Reserve Demand, Interest Rate Control, and Quantitative Tightening

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Abstract: We provide a framework for understanding banks' demand for central bank reserves. The main reserve demand drivers are: The spread between market rates and the interest rate on reserves, banks' liquidity needs (implying that reserves generate a convenience yield), and bank balance sheet costs. Given reserve demand, we show how central banks control equilibrium short rates via interest on reserves, reserve supply and lending/borrowing facilities. We estimate reserve demand for the US from 2009M1-2022M10 and use the estimated reserve demand function to (a) guide the setting of interest on reserves, and (b) assess how much quantitative tightening is feasible.

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1. Introduction

A central bank's supply of reserves plays a central role in monetary policy. Prior to the financial crisis, most central banks focused on conventional monetary policy in which they used variation in the supply of reserves to control a chosen short-term interest rate. The supply of reserves was modest and reserves typically did not earn interest. Central banks were able to change the short-term rate (in the US, the effective federal funds rate) with small changes in reserve supply via open market operations. This suggests that banks were on a steep part of their reserve demand curve. When the zero lower bound became binding during the financial crisis, many central banks turned to unconventional monetary policy, with forward guidance and quantitative easing (QE) being the most prominent. With QE, reserve supply expanded dramatically, and more central banks started paying interest on reserves. This new setting is sometimes referred to as the ample-reserves regime. In this paper, we focus on the role of reserve demand in the ample-reserves regime. We are interested in two issues.

First, what is the role of reserve demand for interest rate control in the ample-reserves setting? What are the drivers of reserve demand? How elastic is reserve demand to the spread between short-term market rates and the interest rate on reserves? What is the mechanics through which central bank facilities set up to keep market rates in a corridor achieve their objectives (in the US, these facilities are the discount window and the overnight reverse repurchase facility)? Answering these questions should help central banks set reserve supply and the array of interest rates they control to ensure that short-term market rates clear around a desired value.

Second, and closely related, to what extent can QE be unwound via quantitative tightening (QT)? Because central banks fund their bond purchases by creating short-term liquid liabilities (mainly reserves), balance sheet reduction comes with a reduction in central bank-provided liquidity. The lower the supply of central bank liquidity, the higher the risk of spikes to funding costs in short-term money markets as those who hold liquid central bank assets may hold on to them to have liquidity available when needed, rather than lending them out to others in needed of funding. Too much quantitative tightening may thus lead to a loss of control over interest rates and to financial instability. This part of our analysis is motivated by the U.S. experience in 2019. This QT episode ended in September 2019 when short-term money market rates spiked sharply, as illustrated in Figure 1.[2] In light of this experience, the risk of an abrupt end to the ongoing balance sheet

[2] Work on the September 2019 yield spikes include Anbil, Anderson and Senyuz (2020), Correa, Du and Liao (2021), Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020), and Copeland, Duffie and Yang (2021).

reduction of the Federal Reserve is a concern among many market participants, as documented in, e.g., Wall Street Journal (2022).

We start by deriving banks' demand for reserves from a bank optimization problem with three main ingredients. First, reserves pay interest. Second, we model transaction cost savings from reserves as a convenience yield on reserves which is increasing in reserves and decreasing in deposits. This approach has parallels to that of Krishnamurthy and Vissing-Jorgensen (2012) who model the safety and liquidity features of Treasury securities using a convenience yield function that is increasing in Treasuries and decreasing in GDP. In the reserve context, the transaction cost savings from holding reserves stem from banks' need to manage the liquid liabilities they have issued. Deposits are the main such liability, but other liquid claims could matter too. Reserves can be used to manage deposits outflows with few costs, unlike less liquid bank assets such a loans or securities. Third, we assume a bank balance sheet cost which is linear in bank assets. We derive banks' reserve demand from the banks' first-order condition for borrowing in the federal funds market and investing in reserves. This first-order condition states that the effective federal funds rate (EFFR) equals the interest rate on reserves (IOR) plus the marginal convenience yield from additional reserves, minus the per-dollar balance sheet cost, thus laying out three drivers of reserve demand. If banks view additional reserves as less and less useful for the management of their net deposit flows, a downward sloping reserve demand results, with reserve demand declining in the market interest rate on alternatives to reserves (such as the EFFR).

We emphasize that the reserve demand curve can be defined relative to any liability used to fund reserves. To realistically model repo borrowing, we introduce a cost of posting collateral in repo contracts (in practice representing foregone securities lending revenues) and derive the reserve demand relative to repos from the banks first order condition for borrowing via repo to fund reserves. The EFFR and repo interest rates are those of most direct interest to the Federal Reserve because it targets the EFFR rate and because the interest rate in the private repo market determines take-up at the overnight reverse repo facility. While our framework is laid out in the institutional context of the United States, it should be straightforward to extend it to other countries with appropriate modifications to account for the specific central bank facilities used.

We next turn to how a central bank controls the equilibrium interest rates given the reserve demand function, again focusing on the institutional setting of the US. We develop a novel graphical framework for this purpose. The Federal Reserve controls the equilibrium short-term interest rate via the setting of the IOR, the supply of reserves, as well as facilities in place to put a ceiling and a floor on the market-clearing interest rate. These facilities are the discount window (at which banks can borrow reserves from the Federal Reserve against collateral) and the overnight reverse repurchase (ONRRP) facility (at which banks, government-sponsored enterprise and money market funds can invests with the Federal Reserve, receiving collateral).

We show the private sector's decisions to borrow/lend at these facilities changes reserve supply to ensure that the market interest rate remains between the floor and ceiling rates (aside from any slippage due to stigma of banks from borrowing at the discount window or due to it taking time for the private sector to react to interest rate incentives).

We compare our framework to prior work, summarized in Ihrig, Senyuz and Weinbach (2020), emphasizing two novelties. First, our reserve demand curve is not directly affected by the floor and ceiling rates. Instead, reserve supply adjusts via private sector take-up decisions to ensure that the market rate clears in the interest rate corridor. Our framework therefore allows us to speak to drivers of take-up at the ONRRP facility which recently has been over \$2T. We show graphically how ONRRP take-up can result from increased reserve supply, from a downward shift to the reserve demand function, or from an increase in the interest rate on the ONRRP facility (for given IOR). Second, our framework emphasizes the role of deposits (and other liquid bank liabilities) in determining the location of the demand curve. Effectively, deposits are a scale variable in the demand function that, in interest rate-quantity space, constitute a demand curve shifter. Although recent work on reserve demand has not focused on the role of deposits, banks' use of reserves to manage deposit flows is at the center of the literature on reserve demand from the period before the ample-reserves regime (see Judson and Klee (2009)). In this earlier regime, reserve demand was driven by reserve requirement and by banks' demand for holding reserves above the regulatory minimum. Banks' need for required reserves followed directly from the amount of money they created in the form of deposits (with reserve requirements set as a percentage of transactions deposits, see Archived Reserve Maintenance Manual). Banks could choose to hold reserves above the regulatory minimum to facilitate transactions while avoiding overdrafts with the Federal Reserve. During the scarce reserve-zero IOR regime, the Federal Reserve carefully modeled the demand for excess reserves and adjusted reserve supply on a daily basis in order to ensure that the federal funds rate traded near the federal funds rate target. By contrast, during the current ample reserve-positive IOR regime, the Federal Reserve does not adjust the size of its balance sheet in response to reserve demand shocks (except when the interest rate floor is binding), instead using the size of its balance sheet to affect employment and inflation.

Having laid out a framework for reserve demand and interest rate control, the second half of the paper turns to empirical estimation of reserve demand and its implications for current monetary policy. We assume that the marginal convenience yield on reserves is linear in log reserves and in log deposits. The banks' first-order condition for borrowing via federal funds and investing in reserves then implies a reserve demand function which links the EFFR-IOR spread to log reserves and log deposits. We estimate this reserve demand function using instrumental variable estimation. Reserves are not exogenous because reserve supply changes in response to reserve demand shocks when ONRRP take-up is not zero (as will be clear from our graphical framework for interest rate control). We instrument log reserves by the log of reserves+ONRRP take-up. From the Federal Reserve's balance sheet, reserves+ONRRP equals assets minus "autonomous factors" (liabilities other than reserves and ONRRP) both of which we argue are plausibly exogenous. In our baseline estimation, we do not instrument for deposits, but we show as a robustness check that instrumenting for deposits has little effect on results. Our baseline estimation implies that reserve demand has a semi-elasticity around -5 with respect to the EFFR-IOR spread -- thus suggesting a very elastic but not flat reserve demand -- and an elasticity above one with respect to deposits. The reduced form of our reserve demand estimation links the EFFR-IOR spread to the log of reserves+ONRRP and log deposits. The fit of this relation is very tight over the estimation period from 2009M1 to 2022M10. We illustrate this by showing that the EFFR-IOR spread has a tight relation to the log of reserves+ONRRP (i.e., Federal Reserve supply of interest-bearing liabilities), adjusted for deposits. This contrasts sharply with the unstable relation between the EFFR-IOR spread and reserves when one does not account shifts in reserves demand due to changes in deposits. Smith and Valcarcel (2021) is an example of recent work on reserve demand that emphasizes reserve demand instability but does not account for deposits.

Using the estimated reserve demand function, we can calculate the predicted EFFR-IOR spread given the Federal Reserve's current quantity of reserves+ONRRP and given current deposits. This guides the setting of the IOR needed to hit a given federal funds target: An IOR set equal to the federal funds target minus the predicted EFFR-IOR spread will result in a predicted federal funds rate equal to the target. Since the predicted EFFR-IOR spread is declining in the supply of reserves+ONRRP, a lower IOR is needed for low supply. We denote combinations of the IOR and Reserves+ONRRP that imply a chosen predicted effective federal funds rate as an *iso-federal funds curve*. This terminology was introduced by Bianchi and Bigio (2022) in a theoretical analysis based on a somewhat different framework than ours. We provide the first empirically estimated iso-federal funds curves in the literature.

We also use the estimated reduced form reserve demand estimation to assess feasible QT. Quantitative tightening is used as one tool to tighten the stance of monetary policy and banks' demand for reserves is central for feasible balance sheet reduction. Leading up to both the prior balance sheet reduction period in 2018-2019 and the current one (starting in 2022), the Federal Reserve has communicated that QT would be limited by the nature of reserve demand. In the 2017 Addendum to its Policy Normalization Principles and Plans, the Federal Open Market Committee (FOMC) stated:

> *"The Committee currently* ***anticipates reducing the quantity of reserve balances****, over time, to a level appreciably below that seen in recent years but larger than before the financial crisis; the*

> *level will reflect the banking system's* ***demand for reserve balances*** *and the Committee's decisions about how to implement monetary policy* ***most efficiently and effectively*** *in the future."*[3]

Our reduced form relation can be used to predict what the EFFR-IOR spread would be at various levels of reserve+ONRRP supply, given the current level of deposits. As of October 2022, the supply of reserves+ONRRP was $5.4T (20.4% of GDP). We show that reducing reserve+ONRRP supply to 7% of GDP ($1.8T) as was done during the policy normalization period leading up to September 2019 would result in a historically low value of the deposit-adjusted supply of reserves+ONRRP and a predicted EFFR-IOR spread much above that in September 2019. We consider more conservative amounts of reduction in reserves+ONRRP. Reserves+ONRRP supply of 11% of GDP ($2.8T) would lead to the same (positive) predicted EFFR-IOR spread as in September 2019 and thus may also be too risky from a financial stability perspective. A more conservative choice would be a reserves+ONRRP supply of 13.5% of GDP ($3.5T) which leads to a predicted EFFR-IOR spread of zero. As an alternative approach, we also consider the current level of ONRRP take-up ($2.2T as of October 2022) as a useful guide to feasible reduction in reserves+ONRRP since ONRRP take-up emerges because the Federal Reserve supply of reserves+ONRRP exceeds reserve demand evaluated at a market interest rate equal to the ONRRP rate. Both approaches imply feasible reserves+ONRRP reduction of around $2T as of October 2022. This translates into a smaller amount of feasible QT (reduction in the size of the Federal Reserves' balance sheet). Since reserves+ONRRP equals Federal Reserve assets minus "autonomous factors", it is prudent to run down assets only to the point that volatility in the autonomous factors will not drive reserves+ONRRP below the value assessed to be feasible.

