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What keeps stablecoins stable? ☆

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ABSTRACT

Using trades between the stablecoin treasury and private investors, we quantify how improved arbitrage design stabilizes the price of the dominant stablecoin, Tether. We identify two 2019 design reforms: migration of Tether from the Omni to the Ethereum blockchain and decentralization of issuance. These reforms increased investor access to arbitrage trading with the treasury, reducing the absolute size of peg deviations by half. Further evidence for the importance of arbitrage design is present in the stability mechanism of the stablecoin DAI and in the creation of authorized merchants for the pegged coin WBTC.

1. Introduction and motivation

Stablecoins peg to a national currency, typically the US dollar, and are used to transact in non-stable cryptoassets more efficiently than using national currencies. They operate on blockchains, distributed ledgers where payments are verified and recorded without need for centralized settlement. By maintaining a collateralized peg, stablecoins achieve much lower volatility than cryptocurrencies such as Bitcoin (BTC), whose volatility relative to the US dollar (USD) is roughly 10 times that between major national currencies (Baur and Dimpfl, 2021). The largest stablecoin is Tether, accounting for over 80 percent of stablecoin capitalization over the period we study. Unlike fixed-rate national currencies, stablecoin pegs like that for

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Tether are maintained wholly via private participants;[1] and unlike exchange-traded funds, there is no subset of private participants pre-authorized to play this role.

In this paper, our focus is on arbitrage design and which design elements contribute most to stability. Our central thesis is that decentralization of issuance and access to arbitrage trades with the issuing treasury are key factors determining the efficiency of the peg.

For national currencies with fixed exchange rates, design focuses on central bank initiative: Foreign reserves are exchanged for domestic currency, adjusting supply to mute deviations from the peg (e.g., when domestic currency trades below the peg, the central bank intervenes to reduce supply by buying domestic currency for foreign reserves, and vice versa). Another mechanism, complementary to the first, is trades initiated not by an issuing institution but by private investors. Suppose for example the price of Tether rises above the pegged rate of 1 USD. Private investors can deposit Tether with the Tether Treasury, receive 1 USD for each in return, and sell Tether in the market for more than 1 USD. The arbitrage increases circulating Tether supply, putting downward pressure on Tether's market price toward parity.

We test these stability mechanisms with three types of empirical evidence. First, we exploit a natural experiment: The April 2019 migration of Tether from the Omni to the Ethereum blockchain. Introduction to the Ethereum blockchain was motivated in part due to its increased network of investors and Ethereum-based (ERC20) tokens, and its relative efficiency in processing payments.[2] This resulted in a large increase in investor access to the Tether Treasury, made possible by reduced transaction costs of operating on the Ethereum blockchain.[3] We find a significant subsequent increase in the number of unique addresses transacting with the Tether Treasury. For example, the Ethereum blockchain has an average of 4.0 unique addresses transacting daily, versus Omni which averaged 1.4 addresses. Consistent with the hypothesis that blockchain efficiency is critical for keeping stablecoins stable, estimates show a resulting decline in the absolute size of peg price deviations by about 50 percent and a decline in the half-life of deviations from 6 days to 3 days.

To sharpen our test of increased peg efficiency due to migration to the Ethereum blockchain, we employ a difference-in-differences (DiD) design using a set of control group stablecoins that share similar institutional features, but did not undergo a structural change of blockchain. This produces a large and statistically significant reduction in peg deviations by about a third relative to the control group, even after controlling for sampling intervals that might contain confounding events. The difference-in-difference estimates are robust to alternative specifications of the structural date: A dynamic specification with quarterly dummies shows that the efficiency gain peaked in the fourth quarter of 2019, consistent with gradual migration to the Ethereum blockchain, with Tether creation on Ethereum surpassing that on Omni by October 2019.

Our second type of empirical evidence focuses specifically on arbitrage flows to determine how arbitrage design mediates flows' stabilizing effect. Flows of Tether from the Treasury to private investors are equal to changes in the supply of Tether in circulation net of changes retained in the account of the Tether Treasury. These netted flows are the economically relevant object for determining price pressure on the secondary market. We estimate the effects of arbitrage flows on prices based on local projections as in Jordà (2005), a procedure that controls for feedback effects in price and flow. We find significant reductions in peg-price deviations due to changes in net flows from the identified changes in arbitrage design.

Our third type of evidence addresses the impact of arbitrage design on the profitability of arbitrage trades. We first compute arbitrage profit based on Tether creations where an investor deposits dollars, obtains Tether at a 1:1 rate, and then sells Tether at a premium in the secondary market. Matching the high-frequency timestamp of deposits with the Treasury with transaction prices, and adjusting for transaction costs (issuer fees, bid-ask spreads, price impact, and gas costs), we find that arbitrage profits are positive on average on both the Omni and Ethereum blockchains. Migration to the Ethereum blockchain resulted in a smaller deposit size, spreads, and profits. This is consistent with the "democratization" of access to arbitrage trades on the Ethereum blockchain leading to smaller spreads and profits per trade. In analysing Tether creations versus redemptions, we find stronger evidence for an arbitrage motive for creations. This asymmetry is principally due to three factors: the higher cost imposed by the Tether Treasury on redemptions, investors' idiosyncratic liquidity needs, and redemptions that arise primarily from moving Tether across blockchains known as chain swaps.[4]

We then turn to implications of arbitrage design in other decentralized finance applications. The peg stability module (PSM) of the DAI stablecoin was introduced on December 18, 2020, as a solution to combat persistent peg-price deviations (Kozhan and Viswanath-Natraj, 2021). Under the PSM, a smart contract enables users to swap the stablecoin USDC with DAI at a 1:1 rate without needing to create a vault and deposit collateral.[5] Wrapped tokens are tokenized versions of other cryptocurrencies. The Wrapped Bitcoin (WBTC) token is an ERC20 stablecoin on Ethereum backed 1:1 by bitcoin. Merchants are authorized participants that can mint (create) or burn (redeem) WBTC tokens. The smart contracts to swap USDC and DAI

[1] Among national exchange rates, strong backing with USD reserves is most similar to the Hong Kong (HK) Currency Board where the central bank maintains dollar reserves to match every HK dollar in circulation.

[2] ERC20 is a standard which provides features including the transfer of tokens from one account to another, measuring the current token balance of an account, and measuring the total supply of the token available on the network. It deploys smart contracts, auto-executing code on the blockchain, to perform these various functions.

[3] For more information on the event, we refer readers to https://www.prnewswire.com/news-releases/huobi-global-offers-deposit-withdrawal-in-tether-erc20-300803113.html.

[4] Redemptions incur a minimum cost of 1,000 USD or 0.1 percent of the trade. For example, refer to https://tether.to/fees/ for details. For more details on chain swaps, we refer readers to Appendix C.

[5] A smart contract is a set of instructions in computer code that defines the conditions of the contract for each counterparty under different scenarios (default etc). Managed by code and visible on the blockchain, it can be verified publicly by all participants on the blockchain.

can only be initiated by investors, and mints and burns of WBTC can only be initiated by merchants. These applications are thus prime examples of decentralized arbitrage. Our results show that in these fully decentralized settings arbitrage design is important for how trades initiated by private investors stabilize price.

Finally, we consider algorithmic stablecoins such as TerraUSD that are typically unbacked. Exploiting the recent collapse of TerraUSD on May 9th, 2022, we show that this category is prone to devaluation risk and speculative attacks when they are under-collateralized. We show that in contrast to dollar-backed stablecoins, there is no clear arbitrage mechanism to restore prices when TerraUSD is priced at a discount. A clear solution to preserve peg stability is through adopting full collateralization, either through liquid dollar reserves or through stable cryptocurrency collateral.

The remainder of the paper is structured as follows. In Section 2 we summarize related literature. In Section 3 we summarize the properties and performance of the major stablecoins and detail the balance sheet and price data used in the analysis. In Section 4 we present empirical evidence. First, we exploit the migration of Tether from the Omni to Ethereum blockchain as an empirical test of the changed arbitrage design. We then test for the stabilizing properties of arbitrage flows, and estimate a measure of arbitrage spreads and profits of Tether deposits and redemptions. In Section 5 we turn to stabilizing mechanisms for other pegged coins. Section 6 concludes.

2. Related literature

We contribute to a growing literature on stablecoins. This includes stablecoin properties and comparisons to traditional financial markets (Bullmann et al., 2019; Dell'Erba, 2019; Arner et al., 2020; Barthelemy et al., 2021; Berentsen, 2019; Eichengreen, 2019; Force et al., 2020; Frost et al., 2020; Kim, 2022), arbitrage in stablecoin and cryptocurrency markets (Makarov and Schoar, 2019; Makarov and Schoar, 2020; Borri and Shakhnov, 2018; Pernice, 2021; Kozhan and Viswanath-Natraj, 2021), theoretical research on the price dynamics of stablecoins, with solutions such as reserve buffers and over-collateralization to avoid speculative attacks and peg discounts (Cong et al., 2021; d'Avernas et al., 2022; Routledge and Zetlin-Jones, 2022; Kwon et al., 2021; Li and Mayer, 2021), intraday price changes that support stablecoins' role as safe havens (Baur and Hoang, 2020; Hoang and Baur, 2020; Baumöhl and Vyrost, 2020; Wang et al., 2020; Bianchi et al., 2020; Gloede et al., 2021), the financial stability, macroeconomic and political economy implications of stablecoins (Cong and Mayer, 2021; Catalini and de Gortari, 2021; Liao and Caramichael, 2022; Allen et al., 2022; Gorton and Zhang, 2021; Gorton et al., 2022; Murakami and Viswanath-Natraj, 2021) and the dynamics of stablecoin issuance and cryptoasset prices (Griffin and Shams, 2020; Wei, 2018; Ante et al., 2020; Kristoufek, 2021). We extend existing work on stablecoins in several ways. Most broadly, we push beyond past work focusing on prices only and address quantities – in particular by analyzing trades between the Tether Treasury and private investors – to address arbitrage as a market-design feature. Results we present here show that stablecoin issuance endogenously responds to deviations of stablecoins' secondary-market rate from the pegged rate.

It is not clear a priori how the process works to keep stablecoins stable – is it supply based, i.e. actively managed centrally by the stablecoin treasury? Or is it demand based, i.e. decentralized private investors that are arbitraging the peg? On supply-based mechanisms, our paper also relates to the role of central bank intervention in maintaining pegs (Fratzscher et al., 2019; Ferreira et al., 2019). Empirical evidence in Fratzscher et al. (2019) shows that central banks typically "lean against the wind" by actively counteracting private trades of market participants, which has a stabilizing effect.[6] In contrast, decentralized stabilization rests on a mechanism similar to how exchange-traded funds trade at prices close to their net asset values (Aldridge, 2016; Marshall et al., 2013; Brown et al., 2021). Stablecoins are fundamentally different in that for ETFs the arbitrage process is not decentralized by design, being conducted instead by a preset group of institutions serving as *authorized participants* that conduct all "creates" and "redeems."

In sum, our paper's focus on change in arbitrage design posits that Tether distribution fundamentally changed in 2019 from the supply-based distribution on Omni to decentralized distribution on the Ethereum blockchain. Our evidence that migration to decentralized Tether creation, with a subsequent increase in access to arbitrage trades with the Treasury, is consistent with our variance decomposition of Tether flows showing that the migration led to a decline in supply-based factors.[7]

3. Definitions and data

3.1. Stablecoin properties and performance

We note two institutional features that explain the growing role of stablecoins as a store of value and medium of exchange. The first is added intermediation costs when trading cryptocurrencies against dollars: On some exchanges, for example, there are longer processing lags for withdrawals of dollars; fees are also often imposed when dollar withdrawals

[6] There are differences between the decentralized structure of stablecoins and FX interventions by a central bank. For example, a central bank is typically concerned with macroeconomic fundamentals like preserving low interest rates and inflation, and is targeting an exchange rate that is based on a set of fundamentals that are macroeconomic. A stablecoin issuer has no equivalent policy function. Secondly, investors can often deposit dollars directly with the stablecoin issuer. In contrast, investors cannot typically initiate trades, or directly deposit currency, with the central bank.

[7] We provide supplementary evidence in Appendix C that Bitfinex indeed dominated flows of Tether from the Treasury to the secondary market on the Omni blockchain, whereas distribution is much wider on the Ethereum blockchain.

are frequent or large.[8] A second institutional feature favoring stablecoins is their usability across a greater cross-section of crypto exchanges. For example, exchanges like Binance and Poloniex do not provide investors with any on-ramp for trading dollars, and only accept stablecoins as a medium of exchange. Total trading volume between Bitcoin and Tether exceeded the trading volume of Bitcoin/USD in 2019.

