amount of staked `ETH` and staking rewards.

Users with holdings below 32 `ETH` can opt to *Pooled staking*, a system where multiple participants combine (or "pool") their `ETH` to participate in the staking process collectively without necessitating individual full-node commitments. As such, all rewards and penalties accrued by the pool's validators are shared among stakers. Typically, staking pools charge fees as a fixed amount or a percentage of the staking rewards.

In *CEX staking*, providers such as Binance and Coinbase offer users centralized and custodial staking services. Staking through CEXs offers users the simplicity and convenience akin to pooled staking, eliminating the need for technical requirements and full-node commitments.

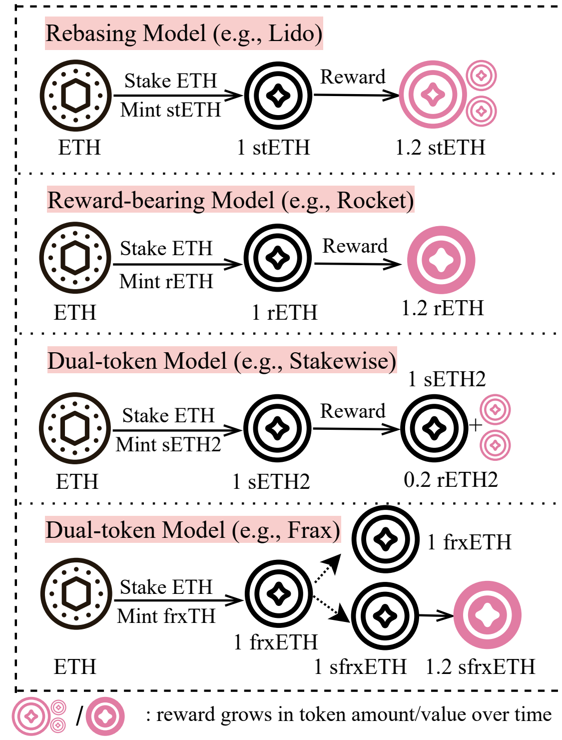


Fig. 1: Illustration of LSD token mechanisms.

## III. Liquid Staking Derivatives

Staking `ETH` on Ethereum helps enhance network security and generates staking rewards. However, it restricts liquidity during the staking period, limiting users' ability to capitalize on market opportunities. In addressing this challenge, the concept of LSD emerged, which serves as a tradable representation encompassing the underlying staked `ETH`, its associated staking rewards and potential penalties (e.g., slashing [20]). Users can acquire LSDs by participating in pooled staking (e.g., Lido) or CEX staking (e.g., Coinbase). These LSDs can be traded instantly in the secondary market. As of the latest update, liquid staking protocols on Ethereum have accumulated a total value exceeding 20B USD[1], securing a leading position across various DeFi sectors.

LSD token mechanisms can be broadly classified into the following categories: *(i)* rebasing model, *(ii)* reward-bearing model, and *(iii)* dual-token model (cf. Fig. 1).

### A. Rebasing Model

Tokens with a rebasing mechanism feature an elastic total supply that can increase or decrease, with the change in supply distributed proportionally among token holders. Stakers' `stETH` balances get adjusted daily to reflect the accumulated rewards. The rebase can be positive or negative, depending

[1] https://defillama.com/protocols/liquid%20staking/Ethereum, access on October 5th, 2023



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on the validators' performance. The rebasing model mitigates the expense associated with reward distribution. Distributing staking rewards among all `stETH` holders using direct transfer calls necessitates an unbounded loop. With rebasing, the `stETH` smart contract can automatically update all the addresses holding `stETH` in a single transaction. However, a rebasing token is difficult to integrate into existing DeFi protocols, as the token's supply changes on a regular basis.

For instance, users who stake $m$ `ETH` on Lido can obtain $m$ `stETH`. Note that `stETH` rebases via the "share" concept. Given the share price $p_{share}(t_0)$ at time $t_0$, a rebase event at time $t_1$ changes the share price to $p_{share}(t_1)$, consequently adjusting users' `stETH` balances from $\frac{m}{p_{share}(t_0)}$ to $\frac{m}{p_{share}(t_1)}$.

$$
\begin{aligned}
p_{share}(t_0) &= \frac{\mathsf{totalEther}(t_0)}{\mathsf{totalShares}(t_0)} \\
p_{share}(t_1) &= \frac{\mathsf{totalEtherWithRewards}(t_1)}{\mathsf{totalShares}(t_0) + \mathsf{shares2mint}(t_1)} \\
&\mathsf{shares2mint}(t_1) = \\
&\frac{\mathsf{rewards} \cdot \mathsf{protocolFee} \cdot \mathsf{totalEther}(t_0)}{\mathsf{totalEtherWithRewards}(t_1) - \mathsf{rewards} \cdot \mathsf{protocolFee}}
\end{aligned} \tag{1}
$$

### *B. Reward-Bearing Model*

Reward-bearing LSDs increase in their values to reflect the accumulated rewards. In contrast to rebasing LSDs, reward-bearing LSDs adopt an alternative design to simplify liquid staking while upholding stakers' seamless access to DeFi opportunities, thus striking a balance between accessibility and functionality. Their supply remains stable, offering a more consistent valuation trajectory. For instance, Rocket Pool offers `rETH`, which represents the tokenized staking assets and the rewards that it gains over time. Notably, as staking rewards are earned, the value of `rETH` appreciates, manifesting through changes in the `rETH/ETH` ratio at time $t$ (cf. Eq. 2), while the holder's `rETH` balance remains unchanged.

$$
\mathsf{rETH/ETH}_t = \frac{\mathsf{totalETHStaked}_t + \mathsf{stakingRewardInETH}_t}{\mathsf{rETHTotalSupply}_t} \tag{2}
$$

### *C. Dual-token Model*

The dual-token model entails two variations of LSDs: *(i)* a base token representing the underlying `ETH` token on a 1:1 basis; and *(ii)* a reward-bearing token that progressively accrues yield, or a reward token held separately by stakers to reflect the net reward. For instance, Frax implements the dual-token model with its `frxETH` and `sfrxETH` tokens, where `frxETH` maintains parity with `ETH` and `sfrxETH` accrues the staking reward. Stakers can choose between holding `frxETH` to yield from liquidity provision in Curve's `frxETH–ETH` liquidity pool, or exchange `frxETH` for `sfrxETH` to earn the staking reward. In contrast, Stakewise implements a different design, where the balance of `ETH` deposits and rewards is reflected in `sETH2` (staking `ETH`) and `rETH2` (reward `ETH`) minted to stakers in a 1:1 ratio. This design avoids rebasing or reward-bearing dynamics, thereby mitigating the potential for impermanent loss when providing liquidity in DEXs.