We caution that there several complicating factors that are difficult to quantify but both suggest that more QT may be feasible than our estimate. First, as the Federal Reserve runs down its balances sheet, someone has to step in to hold more bonds. This may reduce deposits (and thus reserve demand, thereby increasing feasible QT) if households buy more bonds directly, transfer deposits to bond funds, or move deposits to money market funds who in turn fund hedge fund bond purchases via repo lending. Second, in July 2021 the Federal Reserve introduced a Standing Repo Facility (SRF) at which dealers and depository institutions can borrow funds from the Federal Reserve via repo borrowing. The SRF provides liquidity when needed and thus may help reduce the risk of yield spikes for a given level of reserves+ONRRP. Again, this would imply that more QT is feasible than in our estimate.

[3] Policy Normalization Principles and Plans (federalreserve.gov). Similarly, the latest "Principles for Reducing the Size of the Federal Reserve's Balance Sheet" released on 1/26/2022 states that "Over time, the Committee intends to maintain securities holdings in amounts needed to implement monetary policy efficiently and effectively in its ample reserves regime."

In sum, we make four contributions in this paper: First, we develop a simple framework for understanding reserve demand. Second, we show how the Federal Reserve controls the equilibrium market interest rate via the interest rate on reserves, the supply of reserves, as well as facilities in place to put a ceiling and a floor on the market-clearing interest rate. Third, we estimate the reserve demand function for the US over the ample reserves period since 2009, finding a stable relation once the growth in deposits is accounted for. Fourth, we use the estimated reserve demand function to estimate iso-federal funds curves and feasible QT given current levels of deposits as of October 2022.

2. Deriving reserve demand from banks' optimization

This section lays out our framework for understanding reserve demand. We derive reserve demand from banks' optimization in a setting with interest on reserves, a convenience yield from reserves and balance sheet costs. We provide a micro foundation for the convenience yield in Appendix 1.

As background for laying out the framework, Table 1 shows the Federal Reserve balance sheet as of October 26, 2022. Figure 2 illustrates the evolution of the Federal Reserve balance sheet over time, illustrating both the total size and the five liability components. The Federal Reserve's main assets are Treasuries and MBS securities. On the liability side, the largest categories are reserves (banks' deposits with the Federal Reserve), overnight reverse repurchase agreements (repo investments with the Federal Reserve, mainly by money market funds), currency, and the Treasury General Account (the Treasury's deposit account with the Federal Reserve).[4]

To derive banks' reserve demand curve explicitly from bank optimization, consider a typical banking sector balance sheet.

Assets	*Liabilities*
Reserves	Deposits
Securities	Federal funds
Loans	Private repo
	Equity

Reserves earn interest. In addition, they lead to transactions cost savings as liability outflows can be managed with reserve reductions rather than sales of less liquid securities or loans. We model these transactions cost savings as a convenience yield on reserves, i.e., a benefit of holding reserves above and beyond earning the IOR. Our assumed convenience yield function is *v(Reserves,Deposits)* with $v_R'()>0$ (as

[4] The "other" category on the asset side includes bank borrowing from the Federal Reserve at the discount window or via other facilities. None of our results are sensitive to subtracting discount window borrowing from reserves. Conceptually, it is most appropriate to *not* subtract discount window borrowing, as it is a channel through which reserves are increased as will be laid out below.

more reserves lead to increased cost savings and v'_D()<0 (as more deposits increase costs of liquidity management). This convenience yield function is conceptually similar to that for Treasuries in Krishnamurthy and Vissing-Jorgensen (2012). They model the convenience yield on Treasuries using a function *v(Treasuries/GDP)*. Here we allow for the two inputs to enter separately. We assume (and confirm empirically), that v''_R()<0 (as reserves are less and less useful for given deposits) and $v''_{R,D}$()>0 (as additional deposits increase the marginal value of reserves). Appendix 1 provides micro foundations for the *v()* function, showing how it captures saved transactions costs from managing deposit flows with reserves. Assume furthermore that banks face a balance sheet cost of ϕ per dollar of assets, capturing the effect of regulatory requirements. We are particularly interested in the spread of the effective federal funds rate relative to IOR and private repo relative to IOR (by "private repo" we mean repo in the repo market, as opposed to the Federal Reserve's ONRRP facility). We use a function *w*(Private repo) to denote the costs of posting collateral in repo contracts, with w′>*0*.

Profits to equity holders in a given period are then:

$$\pi = r(Reserves)*Reserves + r(Securities)*Securities + r(Loans)*Loans$$
$$-[r(Deposits)*Deposits + r(FF)*FF + r(Private\ repo)*Private\ repo]$$
$$+ v(Reserves, Deposits) - \phi*(Reserves + Securities + Loans) - w(Private\ repo) \quad (1)$$

where r() denotes a return. We use this setup to derive the first-order conditions for bank borrowing via each of the short-term liabilities and investing in reserves. We assume there is no risk involved in federal funds borrowing/lending.

The banks' first-order condition for borrowing in the federal funds market and investing in reserves sets the marginal cost of borrowing via federal funds, r(FF), equal to the marginal benefit of investing in reserves, r(Reserves)+v'_R(Reserves,Deposits)-ϕ, and thus implies

$$r(FF) = r(Reserves) + v'_R(Reserves, Deposits) - \phi \quad (2)$$

Similarly, the banks first-order condition for borrowing via repo and investing in reserves sets the marginal cost of borrowing via repo, r(Private repo)+w'*(Private repo)*, equal to the marginal benefit of investing in reserves, r(Reserves) +v'_R(Reserves,Deposits) - ϕ and therefore implies

$$r(Private\ repo) = r(Reserves) + v'_R(Reserves, Deposits) - \phi - w'(Private\ repo) \quad (3)$$

Adding assumptions about the cost of raising deposit funding one could also derive a first-order condition for borrowing via deposits and investing in reserves. We omit it here as it is of less interest for our purposes.

Adding an assumed functional form for v'_R*(Reserves,Deposits)*, we obtain a version of (2), which we will estimate empirically below.[5]

Result 1. If

$$v'_R(Reserves,Deposits)=d+b*ln(Reserves)+c*ln(Deposits) \quad (4)$$

then banks' first order condition for borrowing via federal funds and investing in reserves is

$$r(FF)\text{-}r(Reserves)=a+b*ln(Reserves)+c*ln(Deposits)+u \quad (5)$$

where a=d-ϕ and we have added an unobserved reserve demand shock *u*. If additional reserves are less and less useful for liquidity management purposes (for given deposits), then b<0, corresponding to v''_R()<0. If additional reserves are more useful when deposits are higher, then c>0, corresponding to $v''_{R,D}$()>0.

Expressing reserve demand as a function of reserve demand drivers, (5) corresponds to a reserve demand function of the following form

$$Reserves = \alpha\ Deposits^{\beta} e^{\gamma*[r(FF)-r(Reserves)]} \varepsilon \quad (6)$$

where $\alpha = e^{-a/b}$, $\beta = -c/b$, γ=1/b, and $\varepsilon = e^{-u/b}$. Equation (6) shows how reserve demand is a function of the interest rate spread between reserves (which earns the interest rate on reserves, r(Reserves), in practice referred to as IOR) and the market interest rate *r* as well as banks' need for liquidity driven by their deposit management.[6] Taking logs in (6),

$$\ln(Reserves) = \ln(\alpha) + \beta * \ln(Deposits) + \gamma * [r(FF) - r(Reserves)] + \ln(\varepsilon) \quad (7)$$

In the money demand literature this would be referred to as a semi-log functional form, meaning that the measure of money (here reserves) enters in logs but the measure of the cost of holding money (here r(FF)-r(Reserves)) enters in levels.[7]

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[5] We focus our estimation on (2) rather than (3) due to not having a good instrument for private repo borrowing inside the w'() function. More on instrumenting below.

[6] Goodfriend (1982) models reserve demand as a function of deposits (either demand or time) and the level of market interest rates. With interest on reserves, the opportunity cost of reserves is the spread between the market interest rates and the interest rate on reserves.

[7] Lucas (2000) models the demand for M1 (currency plus checkable deposits and traveler's checks). He models m=M1/GDP as a function of a nominal interest rate, r. In line with the money demand literature, he considers both a semi-log relation, $m=Be^{-\xi r}$, and a log-log relation, $m=Ar^{-\eta}$. We focus on the semi-log functional form since the measure of the cost of liquidity with IOR is (market interest rate-IOR) which can go negative, implying that the log-log relation is not well-defined (as ln(m)=ln(A) – η ln(r) is not well-defined for negative r).

3. Interest rate control given the reserve demand function

Figure 3, Panel A illustrates reserve demand and supply graphically. It looks very similar to the standard money market diagram for currency consistent with the idea that reserve demand is a form of money demand for banks. While money demand depends on the interest rate spread between the interest rate on money (zero for currency) and the interest rate on short-term market alternatives, banks' demand for reserves depends on the spread between the interest rate on reserves (IOR) and short-term market alternatives. Similarly, money demand depends on households need for liquidity for spending purposes, typically proxied by GDP, while reserve demand depend on banks' need for liquidity.

The reserve demand curve graphed is equation (2), r(FF)=r(Reserves) + v_R'(Reserves,Deposits) – ϕ. The reserve demand curve traces out the interest rate banks are willing to pay to borrow and invest in reserves, as a function of the amount of reserves held. The first determinant of reserve demand is the interest rate on reserves. While currency always earns a rate of zero, the IOR is set by the central bank. Changes to the IOR leads to corresponding vertical shifts in the reserve demand curve. The second reserve demand driver is banks' need for liquidity to manage flows of liquid short-term liabilities, notably deposits. A downward-sloping reserve demand curve emerges if banks have a declining marginal value of holding additional reserves for managing a given amount of deposits. Balance sheet costs such as capital requirements are the third determinant of reserve demand. Such costs make it less profitable for banks to take in liabilities and invest in reserves. Higher balance sheet costs shift the reserve demand curve down.[8] As illustrated in the figure, market equilibrium can involve r<IOR. This can happen when banks can earn interest on reserves, but other investors cannot. In particular, in the US context, money market funds and government-sponsored enterprises do not have access to interest-bearing reserves. Banks may then engage in arbitrage, borrowing from these investors and investing in reserves, but balance sheet costs reduce banks' willingness to compete for funds, potentially resulting in a market-clearing interest rate r that is below the IOR. This will happen if ϕ> v_R'(Reserves,Deposits).

Within our framework, the central bank affects the market equilibrium interest rate via the setting of the IOR (which affects the vertical position of the demand curve) and via the supply of reserves. Below we will provide empirically estimated "iso-federal funds curves" that illustrate combinations of the IOR and reserve (plus ONRRP) supply that lead to a given predicted federal funds rate. To ensure that the market interest rate clears in a desired range, it is furthermore common for central banks to have facilities where financial institutions can borrow from or lend to the central bank. Private-sector use of these facilities changes the

[8] Historically, the main determinant of reserve demand was reserve requirements. However, during the post-GFC period with large reserve supply and interest on reserves, banks hold many more reserves than required. Reserve requirements were set to zero in the US on March 26, 2020.

supply of reserves which keeps the market-clearing interest rate in the desired range most of the time, with any deviations driven by the speed of private sector actions and any stigma of borrowing from the central bank. We illustrate this in Figure 3, Panel B, where the Federal Reserve controls short market interest rates via its administered rates (the interest rates on reserves, overnight reverse repo facility, and the discount window) and reserve supply.

Starting with the ceiling, the discount window allows depository institutions to borrow from the Federal Reserve at the primary credit rate. Banks borrow reserves, so discount window take-up *increases* reserve supply. Suppose reserve supply initially was such that the market clearing interest rate r exceeded the primary credit rate (in the figure, the market was clearing above the point A_{low}). Banks would have an incentive to borrow at the primary credit rate and invest at r. Their doing so would increase reserve supply to the level S_{low}. If banks react quickly, r will never exceed the primary credit rate for long. If there is a stigma to borrowing at the discount window, r can exceed the primary credit rate by the amount of the stigma (in interest rate terms).

Turning to the floor, a broad set of non-bank financial institutions can invest at the Federal Reserve using the ONRRP facility.[9] When they do so, their ONRRP take-up *decreases* reserve supply dollar-for-dollar, as the sum of reserves plus ONRRP take-up is set by the Federal Reserve's chosen balance sheet size (assets) minus the autonomous factors on the Federal Reserve's balance sheet. Suppose reserve supply initially was such that the market clearing interest rate r was below the ONRRP rate (in the figure, the market was clearing below the point A_{high}). Money market funds and GSEs would have an incentive to invest at the ONRRP rate rather than in the market alternative earning r. As a result, reserve supply would fall to the level S_{high}. If money market funds react fast, r will not fall below the ONRRP rate for long.