Stablecoins are typically backed by either dollar collateral or crypto collateral. Of the top six coins by market cap (as of April 1st 2020), five are backed by dollar deposits, the exception being DAI, which is backed by Ethereum.[9] The methods of how dollar collateral itself is managed includes a central issuer in the case of Tether, which acts analogously to the Hong Kong Currency Board. The second-largest stablecoin, USDC, has a more decentralized system of governance, with multiple issuers that have a license to provide USDC tokens. The other three stablecoins managed with dollar collateral, Binance USD Coin, Paxos, and TrueUSD, focus on concerns over the risk of issuer default: In the case of Binance USD coin and Paxos, dollar collateral is backed by FDIC-insured banks, whereas TrueUSD dollar collateral is backed by escrow accounts.[10] The sixth largest coin, DAI, operates a system under which investors deposit Ethereum into a collateralized position that allows them to borrow DAI. The number of DAI they can borrow is limited by a smart (i.e., auto-executing) contract.[11] [12]

Table 1 presents summary statistics on the deviations from peg prices as of March 31st, 2020. [13] The first observation is the high ratio of total reported trading volume to the market capitalization, also referred to as daily velocity.[14] This daily ratio is typically over five for Tether, the largest coin, and is similarly above one for other national-currency-backed coins Paxos (PAX) and TrueUSD (TUSD). For perspective, the daily turnover in spot foreign exchange markets involving the USD as one leg of the transaction is $1.7 trillion over the period 2016–2019, compared to a total supply in circulation of approximately $15 trillion. This implies a daily USD velocity of one tenth, an order of magnitude smaller than stablecoin velocities. A takeaway is that stablecoins are intensively used as vehicle currencies.

Examining the summary statistics in Table 1, stablecoins typically have two-sided distributions, with maximum deviations both below and above the one-to-one parity exceeding 500 basis points (five percent) for Tether (USDT), and of similar magnitudes for the other coins (Fig. 1).[15] We also observe deviation persistence, measured by the half-life of price departures from the peg. The half-lives for all coins range from 1 to 10 days.[16] Persistence of deviations is evidence that the stabilizing mechanisms of these coins are not without frictions or risk. [17]

3.2. Tether balance sheet

To construct the Tether balance sheet, we use blockchain platforms on which the entire history of on-chain transactions involving transfers of Tether is recorded.[18] These platforms contain an api that allows users to access an entire history of Tether transactions, with details on the size, timestamp, and the type of transaction. Tether tokens are created through a "grant" when new Tether tokens are minted. Tether tokens are destroyed through a "revoke" when Tether tokens are redeemed. Transactions between the Treasury and secondary market recipients are recorded as a "simple send", with counter parties listed on the "send" and "receive" sides of the transaction. Transactions are recorded in a series of blocks, and can be retrieved using the blockchain api. [19]

We construct the aggregate stock of Tether, $Q_{Agg,t} = \sum_{i=1}^{N} Q_{i,t}$ as the sum of Tether created across the three principal blockchains, Omni, Ethereum, and Tron over the sample period from October 8th, 2014 to March 31st, 2020. Starting in October 2014, Tether issuance is initially only on the Omni blockchain. We also record the amount of Tether created but retained by the Tether Treasury as reserves. The total amount of Tether Reserves on each blockchain is then equal to $Q_{T,t} = \sum_{i=1}^{N} Q_{T,i,t}$. The usefulness of the Treasury's reserves can be seen as analogous to the accumulation of foreign exchange reserves by a central

[8] For more information, refer to the following announcements by Bitfinex: https://bit.ly/2NEzITW and https://www.bitfinex.com/posts/311. Bitfinex states it takes investors 7 to 15 days to make dollar withdrawals from their platform in order to comply with intermediation procedures. Bitfinex has also introduced a transaction cost of 3% for investors who make more than two dollar withdrawals a month, or for withdrawals of more than $1 million in a given month.

[9] Since November 18, 2019, investors holding single-collateral DAI have transferred their holdings to multi-collateral DAI.

[10] Escrow accounts offer a novel security design. For example, suppose an investor wants to deposit one USD for one TrueUSD token. They first deposit their dollar in a protected escrow account. TrueUSD then provides the escrow account 1 token. Only upon receipt of the token, and once the token is sent to the investor, the escrow account transfers the dollar deposit to TrueUSD. This system minimises settlement risk on both sides.

[11] The contract liquidates underlying Ethereum collateral if the value of that collateral is less than 150% of the corresponding DAI-borrowing value. Agents therefore have an incentive to scale back borrowing by redeeming DAI when Ethereum prices fall in order to prevent their collateral from breaching the 150% level.

[12] An equally important institutional detail is how these coins' collateral is audited. We review audit accountability and transparency measures in Appendix B.

[13] For details on the source of price data, see the data Appendix A.

[14] The reported 24H Volume in Coinmarketcap and other vendors includes all transactions verified on the blockchain.

[15] Plots of peg-price deviations for other major stablecoins are provided in Appendix F.

[16] To measure the half-life, we run an auto-regressive process of order 1 on the deviations, $\Delta = \rho\Delta_{t-1} + u_t$. The half-life, or the time it takes for a shock to dissipate by 50%, is $T = \frac{\log(0.5)}{\log(\rho)}$.

[17] In Appendix G we pin down the fundamentals that explain premiums and discounts. We find that an increase in the intra-day price volatility of the BTC/USDT market leads to Tether-price premiums, evidence that Tether, and other stablecoins, serve as safe havens in the domain of cryptoassets. Stablecoin discounts, on the other hand, generally occur due to risk of insufficient collateral. In October 2018, speculators were uncertain whether Tether was fully collateralized – due to a move by its partner exchange Bitfinex to suspend convertibility of dollar deposits. This event induces a decline in Tether's price and a sharp rise in bid-ask spreads.

[18] Off-chain transactions, such as transactions within a cryptocurrency exchange, are not recorded.

[19] For more detail on the databases, including how the flows are constructed from the addresses of the issuer, see Appendix A.

Table 1
Top 6 stablecoins – peg price deviations.

Sample	Symbol	Market Cap	24H Volume	Mean	SD	Min	Max	Half-Life (days)
04/17–03/20	USDT	$6,400 M	$40,000 M	−20.5	128.9	−960	571	6.4
01/20–03/20	USDC	$705 M	$692 M	6.9	25.0	−21	100	0.8
01/19–03/20	PAX	$245 M	$911 M	7.8	29.6	−100	200	0.5
10/10–03/20	BUSD	$187 M	$49 M	1.4	6.1	−10	50	0.3
06/18–03/20	TUSD	$136 M	$466 M	6.7	59.2	−170	990	0.4
04/18–03/20	DAI	$79 M	$12 M	42.5	128.7	−391	800	4.7

Note: Market capitalization for all coins is based on total value of stablecoins in circulation; 24H Volume is total reported trading volume, from Cryptoslate (as of April 10th, 2020, https://cryptoslate.com/cryptos/stablecoin/). Summary statistics for price deviations from the parity peg are expressed in basis points (100 basis points here equals 1 US cent). Half-Life is in days. Price data are sourced from Coinapi, which reports data from trusted exchanges Bitfinex, Bittrex, and Kraken.

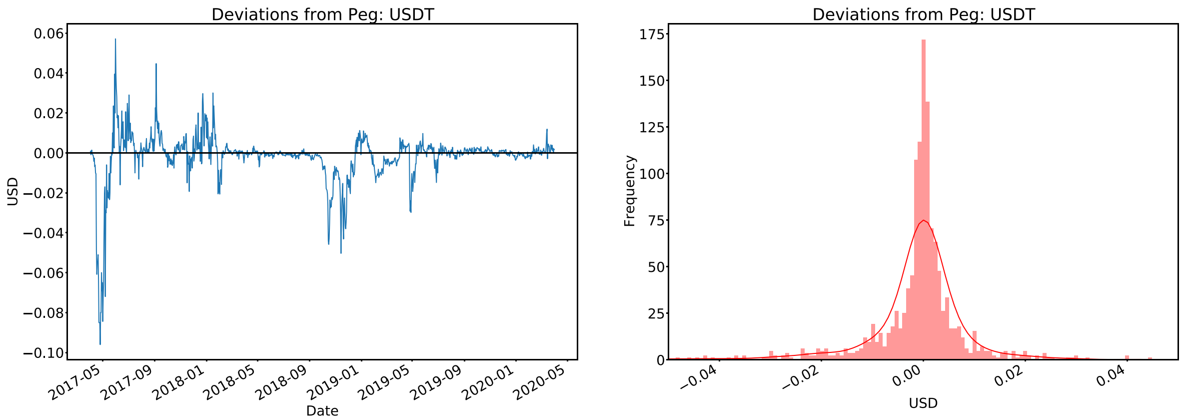

Fig. 1. Tether/USD Deviations from Peg and Histogram of Deviations. Note: Figure plots the deviations of the Tether/USD price from parity (left panel). A positive deviation indicates Tether/USD trades at a premium. The right panel is a histogram of deviations of the Tether/USD peg. Data from Coinapi. Sample is April 1st, 2017 to March 31st, 2020.

bank. This provides the stablecoin issuer a one-sided potency against stablecoin premiums; in the event of a secondary market price above one USD, the Tether Treasury can sell its Tether reserves in the secondary market to restore parity of the peg.[20] The total amount of Tether held by private wallets and exchanges is equal to the total Tether creation net of Tether held in the Treasury's account, given by $Q_{EX,t}$ in Eq. (1).

$$Q_{EX,t} = Q_{Agg,t} - Q_{T,t} \tag{1}$$

Fig. 2 (left) plots the breakdown of Tether by blockchain. While Tether was exclusively created on the Omni blockchain from 2014 through to 2018, there is a gradual migration of Tether from the Omni to Ethereum blockchains starting in April, 2019. Within three months of Tether's introduction to the Ethereum blockchain, we note that it overtakes the Omni blockchain in Tether creation by October 29th, 2019. Fig. 2 (right) plots the total Tether supply, with the division of total Tether held by the Treasury and the secondary market, which included balances held at crypto exchanges, retail investors, and institutional investors. While balances held at the Treasury are typically a small fraction of total Tether in circulation, they reached almost $1 billion USD in 2018, which equates to 25% of total Tether supply.

To construct a proper aggregate measure of net Tether issuance, take first differences of Eq. (1), and define flows from the Treasury to the secondary market, $Flow_{T\to EX,t} = \Delta Q_{EX,t}$, as the change in total Tether net of changes in the Treasury account (Eq. (2)). This controls for changes in Tether that are retained at the Treasury, which do not constitute Tether in circulation for trading by private wallets and exchanges.

$$Flow_{T\to EX,t} = \Delta Q_{Agg,t} - \Delta Q_{T,t} \tag{2}$$

[20] The accumulation of Tether reserves helps guard against stablecoin premiums, but not stablecoin discounts. For example, if Tether trades at a discount, then the Tether Treasury would require investors to redeem their dollar deposits and withdraw Tether from circulation.

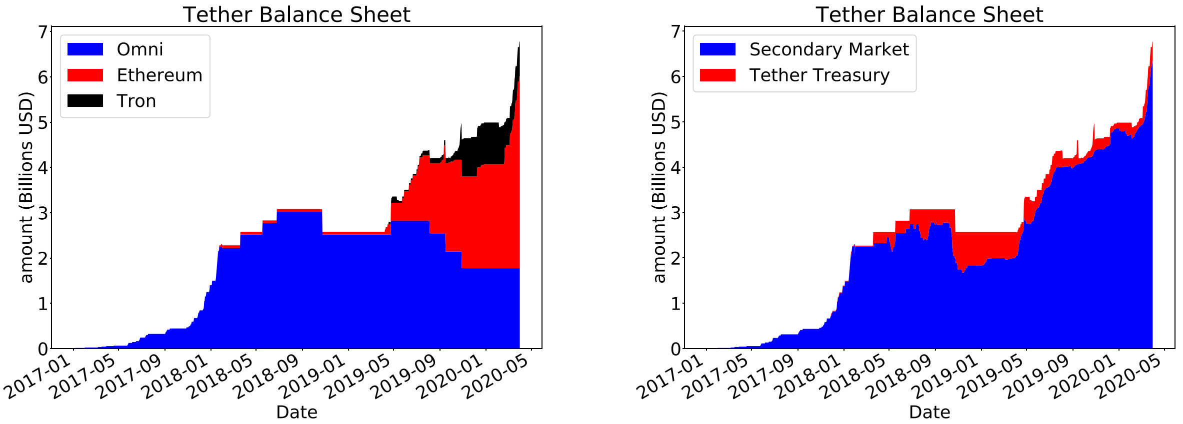

Fig. 2. left panel: Tether/USD Balance Sheet – By Blockchain, right panel: Tether/USD Balance Sheet – Tether held by the Treasury and Other Accounts. Note: The figure plots total Tether supply, divided by blockchain (left), and divided into holdings in the secondary market (by investors and exchanges) and holdings by the Tether Treasury as reserves (right). Flows of Tether to the secondary market, measured using transaction data of the Tether Treasury on the Omni, Ethereum, and Tron blockchains respectively.