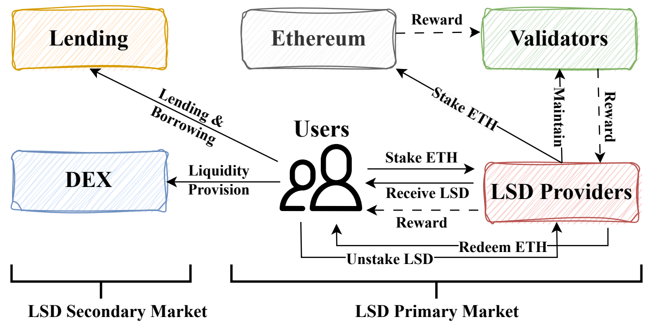


Fig. 2: The primary and secondary markets for LSDs.

## IV. LSD Price Discrepancy and Arbitrages

Users can stake `ETH` on liquid staking platforms to acquire LSDs in the primary market. These LSDs can be utilized to integrate with existing DeFi protocols in the secondary market, including participating in liquidity provision within DEX pools and providing assets on lending platforms (cf. Fig. 2).

In this section, we first investigate the price discrepancy that exists between the LSD primary and secondary markets, which raises arbitrage opportunities with LSDs. Then we bring empirical insights into these arbitrage behaviors, shedding light on the potential entry barriers.

### *A. LSD Price Discrepancy*

LSDs with different token mechanisms exhibit distinct price dynamics. In the subsequent sections, we do not discuss dual-token LSDs due to their relatively low market share.

Rebasing LSDs adjust their token supply for reward distribution. Taking `stETH` as an example, when users stake `ETH` on Lido, they receive an equivalent 1:1 amount of `stETH`. This indicates that the `stETH` to `ETH` price is fixed as $P^{\mathsf{1st}}_{\mathsf{stETH}} = 1$ in the primary market. `stETH` can be traded in the secondary market through DEX such as Curve. While ideally, the secondary market price ($P^{\mathsf{2nd}}_{\mathsf{stETH}}$) should align with $P^{\mathsf{1st}}_{\mathsf{stETH}}$, in reality, a deviation between the two exists (cf. Fig. 3). We crawl 10-minute tick-level data of $P^{\mathsf{1st}}_{\mathsf{stETH}}$ and $P^{\mathsf{2nd}}_{\mathsf{stETH}}$ from Lido and Curve respectively. We calculate the realized volatility [21, 22] of $P^{\mathsf{2nd}}_{\mathsf{stETH}}$ on day $i$ using Eq. 6. We observe an average $\mathsf{RV}_{\mathsf{stETH}}$ of $0.16\%$ and the maximum recorded $\mathsf{RV}_{\mathsf{stETH}}$ of $5\%$. We further calculate the price discrepancy between $P^{\mathsf{1st}}_{\mathsf{stETH}}$ and $P^{\mathsf{2nd}}_{\mathsf{stETH}}$ (cf. Eq. 7). We discover that on average, $P^{\mathsf{2nd}}_{\mathsf{stETH}}$ is $0.83\%$ lower than $P^{\mathsf{1st}}_{\mathsf{stETH}}$. Moreover, we find that $P^{\mathsf{2nd}}_{\mathsf{stETH}}$ deviates significantly from $P^{\mathsf{1st}}_{\mathsf{stETH}}$ from May 7th to May 16th, 2022 due to the crash of `UST/LUNA` on the Terra network [9, 23]. During this period, the price discrepancy widened to 6.9%, reaching its all-time maximum (cf. Fig. 5).

Reward-bearing LSDs, such as `rETH`, accumulate rewards by adjusting their token value, leading to an increase in the `rETH` price in the primary market ($P^{\mathsf{1st}}_{\mathsf{rETH}}$) over time. Consequently, the `rETH` price in the secondary market ($P^{\mathsf{2nd}}_{\mathsf{rETH}}$) is anticipated to align with $P^{\mathsf{1st}}_{\mathsf{rETH}}$. To analyze the price behavior of `rETH`, we gather 10-minutes tick-level $P^{\mathsf{1st}}_{\mathsf{rETH}}$ by querying the Rocket protocol contract. We also collect



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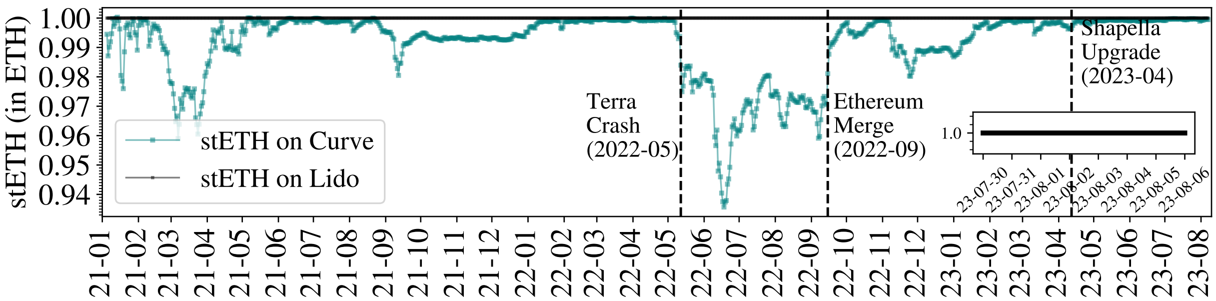


Fig. 3: `stETH` price on different platforms over time. This figure is adapted and extended from [9].

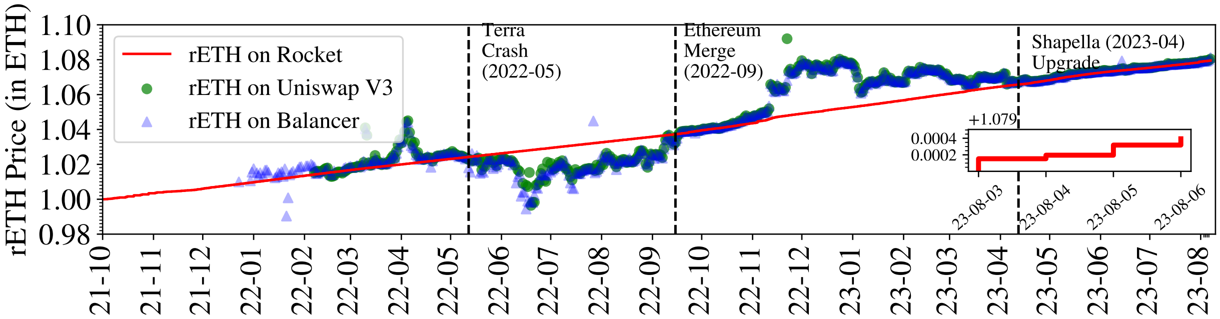


Fig. 4: `rETH` price on different platforms over time.

