What Keeps Stablecoins Stable?

Richard K. Lyons and Ganesh Viswanath-Natraj*

First version: December 21, 2019 (posted SSRN)

This version: November 17, 2022

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.

Keywords: Cryptocurrency, stablecoins, Tether, arbitrage, exchange rates

JEL Classifications: E5, F3, F4, G15, G18

---

*UC Berkeley Haas School of Business and NBER (lyons@haas.berkeley.edu), and Warwick Business School (ganesh.viswanath-natraj@wbs.ac.uk), respectively. Forthcoming in the Journal of International Money and Finance. For detailed comments we thank an anonymous referee, discussants Uday Rajan and Xingyu Zhu, and Dirk Baur, Nic Carter, Will Cong, Barry Eichengreen, Alex Ferreira, Pierre-Olivier Gourinchas, Cam Harvey, Bob Hodrick, Roman Kozhan, Clayton Philippoz, Manju Puri, Raghavendra Rau, Nicholas Sander, Amin Shams, as well as seminar participants at the Australasian Banking and Finance Conference, the University of Cambridge Centre for Alternative Finance, the CEBRA annual meeting, the Georgetown Center for Financial Markets and Policy, the New York Federal Reserve Conference on Digital Assets, the Office of Financial Research, the University of Western Australia Blockchain conference, the University of Warwick Economics and Finance brownbags, and the London Empirical Asset Pricing Workshop. We thank Siravit Rattananon, Arijit Santra, Morgan Kidd, and Ying Chen for valuable research assistance, and the Berkeley Haas Blockchain Initiative for a research grant. Neither author is engaged as an academic expert in litigation involving Tether or Bitfinex.

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 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

[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`.

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 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 (Eichengreen, 2019; Berentsen and Schär, 2019; Bullmann et al., 2019; Dell'Erba, 2019; Arner et al., 2020; Frost et al., 2020; Force et al., 2020;

[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.

Barthelemy et al., 2021), arbitrage in stablecoin and cryptocurrency markets (Makarov and Schoar, 2019, 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 (Routledge and Zetlin-Jones, 2018; Li and Mayer, 2021; Cong et al., 2021; Kwon et al., 2021; d'Avernas et al., 2022), intraday price changes that support stablecoins' role as safe havens (Baur and Hoang, 2020; Hoang and Baur, 2021, 2020; Baumöhl and Vyrost, 2020; Wang et al., 2020; Bianchi et al., 2020; Gloede and Moser, 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; Barthelemy et al., 2021; Kim, 2022) 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

[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.

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 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

[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.

[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.

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 (Figure 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

[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.

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 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 equation (1).

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

Figure 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. Figure 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 equation (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 (equation (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.

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

[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.

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

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-minute 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-

[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/.

ure 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 Figure 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.

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 Figure 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]

[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).

[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.

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-second blocks (the corresponding set of transactions processed by miners on the blockchain) for Ethereum versus 10 minutes 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, cryptocurrency 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 (Figure 5, Left). The right panel of Figure 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 equation (3). The change in the stock of Tether in circulation on blockchain $i \in$ [Omni,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.

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

[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.

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

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 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

[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.

[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 Figure 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)).

and TrueUSD. These stablecoins are closest in design to Tether, with the critical difference being institutional features employed to mitigate counterparty risk.[35]

Figure 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-minute intervals. A visual inspection of Figure 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 equation (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 $\mathbb{1}_{PAX}$ and $\mathbb{1}_{TUSD}$ respectively. The coefficient δ measures the net impact of the structural change on Tether net of any trends observed 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.

[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.

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

$$Y_t = \alpha_0 + \alpha_i \sum_{i \in PAX,TUSD} \mathbb{1}_i + \beta T_i + \gamma post_t + \delta post_t \times T_i + controls_t + u_t \tag{4}$$

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, 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 Figure 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

[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.

[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.

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 equation (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.

$$Y_t = \alpha_0 + \alpha_i \sum_{i \in PAX,TUSD} \mathbb{1}_i + \beta T_i + \gamma post_t + \sum_{q=1}^{Q} \delta_q Q_{t+q} \times T_i + u_t \tag{5}$$

Table 4 presents the results, and Figure 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 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]

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

[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

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 equation (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.

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

The results of our local projections are shown in Figure 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]

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.

[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.

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 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 Figure 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

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

[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.

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 Other Applications

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. 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 Figure 11 we plot daily flows of the swap arrangement

[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.

[47] The smart contract code required to implement the PSM is available online at https://github.com/BellwoodStudios/dss-psm

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]

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

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 equation (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 Figure 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

[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/

[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.

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 Figure 12, we plot daily net mints of WBTC tokens 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 equation (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 equation (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 Figure 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).

[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

[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

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. TerraUSD 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,

[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.

[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.

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 Figure 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 (Figure 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-stabilising 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

[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).

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. 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

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 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

[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.

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.

References

Akram, Q Farooq, Dagfinn Rime, and Lucio Sarno, "Arbitrage in the foreign exchange market: Turning on the microscope," *Journal of International Economics*, 2008, *76* (2), 237–253.

Aldridge, Irene, "ETFs, high-frequency trading, and flash crashes," *The Journal of Portfolio Management*, 2016, *43* (1), 17–28.

Allen, Franklin, Xian Gu, and Julapa Jagtiani, "Fintech, Cryptocurrencies, and CBDC: Financial Structural Transformation in China," *Journal of International Money and Finance*, 2022, p. 102625.

Ante, Lennart, Ingo Fiedler, and Elias Strehle, "The influence of stablecoin issuances on cryptocurrency markets," *Finance Research Letters*, 2020, p. 101867.

Arner, Douglas W, Raphael Auer, and Jon Frost, "Stablecoins: risks, potential and regulation," *Financial Stability Review. Nº 39 (Autumm 2020), p. 95-123*, 2020.

Barthelemy, Jean, Paul Gardin, and Benoît Nguyen, "Stablecoins and the real economy," *Available at SSRN 3973538*, 2021.

Baumöhl, Eduard and Tomas Vyrost, "Stablecoins as a crypto safe haven? Not all of them!," 2020.

Baur, Dirk G and Lai T Hoang, "A Crypto Safe Haven against Bitcoin," *Finance Research Letters*, 2020.

_ **and Thomas Dimpfl**, "The volatility of Bitcoin and its role as a medium of exchange and a store of value," *Empirical Economics*, 2021, *61* (5), 2663–2683.

Berentsen, Aleksander and Fabian Schär, "Stablecoins: The quest for a low-volatility cryptocurrency," 2019.

Bianchi, Daniele, Matteo Iacopini, and Luca Rossini, "Stablecoins and Cryptocurrency Returns: Evidence from Large Bayesian Vars," *Available at SSRN*, 2020.

Borri, Nicola and Kirill Shakhnov, "Cryptomarket discounts," *Available at SSRN 3124394*, 2018.

Brown, David C, Shaun William Davies, and Matthew C Ringgenberg, "ETF arbitrage, non-fundamental demand, and return predictability," *Review of Finance*, 2021, *25* (4), 937–972.

Bullmann, Dirk, Jonas Klemm, and Andrea Pinna, "In search for stability in crypto-assets: Are stablecoins the solution?," *ECB Occasional Paper*, 2019, (230).

Catalini, Christian and Alonso de Gortari, "On the Economic Design of Stablecoins," *Available at SSRN 3899499*, 2021.

Cong, Lin William and Simon Mayer, "The Coming Battle of Digital Currencies," *Available at SSRN 3992815*, 2021.

_ , Ye Li, and Neng Wang, "Token-based platform finance," *Journal of Financial Economics*, 2021.

d'Avernas, Adrien, Vincent Maurin, and Quentin Vandeweyer, "Can Stablecoins be Stable?," *University of Chicago, Becker Friedman Institute for Economics Working Paper*, 2022, (2022-131).

Dell'Erba, Marco, "Stable Cryptocurrencies? Assessing the Case for Stablecoins," *New York University Journal of Legislation and Public Policy, Forthcoming*, 2019.

Eichengreen, Barry, "From Commodity to Fiat and Now to Crypto: What Does History Tell Us?," Technical Report, National Bureau of Economic Research 2019.

_ and Ganesh Viswanath-Natraj, "Stablecoins and Central Bank Digital Currencies: Policy and Regulatory Challenges," *Asian Economic Papers*, 2022, *21* (1), 29–46.

Ferreira, Alex Luiz, Arie Eskenazi Gozluklu, and Joao Mainente, "Central Bank Reserves and Currency Volatility," *Available at SSRN 3409832*, 2019.

Force, ECB et al., "Stablecoins: Implications for monetary policy, financial stability, market infrastructure and payments, and banking supervision in the euro area," Technical Report, European Central Bank 2020.

Foucault, Thierry, Roman Kozhan, and Wing Wah Tham, "Toxic arbitrage," *The Review of Financial Studies*, 2017, *30* (4), 1053–1094.

Fratzscher, Marcel, Oliver Gloede, Lukas Menkhoff, Lucio Sarno, and Tobias Stöhr, "When is foreign exchange intervention effective? Evidence from 33 countries," *American Economic Journal: Macroeconomics*, 2019, *11* (1), 132–56.

Frost, Jon, Hyung Song Shin, and Peter Wierts, "An early stablecoin? The Bank of Amsterdam and the governance of money," 2020.

Gloede, Oliver and Thomas Moser, "Crypto Havens: Are Stablecoins Safe Havens?," *Swiss National Bank Working Paper, presented at SNB-CIF Conference on Cryptoassets and Financial Innovation, 20-21 May 2021, Virtual conference, Swiss National Bank, Zurich, University of Basel, Center for Innovative Finance, Basel*, 2021.

Gorton, Gary B and Jeffery Zhang, "Taming wildcat stablecoins," *Available at SSRN 3888752*, 2021.

_ , Chase P Ross, and Sharon Y Ross, "Making Money," Technical Report, National Bureau of Economic Research 2022.

Griffin, John and Amin Shams, "Is Bitcoin Really Untethered?," *Journal of Finance, Forthcoming*, 2020.

Hoang, Lai T and Dirk G Baur, "How stable are stablecoins?," *Available at SSRN 3519225*, 2020.

_ and _ , "How stable are stablecoins?," *The European Journal of Finance*, 2021, pp. 1–17.

Jordà, Òscar, "Estimation and inference of impulse responses by local projections," *American economic review*, 2005, *95* (1), 161–182.

Kim, Sang Rae, "How the Cryptocurrency Market is Connected to the Financial Market," *Available at SSRN 4106815*, 2022.

Kozhan, Roman and Ganesh Viswanath-Natraj, "Decentralized Stablecoins and Collateral Risk," *WBS Finance Group Research Paper Forthcoming*, 2021.

Kristoufek, Ladislav, "Tethered, or Untethered? On the interplay between stablecoins and major cryptoassets," *Finance Research Letters*, 2021, p. 101991.

Kwon, Yujin, Jihee Kim, Yongdae Kim, and Dawn Song, "The Trilemma of Stablecoin," *Available at SSRN 3917430*, 2021.

Li, Ye and Simon Mayer, "Money Creation in Decentralized Finance: A Dynamic Model of Stablecoin and Crypto Shadow Banking," 2021.

Liao, Gordon Y and John Caramichael, "Stablecoins: Growth Potential and Impact on Banking," 2022.

Makarov, Igor and Antoinette Schoar, "Price discovery in cryptocurrency markets," in "AEA Papers and Proceedings," Vol. 109 2019, pp. 97–99.

_ **and** _ , "Trading and arbitrage in cryptocurrency markets," *Journal of Financial Economics*, 2020, *135* (2), 293–319.

Marshall, Ben R, Nhut H Nguyen, and Nuttawat Visaltanachoti, "ETF arbitrage: Intraday evidence," *Journal of Banking & Finance*, 2013, *37* (9), 3486–3498.

Murakami, David and Ganesh Viswanath-Natraj, "Cryptocurrencies in Emerging Markets: a Stablecoin Solution?," *Available at SSRN 3949012*, 2021.

Pernice, Ingolf Gunnar Anton, "On Stablecoin Price Processes and Arbitrage," in "Financial Cryptography" 2021.

Routledge, Bryan and Ariel Zetlin-Jones, "Currency Stability Using Blockchain Technology," 2018.

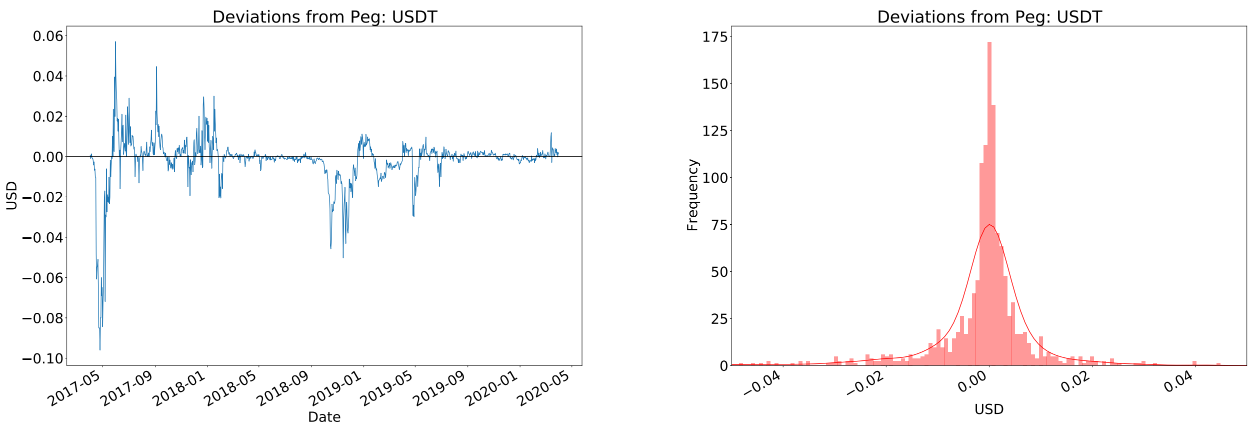
Tetherinc., "Tether: Fiat currencies on the Bitcoin blockchain," 2016.

Wang, Gang-Jin, Xin yu Ma, and Hao yu Wu, "Are stablecoins truly diversifiers, hedges, or safe havens against traditional cryptocurrencies as their name suggests?," *Research in International Business and Finance*, 2020, p. 101225.

Wei, Wang Chun, "The impact of Tether grants on Bitcoin," *Economics Letters*, 2018, *171*, 19–22.