In laying out this framework, we have been deliberately vague about which market interest rate r the framework applies to. When deciding to hold reserves, banks can fund such holdings with a host of liabilities. In that sense, there is not one but many reserve demand functions. The reserve demand function defined relative to a particular liability shows banks' willingness to pay to borrow using that liability and invest in reserves, as a function of the amount of reserves. We illustrate this in Figure 3, Panel C, with separate reserve demand functions for borrowing via federal funds and via repo funding. Federal funds and repo differ in that collateral must be posted in repo borrowing. There is a cost to having to post collateral, which in practice comes from lost revenue from securities lending and is captured by the $w()$-function. The marginal cost of posting collateral shifts down the reserve demand curve defined relative to repo (as it

[9] Eligible counterparties include primary dealers, banks, money market mutual funds, and government sponsored enterprises. Since the ONRRP interest rate has always been below the interest rate on reserves, banks in practice will invest in reserves, not ONRRP.

makes banks' less eager to hold reserves funded with repo). From the perspective of monetary policy, both reserve demand curves are important because they determine market interest rates of importance to the Federal Reserve. The Federal Reserve targets the equilibrium rate in the federal funds market. The rate on private sector repo matters for the Federal Reserve because it is what the Federal Reserve can control directly via the ONRRP facility.

The reserve market and interest control framework laid out above differs from that in prior work such as Ihrig, Senyuz and Weinbach (2020), illustrated in Appendix Figure 1 (this work in turn build on earlier work including Goodfriend (2002)). Ihrig et al (2020) assume that the demand curve flattens out horizontally as it approaches the primary credit rate and as it approaches the ONRRP rate. This implies that interest rate control is achieved partly by these two rates directly controlling the shape of the demand curve. Instead, our framework features a regular downward sloping demand curve along which the marginal value of additional reserves declines with reserve holdings. This reserve demand curve is affected by the IOR, but not directly by the primary credit rate or the ONRRP rate. Instead, these two rates drive the private sector's incentives to take actions that affect reserve supply, thereby keeping the equilibrium rate in the corridor between the primary credit rate and the ONRRP rate. One can thus think of our reserve demand function as capturing the banking sector's marginal value of reserves (i.e., the interest rate the banks would be willing to pay to borrow fund to invest in reserves), before any consideration of central bank borrowing and lending facilities. If the marginal value is above the primary credit rate or below the ONRRP rate, then these facilities will be important. Our framework can thus speak to drivers of take-up in the Fed facilities, an issue of particular importance currently given the large take-up at the ONRRP facility. It also emphasizes that deposits constitute an important demand curve shifter. The fact that banks demand reserves to manage deposits is central in the literature on monetary policy with scarce reserves but recent work on the ample reserves setting has not accounted for deposits as a demand-shifter.

Figure 4 illustrates potential drivers of ONRRP take-up. When thinking about ONRRP take-up, the relevant reserve demand function is the one defined relative to the private repo market interest rate r (in practice, the secured overnight financing rate SOFR is a commonly used measure). Panel A shows that ONRRP take-up can result from an increase in reserve supply. The reserve supply increase could result from balance sheet expansion or a reduction in one of the autonomous factors among Federal Reserve liabilities. As illustrated in Figure 2, the Treasury General Account fell sharply in 2021, a period where ONRRP take-up increased correspondingly. To understand the link between reserve supply and ONRRP take-up, start at point A in Figure 4, Panel A. Suppose that reserve supply is increased from S to S^{new}, leading to an equilibrium at B. Faced with a market rate below the ONRRP rate, investors in short-term money markets (notably money market funds) will move funds from private repo to the ONRRP facility. As a result, reserve supply falls from S^{new} to S_{high} and the market equilibrium moves to A_{high}, at which point ONRRP take-up equals S^{new}-S_{high}. This illustrates how any increase in reserve supply above S_{high} will be converted to ONRRP by non-bank investors because banks' willingness to pay to borrow from these investors and invest in reserves is lower than what the investors can earn at the ONRRP facility.

Figure 4, Panel B illustrates how a reduction in reserve demand is a second potential driver of ONRRP take-up. This could be due to a series of factors: A lower IOR, a decline in deposits, an increase in banks' balance sheet costs, or an increase in the cost of posting collateral in repos. In terms of balance sheet costs, US banks were granted relief from the Supplementary Leverage Ratio (SLR) rules from April 1, 2020, to March 31, 2021. During this period, calculations of capital needed under the SLR omitted Treasuries and reserves. The expiration of SLR relief lines up well with the timing of increased ONRRP take-up in the spring of 2021, as illustrated in Figure 2. To see the link between reserve demand and ONRRP take-up, suppose the equilibrium in Figure 4, Panel B was initially at point *A*. Following a downward shift in reserve demand, the equilibrium moves to point *B* where *r* is below the ONRRP rate. As a result, short-term money market investors will invest less in private repo and instead invest at the ONRRP facility. This moves the equilibrium to A_{high}^{new} where ONRRP take-up equals S-S_{high}^{new} and reserve supply has been reduced by the same amount.

Finally, Figure 4 Panel C shows how ONRRP take-up could result from the Federal Reserve deciding to increase the ONRRP rate, leaving the IOR unchanged. Suppose the equilibrium was initially at A_{high} with some ONRRP take-up. An increase in the ONRRP rate to ONRRP rate^{new} would result in additional ONRRP take-up of S_{high}-S^{new} with reserve supply decreasing by that amount.[10]

4. Reserve demand estimation

We turn next to estimating the reserve demand function for the US in monthly data for 2009M1-2022M10. We address identification issues, discuss the main input series and the need to control for deposits, and then present our estimated return demand function. We use IV estimation and provide both a structural form and a reduced form reserve demand function.

[10] The Federal Reserve increased both the ONRRP rate and the IOR on June 17, 2021. This would not directly lead to increased ONRRP take-up as both the reserve demand curve and the ONRRP rate shifts up by the same amount. It could indirectly increase ONRRP take-up by lowering bank deposits via flows to money market funds, as tend to take place in times of higher rates due to banks not increasing deposits rates one-for-one with the Federal Reserve's administered rates. In practice, only a small fraction of the increased ONRRP take-up in 2021 happened around June 17, 2021.

a. Identification

Estimation of equation (5) by OLS will lead to consistent parameter estimates if reserve demand shocks (the error term, u) are uncorrelated with reserve supply and with deposits.

Are reserve exogenous? Reserves are exogenous if reserve supply does not accommodate reserve demand shocks not controlled for in the regression via deposits. From the Federal Reserve balance sheet in Table 1,

$$\text{Reserves}=\text{Assets}-\text{Autonomous factors}-\text{ONRRP} \quad (8)$$

where Autonomous factors=Currency+TGA+Other. For reserve exogeneity, it would thus be sufficient that each of the three components on the right-hand side of (8) are uncorrelated with the reserve demand shocks in (5):

(1) Assets: The Federal Reserve must set the size of its asset holdings to target other objectives than the reserves market. This is likely to be satisfied as balance sheet policy (QE/QT) targets inflation and employment rather than control over short-term rates.

(2) Autonomous factors: These must move unrelated to any reserve demand shocks included in u. This is plausible due to the deposit control. For example, if a household pays its federal taxes using deposits, this increases the TGA (as the government receives the funds) and lowers reserves (as the household's bank pays the government using reserves and correspondingly debits the household's deposit balance). By not changing its asset size in response to tax payments, the Federal Reserve accommodates a negative demand shock for reserves. Crucially, however, this does not lead to a correlation of reserve supply with u because the negative shock to reserve demand is explicitly captured by controlling for deposits.

(3) ONRRP take-up: This must be zero or uncorrelated with reserve demand shocks. As shown in Figure 2, ONRRP take-up is modest up to March 2021. After this, ONRRP take-up grows and may be correlated with demand shocks. As shown in Figure 4, Panel B, a negative demand shock can drive up ONRRP take-up. This condition is thus unlikely to be satisfied.

Given that condition (3) may not hold, reserves are not exogenous. However, under condition (1) and (2), the sum of reserves and ONRRP is exogenous. We therefore instrument reserves by reserves+ONRRP and estimate equation (5) by IV. We conduct the estimation at the monthly frequency using monthly averages of the available data. The use of monthly (as opposed to daily) data helps to remove the effect of possible endogeneity of reserves+ONRRP associated with high-frequency demand shocks such as those occurring on high payment-flow days.[11] Intuitively, if reserve demand is systematically higher on some days of the month and this is accommodated by the Federal Reserve, then this will lead to higher average reserves+ONRRP in monthly data but will not lead to endogeneity problems in monthly data.

We next turn to whether deposits are exogenous. One could think of factors that would drive a correlation between deposits and the error term u in (5). For example, perhaps deposits are more volatile (on a per dollar basis) when they are larger or smaller, and deposit volatility affects reserve demand. Then deposit volatility would be an omitted variable, causing deposits to be correlated with u. While this is possible, we think it is unlikely to be a material issue and therefore do not instrument for deposits in our baseline estimation. We then provide a robustness check in which we instrument deposits with household financial assets and the level of the interest rate on reserves to show that this leads to very similar results (we will motivate these instruments for deposits below).

The advantage of not instrumenting for deposits in our baseline specification is that deposit data are available with only a short lag while household financial assets are available (from the Financial Accounts of the United States) only with a lag of several months. A reserve demand estimation that does not rely on instrumenting for deposits can thus be updated in real time. This is an advantage for real-time policy making.

b. The main series and the importance of controlling for deposits

We use the FRED database data to obtain all the inputs into our reserve demand estimation. Figure 5 provides a time series plot of the Reserves/GDP ratio and the EFFR-IOR spread using monthly average data since 2009.[12] The policy-induced variation in Reserves/GDP is apparent with the series increasing around the times of QE1, QE2, QE3, after September 2019 (as the FOMC increased reserves due to reserve scarcity) and with the COVID-related LSAPs. Following the end of the QE rounds, Reserves/GDP falls due to a combination of lower reserves and higher nominal GDP.

The Reserves/GDP ratio has a clear negative relation with the EFFR-IOR spread, consistent with the above-described reserve demand framework. However, the relation is unstable in that the EFFR-IOR spread is higher in the later part of the sample for a given Reserves/GDP value. In particular, the EFFR-IOR spread

[11] Describing banks' time-varying demand for reserves, Judson and Klee (2009) explain that "Payment flows tend to be elevated at month-start, mid-month, the twenty-fifth of the month, month-end, and on days after holidays, owing in part to corporate tax due dates, principal and interest payments on securities, and pent-up flows after a long weekend."

[12] We calculate monthly averages from weekly data for reserves and daily data from EFFR-IOR. We assume that GDP was the same across months within the quarter.

is substantially above zero in September 2019 for Reserves/GDP around 7%, in contrast to a negative EFFR-IOR spread in December 2010, when the Reserves/GDP was also around 7%.

To further illustrate the reserve demand function instability when not controlling for deposits, Figure 6 provides scatter plots of the EFFR-IOR spread against ln(Reserves) (Panel A) and Reserves/GDP (Panel B). We have labeled the data points that precede reserve expansions as well as the final data point of our sample, 2022M10. The reserve demand curve appears flatter when reserves expand than when they contract (though the last year of the sample is an exception to this pattern). We will argue, however, that this fact does not mean that there is something fundamentally different about reserve expansions and reserve contractions. Instead, there is an omitted variable that increases reserves demand over time leading to the observed expansion-contraction pattern. This results in a relation that looks like an unstable Phillips curve. Just like time-varying inflation expectations make the Phillips curve unstable if inflation expectations are not considered, time-varying deposits make the reserve demand curve unstable when deposits are not accounted for, and deposits have been increasing (even relative to GDP) over the period since 2009.

Figure 7 illustrates the increase of deposits as a share of GDP over time. The left figure graphs deposits held with all commercial banks relative to nominal GDP, showing a sharp increase starting around 2000. Over the period of ample reserves since 2009, Deposits/GDP increase from 50% in 2009M1 to 68% in 2022M10. The right figure shows various types of deposits. The increase in overall deposits is driven by an increase in demand deposits and other liquid deposits (which include savings accounts). As liquid deposits require more reserve backing (for both economic and regulatory reasons) this fact is particularly pertinent to understanding the instability of reserve demand over time when deposits are not considered.[13]

The fact that deposits is a central driver of reserve demand is common across various types of banking. In *narrow banking*, required reserves equal deposits as deposits are backed one-for-one by reserves. In *fractional reserve banking*, required reserves equal a fraction of deposits. In a scarce reserves version of fractional reserve banking, the central bank restricts the supply of reserves to manage bank lending. Our framework is for the more recent setting of *ample reserves banking,* where reserve demand is driven by the liquid and safe nature of reserves as laid out above.

c. Baseline estimation of the reserve demand function for the US

Table 2, Panel A presents the second stage of our IV estimation of the reserve demand function in equation (5) for the period 2009M1-2022M10, with ln(Reserves) instrumented by ln(Reserves+ONRRP). Table 2,

[13] For simplicity, we use total deposits in our specification. Results are similar if we omit time deposits and focus on demand and other liquid deposits which account for the majority of deposits over our sample (as documented in Figure 7).