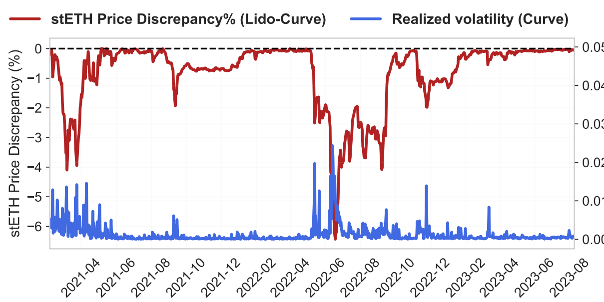


Fig. 5: `stETH` price discrepancy and realized volatility.

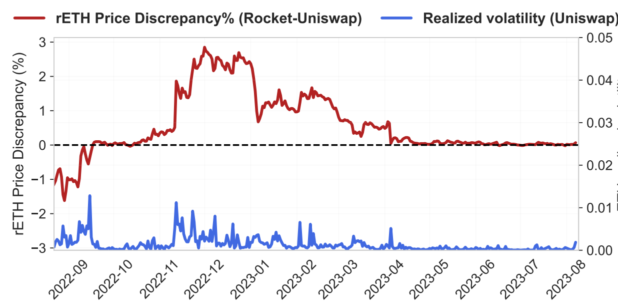


Fig. 6: `rETH` price discrepancy and realized volatility.

$P^{\text{2nd}}_{\text{rETH}}$ by querying Uniswap V3 and Balancer pool contracts respectively. We discover that $P^{\text{2nd}}_{\text{rETH}}$ deviates from $P^{\text{1st}}_{\text{rETH}}$ by an average of $0.22\%$. Furthermore, our data indicates that $P^{\text{2nd}}_{\text{rETH}}$ is less volatile than $P^{\text{2nd}}_{\text{stETH}}$ (cf. Fig. 4). This may be attributed to the fact that as a reward-bearing token, `rETH` can be more seamlessly integrated into DEX designs, given that the supply of `rETH` remains constant over time. Similar to `stETH`, `rETH` has also witnessed substantial volatility following the Terra crash, reaching a peak realized volatility of $3\%$ (cf. Fig. 6). Interestingly, $P^{\text{2nd}}_{\text{rETH}}$ experienced a gradual rebound post-Merge and a notable upward trend subsequent to MakerDAO's introduction of the `rETH` token in November 2022, suggesting a burgeoning rise in investor confidence.

### B. LSD Arbitrages

The price discrepancy between the LSD primary and secondary markets creates arbitrage opportunities. Capitalizing on these opportunities not only enables users to generate profits but also helps restore price equilibrium in different markets.

In the traditional financial market, arbitrage [24] exploits price discrepancies in various markets to secure profits without assuming any risk. Traders capitalize on temporary price differences, buying the asset at a lower price and selling it where it is higher. This approach is also applicable to LSD arbitrage. For example, when $P^{\text{2nd}}_{\text{stETH}} > P^{\text{1st}}_{\text{stETH}}$, users can first stake `ETH` on Lido to receive `stETH` and sell `ETH` immediately in the Curve pool to secure profits. However, in the context of LSD arbitrage, this approach is not entirely risk-free due to *(i)* the uncertainty to withdraw `ETH` before Shapella, and *(ii)* the potential slippage when trading on DEXs.

Note that users can also implement the arbitrage strategy when $P^{\text{2nd}}_{\text{stETH}} < P^{\text{1st}}_{\text{stETH}}$ (cf. Eq. 3). In this scenario, users can initially exchange `ETH` in the Curve pool for `stETH` and subsequently redeem `stETH` on Lido for `ETH`. It is important



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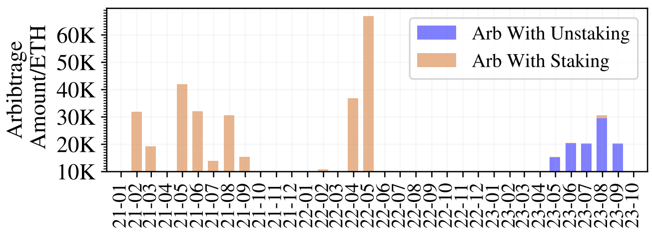


Fig. 7: `stETH-ETH` arbitrage amount.

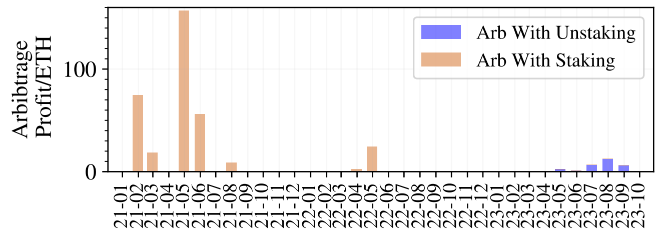


Fig. 8: `stETH-ETH` arbitrage profit.

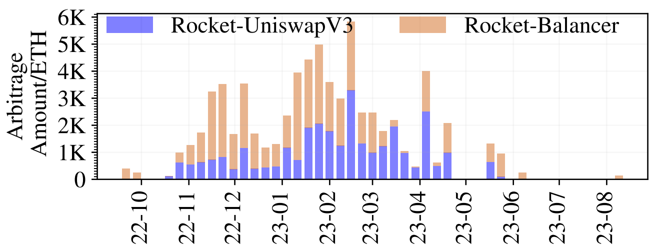


Fig. 9: `rETH-ETH` arbitrage amount.