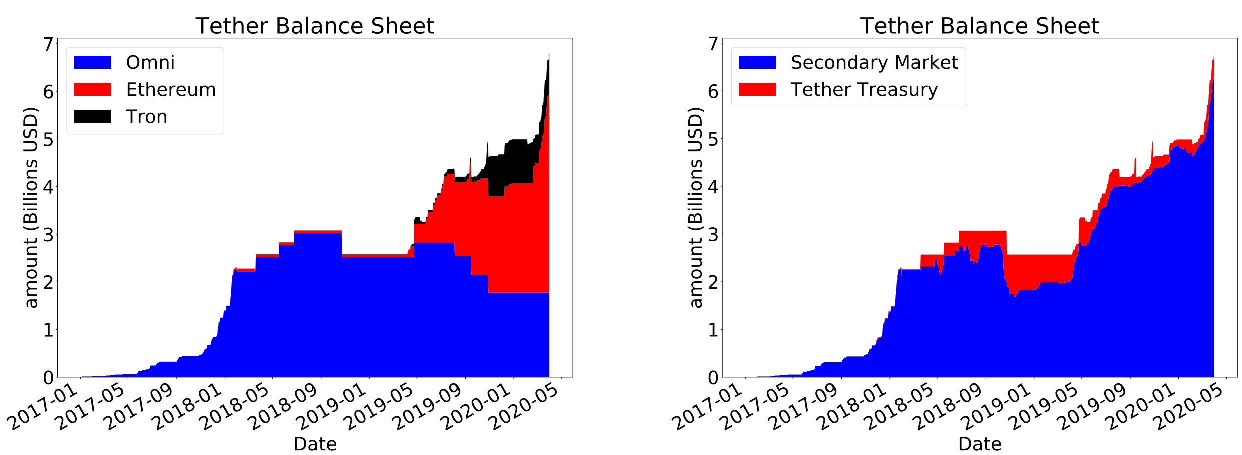
Figures

Figure 1: Tether/USD Deviations from Peg and Histogram of Deviations



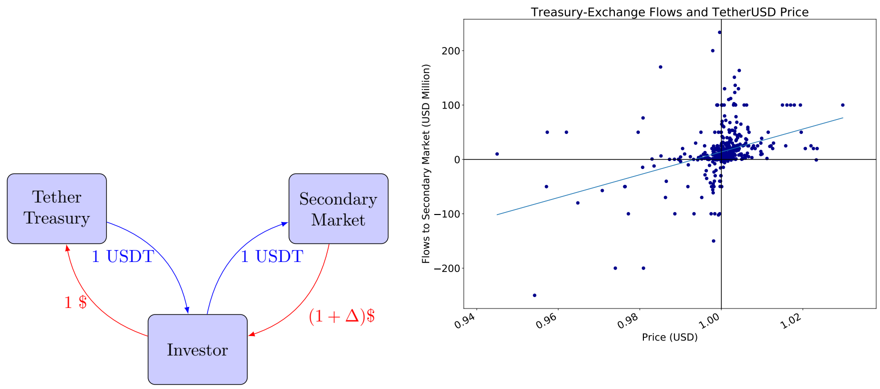
Note: Figure plots the deviations of the Tether/USD price from parity (left panel). A positive deviation indicates Tether/USD trades at a premium. The right panel is a histogram of deviations of the Tether/USD peg. Data from Coinapi. Sample is April 1st, 2017 to March 31st, 2020.

Figure 2: left panel: Tether/USD Balance Sheet – By Blockchain, right panel: Tether/USD Balance Sheet – Tether held by the Treasury and Other Accounts



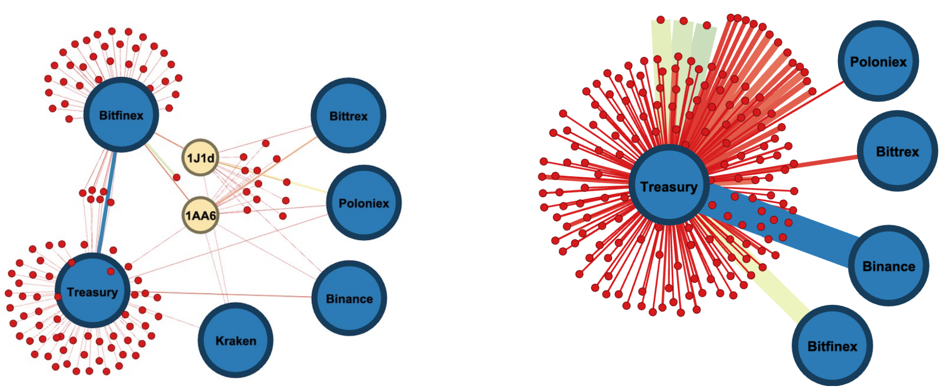
Note: The figure plots total Tether supply, divided by blockchain (left), and divided into holdings in the secondary market (by investors and exchanges) and holdings by the Tether Treasury as reserves (right). Flows of Tether to the secondary market, measured using transaction data of the Tether Treasury on the Omni, Ethereum, and Tron blockchains respectively.

Figure 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



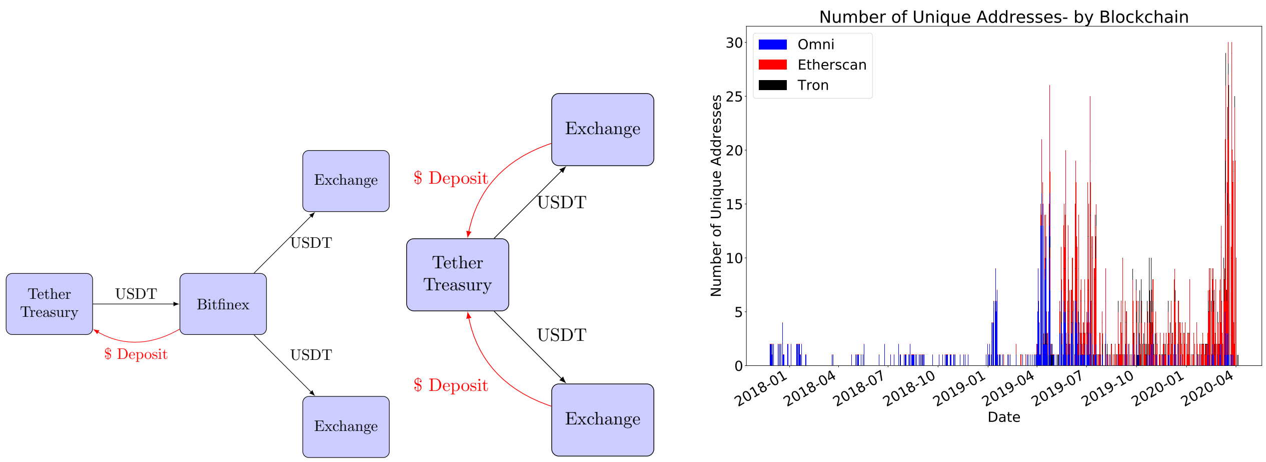
Note: Left: Schematic illustrates an arbitrage trade where the secondary-market price of Tether trades at a premium. An investor makes a dollar deposit with the Tether Treasury, obtains a Tether token (at an exchange rate of 1 Tether per 1 USD), and then sells Tether tokens in the secondary market for 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.

Figure 4: Distribution of Tether on the Omni and Ethereum Blockchains



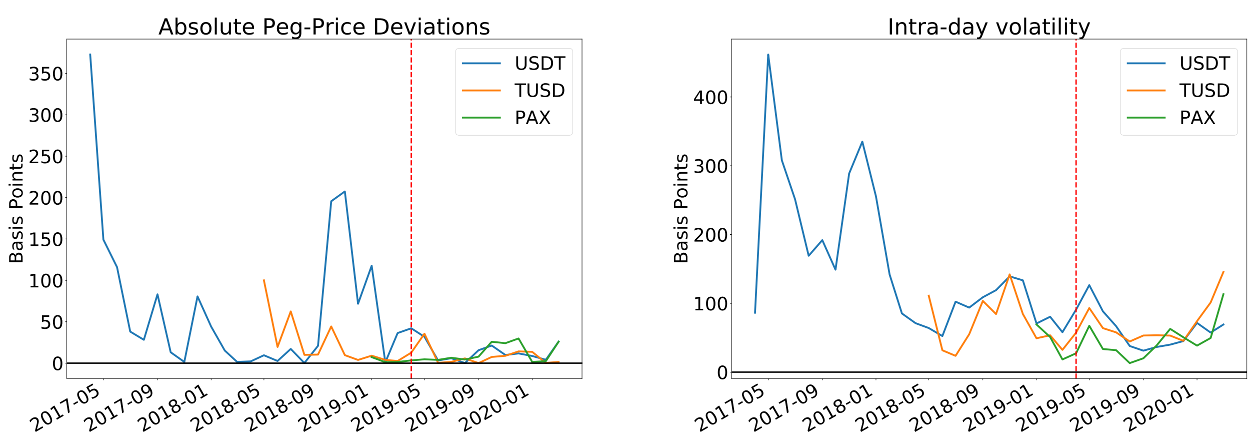
Note: Figure presents the network of transactions from the Tether Treasury to all wallets on the Omni blockchain recorded from October 8th, 2014 through to March 31st, 2020. Transaction history is obtained from https://omniexplorer.info/ for the Treasury wallet address "1NTMakcgVwQpMdGxRQnFKyb3G1FAJysSfz". 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 "0x5754284f345afc66a98fbb0a0afe71e0f007b949". 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/.

Figure 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



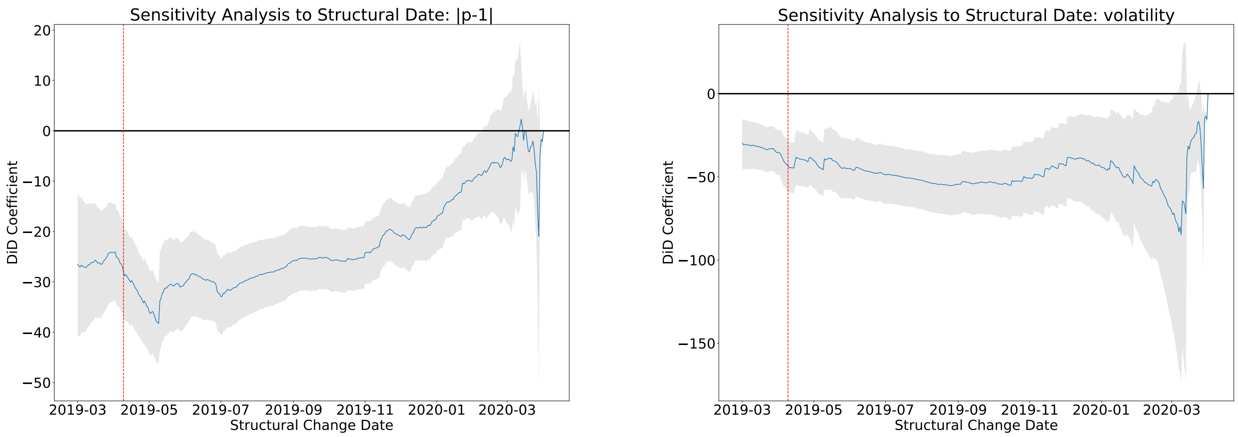
Note: Left figure illustrates the creation of Tether on the Omni and Ethereum blockchains. On the Omni blockchain, Bitfinex deposits dollars into the Tether Treasury. The Tether Treasury then issues Tether tokens at parity (1:1 exchange rate). The newly created tokens are then distributed to other investors 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.

Figure 6: left panel: Absolute peg-price deviations; right panel: intra-day volatility



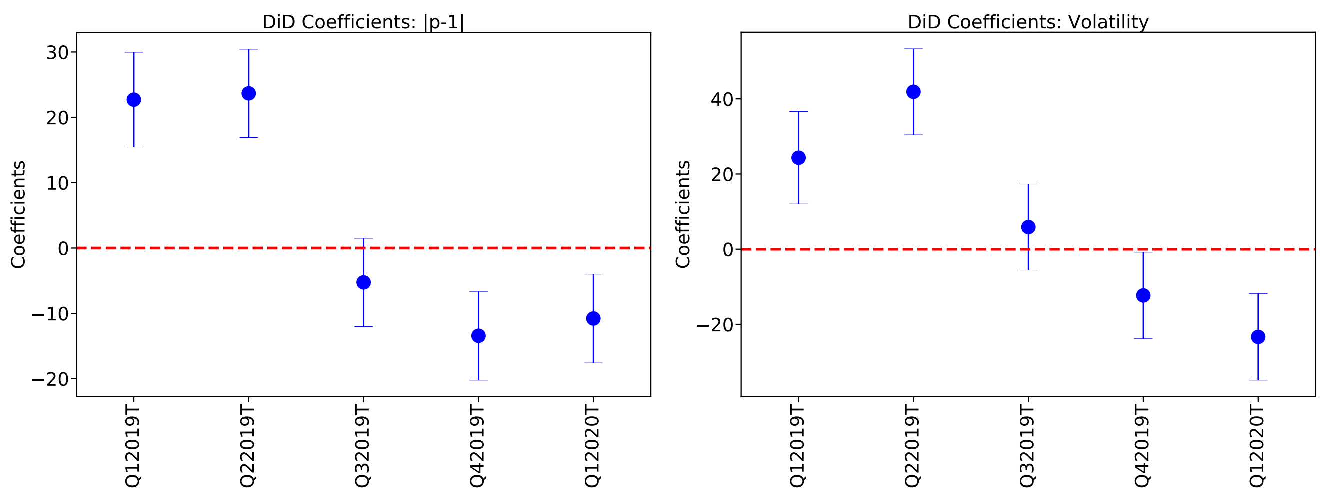
Note: This figure plots average monthly stablecoin prices and intra-day volatility for the treatment (USDT) and the control group stablecoins. The treatment stablecoin is Tether (USDT). The control stablecoins are TrueUSD (TUSD) and Paxos (PAX). The red dotted line indicates the structural change date 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.