3.3. Primary and secondary market prices

An important distinction to make is between primary and secondary market prices. The primary market is the rate at which the Treasury is willing to exchange Tether for dollars. The primary market rate is 1 USDT:USD, with asymmetric transaction costs for deposits and redemptions. While deposits of dollars at the Treasury come with a flat fee of 0.1 per cent, redemptions incur a minimum cost of 1000 USD or 0.1 per cent of the trade. [21] Starting in April 2017, the first secondary market for Tether/Dollar trading was introduced on the Kraken exchange. Trading in the Tether/Dollar pair commenced on Bittrex in May 2018. While Bitfinex facilitated Tether deposits and redemptions at the primary market rate, trading in the secondary market on the exchange only commenced in December 2018. We construct a secondary market price of Tether that is an average price based on secondary market trading on three exchanges.[22] In our empirical analysis, we use the consolidated Tether-USD price to create two measures. The first is peg-price deviations, which is the deviation of the secondary market price from 1. The second is intra-day volatility, which is calculated as the square root of the daily average sum of squared returns over 5-min intervals.

3.4. Arbitrage between primary and secondary market

There are two ways to stabilize the peg. A centralized design requires intervention by the issuer similar to a national exchange rate pegs, in which the central bank is committed to maintaining the peg by buying the domestic currency and selling foreign-currency reserves when the domestic–currency value falls below the peg level, and conversely selling domestic currency when the domestic–currency value rises above the peg level. In this paper we posit a decentralized mechanism is instead driven by the actions of arbitrageurs that exploit differences between the primary and secondary market price.[23] If the secondary market price of Tether is above one dollar, an investor can buy Tether from the Treasury at a one-for-one rate, and sell Tether at the prevailing market rate to profit, resulting in a flow of Tether from the Treasury to the secondary market (Fig. 3, Left). Conversely, when the dollar price of Tether is below 1, an investor can buy Tether at the exchange and sell to the Tether Treasury, resulting in a flow in the opposite direction – from the secondary market to the Tether Treasury. Stability of the Tether/USD peg is maintained here through the actions of investors. Arbitrage by secondary-market participants offers a solution to exchange-rate stability that is decentralized.[24] In the right panel of Fig. 3, we plot daily flows between the Treasury and the secondary market against the Tether price. These flows are more frequent when the Tether price is above the peg. More relevant, the regression line has a clear positive slope, evidence – albeit suggestive – that flows between the Tether Treasury and the secondary market serve to maintain the Tether/USD peg.

[21] For example, refer to https://tether.to/fees/ for details.

[22] We provide more detail on selection of exchanges and price data in Appendix A.

[23] The issuer of Tether has formally stated that it does not intervene in secondary markets to stabilize the market rate. In a statement released on its website, Tether Inc states: (i) Tether does not represent a country or oversee a banking system; (ii) The USDT supply is dictated by consumer demand (all issued USDT has been bought by a consumer at a 1:1 ratio); (iii) Tether does not set or manage any interest rates anywhere; (iv) Tether does not oversee – and is not responsible for – a banking or exchange sector, and does not claim to do so. For full reference, see https://tether.to/a-commentary-on-tether-chainalysis/.

[24] The arbitrage mechanism we outline is taking advantage of a law-of-one-price deviation in currency markets, and follows a line of reasoning similar to arbitrage conditions in foreign exchange markets such as covered interest-rate arbitrage (Akram et al., 2008) and triangular arbitrage of cross-rates in forex (Foucault et al., 2017).

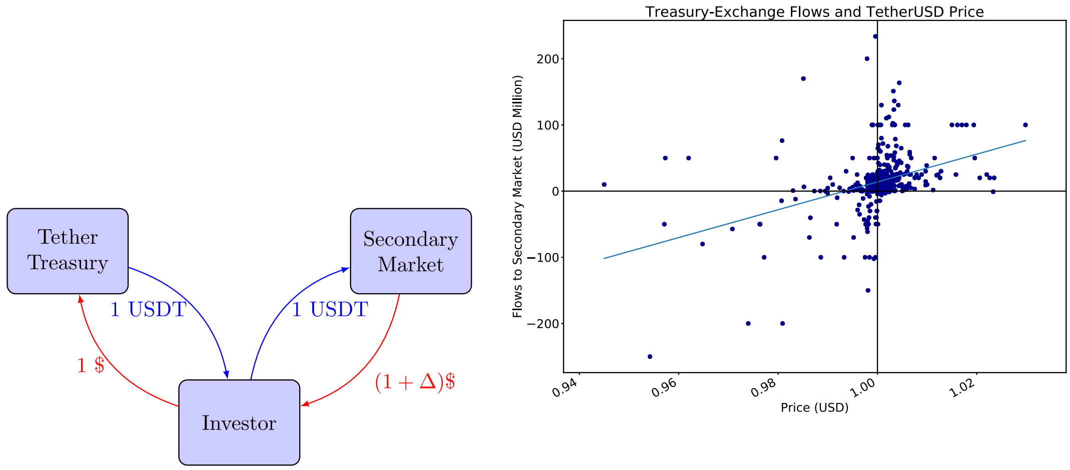

Fig. 3. Left: Arbitrage Flows when Tether Price in Secondary Market is Trading at a Premium; Right: Scatter Plot of Daily Flows from the Tether Treasury to the Secondary Market, and the Tether/USD peg. Note: Left: Schematic illustrates an arbitrage trade where the secondary-market price of Tether trades at a premium. An investor makes a dollar deposit with the Tether Treasury, obtains a Tether token (at an exchange rate of 1 Tether per 1 USD), and then sells Tether tokens in the secondary market for a round-trip profit of Δ. Right: The figure illustrates scatter plot of flows of Tether to the secondary market, and the corresponding Tether/USD price, measured using daily data on secondary-market flows from Omni and Etherscan. Price data are from Coinapi, and use transaction data from trusted crypto exchanges Bitfinex, Bittrex, and Kraken. Sample is April 1st, 2017 to March 31st, 2020.

4. Empirical evidence: tether

4.1. Decentralization of tether issuance

Two key reforms resulted in a decentralization of the arbitrage mechanism: independence of the Tether Treasury from Bitfinex, and migration to the Ethereum blockchain. The Bitfinex cryptocurrency exchange has the same parent as the Tether Treasury. The Bitfinex exchange initially had a monopoly on Tether distribution, by having primary access to deposit dollars with the Tether Treasury to create newly minted Tether tokens, which were then distributed to other exchanges for trading. The left panel of Fig. 4 presents the distribution of Tether across the Omni blockchain. We observe a significant concentration of Treasury flows on Omni going to a single address: the Bitfinex cryptocurrency exchange.[25] Starting on November 27th, 2018 Bitfinex suspended investor convertibility of Tether to Dollars at a 1:1 rate, as it announced secondary market trading in the Tether/USD pair. This resulted in a move to *Tether neutrality* which we identify as independence from the Tether Treasury. [26] Instability of a banking connection led to the suspension of Bitfinex dollar deposits in April 2017 and October 2018, triggering peg discounts as investors price run-risk of Tether and not having sufficient backing to meet redemptions. [27] Independence from Bitfinex is a key efficiency reform as it enables decentralization of the arbitrage mechanism: investors can now directly transact with the Treasury.

The move to decentralization was also facilitated by the migration of Tether to the Ethereum blockchain as the principal blockchain for Tether in circulation. Tether's migration to the Ethereum blockchain is motivated by several factors. First, Tether could now be used more directly as a vehicle for a large number of cryptocurrency investors that use the Ethereum blockchain. Similarly, Tether's value as a vehicle increases by being used as a medium of exchange for a large number of ERC20 tokens that only circulate on the Ethereum network. Second, the Ethereum blockchain also enables higher-frequency arbitrage, with 15-s blocks (the corresponding set of transactions processed by miners on the blockchain) for Ethereum versus 10 min for Omni, which has mining times based on the Bitcoin protocol. Third, cryptocurrency exchanges such as Bittrex and Huobi also cite the Ethereum blockchain as enabling a reduction in transaction costs in Tether withdrawals and deposits. [28] To tap into the benefits of an increased client base and efficiency in payments processing, cryptocur-

[25] For more details on the concentration of Bitfinex on the Omni blockchain, we refer the reader to Appendix C.

[26] For details on the release, see https://www.bitfinex.com/posts/319

[27] For example, see https://www.bitfinex.com/posts/200 for the announcement on the April 2017 suspension and https://medium.com/bitfinex/fiat-deposit-update-October-15th-2018-18ddd276c3fd for the announcement on the suspension of Bitfinex deposits in October 2018. In Appendix G we document significant peg discounts and an increase in bid-ask spreads in response to the October 2018 suspension. Bitfinex has also on occasion obtained lines of credit from Tether for meeting redemption payments, and has been the subject of allegations in which Bitfinex covered up the loss of up to 850 million USD in customer funds. The litigation has settled in March 2021, when Tether and Bitfinex agreed to pay fines of 18.5 million USD and admitted no wrongdoing, and Tether is required to provide quarterly statements of its balance sheet and cannot operate in New York.

[28] For example see a statement from Huobi exchange https://prn.to/2ZkPzw0.

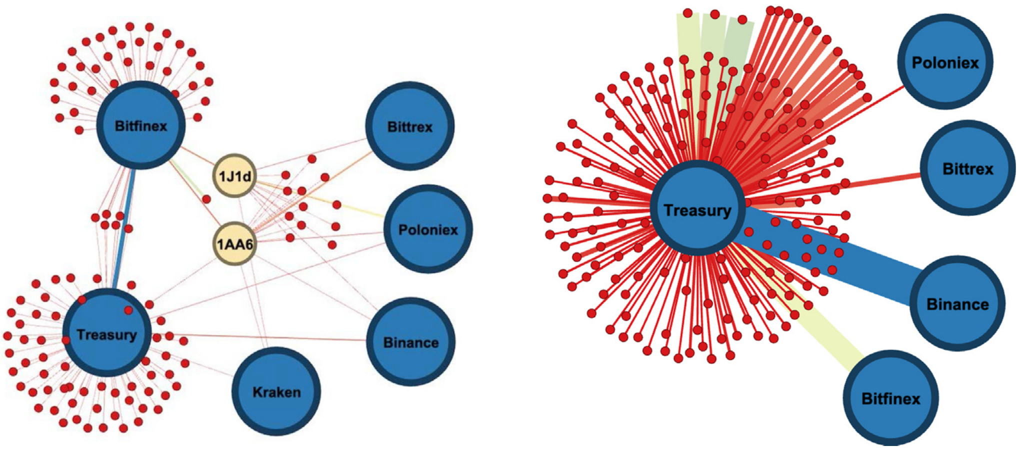

Fig. 4. Distribution of Tether on the Omni and Ethereum Blockchains. Note: Figure presents the network of transactions from the Tether Treasury to all wallets on the Omni blockchain recorded from October 8th, 2014 through to March 31st, 2020. Transaction history is obtained from https://omniexplorer.info/ for the Treasury wallet address "1NTMakcgVwQpMdGxRQnFKyb3G1FAJysSfz". The plot also records absolute flows from Bitfinex to other wallets (only wallets with an absolute transaction value greater than $100 million USD are included to minimize the number of nodes from Bitfinex). Right Figure presents the network of transactions from the Tether Treasury to all wallets on the Ethereum blockchain recorded from January 30th, 2019 through March 31st, 2020. Transaction history is obtained from https://etherscan.io/ for the Treasury wallet address "0x5754284f345afc66a98fb-b0a0afe71e0f007b949". All identified wallets (cryptocurrency exchanges) are labeled. The line thickness between wallets and the Treasury indicate the magnitude of absolute flows, which we measure as the sum total of inflows and outflows of Tether from the Treasury to each wallet. Addresses are labeled based on publicly available information on the Tether rich list https://wallet.tether.to/richlist and https://etherscan.io/..

rency exchanges engaged in a chain swap of Tether from the Omni to Ethereum blockchains. This is a special type of transaction that moves a cryptocurrency from one blockchain to another.[29] [30]

Increased access to the Treasury includes Tether distribution through multiple crypto exchanges that deposit dollars with the Treasury to create Tether tokens (Fig. 5, Left). The right panel of Fig. 5 shows the daily number of unique wallet addresses transacting with the Treasury on the three primary blockchains, Omni, Ethereum, and Tron. Note the sharp increase in unique addresses transacting with the Treasury in 2019. Judging from the count of unique addresses using Tether on the Omni and Ethereum blockchains, the Ethereum network begins to dominate Omni starting in April, 2019.[31] Transactions with the Treasury on the Ethereum blockchain is much less concentrated, with an average of 4.0 unique addresses transacting with the Treasury daily, compared to 1.4 on the Omni blockchain.