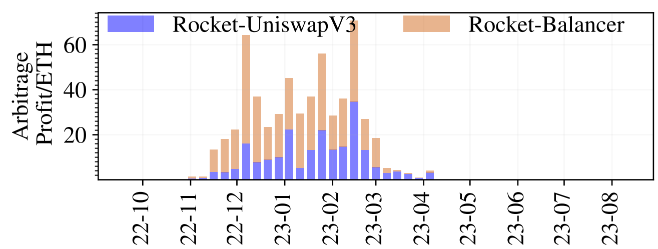


Fig. 10: `rETH-ETH` arbitrage profit.

to note that the arbitrage in this direction is only viable after the Shapella upgrade, as stakers are not allowed to redeem `stETH` for `ETH` before Shapella.

$$\begin{aligned} &\texttt{ETH} \xrightarrow[\text{Lido}]{\text{Stake}} \texttt{stETH} \xrightarrow[\text{Curve}]{\text{Swap}} \texttt{ETH}, \text{ if } P^{\text{2nd}}_{\text{stETH},t} > P^{\text{1st}}_{\text{stETH},t} \\ &\texttt{ETH} \xrightarrow[\text{Curve}]{\text{Swap}} \texttt{stETH} \xrightarrow[\text{Lido}]{\text{Unstake}} \texttt{ETH}, \text{ if } P^{\text{2nd}}_{\text{stETH},t} < P^{\text{1st}}_{\text{stETH},t} \end{aligned} \tag{3}$$

### C. Arbitrage Measurement

*1) Arbitrages of Rebasing-based LSDs:* The price discrepancy, as illustrated in Fig. 3, between a rebased-based LSD in the primary market and the secondary market creates opportunities for arbitrage. To systematically capture historical arbitrage events for `stETH-ETH` across Lido and Curve, we propose the following heuristics:

- *Arbitrage with Staking* (when $P^{\text{2nd}}_{\text{stETH},t} > P^{\text{1st}}_{\text{stETH},t}$): We crawl transactions where a user initially stakes `ETH` on Lido to receive `stETH`, followed by a subsequent swap of `stETH` to `ETH` on Curve. Notably, both the staking and swap events occur within the same transaction.
- *Arbitrage with Unstaking* (when $P^{\text{2nd}}_{\text{stETH},t} < P^{\text{1st}}_{\text{stETH},t}$): We crawl the swap events where a user exchanges `ETH` for `stETH` on Curve after the Shapella upgrade. Subsequently, in separate transactions, the user unstakes `stETH` on Lido to obtain `ETH`.

**Arbitrage Amount and Profit.** We apply our heuristics to analyze `stETH-ETH` arbitrages across Lido and Curve spanning Ethereum blocks 11,473,216 (December 17th, 2020) to 17,866,191 (August 10th, 2023). The results, depicted in Fig. 7 and Fig. 8, reveal that 38 addresses performed 400 transactions for arbitrage with staking. These arbitrages accumulated a total of 200,741 `ETH` with an overall profit of 343 `ETH`. It's noteworthy that over 99% of arbitrages with staking took place prior to June 2022, a period when the price of `stETH` on Curve occasionally exceeded 1.

As for arbitrages in the reverse direction (e.g., with unstaking on Lido), we identify 42 addresses participating in 55,617 `ETH` worth of `stETH-ETH` swaps post-April 2023, resulting in a total profit of 29 `ETH`. In this case, following the swap of $m$ `ETH` to $\frac{m}{p}$ `stETH` on Curve, where the price is 1 `stETH` $<$ $p$ `ETH` (with $p < 1$), arbitrageurs have the flexibility to execute the unstaking transaction at any time. This is due to the constant price of `stETH` on Lido, always fixed at 1, ensuring that arbitrageurs can secure a revenue of $(\frac{1}{p} - 1) \cdot m$ `ETH` after the unstaking process.

*2) Arbitrages of Reward-bearing-based LSDs:* The price of a reward-bearing LSD experiences periodic increments to reflect the accumulative staking reward within the network. As shown in Fig. 4, the price of `rETH` on Rocket Pool witnesses a daily increase whenever the oracle updates the beacon's reward allocations garnered by the validators. Nonetheless, the secondary market price does not consistently align with the primary market price. Such price discrepancies across different platforms can create opportunities for arbitrage.

**Arbitrage Amount and Profit.** We investigate the arbitrage opportunities involving `rETH` on Rocket-Balancer and Rocket-Uniswap V3 from September 30th, 2021, to August 10th, 2023. Our analysis reveals that 373 addresses executed 3,735 arbitrage transactions during this period, resulting in a cumulative exchange of 69,270.7 `ETH` and an overall profit of 577.1 `ETH`. The distributions of `rETH-ETH` arbitrage amounts and profits over time are shown in Fig. 9 and 10 respectively. Interestingly, over 99% of the arbitrages occurred prior to May 2023, aligning with the historical price volatility of `rETH`. This pattern is evident in Fig. 4, which illustrates the nearly identical price trajectories of `rETH` on Uniswap V3, Balancer,



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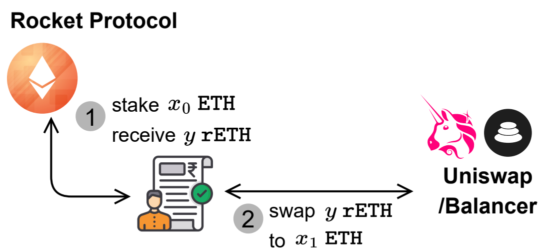



Fig. 11: Arbitrage without flash loan.

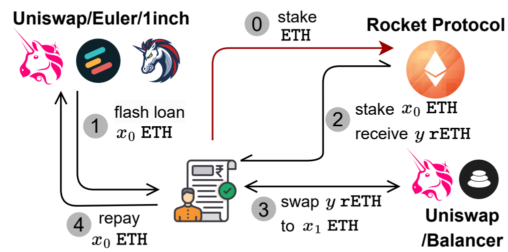



Fig. 12: Arbitrage with flashloan.

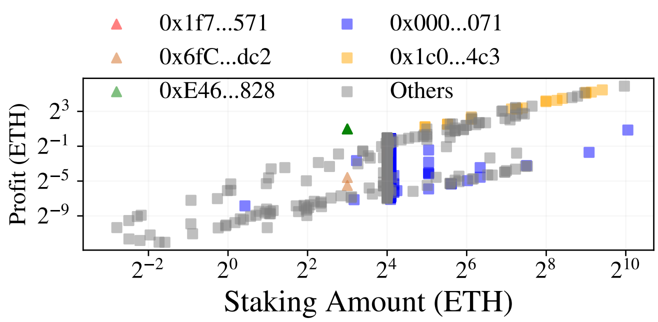



Fig. 13: Arbitrage profit and staking.

and the Rocket protocol after May 2023.

**Arbitrage Strategies Analysis.** Interestingly, we observe that the 3,811 arbitrage transactions were executed by interacting with 35 distinct contract addresses (cf. Table I in Appendix A). Out of these, 10 arbitrage contract addresses, also known as arbitrage bots, were invoked by multiple arbitrageurs. For instance, the address 0x1f7...571 was utilized by 329 arbitrageurs to initiate 1,903 arbitrage transactions from November 7th, 2022 to March 17th, 2023, generating a cumulative profit of 1,257.8 ETH.