Figure 7: Sensitivity Analysis of Difference-in-Difference Coefficients to a Change in the Structural Date



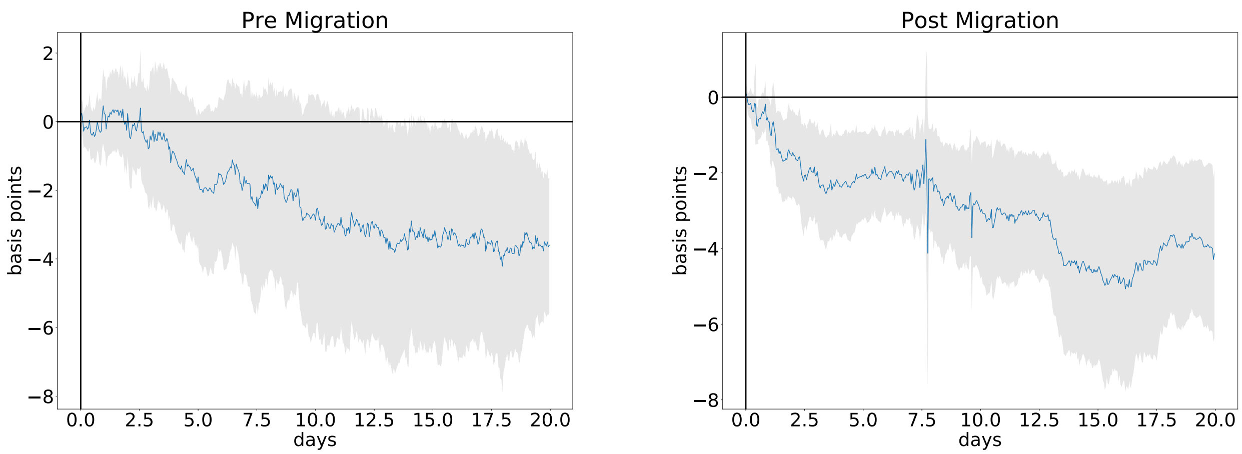
Note: This figure shows the difference-in-difference coefficient δ of the following design: $|p_t - 1| = \beta_t Post_t + \delta_t Post_t \times T_t$ by changing the structural change date $Post_t$. The outcome variable measures the absolute level of peg deviations on the left panel, and intra-day volatility 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.

Figure 8: Difference-in-difference coefficients for dynamic panel specification



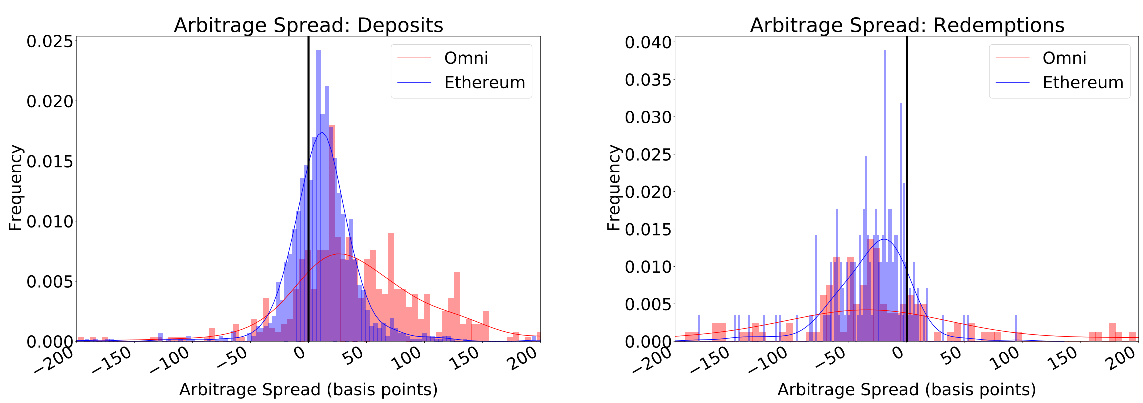
Note: Figure presents coefficients for a dynamic difference-in-difference specification with the absolute level of peg-price deviations (left) and intra-day volatility (right). Coefficients measure the effect of the treatment interacted with each quarter. Price data for USDT consolidates trade data from 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.

Figure 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



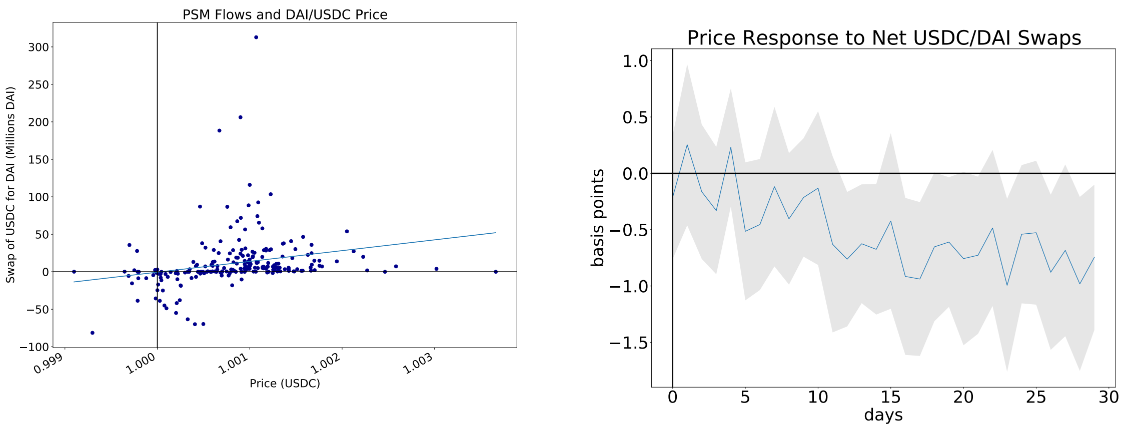
Note: Figure documents the effect of a 1 standard-deviation shock to net secondary-market flows on the price of Tether/USD. Left and right panels are for different sample periods based on the introduction of Tether to the Ethereum blockchain. Data for secondary-market flows are from Omniexplorer and 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.

Figure 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).



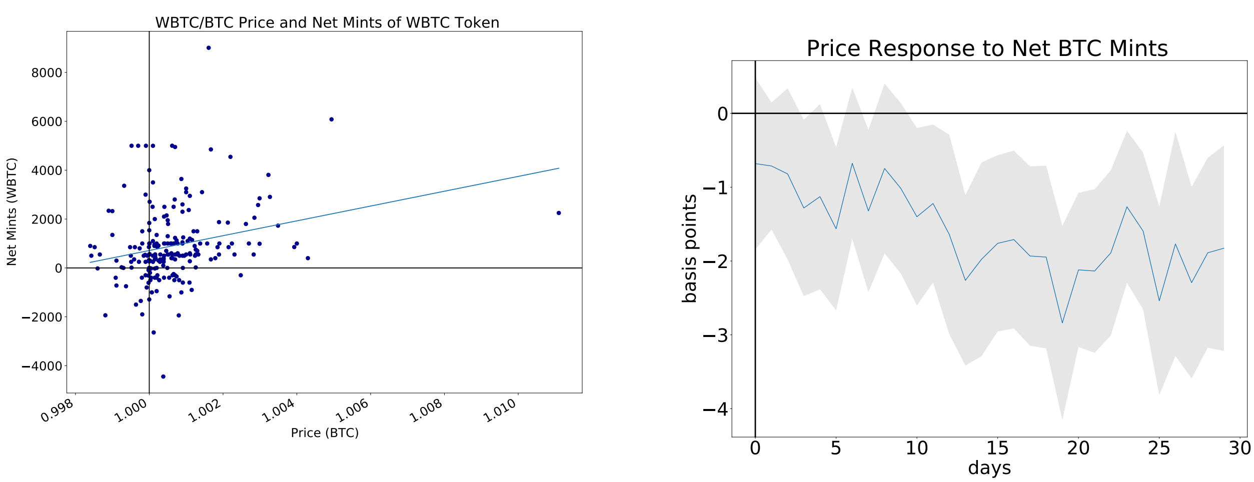
Note: Figure plots histograms of arbitrage spread of Tether deposits (left) and Tether redemptions (right) on the Omni and Ethereum blockchain. Spread, measured in basis points, is the difference between the secondary-market price of Tether and the pegged rate of 1. Spread, measured in basis points, 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.

Figure 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)



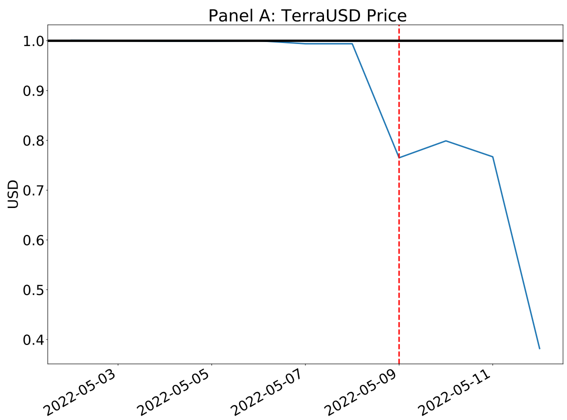
Note: left panel: Schematic illustrates net swaps of USDC against DAI using the PSM against the DAI/USDC price. right panel: Figure documents the effect of a 1 standard-deviation shock to a net swap of USDC for DAI on the DAI/USDC price. Price data are from Coinapi, using coinbase for the DAI/USDC pair. 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.

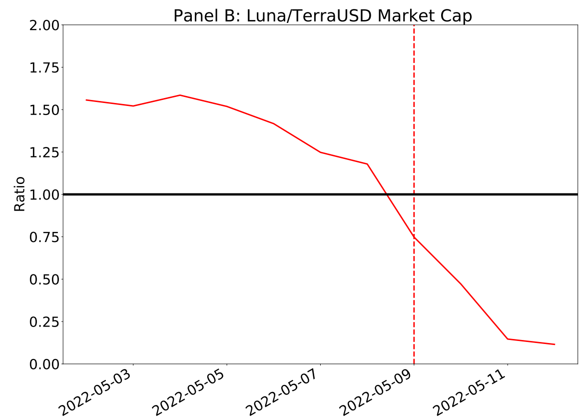
Figure 12: Net mints of WBTC token against the WBTC/BTC Price (left). Response of WBTC/BTC price to 1 standard deviation shock in WBTC net mints (right)



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.

Figure 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.

Tables

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	$6,400M	$40,000M	-20.5	128.9	-960	571	6.4
01/20-03/20	USDC	$705M	$692M	6.9	25.0	-21	100	0.8
01/19-03/20	PAX	$245M	$911M	7.8	29.6	-100	200	0.5
10/10-03/20	BUSD	$187M	$49M	1.4	6.1	-10	50	0.3
06/18-03/20	TUSD	$136M	$466M	6.7	59.2	-170	990	0.4
04/18-03/20	DAI	$79M	$12M	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.

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.

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
	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	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.

Table 4: Difference-in-Difference Design: Dynamic Effects

	I	II	III	IV
	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	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.

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.

Online Appendix to

"What Keeps Stablecoins Stable?"

(Not for publication)

We provide a roadmap of each section of our Appendix.

1. Appendix A provides a summary of the datasets used in the analysis. This includes a description of Tether issuance data used to construct our flow measure, as well as price and transaction data.

2. Appendix B provides a summary of transparency and governance measures undertaken by stablecoins.

3. Appendix C provides statistics on Tether issuance on the Omni and Ethereum blockchains, including key wallets and concentration of flows.

4. Appendix D present results of our DiD specification over a longer sample to control for the Covid pandemic.

5. Appendix E presents an IV estimation to determine how much of the increase in peg efficiency is attributed to decentralized arbitrage.

6. Appendix F presents additional data for other major dollar-backed stablecoins.

7. Appendix G provides empirical evidence of fundamentals of stablecoin premiums and discounts.

A Data

We have four sources, each supporting a different aspect of our analysis.

1. **Coinapi**: Online subscription with access to open, high, low, close, and volume (OHLCV) trade data and order-book data from multiple crypto exchanges.

2. **Omniexplorer and Etherscan**: Blockchain explorers that contain transaction data of individual wallets, used to obtain new issuance/redemptions of stablecoin tokens to compute flows of these tokens to the secondary market.

3. **Cryptocompare**: Price and trading volume data for currencies (based on a representative list of crypto exchanges).

4. **Coinmetrics**: Provides fundamentals data on the network value, computing power of cryptocurrency mining, and number of unique addresses.

Coinapi

Coinapi offers a monthly subscription with access to their data api, which gives historical cryptocurrency OHLCV, trade, and order-book data. We outline in Table A1 the specific trading pairs, coin symbols, and types of data that we employ. To use the api, we followed https://github.com/coinapi/coinapi-sdk, which gives sample code for querying the api.[66] The trade data are used to construct order-flow data, as it has a boolean "taker_side_sell" variable that is a seller-initiated transaction if True, and buyer-initiated if False. Orderbook data for exchanges are also provided, useful for bid and ask prices. To construct bid-ask spreads, we take the highest bid and the lowest ask out of a set of 20 quotes for a specific time period, which gives us a lower bound for the effective bid-ask spread at any given point in time.

[66] Modifications were made to customize results; api requests are limited to 100,000 data points per day.

Table A1: Coinapi Data

Data Type	Coin Symbol	Exchange	Sample Period
OHLCV, Trade and Order-Book Data	USDT_USD	Kraken	04/17-03/20
OHLCV, Trade and Order-Book Data	USDT_USD	Bitfinex	12/18-03/20
OHLCV, Trade and Order-Book Data	USDT_USD	Bittrex	05/18-03/20
OHLCV	USDC_USD	Kraken	01/20-03/20
OHLCV	PAX_USD	Bittrex	01/19-03/20
OHLCV	BUSD_USD	Binance	10/19-03/20
OHLCV	TUSD_USD	Bittrex	06/18-03/20
OHLCV	DAI_USD	Bitfinex	04/18-03/20

Where multiple cryptocurrency exchanges offer the same data, we choose 1 of 10 exchanges that do not have fraudulent trading activity according report filed by the SEC.[67] The report tests exchanges for fraudulent activities (e.g., suspicious variability in bid-ask spreads, systematic patterns in histograms of transaction size) and finds that the exchanges listed in Table A2 do not have the telltale patterns in trading volume or spreads. We note that of the ten exchanges that do not have fraudulent trading activity, two do not offer an onramp for trading national currencies, Binance and Poloniex. Similarly, two platforms, Itbit and Bitflyer, only accepted national currencies at the time the SEC report was written.

Table A2: Trusted Exchanges According to SEC Report

Exchange	National Currencies	Stablecoins
Binance	N	Y
Bitfinex	Y	Y
Bitstamp	Y	Y
Bittrex	Y	Y
Bitflyer	Y	N
Coinbase	Y	Y
Gemini	Y	Y
Itbit	Y	N
Kraken	Y	Y
Poloniex	N	Y

[67] See https://www.sec.gov/comments/sr-nysearca-2019-01/srnysearca201901-5164833-183434.pdf.