To quantify the independence of Tether from Bitfinex, we conduct a simple decomposition in Eq. (3). The change in the stock of Tether in circulation on blockchain $i \in [\text{Omni}, \text{Ethereum}]$ is equal to the sum of the co-variances of each component of flows. This includes changes in the stock of Tether due to changes in the Treasury account, flows of Tether from the Treasury to Bitfinex, and flows of Tether from the Treasury to other investors.

$$var(\Delta Q_t^i) = cov(\Delta Q_{T,t}^i, \Delta Q_t^i) + cov(\Delta Q_{Bitfinex,t}^i, \Delta Q_t^i) + cov(\Delta Q_{Other,t}^i, \Delta Q_t^i) \quad (3)$$

The decomposition gives us a useful proxy for demand versus supply changes in issuance, where Tether flows explained by changes in the holdings of the Treasury or Bitfinex is a proxy for *supply* changes, and the residual due to flows of Tether to other investors a proxy for *demand* changes. On the Omni blockchain, other investors accounts for only 13.7 per cent of the variance of daily changes in the stock of Tether in circulation. Changes in the accounts at the Treasury and Bitfinex account for the remaining 86.3 per cent of flows. Consistent with our narrative of decentralization of Tether issuance on the Ethereum blockchain, the variance of flows explained by other investors rises to 67.2 per cent. The remaining 32.7 per cent is due to changes in the stock in the Treasury account, with only 0.1 per cent due to changes in Tether flows to Bitfinex.[32]

4.2. Peg efficiency of decentralized arbitrage

We hypothesize that an increase in access to the primary market should translate to increased effectiveness of arbitrage in sustaining the peg. For example, if Bitfinex is the only investor that has access to the primary market, then this impairs the

[29] For more information on chain swaps, see https://tether.to/explained-chain-swaps/.

[30] As we note in Appendix C, we record up to $1.0 billion of Tether holdings rebalanced from the Omni to the Ethereum blockchain by the Binance exchange through chain swaps from August 2019 to March 2020.

[31] See https://news.bitcoin.com/erc20-tether-transactions-flip-their-omni-equivalent/ for more details on the change in number of users on Omni and Ethereum blockchains.

[32] The construction of Tether flows to Bitfinex is detailed in Appendix C. We use publicly listed Bitfinex wallets on both the Omni and Ethereum blockchains for our analysis.

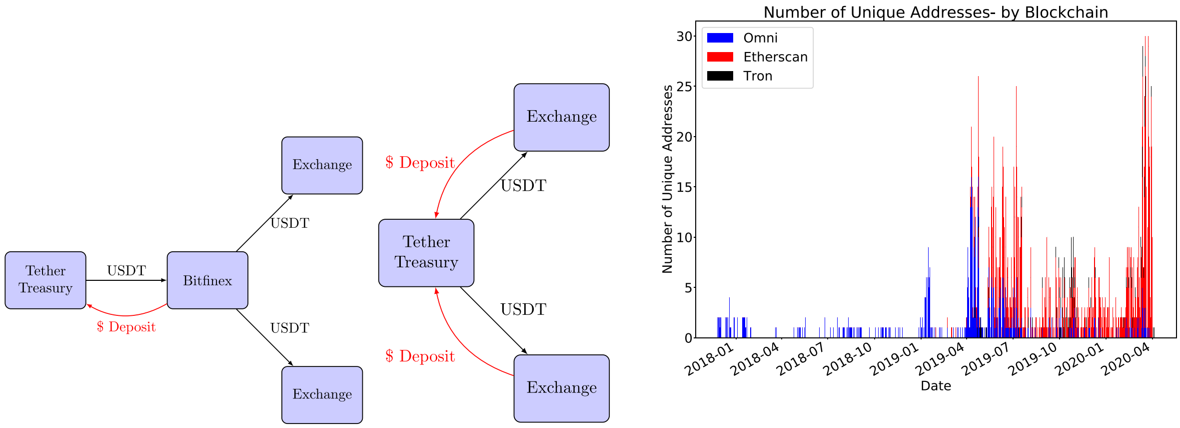

Fig. 5. Left – Distribution of Tether to Secondary Market on the Omni and Ethereum blockchains; Right – Number of Unique Addresses transacting with the Tether Treasury on Omni, Ethereum, and Tron Blockchains. Note: Left figure illustrates the creation of Tether on the Omni and Ethereum blockchains. On the Omni blockchain, Bitfinex deposits dollars into the Tether Treasury. The Tether Treasury then issues Tether tokens at parity (1:1 exchange rate). The newly created tokens are then distributed to other investors and exchanges in the secondary market. On the Ethereum blockchain exchanges directly deposit dollars with the Tether Treasury to create newly minted tokens. Right Figure plots the daily number of unique investor addresses transacting with the Tether Treasury on each blockchain. Data records trades between the Tether Treasury and private investors, obtained from the Omni, Ethereum, and Tron Blockchains. Sample is November 2017 through March 2020..

ability of private investors to arbitrage peg deviations. We first partition our sample of Tether prices into the pre and post periods according to the first week in which we observe a jump in transactions between the Treasury and addresses depositing dollars directly with the Treasury on the Ethereum blockchain, which we identify as April 9th, 2019.[33] Table 2 presents summary statistics. The average size of peg deviations falls substantially, and in particular, note a significantly lower half-life of deviations, measuring 6.5 days in the pre Ethereum blockchain sample, versus 3.3 days in the post period.[34]

Increased efficiency of the Tether peg from April 2019 to March 2020 could be unrelated to the migration to the Ethereum blockchain. Other possible causes include, for example, increased liquidity across cryptocurrency exchanges, technological changes (such as an increased efficiency of mining), or changes in the global demand for cryptocurrencies that use stablecoins as the primary vehicle currency. To rule out alternative hypotheses, we adopt a difference-in-differences design. The set of control currencies we use in our sample are national-currency-backed stablecoins, Paxos and TrueUSD. These stablecoins are closest in design to Tether, with the critical difference being institutional features employed to mitigate counterparty risk.[35]

Fig. 6 plots the stablecoin prices and intra-day volatility for Tether, TrueUSD, and Paxos. We calculate intra-day volatility as the square root of the daily average sum of squared returns over 5-min intervals. A visual inspection of Fig. 6 shows that Tether peg-price deviations and intra-day volatility are larger than the control group, with no evidence of pre-trends in the preceding 2 months leading to Tether migration to the Ethereum blockchain.[36]

Our purpose in using these stablecoins as a control is twofold. First, any common sources of shocks to the stablecoin class as a whole should be captured within the control group. This could be due to investors' transactional demand for crypto investments, the return and volatility structure of cryptocurrencies, and technological advances in crypto markets (new crypto exchanges) that will affect demand for all stablecoins. All stablecoins in the control group operate only on the Ethereum blockchain, providing a suitable control for testing the causal effect of Tether's structural transformation of its currency from the Omni to Ethereum blockchain.

We now test the specification in Eq. (4), where the outcome variable Y_t is either the absolute level of peg deviations, $|p_t - 1|$, or the intra-day volatility of peg deviations σ_t, both measured in basis points. The indicator for treatment T_i takes on a value of 1 for Tether and 0 for the control group currencies. Indicators for Paxos and TrueUSD are given by $\mathbb{1}_{\mathrm{PAX}}$ and $\mathbb{1}_{\mathrm{TUSD}}$ respectively. The coefficient δ measures the net impact of the structural change on Tether net of any trends observed

[33] The first recorded transaction with the Tether Treasury occurred on January 30th, 2019. We note that there are 6 transactions prior to April 9th, 2019. In the week of April 9th, 2019, we note a jump in the number of addresses transacting with the Ethereum blockchain by 24, which corresponds to the jump in April 2019 plotted in Fig. 5.

[34] Tether, in its white paper, states that investors are allowed to deposit dollars directly to obtain Tether tokens at the 1:1 pegged rate (Tetherinc (2016)).

[35] For example, TrueUSD uses a system of escrow, whereas Paxos is insured by FDIC deposits. For more on the technical details of alternative stablecoins, please see Section 3. We do not include USDC and DAI in our control group due to institutional differences. USDC is different in that it does not have a centralized issuer, with multiple issuers being able to grant USDC tokens. DAI, in contrast, is a crypto-collateralized stablecoin, typically backed by Ethereum, and has an independent structure of stability mechanisms.

[36] A reasonable concern that we address in our design is the significance of Tether peg-price deviations in October 2018. Tether experienced large discounts in excess of 500 basis points in response to a speculative attack which we outline in Appendix G. We present our results both for the full sample starting on April 1st, 2017, as well as a balanced panel starting on January 10th, 2019. The balanced panel is therefore robust to pre-trends of the full sample that includes the confounding event.

Table 2
Summary Statistics of Tether/USD Deviations, pre and post introduction of Tether on the Ethereum Blockchain.

Period	Mean	SD	Min	Max	Half-Life (days)
Pre Ethereum Blockchain	−28.2	97.2	−505	298	6.5
Post Ethereum Blockchain	−0.9	47.2	−298	119	3.3

Note: Summary statistics for deviations from the peg are expressed in basis points (100 basis points = 1 US cent). Secondary-market price is based on daily data that averages prices from the Bitfinex, Bittrex, and Kraken exchanges, all three being trusted exchanges, sourced from Coinapi. Sample is divided into 04/17 to 04/19 in the pre period and 04/19 to 03/20 in the post period, with the post date starting on April 9th, 2019. The post period corresponds to when investors can directly transact with the Tether Treasury on the Ethereum blockchain.

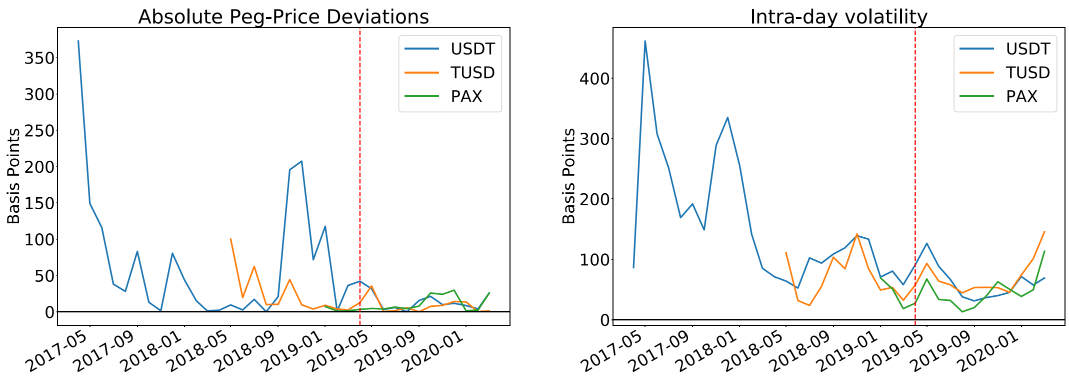

Fig. 6. left panel: Absolute peg-price deviations; right panel: intra-day volatility. Note: This figure plots average monthly stablecoin prices and intra-day volatility for the treatment (USDT) and the control group stablecoins. The treatment stablecoin is Tether (USDT). The control stablecoins are TrueUSD (TUSD) and Paxos (PAX). The red dotted line indicates the structural change date of April 9th,2019 used in the baseline specification. Price data for USDT consolidates trade data from three trusted exchanges: Bitfinex, Bittrex, and Kraken. Price data for the control group comes from Bittrex. Sample is January 10th, 2019 through to March 31st, 2020..

in the control group. The identifying assumption of our analysis is that δ measures the efficiency gain of Tether in migrating to the Ethereum blockchain. Our controls include the daily return and intra-day volatility of Bitcoin.[37] The results are summarized in Table 3. In columns (I) and (II), we impose a standard structural break test by regressing the absolute size and volatility of Tether peg deviations on a post dummy, which takes a value of 1 in April 2019 when Tether issuance migrated to the Ethereum blockchain. We observe on average a 36.9 basis point decline in the absolute level of peg deviations, and a decline in intra-day volatility of 57.2 basis points.

$$Y_t = \alpha_0 + \alpha_i \sum_{i \in PAX,TUSD} \mathbb{1}_i + \beta \mathbb{T}_i + \gamma \mathrm{post}_t + \delta \mathrm{post}_t \times \mathbb{T}_i + \mathrm{controls}_t + u_t \tag{4}$$

The results of our differences-in-differences analysis for the full sample are reported in columns (III) and (IV) of Table 3. There is a net convergence in the stability of peg deviations in Tether during the post period, with a difference-in-difference coefficient on post $\times$ T of -24.0 basis points. This implies a decline in the absolute level of deviations of 24.0 basis points relative to the control group currencies. Similarly, we observe a decline in intra-day volatility of Tether deviations relative to the control group of 40.3 basis points.

A reasonable concern of our full sample estimates is bias due to the presence of confounding events. We control for this by running our specification on a balanced panel for Tether and the control group that starts on January 10th, 2019. The results of the balanced panel are in columns (V) and (VI). Testing for effects using a balanced panel rules out the possibility that the result is driven by trends in Tether peg-prices in the earlier part of the full sample.[38] We still find a statistically significant difference-in-difference coefficient of -29.4 basis points for peg-price deviations and -26.3 basis-points for intra-day volatility. The balanced panel result therefore rules out the possibility that large Tether deviations witnessed in 2018 could be fully explaining the observed results.

4.2.1. Robustness test #1: sensitivity of Treatment date

The migration date in the baseline specification is April 9th, which is the first week in which at least 10 unique addresses transacted on the Ethereum blockchain. We conduct two robustness tests on the difference-in-difference specification. First,

[37] Intra-day volatility is calculated as the square root of the daily average sum of squared returns over hourly intervals

[38] In Appendix G we document two sources of large peg-price deviations in 2018. In January and February of 2018, a crash of BTC led to Tether premiums due to its relative liquidity and stability benefits. Significant discounts in Tether in October 2018 were a response to collateral concerns due to the suspension of dollar deposits at the Bitfinex exchange.