After manually assessing these 35 contract addresses, we discover that 4 of them feature publicly accessible code, with 2 written in Vyper and 2 in Solidity. After a thorough analysis of their transactions and code, we compile their arbitrage strategy particulars, which can be grouped into two categories:

- *Arbitrage without flash loan* (cf. Fig. 11): Upon observing the price disparities of rETH-ETH token pair on Rocket protocol with a price $1\,\texttt{ETH} = p_0\,\texttt{rETH}$ and DEXs (e.g., Balancer and Uniswap V3) with a price of $1\,\texttt{ETH} = p_1\,\texttt{rETH}$, an arbitrageur performs the following process: *(i)* stakes $x_0$ ETH on Rocket protocol to receive $y = x_0 \cdot p_0$ ETH; *(iii)* swaps $y$ ETH to $x_1 = \frac{y}{p_1}$ rETH on DEXs. All these steps occur on a single transaction $\mathsf{tx}_{arb}$. The final profit is $x_1 - x_0 - cost(\mathsf{tx}_{arb})$, where the transaction cost $cost(\mathsf{tx}_{arb})$ includes the gas fees and the fee used to bribe validators.
- *Arbitrage with flash loan* (cf. Fig. 12): Upon observing the price disparities of rETH-ETH token pair, an arbitrageur performs the following process: *(i)* lends $x_0$ ETH from the DeFi platforms supporting flash loans [25] (e.g., Uniswap, Euler, 1inch); *(ii)* stakes $x_0$ ETH on Rocket protocol to receive $y = x_0 \cdot p_0$ ETH; *(iii)* swaps $y$ ETH to $x_1 = \frac{y}{p_1}$ rETH on DEXs; *(iii)* repays the $x_0$ ETH flash loans. All these steps occur on a single transaction $\mathsf{tx}_{arb}$. The final profit of the arbitrage is $x_1 - x_0 - cost(\mathsf{tx}_{arb})$.

**Is there a barrier to engaging in rETH-ETH arbitrage with flash loan?** We identify four rETH-ETH arbitrage bots whose code is publicly accessible. Interestingly, due to the code transparency, any user who witnesses a prosperous on-chain arbitrage transaction $\mathsf{tx}_{arb}$ can replicate the corresponding arbitrageur's strategy. This involves creating a transaction with identical input data as that of $\mathsf{tx}_{arb}$ to invoke the arbitrage bot. By leveraging flash loans, the user can execute this action without the necessity of transferring any ETH to the bots, merely incurring the transaction cost $cost(\mathsf{tx}_{arb})$.

However, this seemingly straightforward "copy-paste" arbitrage approach does not yield practical results. This is because, in real-world scenarios, prior to executing an arbitrage transaction with flash loan, an arbitrageur needs to either stake ETH or await the staking of ETH by other users within the Rocket protocol (see the transactions with index 51 and 52 in block 17,073,005 for instance). Such actions trigger changes in the Rocket protocol which enables further staking[2]. Our findings reveal that at least 2,037 successful flash loan-based rETH-ETH arbitrage transaction $\mathsf{tx}_{arb}$ consistently occurs just after a staking transaction $\mathsf{tx}_{stake}$ issued by the same arbitrageur. In other words, $\mathsf{tx}_{arb}$ and $\mathsf{tx}_{stake}$ are situated in the same block and possess consecutive transaction indexes. Our empirical findings indicate that arbitrageurs encounter a substantial entry barrier, necessitating an average stake of 16 ETH as a prerequisite for participating in rETH arbitrage.

Fig. 13 illustrates the distribution of profits from rETH-ETH arbitrage in relation to the staked amount of ETH. Notably, upon excluding arbitrages involving a staking amount of 16 ETH, a clear linear increase in profits over the staked amount becomes evident, characterized by two distinct slopes. For instance, the arbitrage bot with the address 0x1c0...4c3 generated a total profit of 292.8 ETH, staking a cumulative amount of 4,418.8 ETH. We also analyze the distribution of arbitrages with a staking amount of 16 ETH (cf. Fig. 17), and find that they yielded $0.49 \pm 0.33$ ETH on average.

[2] https://github.com/rocket-pool/rocketpool/blob/master/contracts/contract/deposit



6

## V. Liquidity Provision with LSDs

In this section, our focus shifts to analyzing LP's financial incentives for engaging in liquidity provision with LSDs.

After acquiring LSDs in the primary market, users face two options. They can either opt to retain the LSDs until the Shapella upgrade, at which point they can unstake the LSDs to withdraw `ETH` and receive the associated staking rewards. Alternatively, users may leverage their LSDs to explore wider financial opportunities in the secondary market, such as participating in liquidity provision for DEX pools.

### A. PNL of LSD Liquidity Provision

At the time of writing, Curve stands out as the dominant DEX for `stETH`, whereas Uniswap and Balancer take the lead as the most liquid DEXs for `rETH`. Fig. 18 shows the distribution of LSD trading volume on Curve, Uniswap V3 and Balancer over time. We find that the accumulated trading volume of `stETH` on Curve from February 2021 to August 2023 is 11.2M `ETH`, while the cumulative trading volume of `rETH` is 775K `ETH` since the inception of the `rETH-ETH` pools on Balancer and Uniswap V3 in December 2021 and February 2022. This result suggests that `stETH` experiences more active trading in the secondary market than `rETH`.

In light of the increasing trend of LSD liquidity provision, we aim to examine the Profit and Loss (PNL) experienced by LPs and assess how these PNLs differ among LSDs with distinct token mechanisms. Consider a user intending to add an initial amount of $q_{x,t_0}$ LSD and $q_{y,t_0}$ `ETH` to a LSD-ETH liquidity pool at time $t_0$. Given the spot price of $p^{\mathrm{LP}}_{x,t_0}$, the initial portfolio value is $V^{\mathrm{LP}}_{t_0} = q_{y,t_0} + q_{x,t_0} \cdot p^{\mathrm{LP}}_{x,t_0}$. While users can gain financial benefits through liquidity provision, they may also encounter losses in their portfolio value due to price changes. In particular, the user's PNL originates from four sources: *(i)* the swap fees earned through liquidity provision; *(ii)* the accumulated staking reward; *(iii)* the change in portfolio value due to price volatility; *(iv)* the transaction fees associated with adding and removing liquidity.