Panel B shows the first stage of the IV estimation. Not surprisingly ln(Reserves+ONRRP) is a strong instrument for ln(Reserves), with a t-statistic above 10 and a first-stage R^2 as high as 0.96. Table 2, Panel C shows the reduced form of the IV estimation which simply regresses the EFFR-IOR spread directly on the exogenous variables (ln(Reserves+ONRRP) and ln(Deposits) in this baseline approach where we assume ln(Deposits) is exogenous). *t*-statistics are adjusted for autocorrelation in the residuals in all panels.

In Table 2, Panel A, the EFFR-IOR spread is estimated to be significantly related to both ln(Reserves) and ln(Deposits) with the expected signs and large *t*-statistics (*p*-values below 1 percent). In economic terms, a 10% increase in reserves (an increase in supply tracing out a downward sloping demand curve) lowers the EFFR-IOR spread by 2 basis points. Interpreted within our theoretical framework, this suggests that the marginal value of additional reserves v_R' declines only very slowly with reserves. Another way to state this finding is to calculate the resulting reserve demand semi-elasticity γ in (7). The estimated value of b=-0.2 corresponds to γ=-5, implying that a 10 basis point reduction in the EFFR-IOR spread (making the market rate lower relative to reserves), entices banks to increase reserve holdings by 50 percent. Reserve demand is thus highly elastic with respect to the EFFR-IOR spread. The coefficient on log deposits in Table 2, Panel A, is positive, consistent with the idea that higher deposits increase the marginal value of additional reserves, v_R'. In terms of (7), the estimation implies that the elasticity of reserve demand with respect to deposits is $\beta = -\frac{c}{b} = -\frac{-0.358}{0.2}$ =1.79. A value of β above one means that a one percent increase in deposits leads to more than a one percent increase in reserves and thus that banks invest a higher fraction of deposits in reserves at higher levels of deposits. In our framework, $\beta>1$ means that c exceeds b and thus that v_R' is more sensitive (in absolute value) to log deposits than to log reserves (see equation (4)).

The reduced form estimation in Table 2, Panel C, is useful for understanding the empirical fit of our framework, i.e., how much explanatory power ln(Reserves+ONRRP) and ln(Deposits) have for the EFFR-IOR spread. We find a regression R^2 of 0.895.[14] Figure 8, Panel A illustrates the tight relation between the EFFR-IOR spread and the predicted value from the regression in Table 2, Panel C. Our estimation also implies that there should be a tight link between the EFFR-IOR spread and a measure of supply (ln(Reserves+ONRRP)) adjusted for deposits. The reduced form specification is

$$r(FF) - r(Reserves) = A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits) + U \qquad (9)$$

Rewriting (9) as

[14] To ensure to the high R^2 in Table 2, Panel C, is not simply due to trends in the data, we have also estimated the same relation using 12-month differences. This still results in a high R^2 of 0.72.

$$r(FF) - r(Reserves) = A + B * \left[\ln(Reserves + ONRRP) + \frac{C}{B} * \, ln(Deposits) \right] + U \quad (10)$$

shows that "deposit-adjusted supply" $ln(Reserves + ONRRP) + \frac{C}{B} * \, ln(Deposits)$ should be tightly linked to the EFFR-IOR spread. We illustrate this relation in Figure 8, Panel B, graphing both the EFFR-IOR spread data and the fitted value based on deposit-adjusted supply calculated using the parameter estimates from Table 2, Panel C. The relation between the EFFR-IOR spread and deposit-adjusted supply appears stable over the 2009M1-2022M10 period. Consistent with the usefulness of our framework for understanding the EFFR-IOR spread, September 2019 has the lowest value for deposit-adjusted supply and the highest value of the EFFR-IOR spread. The high EFFR-IOR spread in September 2019 is therefore not surprising once the increasing need for reserves due to higher deposits are accounted for. Given the growth in deposits from 2010 to 2019, a value of Reserves/GDP of 7% was much less accommodative than the same value of Reserves/GDP in 2010.

Figure 8, Panel C repeats Figure 8, Panel B, without taking the log when calculating deposit-adjusted supply. We present this to show that the EFFR-IOR spread has a convex relation to supply when not taking logs, consistent with our graphical framework in Figure 3 where we implicitly assumed that the marginal value of additional reserves fell at a slower rate at higher reserve levels. The tight relations in Figure 8, Panel B and C, contrasts sharply with the unstable relation between the EFFR-IOR spread and reserves shown in Figure 6.

d. Recovering the structural reserve demand shock

We can use the estimated demand curve in Table 2, Panel A to assess whether negative unobserved demand shocks may have contributed to the large take-up at the ONRRP facility since spring 2021. This possibility was illustrated in Figure 4, Panel B. Expressing the estimated demand curve with quantity as dependent variable as in equation (6) and calculating

$$\varepsilon = e^{-u/b} \quad (11)$$

using the estimates of u and b from Table 2, Panel A, we obtain Figure 8, Panel D. The figure shows that the multiplicative reserve demand component fell from around 1.2 in March 2021 (when ONRRP take-up started to increase) to below 0.8 toward the end of the sample. Given reserves around \$3.7T in March 2021, a drop of 0.4*\$3.7T amounts to \$1.5T, which accounts for the majority of the increase in ONRRP take-up. A large negative reserve demand shock reconciles a substantial decline in reserves at the same time as the EFFR-IOR spread has fallen and while deposits have remained fairly stable.

We can only speculate about reasons for the large negative reserve demand shock. One possibility is that banks have become less worried about sudden reductions in deposits as deposits have remained high post-COVID.

e. Robustness: Instrumenting for deposits

An understanding of the drivers of deposits is useful because it may suggest instruments for deposits and it may help predict deposits and thus reserve demand going forward.

Basic portfolio theory implies that deposits should depend on (a) household financial assets and (b) the portfolio weight allocated to deposits as households allocate financial assets between cash-like assets such as deposits, and higher-return assets such as bonds, stocks, mutual funds, etc. The deposit portfolio weight in turn would be expected to depend on the spread between market rates on deposit alternatives and the rate on deposits (a spread that captures the opportunity cost of holding deposits). This spread tends to increase with the level of market interest rates as these have less than full passthrough to deposit rates (e.g., Drechsler, Savov and Schnabl (2017)).

In Figure 9, Panel A, the left graph documents a sharp increase in the ratio of the financial assets of households and non-profits to GDP over our sample period 2009M1-2022M10. The right graph shows that households and non-profits have chosen a remarkably stable portfolio weight for deposits of around 15% over this period.

As a robustness check on our baseline estimates from Table 2, Table 3 presents the corresponding three panels of results when we instrument for both ln(Reserves) (as before) and ln(Deposits). We use the log of the financial assets of households and non-profits as our first instrument for deposits. As our second instrument for deposits, we use the level of short-term interest rates, measured by the IOR. We use the IOR rather than the deposit rate-IOR spread because the latter is affected by banks' deposit setting behavior which could potentially be correlated with reserve demand shocks. Armed with two instruments for deposits, we can perform a test of overidentifying restrictions to assess the validity of the deposit instruments. Since financial assets of households and non-profits are available quarterly (from the U.S. Financial Accounts, Table B.101, line 9), the estimation in Table 3 is done at the quarterly frequency, using data for the last month of the quarter for EFFR-IOR, ln(Deposits) and IOR (using monthly averages as in our earlier analysis).

A comparison of the results in Table 3, Panel A to those in Table 2, Panel A shows that the estimated parameters of the reserve demand function are similar whether deposits are instrumented for or not. Using the Sargan test of over-identifying restrictions, we find an insignificant *p*-value of 0.29, supporting the exogeneity of the instruments for ln(Deposits). The modest difference between our baseline regression in Table 2 and Table 3 suggests that deposit endogeneity is not a substantial factor bearing on our baseline estimation. Table 3, Panel B, shows that the first stage for ln(Deposits) is strong, with ln(Financial assets) being a particularly strong instrument, but the IOR also entering significantly. The estimated coefficient on ln(Financial asset) is around one, consistent with the stable portfolio weight over the sample period. The interest-sensitivity of deposits is -0.035, implying a decrease in deposits of 3.5% for a 100 bps increase in the interest rate. Figure 9, Panel B, illustrates the ability of the instruments to explain variation in ln(Deposits). The fit is tight, with the exception that deposits have not declined following the drop in financial assets in 2022Q2. Table 3, Panel C, shows the reduced form of the IV estimation where we instrument for both ln(Reserves) and ln(Deposits). The R^2 is over 90%, illustrated by the tight fit of this reduced form, which we graph in Appendix Figure 2.

Our discussion of drivers of deposits in the period since the financial crisis is related to that in Acharya and Rajan (2022) and Acharya, Chauhan, Rajan and Steffen (2022). Acharya and Rajan (2022) argue theoretically that higher reserve supply causes the banking sector to issue more liquid claims, including deposits and credit lines. When central banks do QE, banks must hold the additional reserve supply in equilibrium and banks have an incentive to fund reserves with liquid short-term liabilities. These liabilities have low interest rates (relative to other sources of funds, or other assets that could be reduced) and reserves enable banks to manage the liquidity risks from additional liquid liabilities. Their framework thus centers on banks' willingness to *supply* deposits. Acharya et al (2022) test this hypothesis empirically. They provide evidence based on regressing deposit growth on reserve growth in time-series and panel data. We find little role for reserves driving deposits when we include drivers of households' *demand* for deposits. Appendix Table 1, Panel A, column (3), shows that in a horse-race between deposit supply drivers (reserves) and deposit demand drivers (financial assets and the IOR), reserves enter with a *negative* sign. Focusing on liquid deposits, the effect of reserves on deposits is modest when financial assets and the IOR are included, see column (6). The additional explanatory power for ln(Deposits) from adding ln(Reserves) is small, compare column (5) and (6). Acharya et al (2022) use a specification in changes. Similar conclusions emerge from adding household financial assets and the level of interest rates to that specification, as shown in Appendix Table 1, Panel B, where reserves have no significant explanatory power for either deposits or liquid deposit once financial assets and the IOR are included. Of course, QE may have been an important driver of household financial assets in the post-GFC period, but that still puts emphasis on deposit demand, not deposit supply. An additional argument against QE being the main driver of increased deposits, is that in Figure 7 (left), the growth in deposits started around 2000, much before the start of QE in late 2008. Furthermore, while both Deposits/GDP and Reserves/GDP increase in 2020, this increase in deposits may be more related to lockdowns (limiting spending), fiscal stimulus, and increased risk aversion due to COVID-19 than to banks enticing customers with attractive deposits rates to fund their reserve holdings.

Regardless of whether deposits have gone up due to increased deposit supply or increased deposit demand, we agree with Acharya et al (2022) that high deposits make QT harder because they increase banks' reserve demand. We turn next to the implications of our estimated reserve demand function for interest rate control and for estimating feasible QT, given current deposits.

5. Implications of reserve demand for interest rate control

With a downward sloping reserve demand function, the equilibrium Effective Fed Funds rate-IOR spread is decreasing in reserve supply. Therefore, to achieve a desired value for the Effective Fed Funds rate, the Federal Reserve needs to set a lower IOR for a smaller balance sheet than for a larger balance sheet.