Omniexplorer and Etherscan

We use this dataset to construct net flows from the stablecoin issuer to the secondary market. The addresses of the issuers are listed in Table A4. We follow Wei (2018) in obtaining transactions of Tether grants (creation of new tokens) and revokes (redemptions) from the Omniexplorer api.[68] Etherscan is an explorer of all transactions recorded on the Ethereum blockchain, available at `https://etherscan.io/`. This includes transactions for Tether and other national-currency-backed coins. The history of token grants and revokes is exportable to a data-readable format.

For Etherscan, we first need the contract address of each coin, which one can find by searching the ticker ID of the coin (USDT, USDC, PAX and TUSD) in the search portal on `https://etherscan.io/`. The contract addresses are listed in Table A3. To construct stablecoin flows from the Treasury to the secondary market, we use the Treasury addresses of four coins listed in Table A4. Using the following data, we measure net flows in and out of the Treasury wallet, where we net "send" transfers of the stablecoin to the secondary market from "receive" transfers which are stablecoin redemptions.[69] Subtracting net flows into Treasury from the net of grants and revokes of tokens gives a measure of total flows to the secondary market.

Table A3: Stablecoin Contract Addresses

Coin	Blockchain	Contract Address
USDT	Etherscan	0xdac17f958d2ee523a2206206994597c13d831ec7
USDC	Etherscan	0xa0b86991c6218b36c1d19d4a2e9eb0ce3606eb48
PAX	Etherscan	0x8e870d67f660d95d5be530380d0ec0bd388289e1
TUSD	Etherscan	0x0000000000085d4780B73119b644AE5ecd22b376

[68]Please refer to `https://api.omniexplorer.info/` on how to obtain transaction histories.

[69]New stablecoin tokens are created and destroyed through "grants" and "revokes". The address for creating grants and revokes of tokens is *0x0000000000000000000000000000000000000000* for USDC, PAX and TUSD. The address for grants and revokes of Tether tokens on Etherscan is *0xc6cde7c39eb2f0f0095f41570af89efc2c1ea828*, and on the Omni protocol there are two grant/revoke addresses, *3MbYQMMmSkC3AgWkj9FMo5LsPTW1zBTwXL* and *32TLn1WLcu8LtfvweLzYUYU6ubc2YV9eZs*. As we do not have a Treasury address for TUSD, all transactions can be derived from the grant/revoke address. In our analysis in Appendix F, we use coinmetrics which has a daily measure of total TUSD tokens in circulation.

Table A4: Stablecoin Treasury Wallet Addresses

Coin	Blockchain	Wallet Address
USDT	Omni Explorer	1NTMakcgVwQpMdGxRQnFKyb3G1FAJysSfz
USDT	Etherscan	0x5754284f345afc66a98fbb0a0afe71e0f007b949
USDC	Etherscan	0x55fe002aeff02f77364de339a1292923a15844b8
PAX	Etherscan	0x5195427ca88df768c298721da791b93ad11eca65
TUSD	Etherscan	N/A

Cryptocompare

Cryptocompare provides public access to price and volume data based on volume-weighted averages of price quotes and trades from 150 cryptocurrency exchanges, available via their api https://min-api.cryptocompare.com/.[70] We use this resource to measure total traded volume in the Tether/USD and BTC/USD pairs. We also use cryptcompare to determine the daily closing price of non-stable cryptocurrencies BTC, ETH, XRP, BCH, and LTC.

B Transparency and Accountability Measures

Tether publishes its balance sheet daily,[71] which provides a breakdown of the value of its assets (dollar deposits) and liabilities (Tether in circulation on blockchain platforms). While Tether liabilities are accounted for based on the record of transactions on the blockchain, there is a need to audit issuers to verify that the holdings of dollar deposits are secure. For full solvency, the dollar value of assets held in the issuer's accounts must at least equal the dollar value of its liabilities. Audit reports for these top coins assert that they are sufficiently collateralized.

Tether Inc. acknowledges in its white paper that there are potential problems with the security of its dollar deposits. It lists the following five points (Tetherinc., 2016):

1. *We (Tether Inc.) could go bankrupt*
2. *Our bank could go insolvent*
3. *Our bank could freeze or confiscate the funds*
4. *We could abscond with the reserve funds*

[70] For more detail on how quotes and traded volume are calculated, see: https://www.cryptocompare.com/media/27010937/cccagg_methodology_2018-02-26.pdf.

[71] See https://wallet.tether.to/transparencyformoredetails.

5. *Recentralization of risk to a single point of failure*

Of the following points, Tether claims dollar deposits are still redeemable if Tether Inc. goes bankrupt or becomes insolvent. For the third and fourth point, they state that their bank is familiar with holding cryptocurrency deposits, and that absconding with funds is unlikely due to its public charter. The fifth point is the biggest issue with Tether: While Tether in circulation uses a decentralized system of exchange by being on the blockchain, all dollar deposits are held in a centralized issuer. There is settlement risk if the dollar deposits are vulnerable to attack from an outside party. One way for Tether to mitigate the central point of failure is by having sufficient reserves in its balance sheet. This point is tackled differently by newer stablecoins, e.g., Paxos, which has FDIC-insured deposits, and USDC tokens via decentralization of the issuer with multiple licenses to create tokens, and finally by protecting counterparty risk through the use of escrow accounts.

The main transparency measure undertaken by Tether is the publication of its daily balance sheet. As stated in the Tether White Paper (Tetherinc., 2016), Tether follows a "proof of reserves" process in which they account for all liabilities (Tether in circulation) on the blockchain. This includes all platforms Tether currently trades on, the three main platforms being Omni explorer, Ethereum, and Tron according to its balance sheet in April, 2020. Every Tether in circulation is backed, in principle, by a dollar deposit. Tether Inc. releases a daily balance sheet reporting their total dollar deposits. For example, on April 2nd, 2020, their balance sheet, according to `https://wallet.tether.to/transparency`, says the Total Assets, which is the bank deposits, is equal to $6,480,678,611.74, and total Tether in circulation is given by $6,349,160,932.47. The excess of assets over liabilities is $131,517,679.27. As a percentage of total assets, that is approximately 2%. We note that this matches very roughly what a risk-free rate would yield annually on fixed-income instruments.[72]

Audit Reports

Similar to Tether, we have monthly auditing reports for TrueUSD and USDC that are managed by accounting firms Cohen & Co and Grant Thornton respectively. For example, a typical audit report on TrueUSD, from the December 2019 statement, states the following: *"The issued and collateralized TrueUSD...do not exceed the balance of the escrow accounts reported above. The supply of TUSD tokens can be reconciled to transactions within the escrow accounts..."*. Similarly, a statement on USDC's accounting firm Grant Thornton, December 2019 statement, asserts the following: *"USD Coin (USDC) tokens issued and outstanding = $519,628,995 USDC US Dollars*

[72]While not explicit about their interest-bearing assets, the following article documents that Tether does earn interest on its dollar deposits: `https://cryptobriefing.com/tether-interest-stablecoins/`.

held in custody accounts = $520,537,729...the issued and outstanding USDC tokens do not exceed the balance of the US Dollars held in custody accounts." Statements confirm that total assets exceed total liabilities and that the stablecoins are at least 100% collateralized.

C Tether Treasury Flows on Omni and Ethereum

In this section, we document in more detail specific wallet addresses that transact with the Tether Treasury on the Omni and Ethereum blockchains. Here is a summary of our analysis.

1. On the Omni blockchain, the main address transacting with the Tether Treasury is the Bitfinex exchange. Nearly all Tether (up to 90%) in circulation was channelled from the Treasury to Bitfinex in 2017 and 2018.
2. The Ethereum blockchain, in contrast, is much less concentrated, with a total number of 172 unique addresses transacting with the Treasury versus 71 on the Omni blockchain.
3. On the Ethereum blockchain, we find a shift in net flows from the Treasury toward other exchanges. For example, the Binance exchange is the largest recipient of net flows from the Treasury on the Ethereum blockchain in the sample (January 2019-March 2020).

Treasury Transactions on Omni Blockchain

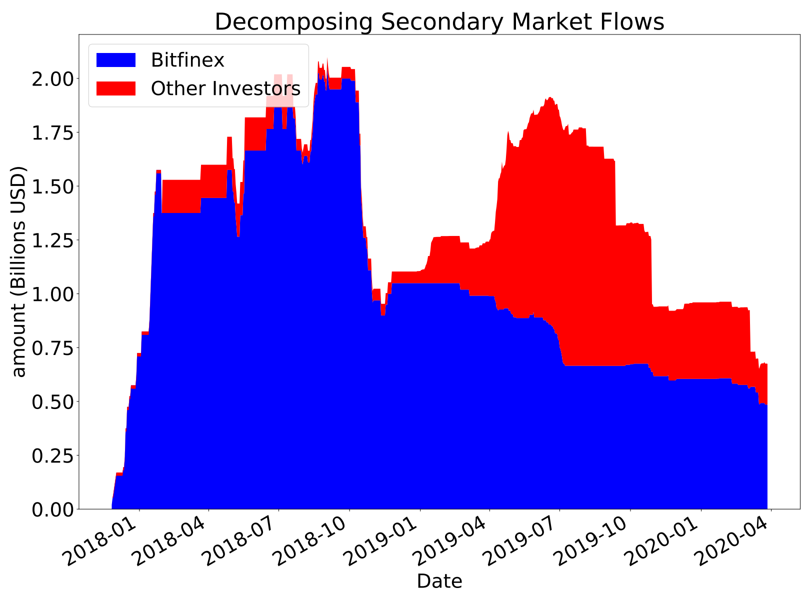
We have the entire history of Tether Treasury transactions on the Omni layer. Using the columns of "reference address" and "sending address" (where the sending address is transferring Tether tokens to the "reference address") we can construct a measure of net flows from the Treasury to each individual address. This provides a measure of bilateral flows from the Treasury to each investor.[73]

Over the entire sample (November 2017-March 2020), we record total net flows of Tether to each wallet address. We observe 71 unique addresses transacting with the Tether Treasury, Tables A5 and A6 record the largest positive and negative net flows respectively on the Omni blockchain. The key address transacting with the Omni layer is the Bitfinex exchange. While it only accounts for 26% of total positive net flows during the entire sample, prior to 2019 Bitfinex was the dominant address. For example, if we restrict our sample to the end of 2018, we observe only 11 unique addresses transacting with the Treasury, and Bitfinex accounted for 83% of outgoing flows from the Treasury during that period. In Figure A1 we plot the cumulative bilateral flows with respect

[73] The flows we report do not yield the final distribution of Tether holdings by each investor. For example, an investor that transacts with the Treasury may then distribute all of its tokens to other exchanges. Our focus on investor transactions with the Treasury is to identify the extent to which direct arbitrage with the Treasury matters for peg efficiency and stability.

to Bitfinex, and classify all other addresses as "Other Investors." We find that nearly all outgoing flows from the Treasury were distributed via Bitfinex until 2019. This is indicative of Tether distribution that begins with dollar deposits first deposited with Bitfinex, which then proceeds to distribute tokens to other exchanges for trading in the secondary market.

Figure A1: Decomposing Flows to the Secondary Market via Bitfinex on the Omni Blockchain.



Note: Decomposes net flows to the secondary market from the Tether Treasury to private wallets on the Omni blockchain. Sample is November 2017 through March 31st, 2020. Up to the end of 2018, nearly all flows to the secondary market are to the exchange Bitfinex. In 2019 we see a shift in composition toward non-Bitfinex wallet addresses on the Omni Blockchain.

Table A5: Omni Explorer: Breakdown of Treasury Net Flows

Address	Net Flow (Tether)	Share	Cumulative Share	Identity
1KYiKJEfdJtap9QX2v9BXJMpz2SfU4pgZw	4.85E+08	0.260	0.260	Bitfinex
3LCx3zGC9wsaF5iLDg8do6TdwfJ9yCcwMn	2.11E+08	0.113	0.374	
1GjgKbj69hDB7YPQF9KwPEy274jLzBKVLh	2.00E+08	0.107	0.481	
16pj8cny6Doga428ZNKuz5eXBikLYf7YD1	1.08E+08	0.058	0.539	
16hvRK9Y7dUhzehy3nMHRfVGPq3vqKR33K	8.02E+07	0.043	0.582	
1GrZG61AoHVn8UZcHiX2gJgAkajRaTo1C3	7.07E+07	0.038	0.620	
1Kqn34iJnzTamYRV2ie2qsD1WEAy6BBhvF	6.79E+07	0.037	0.657	
3D2GQZ741GUiJebeTG2pyWQzHtuK6R9VS9	5.49E+07	0.030	0.686	
1KiJkugknjgW6AHXNgVQgNuo3b5DqsVFmk	5.21E+07	0.028	0.714	
1C9J4C8JwB4q7L97Uyqvo12Wo9xFoZ5aAC	4.70E+07	0.025	0.740	

Note: Table reports top-10 positive net flows of Tether to recipients. A positive net flow is defined as a net flow of Tether to the recipient address. Shares are calculated based on positive net flows only. Dataset records all trades between the Tether Treasury and private wallet addresses on Omniexplorer. We omit Tether grants (issuer) addresses in the list of recipients. Sample from November 2017 to March 31st, 2020. Identity of recipients is noted based on publicly available information on Omniexplorer and the Tether rich list, available at https://wallet.tether.to/richlist .

Table A6: Omni Explorer: Breakdown of Treasury Negative Net Flows

Address	Net Flow (Tether)	Share	Cumulative Share	Identity
1FoWyxwPXuj4C6abqwhjDWdz6D4PZgYRjA	-1.00E+09	7.36E-01	0.736	Binance
13TMLJdKgCnQLiv4Bx65DqpKvgnC2pdLLC	-1.34E+08	9.83E-02	0.834	
1RUBt5inB17W7kjg5ceRhLQa9GgrRtuXt	-1.00E+08	7.35E-02	0.908	
1DUb2YYbQA1jjaNYzVXLZ7ZioEhLXtbUru	-6.98E+07	5.13E-02	0.959	
1Po1oWkD2LmodfkBYiAktwh76vkF93LKnh	-3.70E+07	2.72E-02	0.986	Poloniex
15bQJVbQPsScK4mkjR7Pk2xt6guT2VTLEJ	-1.00E+07	7.35E-03	0.994	
1PktPwDM1h85GW4ab7Xgv83TALXJ71rXLt	-5.00E+06	3.67E-03	0.997	
3GyeFJmQynJWd8DeACm4cdEnZcckAtrfcN	-2.20E+06	1.62E-03	0.999	Kraken
33DunQKkUsvLr4GBTAtAj3KKYueyxeCYLR	-9.60E+05	7.05E-04	0.9995	
1zgmvYi5x1wy3hUh7AjKgpcVgpA8Lj9FA	-4.00E+05	2.94E-04	0.9998	

Note: Table reports top-10 negative net flows of Tether to recipients. Shares are calculated based on negative net flows only. Dataset records all trades between the Tether Treasury and private wallet addresses on Omniexplorer. We omit Tether grants (issuer) addresses in list of recipients. Sample from November 2017 to March 31st, 2020. Identity of recipients is noted based on publicly available information on Omniexplorer and the Tether rich list, available at https://wallet.tether.to/richlist.