Suppose that at time $t_1$, the LSD price changes to $p^{\mathrm{LP}}_{x,t_1}$ and the user can withdraw $q^{\mathrm{LP}}_{x,t_1}$ LSD and $q^{\mathrm{LP}}_{y,t_1}$ `ETH`. User's portfolio value changes from $V_{t_0}$ to $V^{\mathrm{LP}}_{t_1} = q^{\mathrm{LP}}_{y,t_1} + q^{\mathrm{LP}}_{x,t_1} \cdot p_{x,t_1}$. Note that the earned swap fees and accumulated staking rewards are already reflected in $V^{\mathrm{LP}}_{t_1}$ when LP removes liquidity from the pool. Specifically, if the user supplies `stETH` for liquidity provision, the rewards will be manifested in the withdrawal amount of `stETH` (i.e., $q^{\mathrm{LP}}_{x,t_1}$). If the user provides `rETH` to the liquidity pool, the rewards will be expressed through changes in `rETH` price over time. Therefore, we can calculate the liquidity provision PNL using Eq. 4, where function $f(\cdot)$ converts the periodical rate of return to APR.

$$
\begin{aligned}
&V^{\mathrm{LP}}_{t_0} = q_{y,t_0} + q_{x,t_0} \cdot p^{\mathrm{LP}}_{x,t_0},\ V^{\mathrm{LP}}_{t_1} = q^{\mathrm{LP}}_{y,t_1} + q^{\mathrm{LP}}_{x,t_1} \cdot p_{x,t_1} \\
&\mathrm{PNL}^{\mathrm{LP}}_{(t_0,t_1)} = V^{\mathrm{LP}}_{t_1} - V^{\mathrm{LP}}_{t_0},\ \mathrm{APR}^{\mathrm{LP}}_{(t_0,t_1)} = f\left(\frac{\mathrm{PNL}^{\mathrm{LP}}_{(t_0,t_1)}}{V^{\mathrm{LP}}_{t_0}}\right)
\end{aligned} \tag{4}
$$

**Empirical Analysis.** To analyze the APR obtained by users providing LSDs as liquidity in DEXs, we explore transactions that add and remove liquidity in LSDs on Curve, Uniswap V3, and Balancer up to block 17,866,191 (August 7th, 2023). Our investigation identifies 34,682 `AddLiquidity` and 11,985 `RemoveLiquidity` events on the Curve `stETH` pool, 878 `Mint` and 1,328 `collect` events on the Uniswap V3 `rETH` pool, as well as 3,474 `PoolBalanceChanged` events on the Balancer `rETH` pool. Within these events, we identify 194, 464, and 344 liquidity positions in which users have withdrawn all of their LSDs from the Curve, Uniswap V3, and Balancer, respectively. We use Equation 4 to calculate the actual APR of the 1,002 liquidity provision positions.

Figures 16 and 14 show the probability distribution of LSD liquidity provision APR on the three DEXs, excluding and including transaction fees respectively. When making horizontal comparisons, we discover that the LSD liquidity provision APR is likely to be influenced by the underlying token mechanism. Specifically, when transaction fees are not considered, we find that the APRs for 71.7% of the detected `stETH` liquidity provision positions are concentrated around $[-0.1, 0.1]$, whereas only 36.8% of `rETH` liquidity provision positions exhibit APRs fall within the same range. In fact, 21.3% of the `rETH` positions achieve an APR greater than 1. When making a vertical comparison to consider transaction fees, the difference is more pronounced. Our results show that 85.3% of `stETH` liquidity provision positions experience a negative APR, whereas the majority (69.8%) of `rETH` liquidity provision positions achieved a positive APR.

We also note that the performance of liquidity provision for the same LSD varies among different DEX pools. When comparing `rETH` liquidity provision on Uniswap V3 and Balancer, we observe that users on Uniswap V3 are more likely to achieve higher APRs. This difference may be attributed to the concentrated liquidity design of Uniswap V3 [26], allowing users to enhance capital efficiency through liquidity provision.

### B. LSD Liquidity Provision vs Holding Strategy

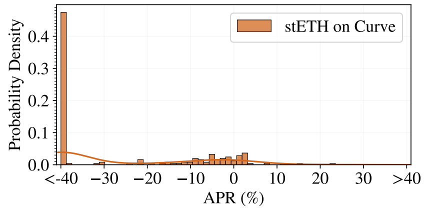
Users are incentivized to supply LSDs for liquidity provision instead of simply holding them due to the prospect of increased profitability. Consequently, we undertake an empirical study to analyze the PNLs associated with these two strategies.

$$
\begin{aligned}
&V^{\mathrm{Hold}}_{t_0} = q_{y,t_0} + q_{x,t_0} \cdot p_{x,t_0},\ V^{\mathrm{Hold}}_{t_1} = q_{y,t_0} + q^{\mathrm{Hold}}_{x,t_1} \cdot p^{\mathrm{LP}}_{x,t_1} \\
&\mathrm{PNL}^{\mathrm{Hold}}_{(t_0,t_1)} = V^{\mathrm{Hold}}_{t_1} - V^{\mathrm{Hold}}_{t_0},\ \mathrm{APR}^{\mathrm{Hold}}_{(t_0,t_1)} = f\left(\frac{\mathrm{PNL}^{\mathrm{Hold}}_{(t_0,t_1)}}{V^{\mathrm{Hold}}_{t_0}}\right)
\end{aligned} \tag{5}
$$

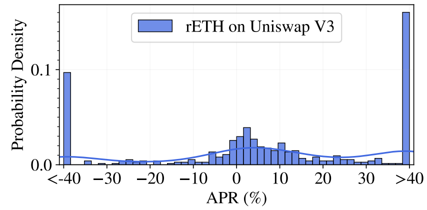
The user has the opportunity to accumulate LSD staking rewards through both strategies, but it's crucial to note that the staking reward for liquidity provision differs from that of holding LSDs, primarily due to the impact of swaps within the liquidity pool. Furthermore, LSDs with different token mechanisms implement varied approaches to distribute staking rewards. `stETH` adopts a rebasing model, while `rETH` utilizes a reward-bearing model, changing the price of `rETH` at time $t_1$ for reward distribution. Hence, the quantity of `ETH` remains unchanged at time $t_1$, whereas the price and quantity of LSDs



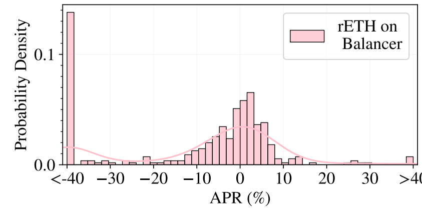
7




(a) ETH-stETH on Curve.

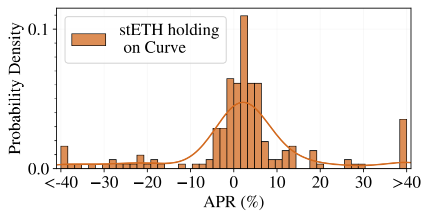



(b) ETH-rETH on Uniswap V3.