Figure 10 illustrates the predicted value for the Effective Fed Funds rate-IOR spread as a function of the supply of Reserves+ONRRP given the current level of deposits. The prediction is based on equation (9), using the parameter estimates for A, B and C from Table 2, Panel C, and deposits of $17.753T as of 2022M10.[15] Reserves+ONRRP is varied from $100B to $7,000B. Observed reserves+ONRRP data for our sample 2009M1-2022M10 range from $662B to $5,811B, indicated by grey shading. The predicted spread is 37 bps higher at the lower end of this range than at the upper range. Accordingly, to achieve a given predicted effective federal funds rate value, the IOR needs to be set 37 bps lower at the lower end of the balance sheet range. In other words, a given predicted effective federal funds rate value can be achieved with a host of balance sheet size-IOR combinations, with lower IOR values needed for smaller quantities of reserves+ONRRP. We denote combinations of IOR and Reserves+ONRRP that imply a chosen predicted effective federal funds rate as *iso-federal funds curves*, using the terminology introduced by Bianchi and Bigio (2022) in a theoretical analysis in a different setup than ours. In our setting, along an iso-federal funds curve with a predicted effective fed funds rate of X:

$$X - r(Reserves) = A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits)$$

which implies

$$r(Reserves) = X - [A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits)] \quad (12)$$

Figure 11 shows our estimated iso-federal funds curves as of 2022M10 (deposits of $17.753T) for X=2% (left) and X=4% (right). To our knowledge these are the first empirically estimated iso-federal funds curves

[15] Predicted EFFR-IOR= -2.193-0.172*ln(Reserves+ONRRP)+0.367*ln(17753)

in the literature. The Federal Reserve can use these curves to guide the setting of the IOR for given balance sheet size. Other central banks could estimate corresponding curves for their jurisdictions.

6. Implications of reserve demand for quantitative tightening

Section 6.a uses our reduced form reserve demand estimation to assess feasible reduction in reserves+ONRRP. Section 6.b suggest that current ONRRP take-up also provides useful information about how much reserves+ONRRP can be tightened. Section 6.c emphasizes that the autonomous factors on central bank balance sheets can be volatile, implying that it would be prudent to run down the central bank's assets by less than the amount of feasible reduction in reserves+ONRRP.

a. Baseline approach

Our reduced form estimation in Table 2, Panel C can be used to guide the feasible reduction in the supply of reserves+ONRRP. As discussed in section 5, for any potential choice of the level of reserves+ONRRP, the reduced form provides a predicted EFFR-IOR spread given the current level of deposits. Figure 12, Panel A repeats the exercise from Figure 10, adding a set of vertical lines marking reserves+ONRRP values of interest. Figure 12, Panel B scales the x-axis by GDP. As of October 2022, reserves+ONRRP was $5.274T (monthly average), amounting to about 20.4% of GDP, illustrated by the rightmost vertical lines in the graphs in Figure 12.[16] Three possible counterfactual levels of Reserves+ONRRP are of particular interest, illustrated by the leftmost vertical lines in Figure 12, Panel A and B.

1. Reserves+ONRRP equal to $1.806T (7% of GDP)

In the previous episode of balance sheet runoff ending in September 2019, the FOMC took actions that lowered (reserves+ONRRP)/GDP to around 7%. As of October 2022, this would correspond to reserves+ONRRP of $1.806T. Our estimated reserve demand function predicts that at this level the EFFR-IOR spread would be 11 bps. This counterfactual is illustrated further in Figure 13. The predicted EFFR-IOR spread of 11 bps would be substantially higher than any values of the spread observed in-sample. The high predicted spread is due to the much higher level of deposits currently (in dollars and as a percent of GDP) than during the last policy normalization cycle. Reserves of $1.806T would therefore result in a historically low (in the period since 2009M1) value of deposits-adjusted supply of reserves+ONRRP.

Does the high predicted value of the EFFR-IOR spread at reserves+ONRRP of 7% of GDP imply that reducing reserves+ONRRP to this level is undesirable? As discussed in Section 5, faced with a high EFFR-IOR spread, the Federal Reserve could adjust the IOR to a lower value to try to ensure that EFFR clears

[16] GDP data for 2022Q4 are available as of time of writing. We assume a monthly GDP growth rate in October 2022 equal to the average monthly GDP growth rate from 2022Q2 to 2022Q3.

near a particular desired value. For any given federal funds rate target (or target range mid-point), the IOR would need to be set about 11 bps below the target to make the EFFR clear at a chosen Fed funds target, on average over the month. However, as illustrated in Figure 1, a high EFFR-IOR has been associated with daily yield spikes in EFFR and especially in repo rates. Reserves+ONRRP of $1.806T would be a risky choice from the perspective of money market stability as deposit-adjusted reserves+ONRRP supply would be much below that in September 2019. The new Standing Repo Facility may help prevent yield spikes at such levels of liquidity supply, but it remains untested.

2. *Reserves+ONRRP equal to $2.840T (11.0% of GDP): Would lead to the same deposit-adjusted reserves+ONRRP as that in September 2019*

In September 2019, deposit-adjusted reserves+ONRRP (i.e., ln(Reserves+ONRRP)+(C/B)*ln(Deposits)), amounted to -12.97. Given deposits of $17.753T as of the end of our sample in 2022M10, deposit-adjusted reserves+ONRRP would equal -12.97 for reserves+ONRRP of $2.840T (corresponding to 11.0% of GDP). This is the predicted level of reserves at which large daily yield spikes may emerge, based on the estimated reduced form reserve demand function and the experience from September 2019 and the months leading up to it.

3. *Reserves equal to $3.495T (13.5% of GDP): A more conservative choice, at which the predicted EFFR-IOR spread is zero*

As an example of a more conservative reduction in reserves+ONRRP, the value of reserves+ONRRP at which the predicted EFFR-IOR spread is 0 is $3.495T as of 2022M10. From Figure 13, this compares to a predicted spread of 4 bps in September 2019 and would thus be a bit less risky in terms of money market stability. A spread of zero is special in that at spreads above zero, banks are holding reserves despite being able to earn more by lending in the federal funds market, suggesting some level of liquidity scarcity.

Overall, our estimated reserve demand function (the reduced form) can be used to guide policy tightening both in terms of the setting of the IOR relative to the mid-point of the target range and in terms of evaluating which amount of reduction in reserves+ONRRP is likely to be risky in terms of money market stability. The above calculations are done for a specific value of deposits, that prevailing in October 2022. As deposits change, so will the reserves+ONRRP level that leads to a given predicted EFFR-IOR spread. This level of reserves+ONRRP can be calculated from equation (9), as estimated in Table 2, Panel C, updating the deposit level from the 2022M10 value. Therefore, one should not think of there being one particular value of reserve+ONRRP supply that will deliver a given amount of tightness of liquidity in money markets. To understand reserve demand going forward, it will be important to monitor the development of deposits. Predicting the evolution of deposits is difficult given its dependence on financial assets which are volatile as well as the fact there is some variation in the portfolio share for deposits. Furthermore, QT may itself affect deposits. As the Federal Reserve reduces its bond holdings during QT, someone else must hold more bonds in equilibrium. This may reduce deposits, if households buy bonds or transfer deposits to bond funds or transfer deposits to money market funds who in turn fund hedge fund bond purchases via repo lending. To the extent that deposits fall, more QT is possible.[17]

In related work, Afonso, Giannone, La Spada and Williams (2021) estimate a reserve demand function in which the EFFR-IOR spread is modeled as a function of the ratio of reserves to banks' total assets. They work with daily data and instrument the reserve-to-asset ratio by the forecast error for this variable 5 days prior, using a VAR to obtain the forecast error. The idea is that the forecast error predicts reserves but will be uncorrelated with reserve demand shocks 5 days later if demand shocks tend to resolve in less than 5 days. Their estimation allows for a time-varying effect (β) of the reserves-to-asset ratio on the EFFR-IOR spread. They estimate β to be significantly negative in 2010-2011 and 2018-2019 but close to zero from 2012-2017, in the 2nd half of 2020, and in 2021. Their results imply that a negative (β) starts to emerge at reserves around 12% of banks' total assets. To compare that with our results, observe that in October 2022, banks' total assets amount to \$22.6T. Reserves of 12% of banks' total assets would thus come to \$2.7T.

We calculate the feasible reserves+ONRRP value as opposed to the feasible reserve value because the Federal Reserve controls reserves+ONRRP while the split between reserves and ONRRP is determined also by the setting of the ONRRP rate and the shape of banks' reserve demand function. If, as would be expected, reductions in reserves+ONRRP first reduce ONRRP take-up to zero, before generating much reduction in reserves, then by the time reserves+ONRRP take-up is reduced to the number in one of our three scenarios, ONRRP is close to zero. Our calculation is then comparable to that of Afonso et al (2021). Their \$2.7T number is close to the number \$2.840T (11.0% of GDP) that we calculate would generate the same deposit-adjusted reserves+ONRRP supply as that in September 2019. Our approach and that of Afonso et al rely on different methodologies. We exploit lower frequency (mainly QE/QT induced) movements in reserves and use a functional form for reserves demand where constant parameters appear to provide a good fit across the 2009M1-2022M10 period. Afonso et al rely on daily reserve variation. On the basis of the functional form that they specify for the reserve demand function, their β parameter is estimated to be time-varying. Despite the different approaches, a key lesson common to both papers, is that running down

[17] It is possible that deposits are unaffected as reserves+ONRRP is reduced. Suppose that ONRRP take-up falls one-for-one with reduction in reserves+ONRRP. Money market funds are the largest investor at the ONRRP facility. If they choose to invest in private repo instead of ONRRP, this could facilitate higher bond holdings on the part of hedge funds, with hedge funds replacing the Federal Reserve as a bond investor. In this case, deposits are unaffected by lower reserves+ONRRP.

reserves to 7% of GDP, as was done in the last policy normalization episode, is likely to lead to strains in short-term money markets.

b. ONRRP take-up as a guide to feasible reduction in reserves+ONRRP

As a complementary approach, the amount of ONRRP take-up is potentially informative for assessing feasible reduction in reserves+ONRRP. This is illustrated in Figure 14. ONRRP take-up is positive because the Federal Reserves's supply of reserves+ONRRP (the black vertical line) is larger than the amount of reserves banks demand when the market interest rate *r* equals the ONRRP rate (the red vertical line). The ONRRP facility "mops up" the excess supply of reserves+ONRRP, thereby ensuring that the market rate (i.e., the rate on private repo) does not fall below the ONRRP rate. This suggests that if the reserves+ONRRP supply was reduced by the amount of the current ONRRP take-up, the market rate would stay at *r*=ONRRP rate, reserves would be unchanged (with the reserve market clearing at point A_{high} throughout) and ONRRP take-up would fall to zero. Given ONRRP take-up of $2.2T in October 2022, this suggests that a correspondingly large reduction in reserves+ONRRP is possible, without lifting the private repo rate above the ONRRP rate floor. Some additional reduction in reserves+ONRRP is possible before the private repo rate exceeds the IOR. Potential effects of balance sheet reduction on deposits are again a complicating factor.

A simple message from this complementary approach to assessing feasible QT is that one should take a reduction of ONRRP take-up toward zero as a signal that markets are getting close to the point at which the rate on private repo starts to exceed the ONRRP rate. This approach is not able to speak to how much additional reduction in supply is possible past that point before the market interest rate-IOR spread exceeds a particular value.

c. Accounting for volatility in the autonomous factors

From the Federal Reserve's balance sheet in Table 1,

$$\text{Reserves+ONRRP=Assets-Autonomous factors} \tag{13}$$

This implies that it is prudent to run down assets only to the point that fluctuations in autonomous factors will not result in reserves+ONRRP below the value assessed to be feasible value (e.g., below *$3.495T* in our third option in section 6.a). The needed buffer to account for volatility in the autonomous factors depends on the risk aversion of the decision maker and the expected volatility in the autonomous factors going forward. A buffer of several hundred billion dollars does not seem unreasonable given recent TGA volatility. The large recent fluctuations in the Treasury General Account is visible in Figure 2.

In Figure 15, we zoom in on year 2019 to illustrate the negative relation between reserves+ONRRP and the TGA. Based on our framework, the underlying reasons for the yield spikes of September 2019 was lower supply of reserves+ONRRP (due to QT) and growth in the size of the banking sector (higher deposits). However, the "final straw" that reduced reserves+ONRRP enough to create yield spikes on September 17, 2019, was an increase in the TGA due to corporate tax payments and Treasury issuance on September 16, 2019 (see Anbil, Anderson and Senyuz (2020)). The TGA increase is visible in Figure 15 as a sharp increase in the blue line around September 17, 2019.

6. Conclusion

Understanding reserve demand is central for achieving interest rate control and assessing feasible QT. We develop a new framework for reserve demand in which it is driven by three main factors: The interest rate spread between short-term money market rates and the IOR, the convenience yield on reserves (due to reserves being valuable for managing deposit flows), and bank balance sheet costs (which limit banks' ability to arbitrage spreads by borrowing at market rates and investing at the IOR). Our framework differs from recent work on reserve demand in an ample-reserves setting by the shape of the reserve demand function, by clarifying how take-up at Federal Reserve facilities helps control reserve supply, and by having a central role for deposits (and other short-term bank liabilities) as a reserve demand shifter.