Table 3
Tests of a structural break in Tether issuance: effects of a migration to the Ethereum blockchain in 2019 on the size and volatility of Tether peg deviations.

	I	II	III	IV	V	VI
	$\|p_t - 1\|$	σ_t	$\|p_t - 1\|$	σ_t	$\|p_t - 1\|$	σ_t
post	−36.87***	−57.20***	−14.18***	−17.62***	−1.07	−7.28*
	(3.47)	(4.02)	(3.48)	(3.70)	(2.01)	(3.79)
T			26.93***	37.85***	28.81***	27.60***
			(2.94)	(3.33)	(3.28)	(2.37)
post × T			−24.00***	−40.26***	−29.41***	−26.32***
			(4.87)	(5.46)	(4.82)	(4.45)
$\mathbb{1}_{PAX}$			−3.40*	−19.37***	−5.00***	−14.53***
			(1.95)	(2.64)	(1.70)	(2.68)
$\mathbb{1}_{TUSD}$			−0.98	4.03*	−6.15***	7.03***
			(2.26)	(2.17)	(1.63)	(2.05)
R_{BTC}	0.0045	−0.0014	0.0012	0.0034	0.0002	0.0024
	(0.0041)	(0.0061)	(0.0026)	(0.0036)	(0.0017)	(0.0027)
σ_{BTC}	0.04***	0.17***	0.03***	0.16***	0.02***	0.13***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
R-squared	0.12	0.44	0.12	0.46	0.08	0.39
No. observations	957	957	1984	1984	1276	1276
Sample	Full	Full	Full	Full	Balanced	Balanced

Note: Table presents regressions of the absolute level and volatility of deviations of the peg. The absolute level of deviations is denoted by $|p_t - 1|$, and σ_t is calculated based on a measure of intra-day volatility of the price, both measured in basis points. The post dummy $Post_t$ takes a value of 1 from April 9th, 2019. The Treatment dummy T takes a value of 1 for USDT, and 0 otherwise. Control group currencies include TrueUSD, Paxos. σ_{BTC} is the intra-day volatility of the BTC/USDT price sourced from the Binance exchange, measured in basis points. R_{BTC} is daily BTC/USDT returns sourced from Cryptocompare, measured in basis points. Full sample for columns (I) through to (IV) is April 1st, 2017 to March 31st, 2020. Balanced panel for columns (V) and (VI) is from January 10th 2019 to March 31st 2020. Price data for currencies obtained from coinapi, and use closing prices from exchanges Kraken, Bitfinex, and Bittrex. White heteroscedasticity robust standard errors are used in estimation. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

we test whether the reported regressions are sensitive to the choice of the migration date. For example, the full effects of migration are likely to be realized months after April 2019, as users only gradually transferred their Tether holdings.[39] In Fig. 7, we perform a sensitivity analysis of the date of structural change by recording the difference-in-difference coefficients for alternative structural change dates. The presence of a treatment effect is robust to alternative dates: the peak treatment effect of −38 basis points occurs on May 8th, approximately a month after the structural change date of the baseline specification.

4.2.2. Robustness test #2: Dynamic time trend to the pre-post migration

We extend the specification to account for a dynamic trend in the post period in Eq. (5). The difference-in-difference coefficient δ traces the net effect of structural change across each quarter in the balanced sample, from 2019Q1 to 2020Q1. By tracing the net impact across quarters, we test the hypothesis that the structural change is not a step function, but reflects a gradual increase in arbitrage access. For example, we note that Tether creation on the Ethereum blockchain only exceeded Tether on Omni by the end of October 2019, months after the date of structural change. Cryptocurrency exchanges transferred Tether tokens from Omni to Ethereum for months through a series of chain swaps in which Tether holdings are rebalanced across blockchains.[40] Therefore we would not expect an immediate decline in peg deviations following the migration, but a gradual decline over a wider event window.

$$Y_t = \alpha_0 + \alpha_i \sum_{i \in PAX,TUSD} \mathbb{1}_i + \beta \mathbb{T}_i + \gamma \mathrm{post}_t + \sum_{q=1}^{Q} \delta_q \mathbb{Q}_{t+q} \times \mathbb{T}_i + u_t \tag{5}$$

Table 4 presents the results, and Fig. 8 plots the difference-in-difference coefficients in columns (III) and (IV). Peg price-deviations relative to the control group is given by the coefficients of interest for each quarter interacted with the dummy for Tether. The coefficients document a trend increase in Tether efficiency. Tether peg-price deviations in 2019Q1 and 2019Q2 are 22.7 and 23.7 basis points higher relative to the control group. In contrast, Tether peg-price deviations decline relative to control group stablecoins during 2019Q4 and 2020Q1, with estimates of −13.4 and −10.8 basis points respectively. Intra-day volatility follows a similar qualitative pattern in efficiency. In 2019Q2, it is 42.0 basis points higher relative to the control

[39] A potential concern with the post period is the April 30th, 2019 report on Tether backing being only 74% in the form of cash or cash equivalents. For details on the announcement, we refer the reader to https://www.coindesk.com/tether-lawyer-confirms-stablecoin-74-percent-backed-by-cash-and-equivalents. There was no visible market reaction to the April 30 report, with Tether continuing to have two-sided deviations. Tether asserts that they are backed by dollar reserves fully and releases a balance sheet daily showing Tether assets and liabilities match (with Assets > Liabilities suggesting earnings from interest-bearing assets). The definition of "cash or cash equivalents" does not include various interest-bearing assets on the balance sheet.

[40] We provide a list of major chain-swap events in Appendix C.

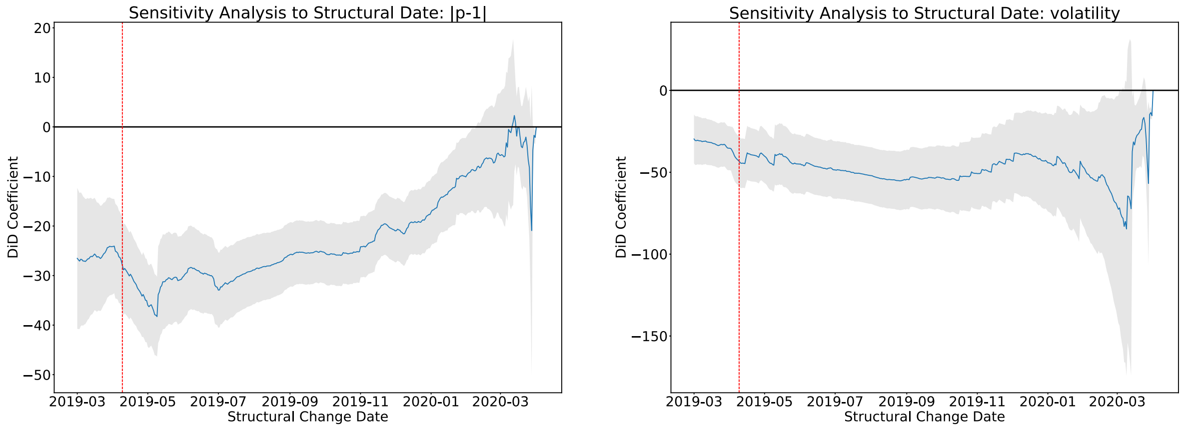

Fig. 7. Sensitivity Analysis of Difference-in-Difference Coefficients to a Change in the Structural Date. Note: This figure shows the difference-in-difference coefficient δ of the following design: $|p_t - 1| = \beta_t Post_t + \delta_t Post_t \times T_t$ by changing the structural change date $Post_t$. The outcome variable measures the absolute level of peg deviations on the left panel, and intra-day volatility of peg price deviations on the right panel. The treatment currency is Tether (USDT), and control group currencies are TrueUSD (TUSD) and Paxos (PAX). The red dotted line indicates the structural change date of April 9th used in the baseline specification. White heteroscedasticity-robust standard error bands are reported at a 5% significance level. The sample is January 10th, 2019 to March 31st, 2020..

Table 4
Difference-in-difference design: dynamic effects.

	I	II	III	IV
	$\|p_t - 1\|$	σ_t	$\|p_t - 1\|$	σ_t
Q12019	23.16***	14.05***	6.40***	5.59
	(2.47)	(3.58)	(2.27)	(4.35)
Q22019	24.45***	52.43***	6.73***	28.35***
	(2.34)	(3.39)	(2.02)	(3.88)
Q32019	−10.65***	−9.38***	0.56	2.62
	(2.33)	(3.38)	(2.04)	(3.91)
Q42019	−6.53***	−14.40***	12.85***	16.57***
	(2.33)	(3.38)	(2.08)	(3.98)
Q12020	−7.58***	12.25***	9.16***	54.55***
	(2.34)	(3.39)	(2.06)	(3.94)
Q12019 × T			22.71***	26.40***
			(3.70)	(7.09)
Q22019 × T			23.67***	42.03***
			(3.45)	(6.60)
Q32019 × T			−5.26	5.94
			(3.44)	(6.60)
Q42019 × T			−13.43***	−13.02**
			(3.46)	(6.64)
Q12020 × T			−10.79***	−24.36***
			(3.46)	(6.64)
R-squared	0.29	0.31	0.12	0.14
No. observations	446	446	1274	1274

Note: Table estimates a dynamic difference-in-difference specification where the treatment is interacted with each quarter. The absolute level of deviations is denoted by $|p_t - 1|$, and σ_t is calculated based on a measure of intra-day volatility of the price, both measured in basis points. Price data for USDT consolidates trade data from three trusted exchanges: Bitfinex, Bittrex, and Kraken. Price data for the control group of stablecoins comes from Bittrex. Sample is January 10th, 2019 through March 31st, 2020. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

group, the coefficient then declines to −13.0 and −24.4 basis points by 2019Q4 and 2020Q1 respectively. The results are consistent with a *gradual* increase in peg efficiency, with Tether migration to Ethereum occurring over a period of months following the date of structural change. [41]

[41] One concern is that the end of our sample coincides with the Covid pandemic. In Appendix D we show that our results are robust to a longer sample (to December 2021) that controls for the Covid pandemic. In particular, the increase in peg efficiency primarily occurred before the Covid pandemic. A second empirical concern is controlling for idiosyncratic shocks to Tether during the migration period that can explain an increase in peg efficiency. For example, in May 2019 Bitfinex raised 1 billion USD through the sale of LEO utility tokens to be traded on Bitfinex and other iFinex platforms. Increased trust in Tether and its affiliated Ifinex network is an alternative explanation to our evidence on decentralization and Tether's independence from Bitfinex. To identify how much of the increase in peg efficiency is due to decentralized arbitrage, we propose an instrumental variable approach. Using growth of the users as an instrument for addresses transacting with the Tether treasury, we show an increase in decentralization leads to an increase in peg efficiency, and attribute up to 50 per cent of the increase in peg efficiency due to decentralization of arbitrage access. The results are in Appendix E.

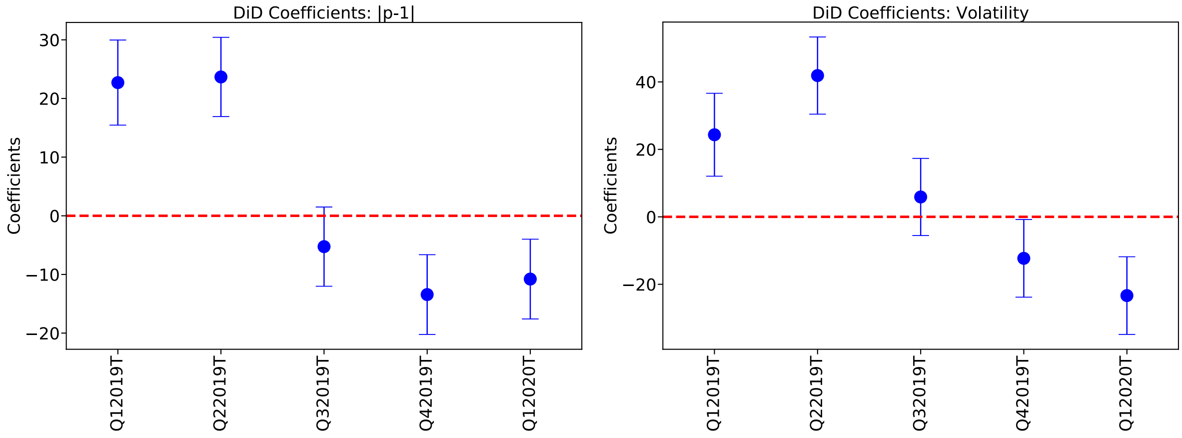

Fig. 8. Difference-in-difference coefficients for dynamic panel specification. Note: Figure presents coefficients for a dynamic difference-in-difference specification with the absolute level of peg-price deviations (left) and intra-day volatility (right). Coefficients measure the effect of the treatment interacted with each quarter. Price data for USDT consolidates trade data from three trusted exchanges: Bitfinex, Bittrex, and Kraken. Price data for the control group of stablecoins comes from Bittrex. Sample is January 10th, 2019 through March 31st, 2020. White heteroscedasticity-robust standard-error bars are plotted to construct a 95 percent confidence interval around coefficient estimates..