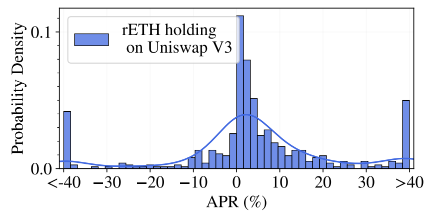



(c) ETH-rETH on Balancer.

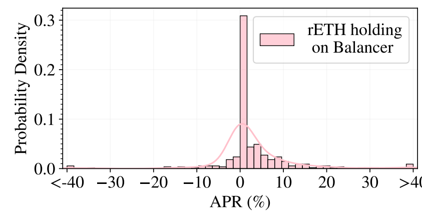
Fig. 14: Distribution of LSD liquidity provision Net APR on DEXs (including transaction fees).




(a) ETH-stETH On Curve.

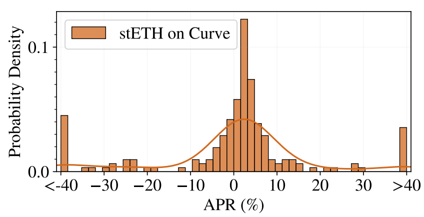



(b) ETH-rETH On Uniswap V3.

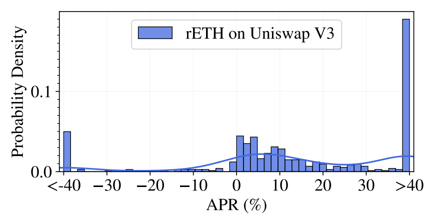



(c) ETH-rETH On Balancer.

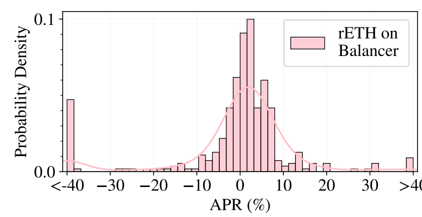
Fig. 15: Distribution of LSD holding Net APR without providing liquidity into DEXs.




(a) ETH-stETH on Curve.




(b) ETH-rETH on Uniswap V3.




(c) ETH-rETH on Balancer.

Fig. 16: Distribution of LSD liquidity provision APR on DEXs (excluding transaction fees).

change based on the underlying token mechanisms. The PNL of the holding strategy can be derived using Eq. 5.

**Empirical Analysis.** For the 1,002 identified liquidity positions, we simulate their portfolio value at $t_1$ as if users had chosen to hold the corresponding LSD. As rETH is based on a reward-bearing model (cf. Fig. 1), the holding amounts at $t_0$ and $t_1$ are the same, i.e., $q_{\texttt{rETH},t_0} \equiv q_{\texttt{rETH},t_1}$. For stETH, which is based on a rebasing model, we query the underlying Lido contracts to obtain the values of $\mathsf{totalEther}(t)$ and $\mathsf{totalShares}(t)$ at a given time and apply Eq. 1 to compute the newly holding amount of stETH at $t_1$. We finally calculate the holding PNL and APR by using Eq. 5.

In total, we find that 660 $(66\%)$ identified liquidity positions can achieve a higher APR by holding the LSDs than supplying it to DEXs. Specifically, as depicted in Fig. 15, the distribution of the holding APR for both stETH and rETH closely approximates a normal distribution, with average values ranging between $-14\%$ and $14\%$. Upon comparing the holding APR in Fig. 15(a) and the Net APR of stETH liquidity provision on Curve in Fig. 14(a), it becomes apparent that users are likely to achieve a positive APR if they opt to hold stETH or rETH in their wallets. This is primarily because they can avoid incurring transaction fees associated with adding and removing liquidity on Curve. Conversely, users who choose to provide rETH on Uniswap V3 may have a higher probability (see the bars of "$> 40$" in Figures 14(b) and 15(b)) of attaining a substantial APR compared to holding rETH, but they also face an increased risk of potential asset losses (see the bars of "$< -40$" in Figures 14(b) and 15(b)).

## VI. Conclusion

This paper provides an empirical study on LSDs. We first systematize the existing LSD token mechanisms and analyze their functionality in the distribution of staking rewards. Subsequently, we quantify price discrepancies for stETH and rETH across primary and secondary markets. We identify the historical arbitrages associated with LSDs, analyze strategies adopted by arbitrageurs, and shed light on potential entry barriers within this domain. Moreover, we measure the APR achieved by LPs who supply LSDs to DEXs. We hope that our study can inspire further research into the analysis and design of LSDs.



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## Appendix

### Supplementary Information

$$\mathsf{RV}_{\mathsf{stETH},i} = \sqrt{\sum_{j=1}^{144} \left(\frac{P^{\mathsf{2nd}}_{\mathsf{stETH},tick_{i,j+1}}}{P^{\mathsf{2nd}}_{\mathsf{stETH},tick_{i,j}}}\right)^2} \tag{6}$$

$$\mathsf{PD}_{\mathsf{stETH},i} = \mathsf{avg}\left(\sum_{j=1}^{144} \frac{P^{\mathsf{2nd}}_{\mathsf{stETH},tick_{i,j}} - P^{\mathsf{1st}}_{\mathsf{stETH},tick_{i,j}}}{P^{\mathsf{1st}}_{\mathsf{stETH},tick_{i,j}}}\right) \tag{7}$$

Eq. 6 and 7 are used to calculate the price discrepancy between the LSD primary market and secondary market.

Table I summarizes the information of `rETH` arbitrages on Unsiwap V3 and Balancer. Fig. 17 depicts the profit distribution for `rETH` arbitrages with staking 16 `ETH`. Fig. 18 shows the distribution of LSD trading volume on three DEXs (i.e., Curve, Balancer, and Uniswap V3) over time.