Chain Swaps

We note there are some addresses that have net negative flows of Tether on the Omni blockchain, i.e., Tether redemptions. The largest negative net flow recorded is with the Binance exchange, with a total of approximately $1 billion worth of Tether redemptions. Many of the transactions between the Binance exchange and the Tether Treasury on Omni explorer can be explained as chain swaps.

This is a special type of transaction that moves a cryptocurrency from one blockchain to another.[74] In this case, many of the redemptions we see on the Omni blockchain are actually chain swaps; the Binance exchange is effectively transferring its Tether tokens to the Ethereum blockchain.[75] The two legs of the chain swap are:

1. On the Omni blockchain, Binance will redeem all Tether tokens, and Tether will burn these tokens, reducing the Tether supply.

2. The redemptions of Tether are directly offset by the Tether Treasury on the Ethereum blockchain sending tokens to Binance's address on the Ethereum blockchain.

The chain swap is neutral with respect to Tether supply. We identify the following chain-swap events based on public announcements by Tether, and record them in Table A7.

Table A7: Chain Swaps of Tether from the Omni to the Ethereum Blockchain

Exchange	Date	Amount (million Tether)	Blockchain (Redemptions)	Blockchain (Creation)
Bittrex	August 5th, 2019	275	Omni	Ethereum
Binance	September 12th, 2019	300	Omni	Ethereum
Binance	October 29th, 2019	300	Omni	Ethereum
Binance	December 9th, 2019	200	Omni	Ethereum
Binance	February 20th, 2020	300	Tron	Ethereum
Binance	March 4th, 2020	200	Omni	Ethereum

Note: Table records all chain swaps from the Omni to the Ethereum blockchain. Public announcements are from Tether's tweets page https://twitter.com/Tether_to/. Sample from November 2017 to March 31st, 2020. Blockchain redemptions refers to the burning of Tether tokens, and represents a flow of Tether from the exchange to the Tether Treasury. Blockchain (creation) refers to an outgoing flow of Tether from the Treasury to the exchange on the new blockchain.

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

[75] Motivation for chain swaps is driven by rebalancing of Tether across blockchains based on client demands. For example, if there is a larger network of clients on the Ethereum blockchain, cryptocurrency exchanges have an incentive to chain swap Tether from Omni to Ethereum in order to meet client demands on Ethereum.

Ethereum Blockchain

Trades on the Ethereum blockchain are recorded on Etherscan, a block explorer and analytics platform for Ethereum. The block explorer data is of a similar format to Omni, with the "reference address" and "sending address" named "To" and "From" respectively. We aggregate net bilateral flows from the Treasury to each investor in our sample on Etherscan, which dates from January 2019 through March 31st, 2020. We find 172 unique addresses transacting with the Tether Treasury on Etherscan during our sample from January 2019 to March 31st, 2020. Based on Table A8, the largest positive cumulative flow to a single address is identified as belonging to the Binance exchange. The top-10 addresses account for up to 60% of the total positive net flows on the Ethereum blockchain. This drives home our point that on the Ethereum blockchain a larger set of investors are accessing the Treasury directly. In contrast, Bitfinex, which had a monopoly on distribution on the Omni layer, has negative flows with respect to the Tether Treasury. For two identified Bitfinex addresses, we observe negative net flows during our sample period, suggesting Bitfinex is burning tokens on the Ethereum network (Table A9). In our dataset, a large number of users transacting with the Treasury remain "unnamed" and the addresses therefore unidentified. A possible concern with our analysis is that the same decision-maker may hold multiple wallet addresses. This would violate our interpretation of a one-to-one mapping from unique addresses to unique investors transacting with the Treasury. But the one-to-one interpretation is not necessary for our analysis. Rather, what we have shown is that access to the Treasury was indeed democratized on the Ethereum blockchain, with multiple exchanges being able to deposit dollars directly with the Treasury and in fact doing so. As we discuss in the paper, reasons for Tether having migrated to the Ethereum blockchain and increasing access to arbitrage include: (i) efficiency in deposit/withdrawal process, (ii) arbitrage that is higher frequency, and (iii) increased network effects, with a larger client base and more tokens using the Ethereum blockchain.

Table A8: Ethereum Blockchain: Breakdown of Treasury Positive Net Flows

Address	Net Flow (Tether)	Share	Cumulative Share	Identity
0x3f5ce5fbfe3e9af3971dd833d26ba9b5c936f0be	8.00E+08	0.161	0.161	Binance
0xf44e17140b4c32ef1e9fab15cbcb14074bd832ee	5.00E+08	0.100	0.261	
0x0c7719f1d7ed41271cbba92ec153afa6610228f8	4.73E+08	0.095	0.356	
0x8bb00060531339d1bb24b804c2f1dd5ea84f6857	4.50E+08	0.090	0.447	
0xb1fa690155821bf9191d609593b556048aca517c	1.58E+08	0.032	0.478	
0xf2103b01cd7957f3a9d9726bbb74c0ccd3f355d3	1.55E+08	0.031	0.509	
0xeeb832aa50517d87a58926437b1a3fcfbdae8f6c	1.46E+08	0.029	0.539	
0xe0507a0e9fa4885a9c470567a342281627cdc7be	1.40E+08	0.028	0.567	
0x2db8a54c3d3b16146efaf7b9a776d94e259c8d80	1.37E+08	0.028	0.594	
0x3bfc9abd438306bb2830ae3fac0ad10348a2242c	1.32E+08	0.027	0.621	

Note: Table reports top-10 positive net flows of Tether to recipients. Data include all trades between the Tether Treasury and private investors. We omit Tether grants (issuer) addresses in the list of recipients. Sample from January 2019 to March 31st, 2020. Identity of recipients is provided where possible based on publicly available information in the Etherscan database.

Table A9: Ethereum Blockchain: Breakdown of Treasury Negative Net Flows

Address	Net Flow (Tether)	Share	Cumulative Share	Identity
0x742d35cc6634c0532925a3b844bc454e4438f44e	-3.84E+08	0.501	0.501	Bitfinex 2
0x876eabf441b2ee5b5b0554fd502a8e0600950cfa	-3.03E+08	0.396	0.898	Bitfinex 3
0xa910f92acdaf488fa6ef02174fb86208ad7722ba	-6.85E+07	0.089	0.987	Poloniex
0x0eebbb51cdee449fcfa9ed497c028a6f6080d962	-6.94E+06	0.009	0.996	
0x955cc527a36f125f367078db8b064f1b60df549f	-1.56E+06	0.002	0.998	
0xf9b4b3ad5ae1325579660959a39be343c4135027	-7.44E+05	0.001	0.999	
0xffec0067f5a79cff07527f63d83dd5462ccf8ba4	-5.00E+05	0.001	1.000	Nexo

Note: Table reports top-10 negative net flows of Tether to recipients. Data include all trades between the Tether Treasury and private investors. We omit Tether grants (issuer) addresses in list of recipients. Sample from January 2019 to March 31st, 2020. Identity of recipients is provided where possible based on publicly available information in the Etherscan database.

D DiD specification: Controlling for Covid pandemic

In this section we show our DiD results are robust to a longer sample that includes the Covid pandemic. Our sample is now extended to December 31st, 2021.[76] Using this longer sample, we repeat the DiD specification in equation (4). The coefficient δ measures the net impact of the structural change on Tether net of any trends observed in the control group. The results are summarized in Table A10. Our results are robust to the longer sample. The results of the balanced panel are in columns (V) and (VI). We still find a statistically significant difference-in-difference coefficient of -33.9 basis points for peg-price deviations and -35.1 basis-points for intra-day volatility. In columns (VII) and (VIII), we control for the Covid sample with $postQ12020$, a dummy variable that takes a value of 1 for April 1st, 2020 to December 31st, 2021. Controlling for the pandemic, our DiD coefficients remain significant, with a coefficient of -28.6 basis points for peg-price deviations and -23.6 basis points for intra-day volatility. A fraction of the efficiency gains are absorbed by the interaction of postQ12020 with treatment. During the postQ12020 there is a relative efficiency gain of -8.1 basis points for peg-price deviations and -17.7 basis points for intra-day volatility relative to the control group. However, we find the majority of the efficiency gain in Tether peg-prices happen prior to the Covid pandemic, consistent with our narrative of increased arbitrage access leading to efficiency gains as Tether is issued on the Ethereum blockchain.

We repeat our two robustness tests on the difference-in-difference specification using the longer sample. First, we test whether the reported regressions are sensitive to the choice of the migration date. In Figure A2, 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. In particular, the DiD coefficients get smaller as the structural change date is extended to the post Covid sample–again reinforcing the result that the increase in peg efficiency occurred in 2019.

Finally, we repeat the specification for the dynamic trend in the post period in equation (5). The difference-in-difference coefficient δ traces the net effect of structural change across each quarter in the balanced sample, from 2019Q1 to 2021Q4. 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. Figure A3 plots the difference-in-difference coefficients. 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 27.9 and 29.3 basis points higher relative to the

[76] The results in the main body of the paper are based on a sample to March 31st, 2020.

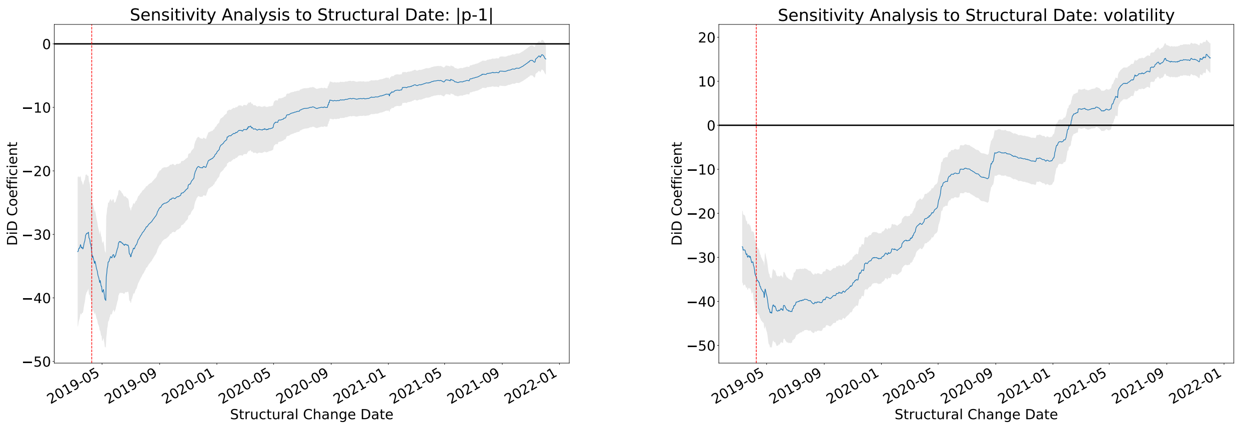
control group. In contrast, Tether peg-price deviations decline relative to control group stablecoins from 2019Q3 to 2021Q4. Intra-day volatility follows a similar qualitative pattern in efficiency. The results are consistent with a *gradual* increase in peg efficiency, with Tether migration to Ethereum occurring over a period of months following the date of structural change.

Table A10: 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	VII	VIII
	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	σ_t	$\lvert p_t - 1\rvert$	σ_t
post	-47.26***	-56.06***	-19.82***	-26.11***	-5.48***	-2.69	-0.98	1.69
	(3.25)	(2.35)	(3.23)	(3.83)	(1.36)	(2.96)	(1.84)	(3.35)
T			27.54***	13.88***	28.61***	13.49***	28.61***	13.48***
			(2.85)	(2.62)	(3.29)	(1.80)	(3.29)	(1.80)
post × T			-28.81***	-30.38***	-33.88***	-35.06***	-28.57***	-23.57***
			(4.54)	(4.55)	(4.54)	(3.37)	(4.83)	(3.88)
postQ12020							-7.23***	-7.07***
							(1.46)	(2.59)
postQ12020 × T							-8.07***	-17.72***
							(1.91)	(2.91)
$\mathbb{1}_{PAX}$			1.65	16.39***	-1.35	12.95***	-1.50	12.79***
			(1.79)	(2.42)	(1.37)	(2.03)	(1.38)	(2.04)
$\mathbb{1}_{TUSD}$			-3.4779*	4.08*	-8.28***	-2.23	-8.17***	-2.13
			(2.01)	(2.15)	(1.33)	(1.69)	(1.33)	(1.69)
R_{BTC}	0.003	-0.0003	0.0010	0.0001	0.0002	-0.0012	-0.0001	-0.0016
	(0.0028)	(0.0027)	(0.0017)	(0.0019)	(0.0010)	(0.0018)	(0.0010)	(0.0017)
σ_{BTC}	0.04***	0.10***	0.02***	0.0914***	0.011***	0.07***	0.01***	0.07***
	(0.008)	(0.009)	(0.005)	(0.006)	(0.003)	(0.006)	(0.003)	(0.006)
R-squared	0.21	0.48	0.17	0.28	0.09	0.19	0.14	0.21
No. observations	1597	1597	3753	3753	3045	3045	3045	3045
Sample	Full	Full	Full	Full	Balanced	Balanced	Balanced	Balanced

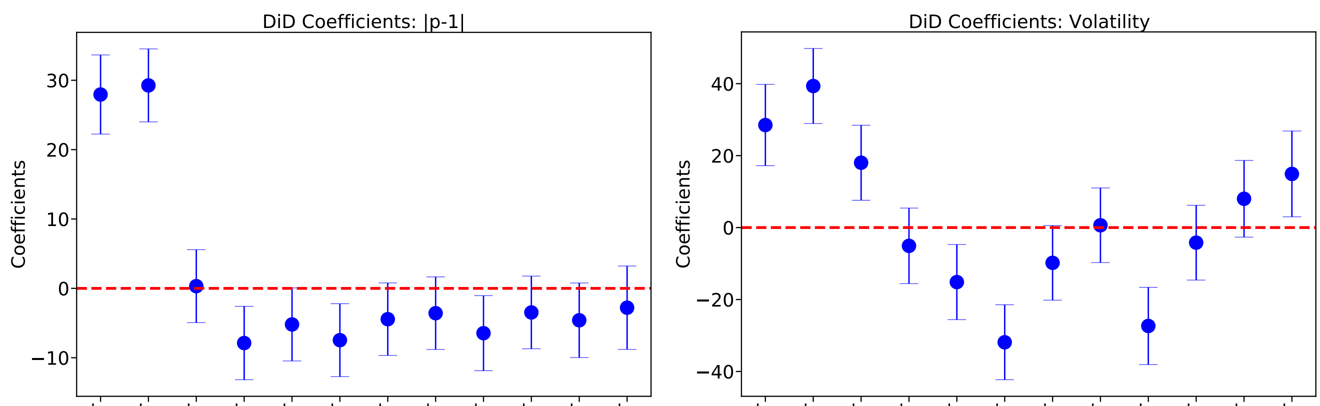
Note: Table presents regressions of the absolute level and volatility of deviations of the peg. The absolute level of deviations is denoted by $|p_t - 1|$, and σ_t is calculated based on a measure of intra-day volatility of the price, both measured in basis points. The post dummy $Post_t$ takes a value of 1 from April 9th, 2019. The Treatment dummy T takes a value of 1 for USDT, and 0 otherwise. postQ12020 takes a value of 1 from April 1st, 2020. 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 December 31st, 2021. Balanced panel for columns (V) through to (VIII) is from January 10th 2019 to December 31st 2021. 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.