4.3. Stablecoin prices and issuance flows

We have provided evidence of a decentralized mechanism for peg stability: migration to the Ethereum blockchain led to an increase in arbitrage access, and an increase in the efficiency of the peg. A testable implication of the arbitrage mechanism is that flows from the Treasury to the secondary market should be stabilizing, by moving peg price deviations toward zero. We conduct local projections (based on Jordà (2005)) of the value of net inflows from the Treasury to the secondary market on the level of deviations from Tether's parity peg. We denote $Flow_{T\Rightarrow EX,h}$ as total flows from the Treasury to the secondary market, measured at an hourly frequency.[42] The change in the Tether dollar price, $P_{t+h} - P_{t-1}$, is projected on the level of arbitrage flows of investors in Eq. (6), allowing for feedback effects using lagged price and flows as controls. We hypothesize a negative coefficient β_h, which suggests that positive flows to the secondary market have a stabilizing impact on price.

$$P_{t+h} - P_{t-1} = \alpha + \beta_h Flow_{T\Rightarrow \mathrm{EX},t} + \sum_{k=1}^{L} \delta_k Flow_{T\Rightarrow EX,t-k} + \sum_{k=1}^{L} \gamma_k (P_{t-k-1} - P_{t-k-2}) + u_t h = 0, 1, 2, \ldots \tag{6}$$

The results of our local projections are shown in Fig. 9. Consistent with our hypothesis, arbitrage flows from investors have a stabilizing effect on the Tether/USD price. After dividing our sample based on the introduction of Tether to the Ethereum blockchain, we find a significant price impact of arbitrage flows in the post period, confirming that increased direct access of investors to the Treasury supports the arbitrage mechanism. In the period post migration to the Ethereum blockchain, we measure a price impact of approximately 5 basis points in response to a one standard-deviation shock in secondary-market flows (approximately 7.5 Million USD based on hourly data). [43]

4.4. Arbitrage profits on the omni and ethereum blockchains

We compute a proxy for the profitability of arbitrage trades. For deposits, we assume an arbitrage sequence where an investor deposits dollars with the Tether Treasury, and then contemporaneously sells Tether in the secondary market. The arbitrage spread is then defined, in USD, as the difference $p_{USDT} - 1$, where p_{USDT} is the dollar price of Tether at the exchange. For redemptions, the arbitrage sequence is when an investor buys Tether contemporaneously in the market, and redeem Tether tokens to the Treasury at a 1:1 rate. The arbitrage spread is then defined, in USD, as the difference $1 - p_{USDT}$, where p_{USDT} is the dollar price of Tether at the exchange. We match the timestamp of investor Treasury deposits and redemptions with the secondary-market price of Tether based on minute-frequency price data from a volume weighted average price from Bitfinex, Bittrex, and Kraken, three of the most liquid exchanges in the Tether/Dollar market. We then calculate arbitrage spreads and profits net of transaction costs. First, we subtract deposit and withdrawal fees imposed by the Tether Treasury. Deposits of dollars at the Treasury come with a flat fee of 0.1 per cent, redemptions incur a minimum cost of 1000 USD or 0.1 per cent of the trade. [44] Second, we assume the transaction price is at the mid-point between bid and

[42] A positive flow to the secondary market is equivalent to a net positive deposit of dollars with the Tether Treasury, aggregated at a daily frequency.
[43] While our analysis in this section focuses on Tether, as it represents approximately 80% of the current stablecoin market, our analysis applies more generally to the class of national-currency-backed stablecoins. We provide analysis for other national-currency-backed coins in Appendix F.
[44] For example, refer to https://tether.to/fees/ for details.

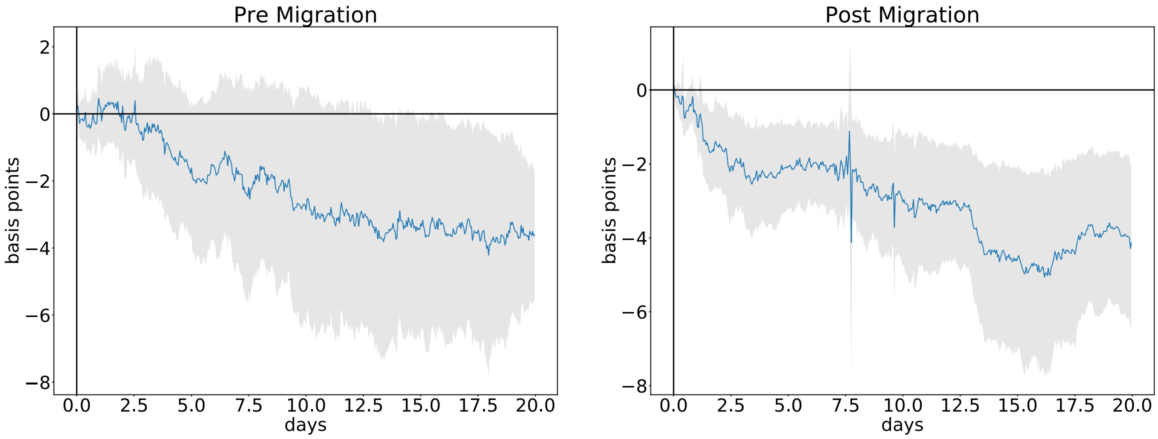

Fig. 9. Response of Tether/USD price to 1 standard deviation shock in flows to the secondary market; left panel – Pre Ethereum blockchain; right panel – Post Ethereum blockchain. Note: Figure documents the effect of a 1 standard-deviation shock to net secondary-market flows on the price of Tether/USD. Left and right panels are for different sample periods based on the introduction of Tether to the Ethereum blockchain. Data for secondary-market flows are from Omniexplorer and Etherscan. Price data are from Coinapi, and take an average of trade-price data from the following trusted exchanges: Bittrex and Kraken. Sample is hourly data from April 1st, 2017 to March 31st, 2020. 24 lags are included in the baseline specification. Gray area deNotes 95% confidence interval using White heteroscedasticity-robust standard errors..

ask, we subtract half the bid-ask spread. Third, to estimate slippage costs, we use our prior estimates on the price impact of arbitrage flow, where we find a 1 standard deviation change in arbitrage flow to the secondary market (approximately 7.5 million USD) leads to a 5 basis point decline in the Tether price. For example, for a deposit of 1 million, the slippage cost is then calculated as $\frac{1}{7.5} \times 5 = \frac{2}{3}$ basis points. Fourth, we account for gas fees on the Ethereum blockchain.[45]

A histogram of arbitrage spreads (including a measure net of transaction costs) for deposits and redemptions on the Omni and Ethereum blockchains is provided in Fig. 10. The distribution of arbitrage spreads is more dispersed on the Omni blockchain, and both blockchains have a majority of deposits, 87% and 84% respectively, that coincide with a secondary-market price above the peg. We summarise the statistics of arbitrage profits, deposits, and spread for the Omni and Ethereum blockchains in Table 5. Following the migration to the Ethereum blockchain, the average size of deposits fell from 7.6 to 4.1 USD million. Second, arbitrage spreads on deposits (net of transaction costs) shrink from an average of 47.1 basis points on Omni to 13.5 basis points on Ethereum. Consequently, median arbitrage profits (net of transaction costs) shrink from an average of 0.004 to 0.001 USD million. In contrast to our results on Tether deposits, the majority of Tether redemptions earn negative arbitrage spreads and profits.[46] Following the migration to the Ethereum blockchain, the average size of redemptions fell from 27.4 to 8.7 USD million. Second, arbitrage spreads (net of transaction costs) shrink from an average of -37.5 basis points on Omni to -111.7 basis points on Ethereum. Median arbitrage profits (net of transaction costs) slightly increase from an average of -0.012 to -0.008 USD million.

In analysing Tether deposits and redemptions, we find stronger evidence for an arbitrage motive based on deposits of Tether, but not for redemptions of Tether. The main reason is an asymmetry in deposit and redemption fees: while deposits incur a flat fee of 10 basis points, redemptions incur a minimum 1,000 USD withdrawal. Redemptions may also occur due to institutional features such as chain swaps, in which Tether tokens are transferred from one blockchain to another, or speculation on collateral risk. The bottom line: increased investor access on the Ethereum blockchain has reduced the extent of arbitrage opportunities. The corresponding decline in the average size of trades, spreads and profits is consistent with a "democratization" of access to arbitrage trades.

5. Decentralized arbitrage: other coins

5.1. Decentralized stablecoins

The preceding discussion focused on national-currency backed stablecoins. We now provide evidence of the importance of arbitrage design for coins backed by other cryptoassets. The peg stability module (PSM) of the DAI stablecoin was introduced on December 2020 as a solution to combat persistent peg-price deviations (Kozhan and Viswanath-Natraj, 2021). Initially, DAI was created by adding different collateral types (ETH, USDC) in a vault, and borrowing a fraction as DAI tokens.

[45] Gas is a measure of the amount of ether (ETH) a user pays to perform a given activity, or batch of activities, on the Ethereum network. These transaction costs are analogous to commissions on exchanges, however these costs are paid to the miners who authenticate the transactions on the Ethereum blockchain. As we do not have transaction level gas fees, we use a daily index of ETH gas prices from coinmetrics network statistics as a proxy.

[46] In our summary statistics, we exclude any redemptions that are less than 1000 USD, as these transactions incur a redemption fee of 1000 USD.

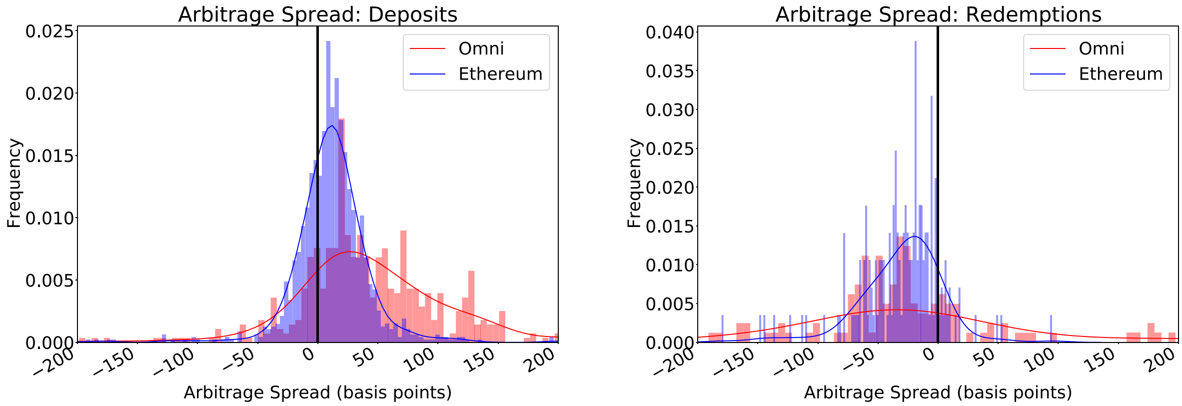

Fig. 10. Arbitrage spreads calculated as the peg-price deviation $p_t - 1$ at the timestamp of the deposit (left). Arbitrage spreads net of transaction costs (right). Note: Figure plots histograms of arbitrage spread of Tether deposits (left) and Tether redemptions (right) on the Omni and Ethereum blockchain. Spread, measured in basis points, is the difference between the secondary-market price of Tether and the pegged rate of 1. Spread, measured in basis points, is the difference between the pegged rate of 1 and the secondary-market price of Tether. Secondary-market price is based on minute-frequency data that averages prices from the Bitfinex, Bittrex, and Kraken exchanges, sourced from Coinapi. Spread$_c$ is a spread net of transaction costs, which includes bid-ask spreads and an estimate of slippage cost due to the price impact of the trade. Sample is July 12th, 2018 (from which bid-ask prices on the Kraken exchange order book is available) to March 31st, 2020..

Table 5
Summary statistics of arbitrage spreads on the omni and ethereum blockchains.

	Deposit						Redemption					
	Omni			Ethereum			Omni			Ethereum		
	Size	Spread	Profit	Size	Spread	Profit	Size	Spread	Profit	Size	Spread	Profit
Count	542	542	542	1346	1346	1346	139	139	139	171	171	171
Mean	7.591	47.114	−0.112	4.100	13.474	−0.013	27.437	−37.541	−0.034	8.689	−111.698	−0.048
std	36.272	86.437	1.456	16.528	41.320	0.292	50.199	164.206	1.260	13.184	387.475	0.103
min	0.002	−604.333	−30.217	0.001	−206.700	−6.201	0.010	−753.507	−7.215	0.003	−3382.151	−0.870
25%	0.597	11.659	0.001	0.541	−2.731	−0.000	3.000	−65.589	−0.062	1.000	−70.319	−0.037
50%	1.498	37.441	0.004	1.798	11.233	0.001	10.000	−33.000	−0.012	2.990	−42.301	−0.008
75%	3.996	79.130	0.013	4.000	25.394	0.005	30.000	5.017	0.001	10.000	−22.367	−0.002
max	500.000	423.167	0.482	300.000	493.949	0.204	300.000	406.167	8.123	73.000	84.833	0.085

Note: Table records statistics on Tether Treasury deposit size, arbitrage spread, and profit (calculated as arbitrage spread times deposit size, trade-by-trade). Spread, measured in basis points, is the difference between the secondary-market price of Tether and the pegged rate of 1. Secondary-market price is based on minute-frequency data that averages prices from the Bitfinex, Bittrex, and Kraken exchanges, sourced from Coinapi. Spread is a spread net of transaction costs, which includes deposit and redemption fees, bid-ask spreads and an estimate of slippage cost due to the price impact of the trade. Profit is computed as the product of spread and size of deposit or redemption, and is measured in USD Millions. Sample is July 12th, 2018 (from which bid-ask prices on the Kraken exchange order book is available) to March 31st, 2020.