Empirically, reserve demand is negatively related to the EFFR-IOR spread with a semi-elasticity of -5 over the 2009M1-2022M10 period. We document a stable reduced form for the reserve demand curve once deposits are accounted for, finding a tight negative relation between the EFFR-IOR spread and deposit-adjusted reserves+ONRRP supply. Our estimation exploits monthly variation and assumes that most of the variation in reserves+ONRRP supply at the monthly frequency is not due to reserve supply accommodating demand shocks but instead driven by monetary policy, notably the rounds of quantitative easing and tightening over the sample.

Our estimated reserve demand function can be used to guide policy tightening both in terms of the setting of the IOR relative to the mid-point of the target range and in terms of assessing how much reserves+ONRRP supply can be reduced before a liquidity shortage may emerge. Our estimated reduced form implies that due to increasing deposits (even relative to GDP), liquidity strains may emerge much before reserves+ONRRP was reduced to 7% of GDP as was done during policy normalization leading up to September 2019. Based on two complementary approaches, we assess that a reduction in reserves+ONRRP by at least $2T appears feasible, though the evolution of deposits, the value of the Standing Repo Facility and volatility in the autonomous balance sheet factors makes for substantial uncertainty in this assessment.

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Appendix 1. Micro founding the convenience yield on reserves

Consider the setup from section 2, adding detail on the bank's liquidity management problem.

Suppose deposits may change and that net deposit outflows, as a fraction of the initial deposit level, is a random fraction $\tilde{F}$ of deposits, with $\tilde{F}$ distributed uniform(-k,k), with k≤1.

Assume that deposit outflows met using reserves incur no transactions costs while deposit outflows that cannot be met using reserves must be made by reducing holdings of bonds. Suppose that selling bonds results in transactions costs TC(Amount sold), where $TC(x)=\delta * x^2$, an increasing and convex function.

For given Reserves (R) and Deposits (D), bonds sold is then a random variable max($\tilde{F}$D-R,0) resulting in transactions costs being a random variable $\widetilde{TC}=\delta*[\max(\tilde{F}D-R,0)]^2$. Therefore,

$$E(\widetilde{TC}) = \int_{-k}^{k} \delta[\max(FD-R,0)]^2 f(F)dF = \int_{\frac{R}{D}}^{k} \delta(FD-R)^2 \frac{1}{2k} dF \quad \text{(A1)}$$

$$= \frac{\delta}{2k}\left[\frac{1}{3D}(FD-R)^3\right]_{\frac{R}{D}}^{k} = \frac{\delta}{2k}\frac{1}{3D}(kD-R)^3 \quad \text{(A2)}$$

Define the function *v(Reserves,Deposits)* as expected transactions costs savings from holding reserves: *v(Reserves,Deposits)=-*$E\left(\widetilde{TC}(Reserves, Deposits)\right)$. It follows from (A2) that the marginal convenience benefit from reserves is positive (saved transactions cost)

$$v_R'(Reserves, Deposits) = -\frac{\partial E(\widetilde{TC})}{\partial R} = \frac{\delta}{2k}\frac{1}{D}(kD-R)^2 > 0 \quad \text{(A3)}$$

while the marginal convenience benefit from deposits is negative (additional transactions costs)

$$v_D'(Reserves, Deposits) = -\frac{\partial E(\widetilde{TC})}{\partial D} = -\frac{\delta}{2k}\left[\frac{k}{D}(kD-R)^2 - \frac{1}{D^2}\frac{1}{3}(kD-R)^3\right] \quad \text{(A4)}$$

$$= -\frac{\delta}{2k}\frac{1}{D}(kD-R)^2\left[k - \frac{1}{3D}(kD-R)\right] = -\frac{\delta}{2k}\frac{1}{D}(kD-R)^2\left[\frac{1}{3D}(2kD+R)\right] < 0 \quad \text{(A5)}$$

As for the second derivatives, it follows from (A3) that $v_R'(Reserves, Deposits)$ is decreasing in reserves and increasing in deposits:

$$v_R''(Reserves, Deposits) = -\frac{\delta}{k}\frac{1}{D}(kD-R) < 0 \quad \text{(A6)}$$

for R<kD and

$$v_{R,D}''(Reserves, Deposits) = \frac{\delta}{2k}\frac{(kD-R)}{D}\frac{(kD+R)}{D} > 0 \quad \text{(A7)}$$

for R<kD.

Equation (A3) can be expressed as

$$v_R'(Reserves, Deposits) = \frac{\delta}{2k}\frac{1}{\exp(lnD)}(\mathrm{k} * \exp(\mathrm{lnD}) - \exp(\mathrm{lnR}))^2 \qquad \text{(A8)}$$

A first-order Taylor approximation around values $\mathrm{lnD_0}$ and $\mathrm{lnR_0}$ gives

$$v_R'(Reserves, Deposits) \approx \frac{\delta}{2k}\frac{1}{D_0}(\mathrm{k}D_0 - R_0)^2$$

$$-\frac{\delta}{k}\frac{1}{D_0}(\mathrm{k}D_0 - R_0)^{*}R_0 * [lnR - lnR_0]$$

$$+\frac{\delta}{2k}\frac{(\mathrm{k}D_0 - \mathrm{R})}{D_0}\frac{(\mathrm{k}D_0 + \mathrm{R})}{D_0}D_0 * [lnD - lnD_0] \qquad \text{(A9)}$$

which is the micro-founded version of (4) in Result 1.

We note that our micro foundations for the expected transactions costs are related to those of Frost (1971). He models banks' demand for excess reserves in an environment with no interest on reserves and assumes that banks face a fixed cost of adjusting their securities holdings, along with a constant variable cost of adjustment. We model banks' demand in an environment with interest on reserves and assume quadratic adjustment costs for securities. In both settings, the expected transactions costs savings from reserves lower their yield relative to other assets.

Table 1. Federal Reserve balance sheet, October 26, 2022

The table is based on data from the Federal Reserve's H.4 release.

Assets ($B)		Liabilities ($B)	
Treasuries	5,609	Reserves	3,108
MBS	2,679	Overnight reverse repurchase agreements	2,187
Other	485	Currency	2,285
		Treasury general account	557
		Other	636
	8,773		8,773

Table 2. Reserve demand estimation, instrumenting for reserves

Monthly data, 2009M1-2022M10. IV estimation. t-statistics are robust to autocorrelation up to order 12. *** indicates statistical significance at the 1% level.

Panel A. Second stage

	Dependent variable: (Effective federal funds rate-IOR)
ln(Reserves)	-0.200***
	(t=-10.44)
ln(Deposits)	0.358***
	(11.86)
Constant	-1.900***
	(-10.64)
N (months)	166

Panel B. First stage for ln(Reserves)

	Dependent. variable: ln(Reserves)
ln(Reserves+ONRRP)	0.860***
	(t=14.07)
ln(Deposits)	-0.049
	(-0.47)
Constant	1.467
	(1.64)
N (months)	166
R^2	0.960

Panel C. Reduced form

	Dependent. variable: (Effective federal funds rate-IOR)
ln(Reserves+ONRRP)	-0.172***
	(t=-18.78)
ln(Deposits)	0.367***
	(23.81)
Constant	-2.193***
	(-21.12)
N (months)	166
R2	0.895

Table 3. Reserve demand estimation, instrumenting for both reserves and deposits

Quarterly data (last month of the quarter), 2009Q1-2022Q2. t-statistics are robust to autocorrelation up to order 4. *** indicates statistical significance at the 1% level.

Panel A. Second stage

	Dependent variable: (Effective federal funds rate-IOR)
ln(Reserves)	-0.207***
	(t=-11.53)
ln(Deposits)	0.377***
	(12.92)
Constant	-2.025***
	(-11.62)
N (quarters)	54

Panel B. First stages for ln(Reserves) and ln(Deposits)

	Dependent variable: ln(Reserves)	Dependent variable: ln(Deposits)
ln(Reserves+ONRRP)	0.845***	-0.029
	(t=8.53)	(t=-0.85)
ln(Financial assets)	0.035	1.091***
	(0.24)	(20.65)
IOR	-0.010	-0.035***
	(-0.31)	(-2.62)
Constant	0.746	-2.671***
	(0.66)	(-7.43)
N (quarters)	54	54
R^2	0.971	0.987

Panel C. Reduced form

	Dependent. variable: (Effective federal funds rate-IOR)
ln(Reserves+ONRRP)	-0.198***
	(t=-17.57)
ln(Financial assets)	0.430***
	(21.87)
IOR	-0.020***
	(-4.88)
Constant	-3.378***
	(-23.02)
N (quarters)	54
R^2	0.905

Figure 1. Yield spikes in September 2019

Daily data, April 2018 to October 2022. The series graphed are the effective federal funds rate (the short-term market rate at which banks and government-sponsored enterprises lend to each other in the federal funds market), the Secured Overnight Financing Rate (a measure of the cost of borrowing cash against Treasury collateral using repo contracts), and the interest rate on reserves set by the Federal Reserve.

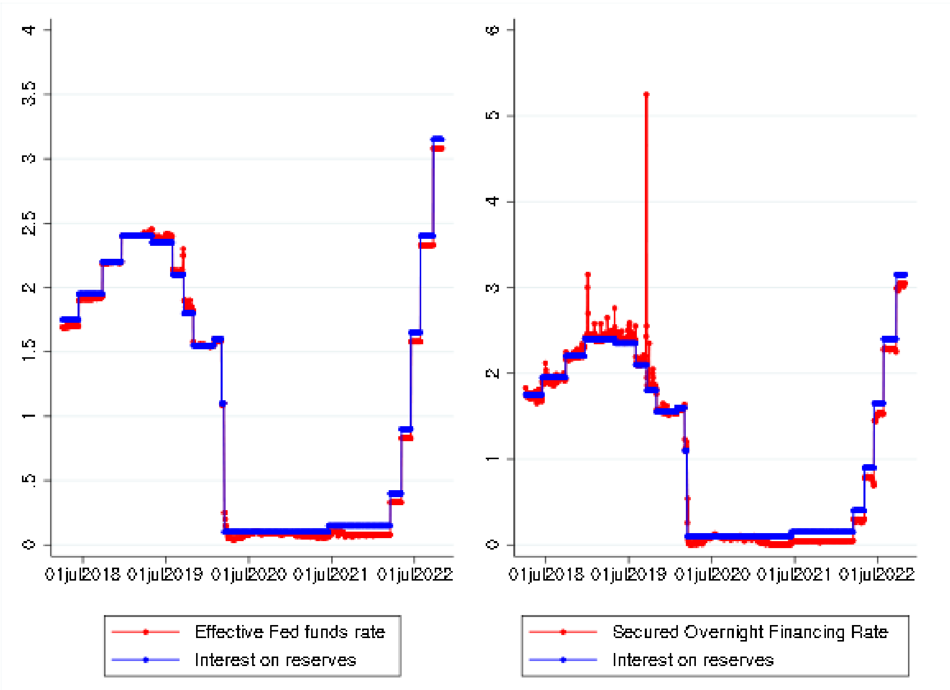


Figure 2. The Federal Reserve's balance sheet, 2006M1-2022M10

The figure is based on data from the Federal Reserve's H.4 release. Data are monthly averages.