Figure A2: 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 December 31st, 2021.

Figure A3: 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 December 31st, 2021. White heteroscedasticity-robust standard-error bars are plotted to construct a 95 percent confidence interval around coefficient estimates.

E Decentralized Arbitrage and Peg Efficiency: IV approach

The difference-in-difference test controls for factors that apply to all stablecoins, such as an increase in liquidity across all exchanges, or common network effects. The test is limited in dealing with confounding factors that are Tether specific. For example, an increase in peg efficiency during the post-migration period may have occurred due to idiosyncratic shocks to Tether, such as an announcement on Tether audits, or by affecting expectations of Tether credibility. An instrumental variables specification that addresses Tether-specific confounding factors is stated in equations (8) and (9). Equation (8) is our first stage, and regresses the daily number of addresses transacting with the Treasury, $N_{USDT,T,t}$, on the proposed instrument N_{IV}. The instrument measures the daily total number of addresses transacting with a set of national-currency backed stablecoins, USDC, Paxos, and TrueUSD that operate on the Ethereum blockchain. In the second stage, we regress peg efficiency outcome Y_t on the instrumented number of addresses of the Tether Treasury as the explanatory variable of interest. The coefficient β_{IV} measures a plausibly exogenous increase in investor access attributed to increased users on the Ethereum network employing stablecoins as a vehicle to satisfy increased transactional demand.

$$N_{USDT,T,t} = \alpha_1 + \beta_1 N_{IV,t} + \epsilon_{USDT,t} \tag{8}$$
$$Y_t = \alpha_2 + \beta_{IV} \hat{N}_{USDT,T,t} + e_t \tag{9}$$

The two identifying assumptions needed are instrument relevance and exclusion listed in equations (10) and (11) respectively. Instrument relevance is satisfied due to common network effects: an increase in the value of the Ethereum network, or increased demand for ERC-20 tokens, will drive an increase in the number of holders using all stablecoins. Therefore we expect an increase in users of Tether on the Ethereum network to be correlated with an increase in users holding other stablecoins. A scatterplot of total users of Tether and other stablecoins in the left panel of Figure A4 confirms our hypothesis that demand for stablecoins has a common factor. The right panel of Figure A4 plots the number of addresses transacting with the Tether Treasury against our proposed instrument. The exclusion restriction states that the number of users holding a set of other stablecoins on the Ethereum network are plausibly exogenous to idiosyncratic shocks to the Tether peg, which we define accordingly as ϵ_{USDT}. Therefore, the identifying assumption is that the instrument leads to an increase in the number of addresses transacting with the Tether Treasury **only** through a channel of common network effects on the Ethereum blockchain.

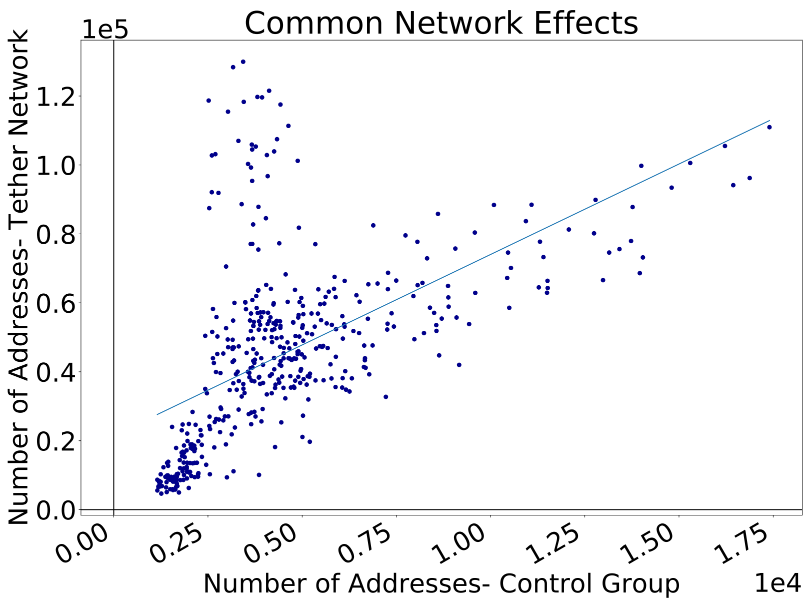
$$cov(N_{USDT,T}, N_{IV}) \neq 0 \tag{10}$$
$$cov(N_{IV}, \epsilon_{USDT}) = 0 \tag{11}$$

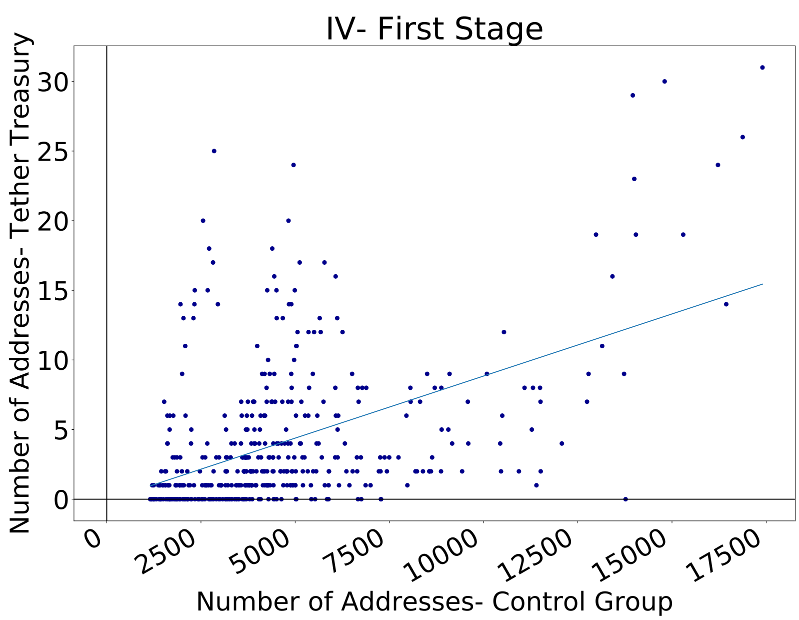
We now test whether the absolute level and volatility of peg deviations are directly impacted by the number of unique addresses transacting with the Treasury, $N_{USDT,T}$ in the columns (I) and (II) of Table A11. The reduced form estimates suggest a 1-unit increase in investor addresses transacting with the Treasury leads to a decline in peg deviations by 3.1 basis points, and a decline in volatility of peg deviations by 5.4 basis points.[77]

The results of our IV specification are documented in columns (III) through to (V) of Table A11. We first test instrument relevance in the first stage in column (III). A unit increase in the number of addresses holding control group stablecoins predicts a 0.0009 increase in the number of addresses transacting with the Tether Treasury. A partial F statistic of 178.53 indicates a sufficiently strong instrument for the first stage. In columns (IV) and (V), we present the second-stage results on the effect of the instrumented number of Treasury addresses on peg-price deviations and volatility. A unit increase in the number of addresses transacting with the Treasury leads to decline in the absolute size of peg deviations of 9.2 basis points, and a decline in the intra-day volatility of peg deviations of 15.4 basis points. Based on our estimates, we can compute how much of the increase in peg efficiency from the introduction of the Ethereum blockchain is due to direct arbitrage. The Ethereum blockchain has an average of 4.0 addresses transacting daily, versus the Omni layer which averaged 1.4 addresses per day. The net decline in the absolute size of deviations due to direct arbitrage is then $9.2 \times 2.6 \approx 24$ basis points. Given an efficiency gain of approximately 52 basis points from the Omni to Ethereum blockchain as estimated in Table 3 (based on the full sample), approximately 50% of the efficiency gain is attributed to direct arbitrage access.

[77]We do not mean to suggest a 1:1 mapping from each unique wallet address to a unique investor. This may overstate the number of unique investors transacting with the Treasury if, for example, a single investor holds multiple unnamed wallet addresses. We provide the full extent of our information on the identity of wallets transacting with the Tether Treasury in Appendix C. While we note the Ethereum network has a significant number of unnamed wallets, we find an increased presence of multiple cryptocurrency exchanges transacting with the Treasury on the Ethereum blockchain.

Figure A4: Instrument Test: scatter plot of the number of daily addresses transacting with the Tether Treasury with the total number of wallets holding a control group of stablecoins





Note: Figure presents a scatter plot of the daily total users of Tether (left) and the number of unique addresses transacting with the Tether Treasury (right) against the corresponding number of addresses that hold a control group of stablecoins USDC, Paxos, and TrueUSD. The total number of addresses using each stablecoin are given by the $Network$ variable available on Coinmetrics. The number of addresses transacting with the Treasury is calculated using the history of Tether transactions available via the Omni, Ethereum, and Tron blockchains. Sample period is April 1st, 2017 to March 31st, 2020.

Table A11: Effects of the number of unique addresses transacting with the Tether Treasury on the size and volatility of Tether peg deviations

	I	II	III	IV	V
	$\lvert p_t - 1\rvert$	σ_t	$N_{USDT,T}$	$\lvert p_t - 1\rvert$	σ_t
N	-3.07***	-5.36***		-9.17***	-15.41***
	(0.53)	(0.88)		(1.40)	(2.26)
N_{IV}			0.0009***		
			(0.0001)		
R-squared	0.01	0.02	0.42		
No. observations	1093	1093	1093	1093	1093
IV First Stage	No	No	Yes	No	No
IV Second Stage	No	No	No	Yes	Yes

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. $N_{USDT,T}$ measures the daily number of unique addresses transacting with the Tether Treasury on the blockchain platforms of Omni, Ethereum, and Tron. N_{IV} measures the total number of addresses transacting with a control group of stablecoins, USDC, Paxos, and TrueUSD. In columns (III) and (IV) we instrument $N_{USDT,T}$ with the daily number of addresses transacting with a set of control group stablecoins, USDC, Paxos, and TrueUSD. Sample is April 1st, 2017 to March 31st, 2020. Price data for currencies obtained from coinapi, and use closing-price data from exchanges Kraken, Bitfinex, and Bittrex.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.

F Other Centralized Stablecoins

We provide supplementary evidence on other national-currency-backed stablecoins. USDC, Paxos, and TrueUSD are among the largest 5 coins by market capitalization as of March, 2020, and are national-currency-backed like Tether. They differ from Tether: USDC decentralises the primary issuer to have multiple issuers with licenses to create USDC tokens; Paxos dollar deposits are insured by FDIC banks; and TrueUSD uses a system of escrow accounts in transactions between investors and the stablecoin issuer. All of these systems assert 100% backing by US-dollar collateral.

We subdivide this section into the following:

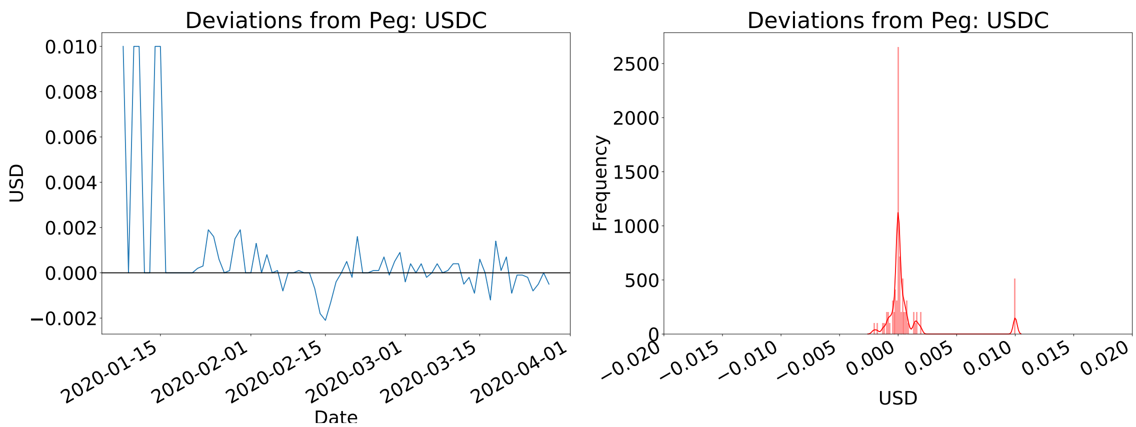
1. Transaction prices and histograms showing a two-sided distribution of deviations.