While over-collateralized positions can preserve stability, liquidation risk to investors and valuation effects on collateral made it difficult for arbitrageurs to stabilize the peg. In response, the governance protocol introduced the PSM, a smart contract that enables users to swap USDC with DAI at a 1:1 rate without needing to create a vault or deposit collateral.[47]

The smart contracts to swap USDC and DAI can only be called by investors, making the PSM a prime example of arbitrage that is fully decentralized. For example, if the secondary market price of DAI is above one USDC, an investor can swap USDC for DAI with the Maker governance protocol at a one-for-one rate, and sell DAI at the prevailing market rate to profit. Conversely, when the DAI price is less than 1 USDC, an investor can swap DAI for USDC, resulting in a flow in the opposite direction. In the left panel of Fig. 11 we plot daily flows of the swap arrangement between private investors and the MakerDAO protocol and also the DAI/USDC price.[48] Consistent with improved arbitrage design, investors typically use the PSM to swap USDC for DAI when DAI trades at a premium to USDC in the secondary market.[49]

$$P_{t+h} - P_{t-1} = \alpha + \beta_h Flow_t + \sum_{k=1}^{L} \delta_k Flow_{t-k} + \sum_{k=1}^{L} \gamma_k (P_{t-k-1} - P_{t-k-2}) + controls_t + u_t h = 0, 1, 2, \ldots \tag{7}$$

[47] The smart contract code required to implement the PSM is available online at https://github.com/BellwoodStudios/dss-psm
[48] Data on the net swaps of USDC for DAI in the PSM is available at https://makerburn.com, and prices are from coinapi using the Coinbase exchange.
[49] For more details on how the PSM works, we refer readers to https://community-development.makerdao.com/en/learn/governance/module-psm/

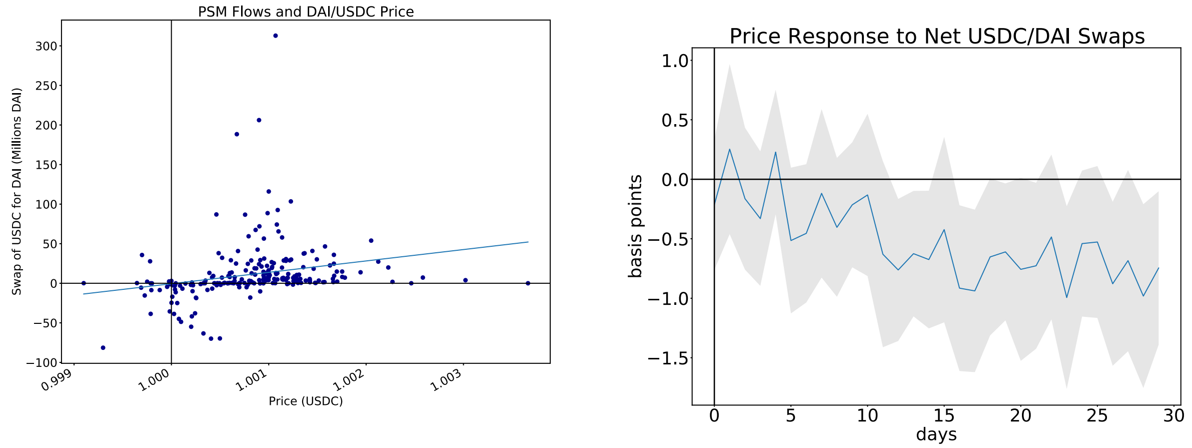

Fig. 11. Swaps of USDC for DAI tokens under peg stability module (PSM) against the DAI/USDC Price (left). Response of DAI/USDC price to 1 standard deviation shock in PSM flows (right). Note: left panel: Schematic illustrates net swaps of USDC against DAI using the PSM against the DAI/USDC price. right panel: Figure documents the effect of a 1 standard-deviation shock to a net swap of USDC for DAI on the DAI/USDC price. Price data are from Coinapi, using coinbase for the DAI/USDC pair. Sample is daily data from 28th December, 2020 to October 28th, 2021. 1 lag is included in the baseline specification. Controls include ETH returns and intra-day volatility. Gray area deNotes 95% confidence interval using White heteroscedasticity-robust standard errors..

A testable implication of the arbitrage mechanism is that adding the swap arrangement should increase stability.[50] We conduct local projections (based on Jordà (2005)) of the value of swaps of USDC for DAI on the level of deviations of the DAI/USDC peg. We denote $Flow_{PSM,t}$ as total swaps of USDC for DAI, measured at a daily frequency. The change in the DAI/USDC price, $P_{t+h} - P_{t-1}$, is projected on the level of arbitrage flows of investors in Eq. (7), allowing for feedback effects using lagged price and flows, and controlling for ETH/USD returns and intra-day volatility.[51] A negative coefficient β_h indicates that positive flows to the secondary market have a stabilizing impact on price. The results of local projections are in the right panel of Fig. 11. Consistent with our hypothesis, arbitrage flows from investors have a stabilizing effect on the DAI/USDC price. We measure a peak price impact of approximately 1.5 basis points in response to a one standard-deviation shock in secondary-market flows (approximately 32.4 million USD based on daily data).

5.2. Wrapped tokens

Wrapped tokens are tokenized versions of other cryptocurrencies. A crucial difference between a stablecoin and a wrapped token is that the latter pegs to an asset on the blockchain.[52] The WBTC token is an ERC20 stablecoin on Ethereum backed 1:1 by native bitcoin, with approximately 1 per cent of Bitcoin in circulation locked to create WBTC tokens as of November 2021. WBTC is a unique solution to the inter-operability of blockchains.[53] Bitgo is currently a custodian of assets and holds native BTC assets. All transfers are authenticated using a multi-signature (multisig) procedure.[54] Accounts of native bitcoin can be audited and verified on-chain, to ensure that the 1:1 backing is maintained.

WBTC has a decentralized arbitrage design. Merchants are authorized participants that can mint (create) or burn (redeem) WBTC tokens, and interface with both the custodian of native Bitcoin assets on one side and investors wanting to exchange BTC/WBTC on the other.[55] Importantly, the custodian Bitgo cannot initiate transactions, all mints and burns are initiated by a merchant.[56] Consider the WBTC token trading at a premium on an exchange. Merchants have an incentive to mint WBTC tokens and deposit WBTC with the custodian at a 1:1 rate, and sell it in the secondary market. Conversely, merchants can buy WBTC tokens at a discount and burn WBTC tokens at par. In the left panel of Fig. 12, we plot daily net mints of WBTC tokens

[50] For a comprehensive discussion of the DAI peg and the PSM, we refer readers to Kozhan and Viswanath-Natraj (2021), which is the first paper to document the effect of the PSM on peg efficiency. Kozhan and Viswanath-Natraj (2021) focus, through a model and empirical evidence, on the role of risky Ethereum collateral as a limit to arbitrage and leading to the DAI-peg instability. The PSM is designed as a solution to peg stability by enabling arbitrageurs access to a USDC/DAI swap trade, reducing the limits to arbitrage. Here we complement their findings by documenting how the swap arrangement of USDC for DAI leads to price stabilization.

[51] Intra-day volatility is calculated as the square root of the daily average sum of squared returns over hourly intervals

[52] The DAI PSM makes the DAI stablecoin a wrapped USDC token. However DAI functionality still allows users to deposit alternative currencies (ETH) as collateral in vaults to create DAI tokens; thus, DAI tokens can be backed by other currencies as well as USDC.

[53] As an ERC-20 token that maps to BTC, it allows users to trade a synthetic BTC token on DeFi applications, including lending protocols like Compound and decentralized exchanges like Uniswap.

[54] Multisig is a process requiring multiple keys to authorize a Bitcoin transaction, rather than a single signature from one key. This is more secure as it avoids a single-point of failure

[55] A list of merchant institutions can be found at https://wbtc.network/dashboard/partners. There are 34 registered merchants for WBTC trading as of November 1st, 2021.

[56] https://forum.makerdao.com/t/state-of-wrapped-bitcoin-wbtc/6800

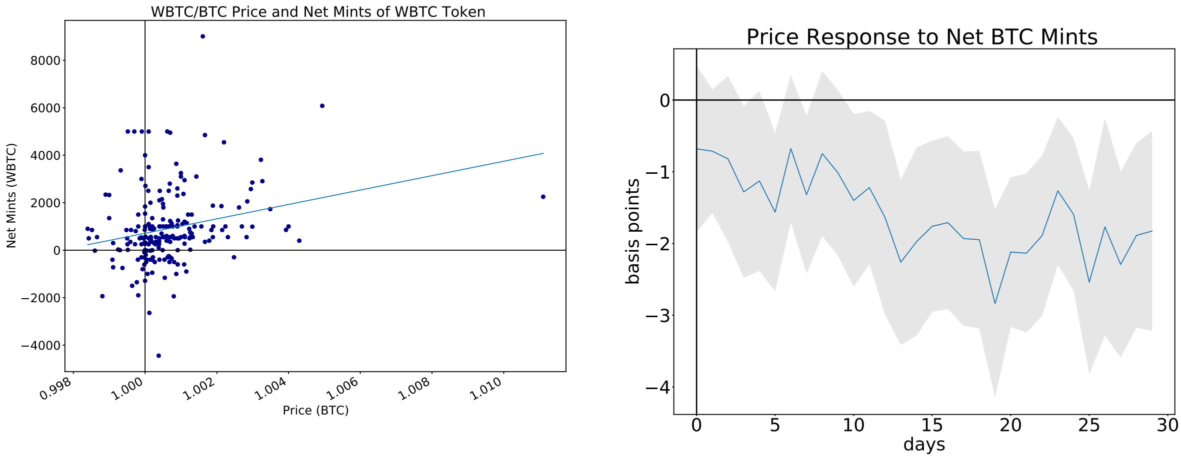

Fig. 12. Net mints of WBTC token against the WBTC/BTC Price (left). Response of WBTC/BTC price to 1 standard deviation shock in WBTC net mints (right). Note: left panel: Schematic illustrates net mints of WBTC against WBTC using the PSM against the WBTC/BTC price. right panel: Figure documents the effect of a 1 standard-deviation shock to a net mint of WBTC token on the WBTC/BTC price. Price data are from Coinapi, using the Binance exchange for the WBTC/BTC pair. Sample is daily data from August 31st 2020 to October 28th, 2021. 1 lag is included in the baseline specification. Controls include BTC returns and intra-day volatility. Gray area deNotes 95% confidence interval using White heteroscedasticity-robust standard errors..

and WBTC/BTC prices from Binance, which is the most liquid exchange offering the WBTC/BTC pair during our sample.[57] Consistent with our hypothesis, merchants typically mint WBTC tokens when they trade at a premium with respect to native Bitcoin in the secondary market.

We conduct local projections of $Flow_{BTC,t}$ as total net mints of WBTC, measured at a daily frequency. Using the same specification in Eq. (7), the change in the WBTC/BTC price, $P_{t+h} - P_{t-1}$, is projected on the level of arbitrage flows of investors in Eq. (7), allowing for feedback effects using lagged price and flows, and controlling for BTC/USD returns and intra-day volatility.[58] We hypothesize a negative coefficient β_h, which would indicate that positive flows to the secondary market have a stabilizing price impact. Consistent with our hypothesis, arbitrage flows from investors have a stabilizing effect on the WBTC/BTC price. The results of our local projections are shown in the right panel of Fig. 12. We measure peak price impact at about 3 basis points in response to a one standard-deviation shock in the net mints of WBTC tokens (approximately 1187 WBTC based on daily data).

5.3. Global stablecoins and CBDCs

The decentralized arbitrage mechanism that we have explained can in principle be applied to the stabilization of both global stablecoins and CBDCs. Facebook announced in 2019 its intention to launch Diem – a global stablecoin. The proposed Diem stablecoin will have designated Dealers (DDs) that interface with both the Diem Association on one side and Diem users on the other.[59] DDs will be responsible for keeping the stablecoin stable. If the price of DiemUSD rises above 1 USD, it is the dealer's role to deposit 1 USD with the Diem Network and sell that additional DiemUSD into the secondary market, earning a profit on the transaction and driving the price down toward 1 USD. DDs will typically be large financial institutions, with sufficient regulatory capital to scale these arbitrage opportunities.[60]

Turning to CBDCs, the Digital Currency Economic Payment (DCEP) project of China's central bank maintains the value of 1 unit of China's digital Yuan to the National currency. The tiered structure of China's digital currency system follows a similar setup to the proposed Diem stablecoin, and includes wholesale transactions between Central Banks and Commercial Banks. Commercial Banks then issue DCEP to retail users. In this way, the digital token is issued by the central bank and then backed 1-for-1 by local-currency reserves at domestic banks. If the digital token is priced above par, the domestic bank can buy digital currency tokens from the central bank at a 1:1 rate, and sell them in the secondary market. This process will in principle keep the value of the digital token pegged at a 1:1 rate to the local currency.