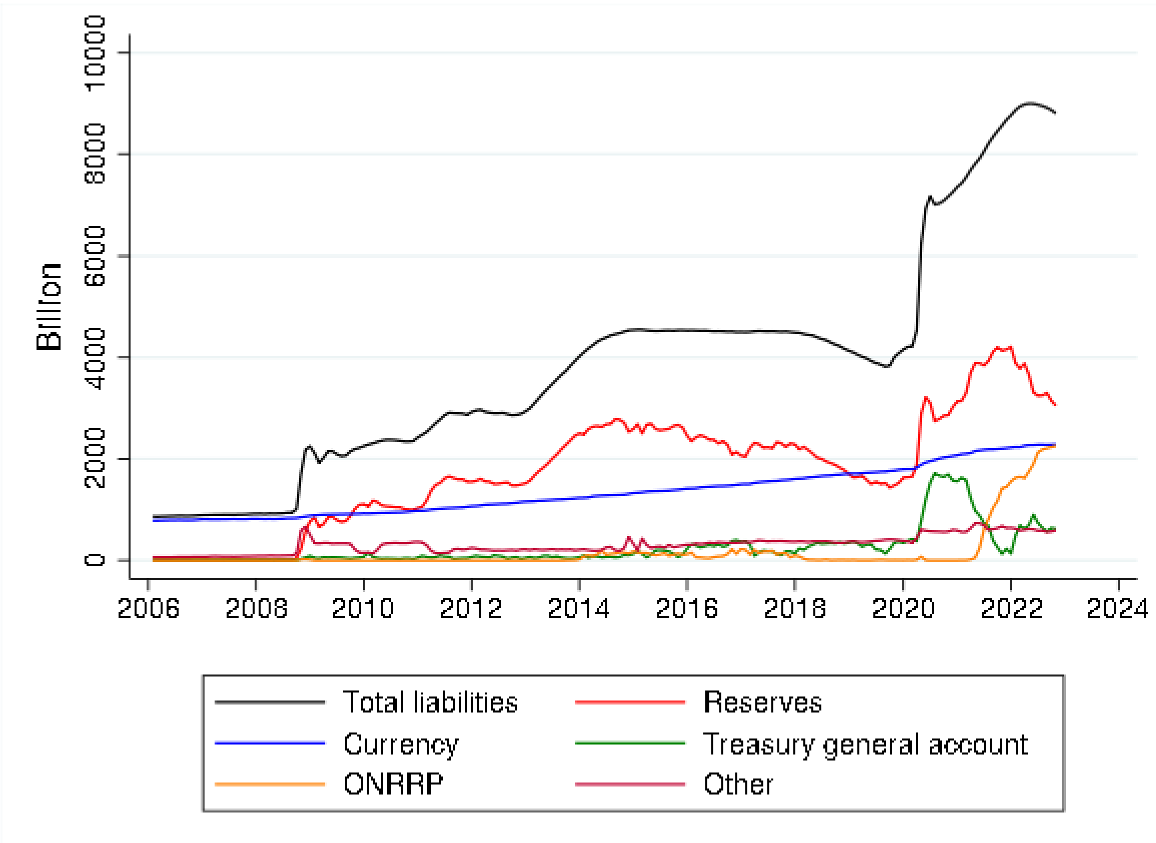
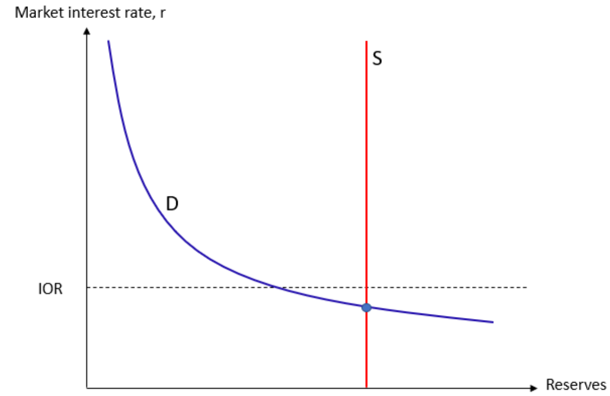
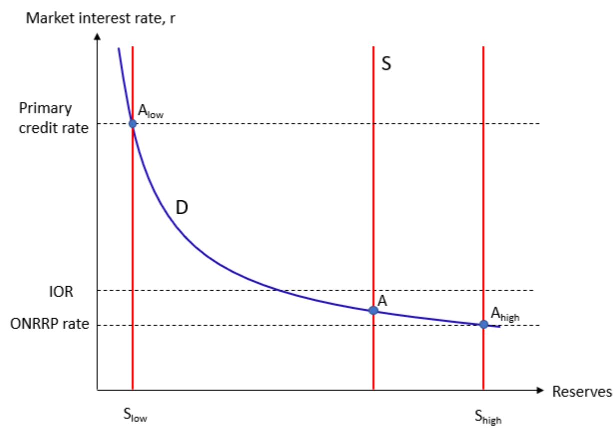


Figure 3. Graphical framework

Panel A. Reserve demand and supply



Panel B. Interest rate control



Panel C. Determination of different market interest rates

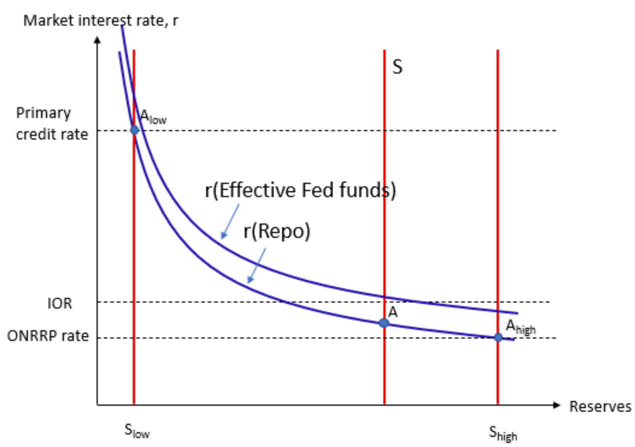
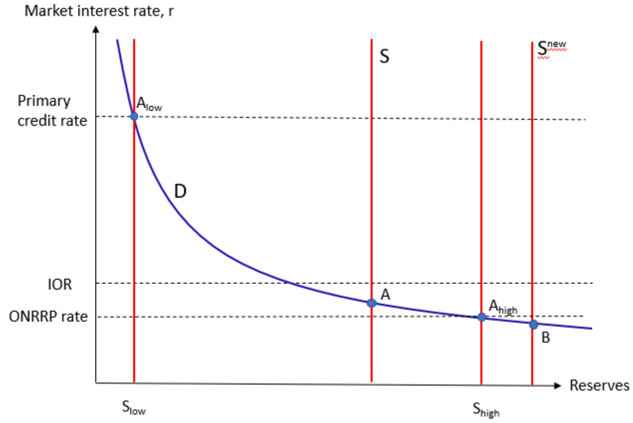
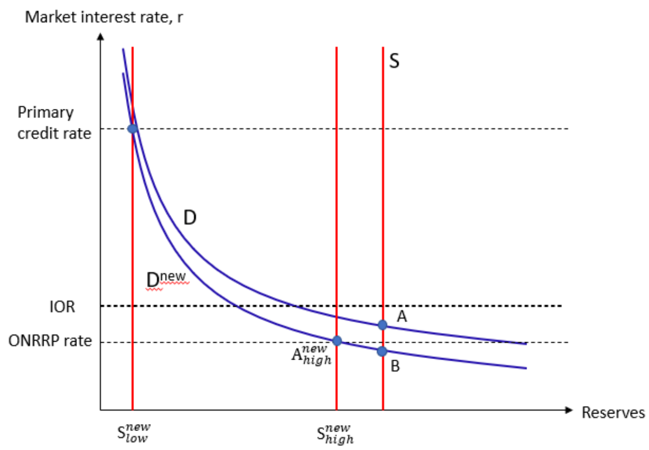


Figure 4. Potential drivers of ONRRP take-up

Panel A. Increased reserve supply (due to, e.g., a reduction in the Treasury General Account)



Panel B. Decreased reserve demand (due to, e.g., lower deposits or higher balance sheet costs)



Panel C. An increase in the ONRRP rate for given IOR

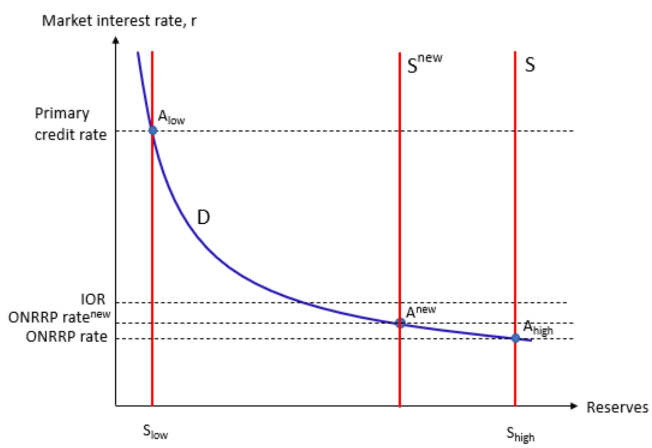


Figure 5. (Effective Federal Funds Rate)-IOR spread and Reserves-to-GDP, time series plot

Monthly data (averages), 2009M1-2022M10

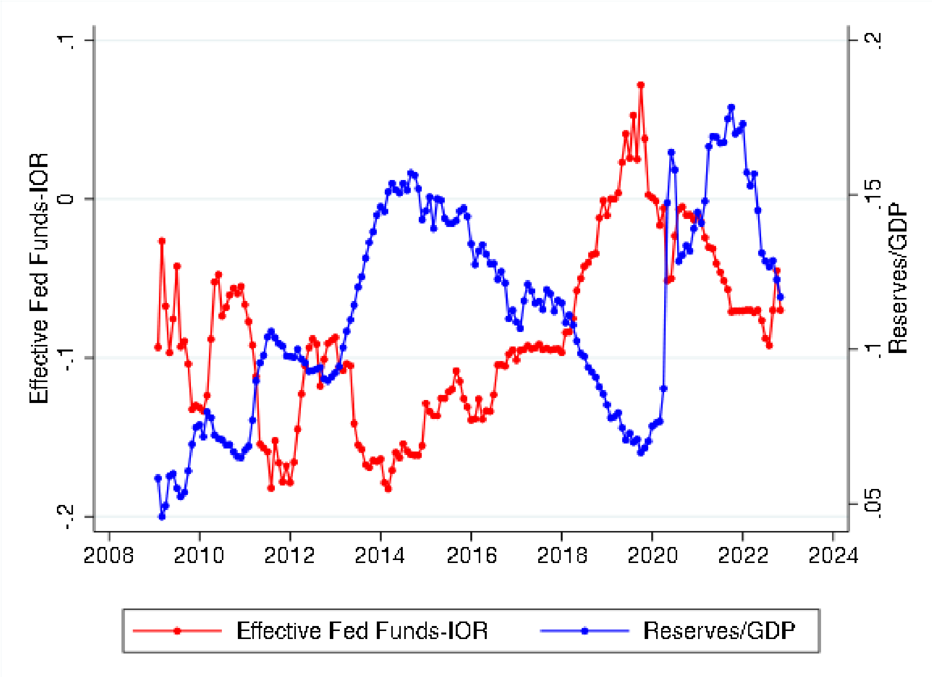
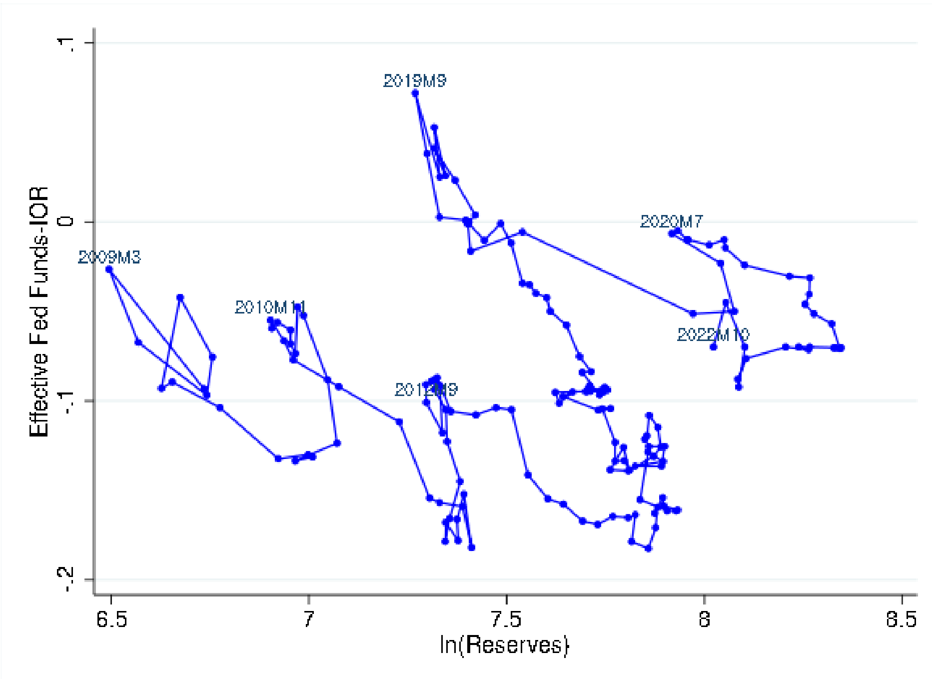


Figure 6. (Effective Federal Funds Rate)-IOR spread and Reserves, scatter plot

Monthly data, 2009M1-2022M10.