2. Balance sheets and secondary-market flows.

Transaction Price and Histogram of Deviations

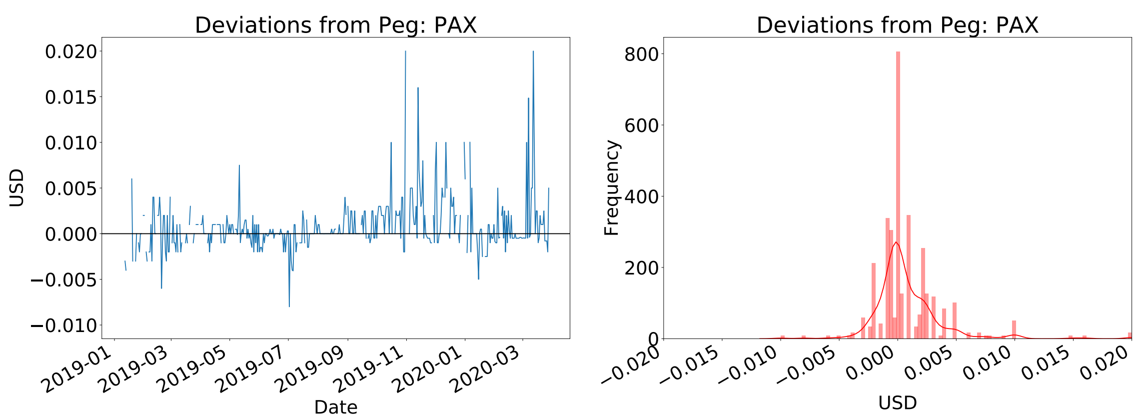
We plot transaction-price deviations from the peg for USDC, Paxos, and TrueUSD. Data are from Coinapi for all coins. We make two general observations based on the following Figures A5, A6, and A7. The first is that deviations are two-sided – these stablecoins trade at both premiums and discounts to the dollar parity peg. The second observation is that deviations are typically persistent, and as indicated in section 1, we note a half-life of deviations that ranges from 5 to 10 days for most coins.

Figure A5: USDC/USD Deviations from Peg and Histogram of Deviations



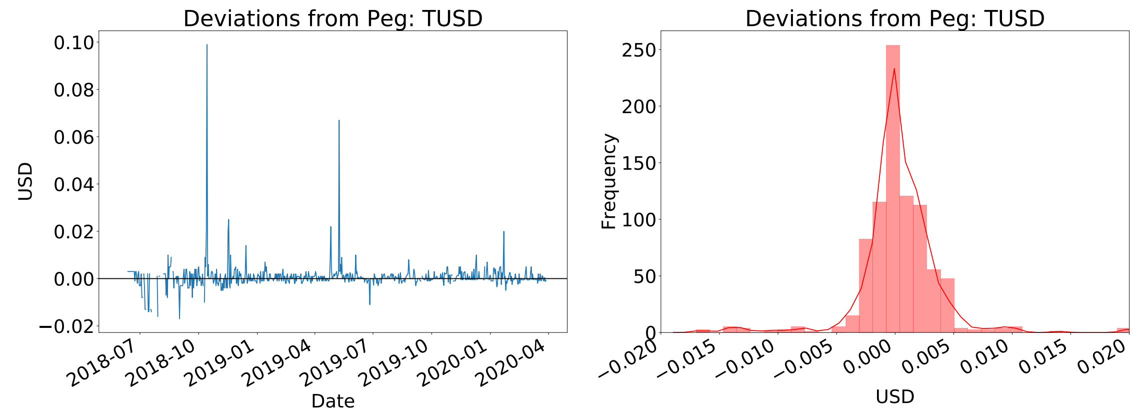
Note: Figure plots deviations of the USDC peg from parity (left panel). A positive deviation indicates USDC trades at a premium. right panel is a histogram of deviations of the USDC peg. Data from Coinapi. Sample is January 10th, 2020 to March 31st, 2020.

Figure A6: PAX/USD Deviations from Peg and Histogram of Deviations



Note: Figure plots the Paxos deviations of the peg from parity (left panel). A positive deviation indicates Paxos trades at a premium. right panel is a histogram of deviations of the Paxos peg. Data from Coinapi. Sample is January 2019 to March 31st, 2020.

Figure A7: TUSD/USD Deviations from Peg and Histogram of Deviations

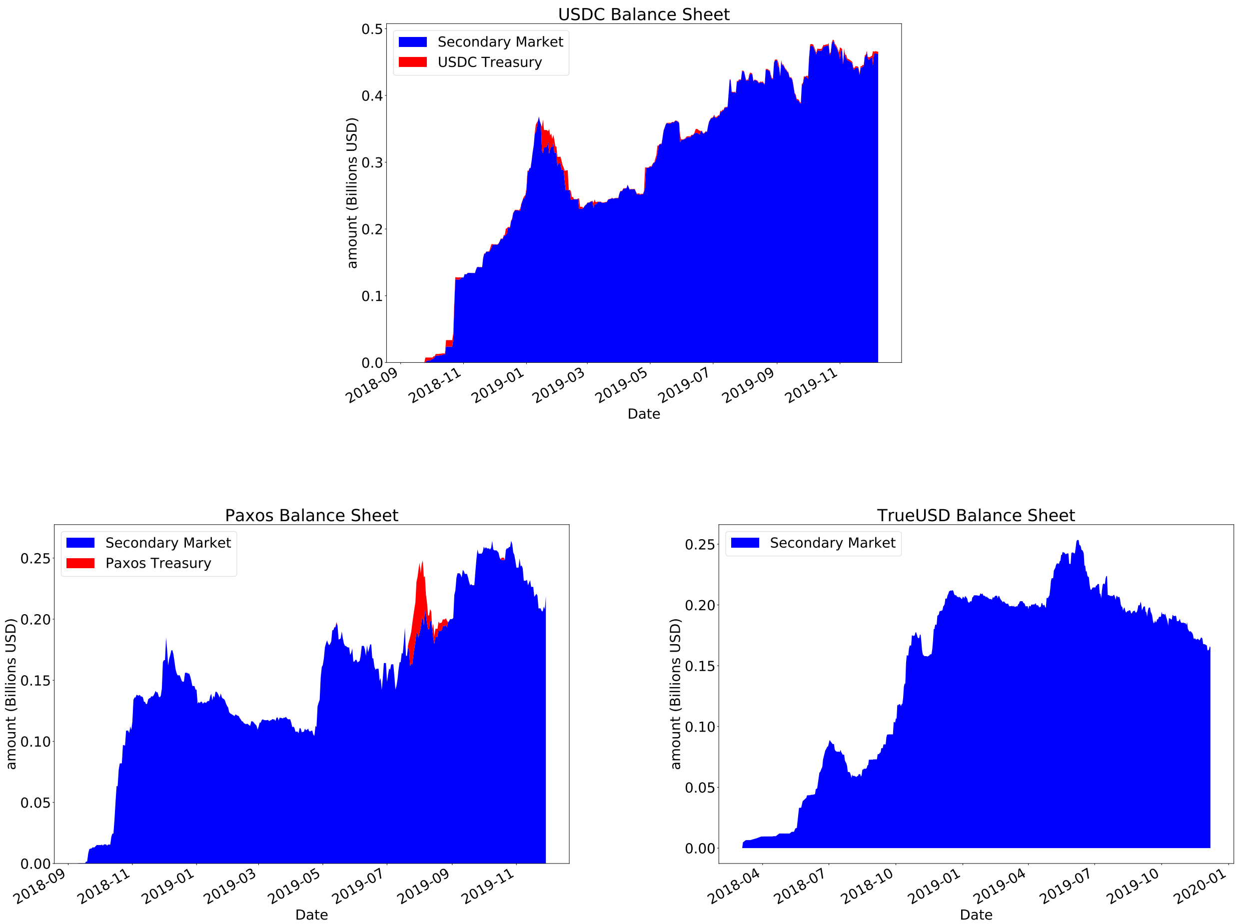


Note: Figure plots the deviations of the TrueUSD peg from parity (left panel). A positive deviation indicates TrueUSD trades at a premium. right panel is a histogram of deviations of the TrueUSD peg. Data from Coinapi. Sample is June 2018 to March 31st, 2020.

F.0.1 Balance Sheets of Other Stablecoins

We plot here the balance sheets of other major stablecoins. The data platform we use is Etherscan, which records the entire set of transactions of a given stablecoin on the blockchain. To use Etherscan, we identify the wallet address of the issuer, and the wallet address of the Treasury (where applicable). We can then use the api to extract a set of transactions of a given wallet. Transactions are classified as a "from" or "to". The underlying assumption is that for the set of transactions involving the primary issuer, if the issuer is "from" this indicates a flow from the issuer to the secondary market. Conversely, "to" indicates redemptions and a withdrawal of stablecoin tokens from circulation. Sample period is from introduction of a given coin to Etherscan to November 2019.

Figure A8: Balance Sheet for USDC, Paxos, and TrueUSD



Note: Figure plots the balance sheet of USDC, Paxos, and TrueUSD. Balance-sheet data from Etherscan.

F.1 Dollar Backed Stablecoins

We analyze the stabilizing properties of issuance flows for other dollar backed stablecoins TrueUSD and Paxos. Both of these stablecoins operate on the Ethereum blockchain, but differ in the way stablecoins are audited, with dollar reserves backed by FDIC-insured banks in the case of Paxos, and backed by escrow accounts in the case of TrueUSD dollar. Similar to our construction of the Tether balance sheet, we can construct the aggregate stock of stablecoins in circulation $Q_{Agg,t}$, and the stock of stablecoins held by the Treasury account $Q_{T,t}$. The total amount of the stablecoin held by private wallets and exchanges is equal to the total stablecoin creation net of stablecoins held in the Treasury's account, given by $Q_{EX,t}$ in equation (12). To construct a proper aggregate measure of net stablecoin issuance, take first differences of equation (12), and define flows from the Treasury to the secondary market, $Flow_{T\rightarrow EX,t} = \Delta Q_{EX,t}$, as the change in total stablecoins in circulation net of changes in the Treasury account (equation (13)).

$$Q_{EX,t} = Q_{Agg,t} - Q_{T,t} \tag{12}$$

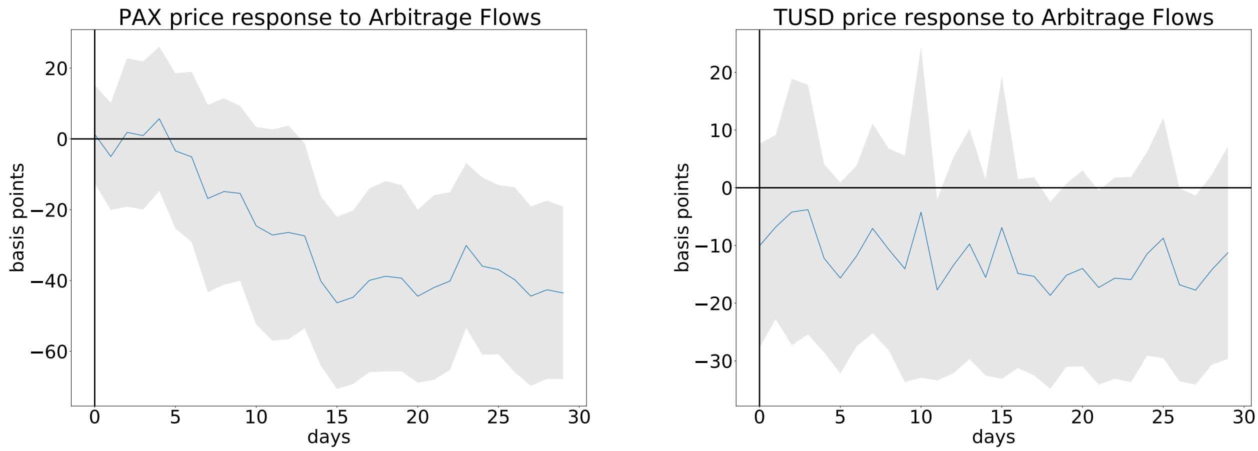
$$Flow_{T\Rightarrow EX,t} = \Delta Q_{Agg,t} - \Delta Q_{T,t} \tag{13}$$

Flows from the Treasury to the secondary market should be stabilizing, by moving peg price deviations toward zero. As before, 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 a daily frequency.[78] The change in the stablecoin dollar price, $P_{t+h} - P_{t-1}$, is projected on the level of arbitrage flows of investors in equation (14), 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. The results for Paxos and TrueUSD in Figure A9 suggest a stabilizing effect, on the order of 40 basis points for Paxos and 10 basis points for TrueUSD (for a one-standard-deviation shock in net flows to the secondary market).

$$\begin{aligned} P_{t+h} - P_{t-1} = \alpha + \beta_h Flow_{T\Rightarrow \mathrm{EX},t} + \sum_{k=1}^{L} \delta_k Flow_{T\Rightarrow EX,t-k} + \\ \sum_{k=1}^{L} \gamma_k (P_{t-k-1} - P_{t-k-2}) + u_t \qquad h = 0, 1, 2, \ldots \end{aligned} \tag{14}$$

[78] 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.

Figure A9: Response of Paxos (Left panel) and TrueUSD (Right) Prices to a Unit Standard Deviation of Flows to the Secondary Market



Note: Figure documents the effect of a 1 standard deviation shock to net secondary market flows on the price of Paxos and TrueUSD. Data for secondary-market flows from Etherscan. Price data from Coinapi. Sample is January 2019 to March 2020 in left panel, and June 2018 to March 2020 in right panel. Gray area denotes 95% confidence interval using White heteroscedasticity robust standard errors.

G Fundamentals of Peg Deviations

In this section we test channels through which stablecoins trade at a premium or discount. We present evidence that premiums arise in times of increased volatility in non-stable cryptocurrency markets. Notable examples include the crash of Bitcoin in early 2018 and the COVID-19 crisis of 2020. We document an example of speculation on Tether in October 2018, when Bitfinex temporarily suspended convertibility of dollar deposits. This signalled to investors that Tether may not have been fully collateralized, and Tether traded at a discount of approximately 500 basis points, with significant increases in bid-ask spreads. All data used in this section, including transaction data used to construct order flow, are discussed further in the data Appendix A.

G.1 Liquidity Fundamentals

We quantify factors that determine pricing in the Tether/USD market. We identify two such factors, order flow, which is a measure of net buying pressure, and cryptocurrency volatility. Determinants of Tether's value are difficult to model in traditional ways, e.g., with macroeconomic fundamentals such as inflation and interest-rate differentials. We draw instead from the medium-of-exchange role in monetary theory to posit that the price of Tether is driven by factors connected to Bitcoin- and Tether-market liquidity.

Order Flow

The first determinant of Tether returns we examine is order flow. Order flow is a measure of net buying pressure in the secondary market and, viewed through the lens of information models in microstructure theory, is the primary means through which dispersed information in the market is expressed and aggregated in price-setting. We construct a measure of order flow using transaction data provided by cryptocurrency vendor Coinapi. This includes a history of trades from a series of exchanges that trade in the Tether/USD pair.[79] This dataset provides the timestamp of each trade, together with the amount of underlying Tether in each trade, and a true-or-false variable *taker side sell* which we use to construct the sign of each transaction.