5.4. Algorithmic stablecoins and TerraUSD collapse

Algorithmic stablecoins are led by TerraUSD, which reached a peak marketcap of 40 USD billion in April 2022. Unlike their centralized counterparts, they are more capital efficient as they do not rely on full collateralization by dollar reserves. Ter-

[57] Data on WBTC mints and burns is taken from https://wbtc.network/dashboard/order-book.
[58] Intra-day volatility is calculated as the square root of the daily average sum of squared returns over hourly intervals
[59] On the consumer-facing side, DDs will interact mainly with Virtual Asset Service Providers (VASPs), large entities that provide financial services to end users.
[60] Dealers have role similar to that of ETF authorized participants.

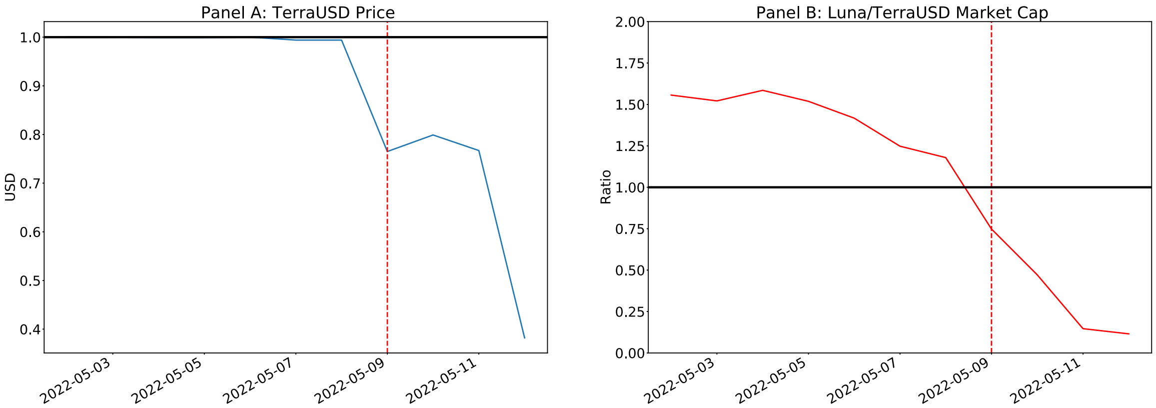

Fig. 13. TerraUSD price on 10 May 2022 (left). Ratio of value of TerraLuna to TerraUSD. Note: left panel: Sample is daily data for UST/USD is obtained for the Coinbase exchange from coinapi. right panel: Sample is daily data on market cap of TerraUSD and Luna obtained from coinmarketcap. .

raUSD is instead backed by Luna, which is the native token of the Terra blockchain. Users can create USD worth of TerraUSD stablecoins by burning 1 USD of Luna. The Luna token is used to pay fees for validating transactions on the blockchain, staking tokens in governance votes, and earning yields on DeFi lending protocols. [61]

The TerraUSD is pegged to 1 USD through a simple arbitrage mechanism. For example, consider the case where the TerraUSD price is above parity. In this instance, an investor can sell 1 USD worth of Luna and buy TerraUSD for 1 USD. They can then sell TerraUSD in the secondary market to make an arbitrage profit. Conversely, when the dollar price of TerraUSD is below one, an investor can buy TerraUSD at the exchange and sell TerraUSD for 1 USD worth of Luna tokens. A major concern with the arbitrage mechanism is that it is not risk-free: investor profits are driven by expectations of the valuation of the governance token.

Algorithmic stablecoins are prone to devaluation risk and speculative attacks when they are under-collateralized. In the left panel of Fig. 13, we witness large peg discounts starting on 9th May 2022, in which TerraUSD traded at a closing price of 75 cents, before dropping to 40 cents by 12th May. As an insurance against peg discounts, the TerraUSD treasury has a Bitcoin reserve that it can use to support the TerraUSD peg if there is insufficient Luna to meet redemptions. When Bitcoin reserves were at their peak of 1.8 billion USD in early May, they reached approximately 10% of the TerraUSD market cap of approximately 18 USD billion. However, the Bitcoin reserves became fully depleted as they were sold off to defend against the speculative attack.

When the TerraUSD peg is broken, this triggers a loss of confidence in the blockchain and the governance token. This feedback can and did generate a spiral of falling Luna and TerraUSD prices. The ratio of the value of Luna to the circulating supply of TerraUSD declines to approximately 0.1 on 12th May (Fig. 13, right). Therefore, there is not enough Luna to redeem the outstanding value of all TerraUSD in circulation at par.[62] The arbitrage loop of redeeming TerraUSD at 1 USD and buying Luna tokens fails as investors lose confidence in the peg-stabilizing mechanism.[63]

Comparing the design of TerraUSD to alternative systems such as dollar-backed stablecoins like Tether and over-collateralized crypto-backed coins like DAI, we note that there exists no equivalent arbitrage mechanism between the primary and secondary markets.[64] Critically, the governance token Luna is unsuitable as collateral backing since it is systemically

[61] Although TerraUSD is backed by cryptocurrency collateral, we differentiate TerraUSD from decentralized stablecoins like DAI, which is backed by multiple collateral types and has features like over-collateralization and smart contracts to enforce liquidation in the event positions are under-collateralized. TerraUSD is instead backed by tokens native to its blockchain. We find the governance token Luna is unsuitable as collateral backing since it is systemically dependent on the value of the TerraUSD token and the growth of the Terra blockchain, with equilibria in which both the collateral and stablecoin prices jointly fall.

[62] The spiral in Luna and Terra prices observed in May 2022 is in part due to a decline in demand for TerraUSD on Anchor. Anchor is a lending protocol that offers users the ability to deposit Luna as collateral ("staking" Luna) and borrow TerraUSD tokens, creating a demand for TerraUSD. The negative sentiment on Terra-Luna led to a decline in the demand for TerraUSD on the protocol. As users redeem TerraUSD and mint Luna tokens, the price of Luna depreciates. This in turn causes a decline in the amount of Luna deposited in the protocol, leading to less borrowing of TerraUSD, and a downward spiral of TerraUSD and Luna prices.

[63] While we focus on equilibria in which peg discounts occur, we can also consider an alternative equilibrium in which user growth on the blockchain grows strongly. This increases the value of the governance token Luna and simultaneously the demand for the TerraUSD stablecoin, which is used in all of the applications built on the Terra blockchain. In this scenario, TerraUSD trades at a premium and relies on the following arbitrage mechanism: Luna holders burn 1 USD worth of Luna to mint 1 USD worth of Terra token and sell it at a profit. The arbitrage mechanism is therefore more effective in periods when the Terra token trades at a premium and the Luna token is appreciating.

[64] The TerraUSD crisis did not spillover to other stablecoins, however temporary contagion effects were seen on May 12th 2022, when Tether experienced intra-day discounts of up to 5 cents in response to large sell trades on the FTX exchange. Tether prices rebounded toward parity intra-day, and we note significant redemption requests by the Tether treasury to accommodate the reduced demand for Tether. Tether market cap declined by 8 USD Billion from 82.8 USD Billion on May 11th to 74.1 USD Billion on May 18th (estimates from coinmarketcap). These redemptions are consistent with the arbitrage mechanism we put forward in the paper, and were required for Tether to maintain its peg. For more details on the Tether discounts, we refer readers to https://blog.kaiko.com/whats-driving-tether-s-de-pegging-f49db1e55b33

dependent on the value of the TerraUSD token and the growth of the Terra blockchain. One natural solution is for TerraUSD to be backed fully by stable collateral, ideally liquid US dollar reserves, or its equivalent in stablecoins on the blockchain. Another solution is to maintain over-collateralization through smart contracts. For example, if the ratio of collateral to stablecoin falls below a threshold, the system requires liquidation of the stablecoin to preserve full collateralization and peg stability.

6. Conclusion

Our paper focused on the design of stablecoins that are backed by national currencies, specifically Tether (USDT), the most liquid and heavily traded stablecoin. As a function of backing collateral, there are three basic categories: national-currency backed, cryptocurrency backed, and algorithmic (unbacked). Our results on Tether are thus best interpreted as applying to the first of these. Focusing on the design of arbitrage processes as key to keeping centralized stablecoins stable, we identify which arbitrage-process elements best account for issuance. Our bottom line: decentralized issuance and increased access to the stablecoin treasury are critical factors in determining the efficiency of the peg.

We provide concrete evidence of arbitrage design through an analysis of key 2019 reforms. First, we exploit the April 2019 migration of Tether from the Omni to the Ethereum blockchain, which resulted in a large increase in arbitrageur access to the Tether Treasury. We employed a difference-in-differences design using a set of control group stablecoins that share similar institutional features, but did not undergo a structural change of blockchain. This produces a large and statistically significant reduction in peg deviations. The second way we test the stability mechanism focuses specifically on arbitrage flows. We find that a one standard-deviation change in net flows (approximately 7.5 million USD based on hourly data) reduces peg-price deviations by up to 5 basis points, consistent with arbitrage being the central stabilizing mechanism. We also provide evidence on the profitability of arbitrage trades. Migration to the Ethereum blockchain resulted in a smaller deposit size, spreads, and profits. This is consistent with the "democratization" of access to arbitrage trades on the Ethereum blockchain leading to smaller spreads and profits per trade.

We then turn to several more recent decentralized finance applications. The peg stability module (PSM) of the DAI stablecoin was introduced as a solution to combat persistent peg-price deviations (Kozhan and Viswanath-Natraj, 2021). The smart contracts to swap USDC and DAI can only be called by investors. Similarly, the Wrapped Bitcoin (WBTC) token is an ERC20 stablecoin on Ethereum backed 1:1 by native bitcoin. In that case, merchants are authorized participants that can mint (create) or burn (redeem) WBTC tokens. For both of these arbitrage designs, we find evidence that trades initiated by private investors stabilize price. Next, we turn to implications of arbitrage design for Facebook's Diem stablecoin and central bank digital currencies (CBDCs). In both these cases, dealers and commercial banks will play the role of authorized merchants to conduct arbitrage that will maintain pegged values. Finally, we consider an alternative system of peg maintenance. Algorithmic stablecoins such as TerraUSD that are typically unbacked. The recent collapse of TerraUSD shows that this category is prone to devaluation risk and speculative attacks when they are under-collateralized. In contrast to dollar-backed stablecoins, there is no clear arbitrage mechanism to restore prices when TerraUSD is priced at a discount.

We conclude with policy recommendations for stablecoin and CBDC oversight. First, there is room for increased regulatory guidance on what it means for a stablecoin to be fully backed by sufficiently liquid reserves, or the prudence of having backstops such as insurance provided by a central bank. For example, stablecoins that are backed by assets that may be illiquid in a crisis, such as commercial paper held by money market funds in 2008, are susceptible to bank-like runs when the value of redemptions exceeds the amount of liquid reserves (Eichengreen and Viswanath-Natraj, 2022). A potential solution to minimising run-risk is real-time audits through a proof-of-reserve system. Third party verification of the stablecoin-issuer assets at a block-time frequency can mitigate run-risks and custodial risk of an issuer absconding with funds off-chain.[65]

Second, our paper shows that access to the primary market matters for the efficiency of arbitrage design. To take advantage of pricing discrepancies between primary and secondary markets, we recognize that stablecoin stability relies on sufficient arbitrage capital among participants that a given market design is relying on. Regulatory frameworks should, ceteris paribus, increase access to arbitrage trades. This could involve, for example, extending the set investors that have access to the primary market when the capital of existing participants is low; or in the case of a CBDC, reducing the costs of obtaining a license to transact with the central bank.

Finally, it has never been our intention in this paper to defend Tether or its own operating policies – we are simply bringing objective analysis to questions we judge to be of consequence. While the focus of our paper is on arbitrage design, the increased global importance of stablecoins makes them a systemically important part of how cryptocurrency markets function. The increasing role they play in facilitating speculation and the role that financial intermediaries play can spillover to other asset markets, as evident in the effects of stablecoin issuance on commercial paper (Barthelemy et al., 2021; Kim, 2022). Understanding the implications for financial stability and designing optimal regulations are promising areas of future work on stablecoins.

[65] An example of proof of reserve is provided by the blockchain firm Chainlink https://chain.link/proof-of-reserve. As mentioned on their website, they provide three functions: (i) Automated audits into your decentralized application to help decrease risk and increase efficiency; (ii) Publish reliable, timely, and immutable audit reports on-chain to help bring new levels of transparency; and (iii) Prevent systemic failures in DeFi applications and protecting users from unexpected fractional reserve activity. An example of a stablecoin that uses Chainlink's proof of reserve is TrueUSD. Wrapped tokens like WBTC are also audited through Chainlink.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jimonfin.2022.102777.

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