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| Contracts | # Arbitrageurs | # Arbitrages on Balancer | # Arbitrages on UniswapV3 | Arbitrage Profit (ETH) | Arbitrage Amount (ETH) | Arbitrage Interval | Code Public | Code Type | Flash Loan |
|---|---|---|---|---|---|---|---|---|---|
| 0x1f7...571 | 329 | 1406 | 497 | 1257.8 | 30433.5 | 2022/11/07-2023/03/07 | ✓ | Vyper | ✓ |
| 0x000...071 | 1 | 124 | 631 | 159.8 | 14117.9 | 2022/12/09-2023/04/16 | ✗ | - | |
| 0x000...14C | 1 | 311 | 62 | 181.0 | 6771.4 | 2022/10/29-2022/12/02 | ✗ | - | |
| 0x005...200 | 2 | 0 | 194 | 16.1 | 2761.5 | 2022/10/28-2023/04/17 | ✗ | - | |
| 0xE46...828 | 24 | 80 | 28 | 79.3 | 1807.1 | 2023/01/24-2023/04/18 | ✓ | Vyper | ✓ |
| 0xa03...f61 | 1 | 0 | 95 | 13.8 | 1519.2 | 2023/01/17-2023/02/03 | ✗ | - | |
| 0x000...d00 | 4 | 81 | 10 | 61.3 | 1482.6 | 2022/11/01-2023/04/13 | ✗ | - | |
| 0x7FB...a52 | 1 | 33 | 19 | 28.8 | 1292.8 | 2022/10/18-2022/10/29 | ✗ | - | |
| 0x294...C72 | 2 | 22 | 14 | 20.3 | 551.5 | 2022/12/13-2023/03/12 | ✗ | - | |
| 0x6fC...dc2 | 8 | 0 | 22 | 1.3 | 483.8 | 2023/03/30-2023/04/18 | ✓ | Solidity | ✓ |
| 0x6C6...64e | 1 | 0 | 20 | 0.5 | 229.9 | 2022/11/03-2022/12/01 | ✗ | - | |
| 0x1c0...4c3 | 1 | 19 | 0 | 292.8 | 4418.8 | 2023/04/18-2023/08/07 | ✗ | - | |
| 0xb7E...74b | 1 | 17 | 0 | 13.6 | 271.9 | 2023/02/04-2023/02/20 | ✗ | - | |
| 0x7f0...00d | 1 | 0 | 17 | 1.1 | 271.9 | 2023/01/09-2023/01/13 | ✗ | - | |
| 0x700...d6d | 1 | 0 | 15 | 1.5 | 239.9 | 2023/02/11-2023/02/15 | ✗ | - | |
| 0x589...88F | 1 | 0 | 12 | 0.2 | 304.3 | 2022/10/26-2022/11/02 | ✗ | - | |
| 0xA7b...E3f | 1 | 6 | 5 | 5.9 | 175.9 | 2023/03/15-2023/03/25 | ✗ | - | |
| 0x16D...11c | 1 | 0 | 10 | 0.2 | 357.3 | 2023/04/16-2023/04/18 | ✗ | - | |
| 0xA90...5d1 | 1 | 8 | 1 | 5.2 | 144.0 | 2022/11/03-2022/11/06 | ✗ | - | |
| 0x05A...d9E | 1 | 0 | 8 | 0.9 | 127.9 | 2023/02/20-2023/03/07 | ✗ | - | |
| 0x91A...a8e | 1 | 0 | 7 | 0.8 | 135.0 | 2022/12/04-2023/03/15 | ✗ | - | |
| 0x86e...e71 | 2 | 6 | 0 | 129.9 | 2161.5 | 2023/04/05-2023/04/10 | ✗ | - | |
| 0x1A6...d8a | 1 | 6 | 0 | 4.8 | 96.0 | 2023/01/30-2023/02/02 | ✗ | - | |
| 0x321...c7b | 1 | 4 | 0 | 12.5 | 343.8 | 2022/09/19-2022/09/23 | ✓ | Solidity | ✓ |
| 0xF33...742 | 2 | 0 | 3 | 0.2 | 374.8 | 2023/05/13-2023/05/20 | ✗ | - | |
| 0x414...507 | 1 | 3 | 0 | 2.4 | 48.0 | 2023/02/27-2023/03/05 | ✗ | - | |
| 0xCCf...923 | 1 | 3 | 0 | 23.2 | 337.7 | 2023/06/11-2023/06/15 | ✗ | - | |
| 0xc68...ee4 | 1 | 0 | 3 | 0.5 | 48.0 | 2023/02/17-2023/02/18 | ✗ | - | |
| 0xcb3...255 | 2 | 0 | 2 | 0.2 | 362.9 | 2023/05/12-2023/05/14 | ✗ | - | |
| 0xEEE...35e | 2 | 2 | 0 | 46.4 | 649.7 | 2023/07/12-2023/08/01 | ✗ | - | |
| 0x6C6...d45 | 1 | 1 | 0 | 6.5 | 174.9 | 2022/09/23-2022/09/23 | ✗ | - | |
| 0x0c1...d05 | 1 | 1 | 0 | 8.3 | 119.9 | 2023/06/23-2023/06/23 | ✗ | - | |
| 0x43a...420 | 1 | 1 | 0 | 4.5 | 124.9 | 2022/09/20-2022/09/20 | ✗ | - | |
| 0xD05...05d | 1 | 0 | 1 | 0.1 | 16.0 | 2022/12/02-2022/12/02 | ✗ | - | |
| 0xf35...94D | 1 | 1 | 0 | 2.0 | 32.0 | 2023/04/18-2023/04/18 | ✗ | - | |

TABLE I: Contract addresses for `rETH-ETH` arbitrage bots from September 30th, 2021, to August 10th, 2023.

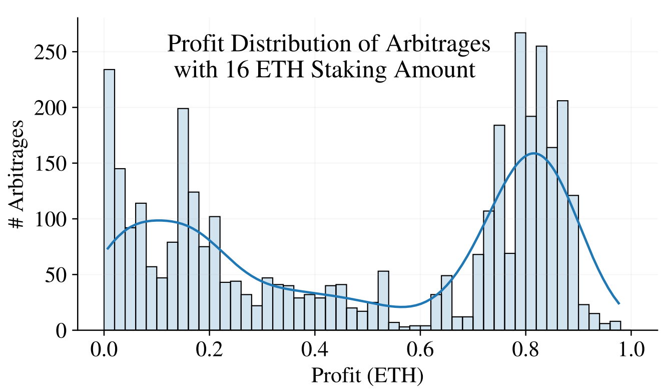


Fig. 17: Profit distribution for arbitrages with staking 16 `ETH`.

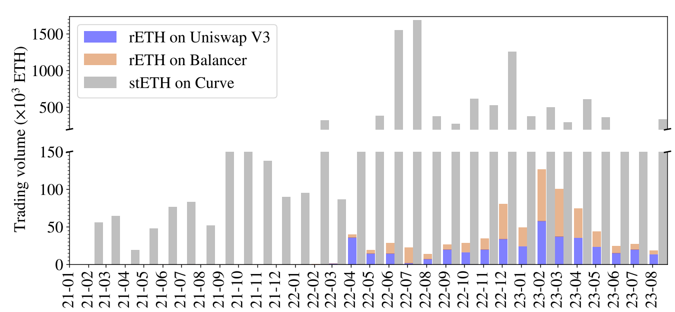


Fig. 18: LSD trading volume on Curve, Balancer, and Uniswap V3 over time.


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