The exchange follows a maker-taker structure. The market maker is the provider of liquidity, and typically submits limit orders to the exchange with a specified bid and ask price. The takers are typically private investors who submit market orders for Tether, and are initiating the transaction. When the *taker side sell* column reads true, this signifies that the taker is selling Tether and buying USD. The price they are willing to sell Tether is the bid price offered by the market maker. Conversely, when *taker side sell* is false, the taker is buying Tether and selling USD. They buy Tether at the ask price offered by the market maker. Using this signing convention we can construct a measure of order flow as the difference between buyer- and seller-initiated transactions, expressed in the following equation where T_k is the transaction, B indicates it is buyer-initiated, S indicates it is seller-initiated, and V_{T_k} is the amount of the transaction.

$$OF_t^{vol} = \sum_{k=t_0}^{k=t} V_{T_k}(1[T_k = B] - 1[T_k = S]) \tag{15}$$

Volatility of Cryptocurrency Markets

We construct a measure of intra-day price volatility in the BTC/USDT market. To calculate intra-day volatility, we use transaction data of the BTC/USDT pair in the Binance exchange at 5-minute intervals to construct 5-minute returns. We then calculate the average sum of squared returns over 5-minute intervals over the trading day, and take the square root. This fundamental captures the safety premium of Tether; in market downturns, investors want to liquidate to a store of value. Stablecoins have lower intermediation costs and lower latency time of transactions, with bank wires taking significantly longer than a transaction executed on the blockchain. We hypothesize that this results in investors choosing to liquidate unstable cryptocurrencies to stablecoins, as opposed to dollars, causing Tether to trade at a premium in times of increased risk in

[79] Exchanges that trade significantly in Tether/USD are Bitfinex and Kraken. For the baseline results we use the Kraken exchange as it has the highest volume of trades, and the earliest history (starting in April 2017).

cryptocurrency markets.

We now regress the deviation of the Tether price from the peg, $p_t - 1$, on signed order flow OF_t, as well as a measure of intra-day price volatility of the BTC/USDT pair, $\sigma_{BTC,t}$, as expressed in equation (16).

$$p_t - 1 = \alpha + \beta_1 OF_t + \beta_2 \sigma_{BTC,t} + u_t \tag{16}$$

Table A12 provides evidence that liquidity fundamentals have an important role in explaining deviations from the peg. In column (I), we present the results of regression 16 for the full sample. We then condition on subsets of the sample in columns (II), (III), and (IV). In column (II) we condition on the USDT price being within 1 standard deviation of parity. In columns (III) and (IV) we condition on price being more than 1 standard deviation below parity, and greater than 1 standard deviation above parity respectively. We find positive effects of an increase in Bitcoin volatility on the Tether price. Based on column (I), a 1 per cent (100 basis point) increase in BTC/USDT intra-day price volatility raises the price of Tether by approximately 5 basis points, all else equal. This suggests a potential risk-hedging motive for holding Tether in periods of extreme Bitcoin volatility. One of Tether's features is its store-of-value function for crypto investors.

Table A12: Determinants of Tether/USD Price – Liquidity Fundamentals

	I	II	III	IV
	$p_t - 1$	$p_t - 1$	$p_t - 1$	$p_t - 1$
OF	21.98***	10.92***	13.22	22.31***
	(3.33)	(1.46)	(13.03)	(7.37)
σ_{BTC}	0.05***	0.03***	-0.01	0.03
	(0.01)	(0.01)	(0.05)	(0.03)
Intercept	-18.92***	-6.51*	-177.68***	112.35***
	(5.00)	(3.58)	(20.04)	(15.19)
R-squared	0.11	0.14	0.03	0.08
No. observations	953	802	70	79
Full Sample	Y	N	N	N
$\|p_{t-1} - 1\| < 1sd$	N	Y	N	N
$p_{t-1} - 1 < -1sd$	N	N	Y	N
$p_{t-1} - 1 > 1sd$	N	N	N	Y

Note: Table presents regressions of the deviation from parity in the USD price of Tether on variables capturing liquidity in the Tether/USD and BTC market. OF measures order flow and is constructed as the net of buyer-initiated transactions for the Tether/USD pair, where a buy transaction is signed positively when the buyer of Tether is initiating the trade. σ_{BTC} is the intra-day volatility of the BTC/USDT price sourced from the Binance exchange, measured in basis points. Sample is April 1st, 2017 to March 31st, 2020 and consolidates trade data from three trusted exchanges: Bitfinex, Bittrex, and Kraken. 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.

G.2 Stablecoin Premiums

Why do Tether and other stablecoins exhibit safe-haven properties? In periods of risk, investors need to liquidate into a store of value. Portfolio rebalancing toward Tether and other stablecoins provide this function with minimal intermediation costs. As noted, on some exchanges for example, there are long processing lags for dollar withdrawals to comply with intermediation procedures. Fees are also often imposed when dollar withdrawals are frequent or large.[80] We provide evidence of safe-haven demand with reference to the *Black Thursday* Crypto event.

The COVID-19 economic crisis resulted in a collapse of the BTC market of approximately 40%,

[80]For more information, see announcements by Bitfinex: https://bit.ly/2NEzITW and https://www.bitfinex.com/posts/311. As noted previously, Bitfinex states it will take investors 7 to 15 days to make dollar withdrawals from their platform in order to comply with intermediation procedures. Bitfinex has also introduced transaction costs of a 3% fee for investors who make more than two dollar withdrawals a month, or for withdrawals larger than $1 million in a given month.

as it fell from approximately $8,000 to $5,000 from March 12th to 13th. Amidst the widespread sell-off in cryptocurrency markets, there were clear efforts by investors to liquidate into a store of value. To gauge investors incentive to liquidate into a store of value quickly, we use the Ether Network's gas prices. These prices are denominated in GWEI which is equivalent to one-billionth of one ETH, and they are typically an average of 10 GWEI per transaction. Critically, these units of GWEI provide a proxy for transactions' latency time. For example, on March 29th, 2020, the Ether gas station states that there is transaction cost of 8 units of GWEI for a transaction time less than 2 minutes, 5 units of GWEI for a transaction time less than 5 minutes, and 3 units of GWEI for a transaction time less than 30 minutes.[81]

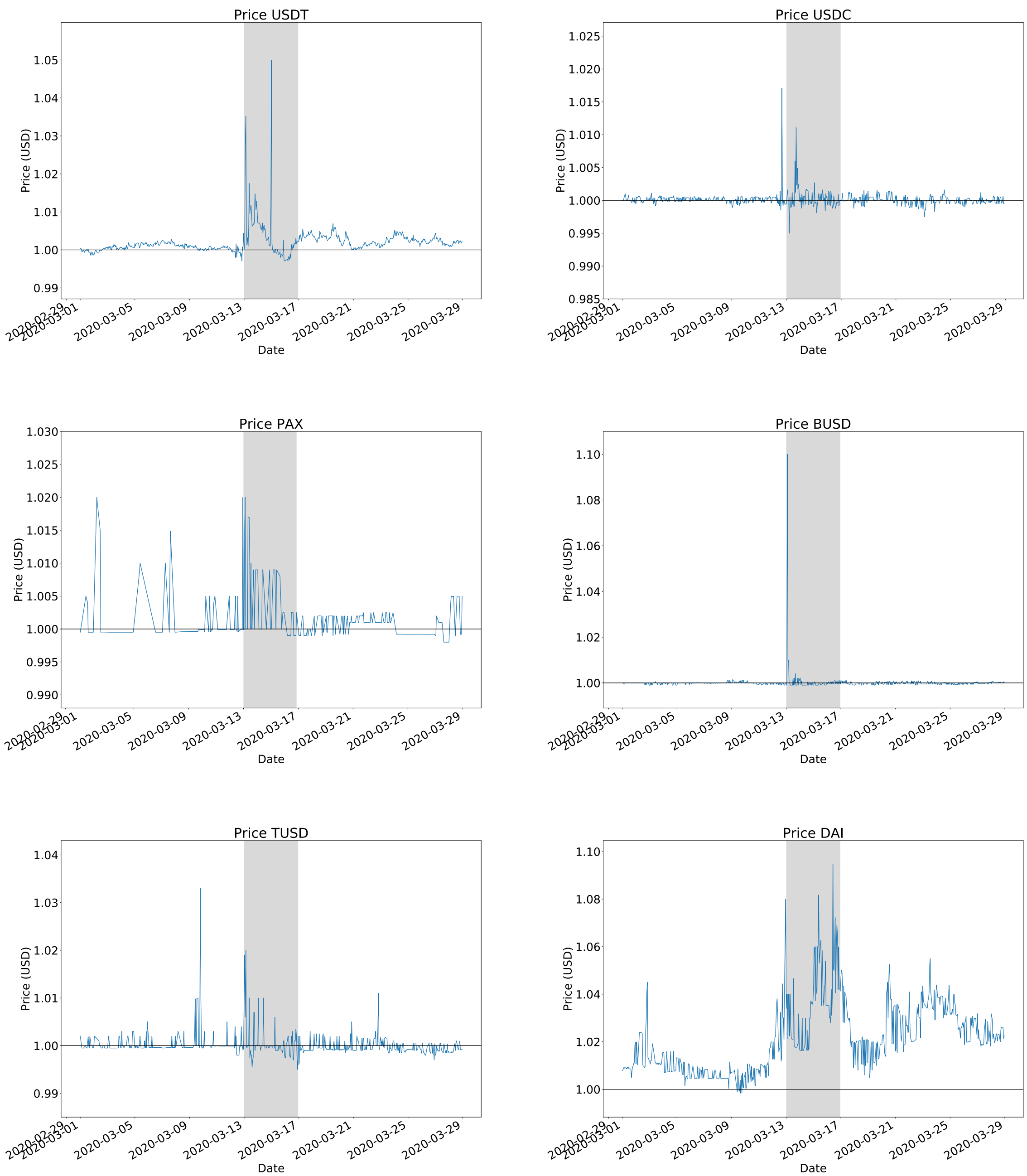
On March 12th, the average gas prices temporarily spiked to over 100 GWEI per transaction from the 10 GWEI average seen just one day prior. There was congestion on the Ethereum blockchain as investors wanted to liquidate unstable cryptocurrencies into stablecoins. The rise in gas costs reflected the cost of latency time; investors were willing to pay more gas costs to liquidate faster.[82]

We plot in Figure A10 the USD price response of the six largest coins by market cap, based on data in March 31st, 2020. Shaded areas indicate the period in which the price of Bitcoin fell by 50%. In all cases, we see a rise in the price of stablecoins of approximately 500 basis points. The largest increase is for BinanceUSD coin, the stablecoin issued by the Binance cryptocurrency exchange. A potential reason why BinanceUSD trades at a premium to the dollar is because Binance platforms do not allow conversion to national currencies directly. Therefore, for investors on the Binance exchange, converting to BinanceUSD is a good option for reducing latency time.

[81] Gas prices, as well as daily amounts of Ether Gas used, are provided in https://ethgasstation.info/.

[82] For more information see https://blockonomi.com/ethereum-gas-prices-surged/.

Figure A10: Response of stablecoin prices to negative price shock of Bitcoin in March, 2020

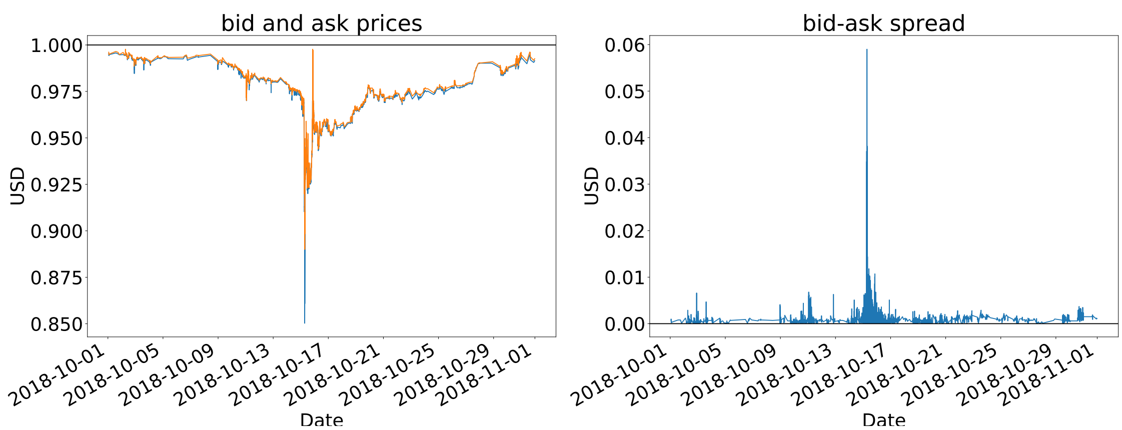


Note: Price (in USD) of 6 largest stablecoins by market cap during March 31st, 2020. Price data are from Coinapi and are hourly, available on cryptocurrency exchanges Binance, Bitfinex, Bittrex, and Kraken. Shaded areas indicate the period when the price of Bitcoin fell approximately 50% from March 12th to March 13th.

G.3 Stablecoin Discounts

Stablecoin discounts can be due to mismanagement by the issuer, a lack of collateral, or speculation. A speculative attack on Tether occurred on 11th October, 2018. On that day, Bitfinex decided to temporarily pause national-currency deposits (USD, GBP, EUR, JPY) for certain customer accounts in the face of processing complications.[83] Figure A11 shows the unfolding of this event on Tether's dollar price and on measures of bid-ask spreads. Tether transaction prices fall to 95 cents on October 15th. While the whole-sample average bid-ask spread is between 0.1 and 0.15 of a cent, with a standard deviation of 0.2 cents, there are evident spikes in bid-ask spreads, suggesting an information asymmetry in response to speculative events. In particular, the sharp fall in bid and ask prices corresponds to a spike in the width of the spread of 6 cents (600 basis points). Widening bid-ask spreads is consistent with a story of increased collateral risk as buyers and sellers of Tether are unsure of the fundamental trading price and whether others might have superior information.

Figure A11: Tether/USD prices and Bid-Ask Spreads



Note: Schematic illustrates the movement in Tether/USD price and bid-ask spreads. Transaction, bid, and ask prices from Coinapi trade and order-book data. Volume data are from Cryptocompare. Sample is October 2018.

[83] See https://twitter.com/bitfinex/status/1051750465782906880?lang=en.