Panel A. Log reserves



Panel B. Reserves-to-GDP

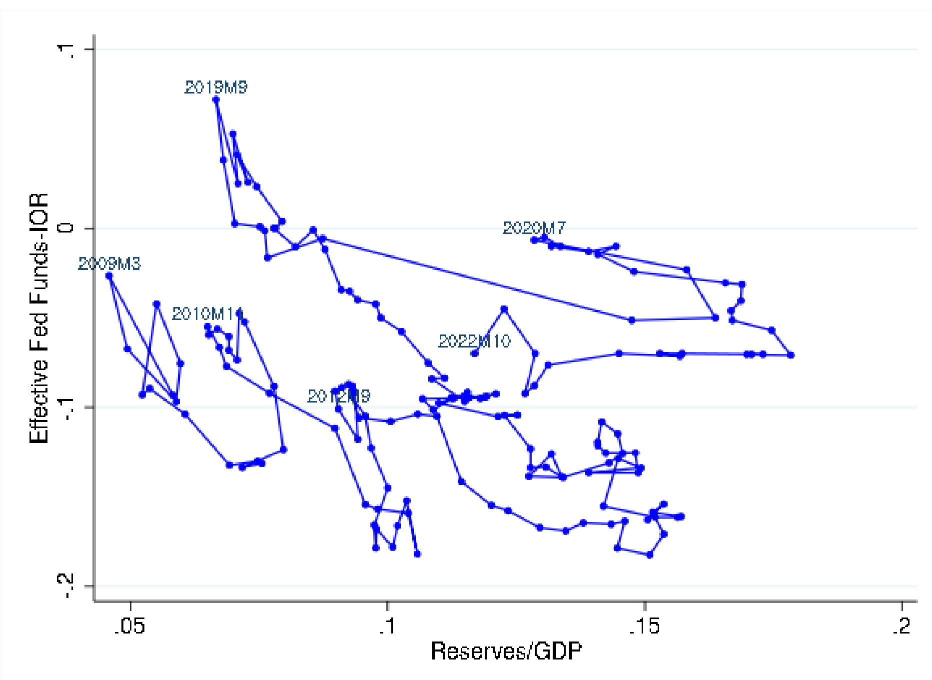


Figure 7. Deposits

In the left figure, deposits are for all commercial banks, from the Federal Reserve's H8 release (via FRED). The right figure is based on data from both the H8 and H6 releases, as noted. Data are monthly averages for 1986M1-2022M10 (left figure) or 1986M1-2022M9 (right figure).

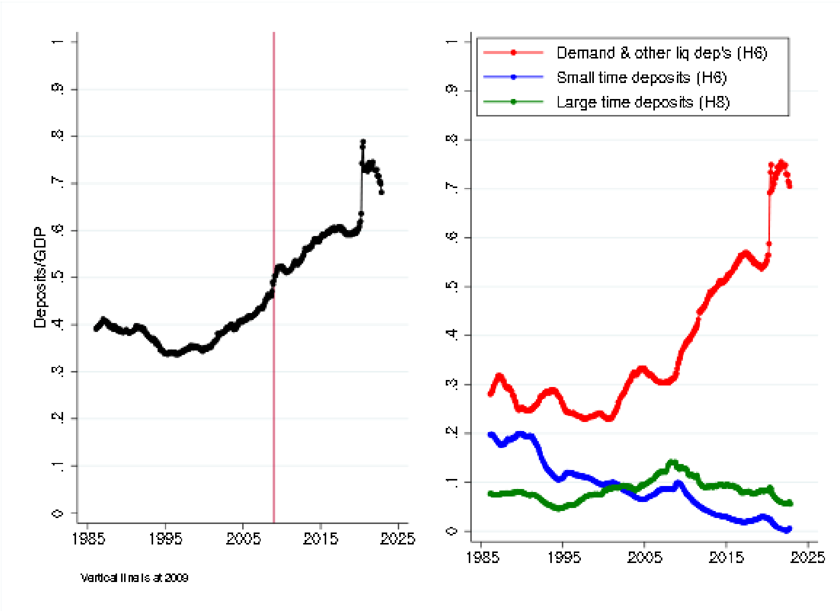
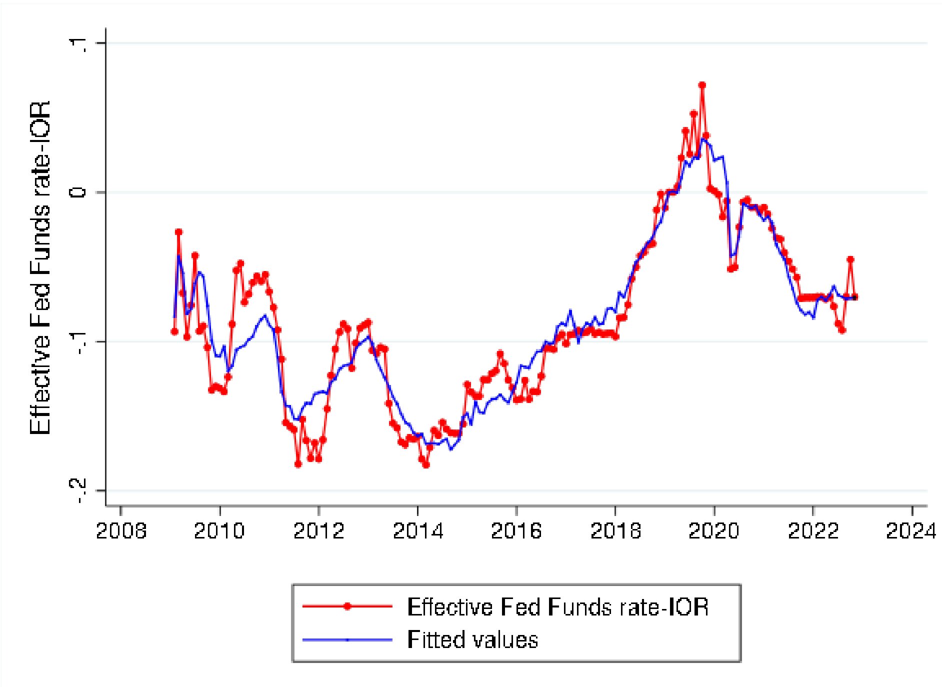


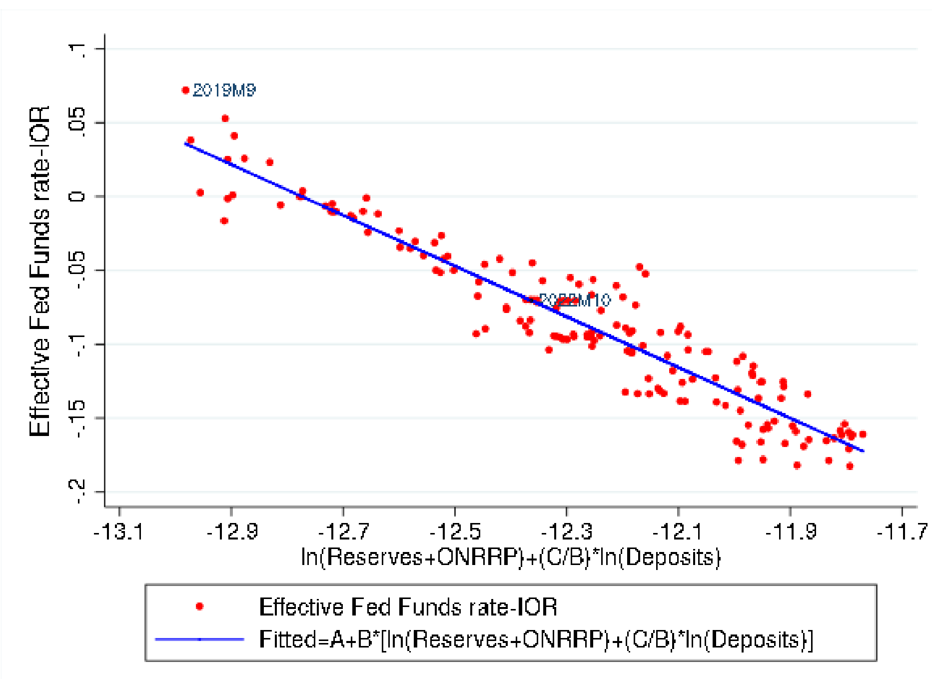
Figure 8. Fit of estimation

The fitted lines in both panels are based on the regression in Table 2, Panel C.

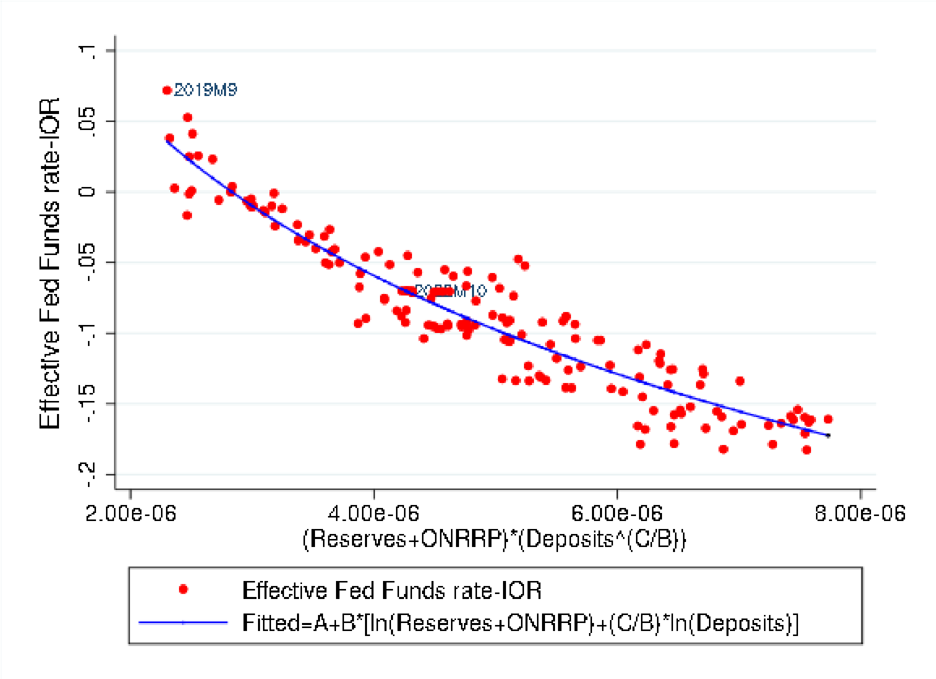
Panel A. Time series plot of (Effective Federal Funds Rate)-IOR spread and fitted values



Panel B. (Effective Federal Funds Rate)-IOR spread and fitted values as function of deposit-adjusted supply



Panel C. (Effective Federal Funds Rate)-IOR spread and fitted values as function of deposit-adjusted supply, non-log x-axis



Panel D. Estimated reserve demand shock

The figure is based on the reserve demand estimation in Table 2, Panel A. The vertical line indicates the end of March 2021.

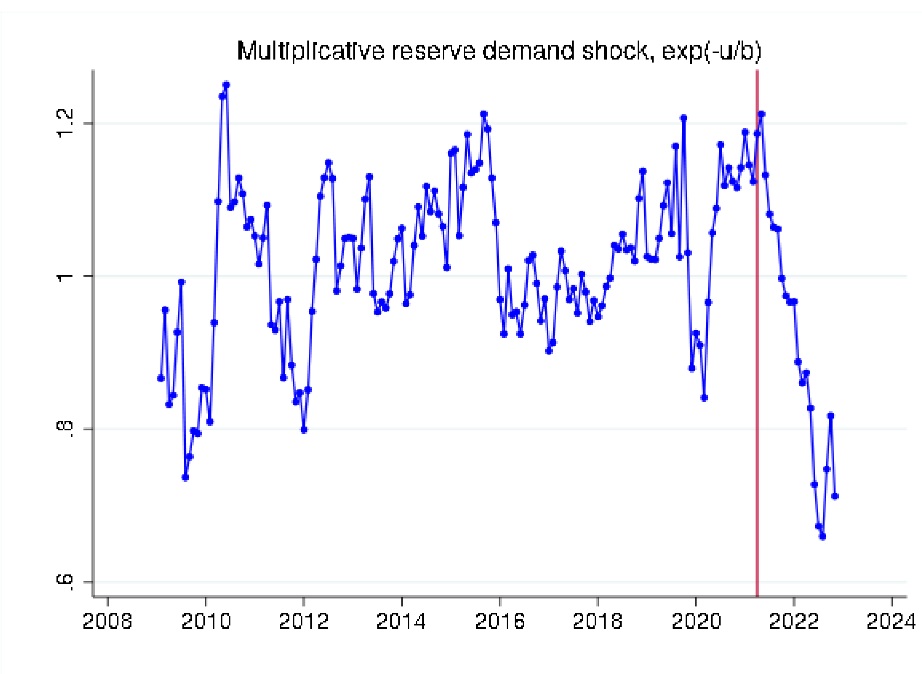
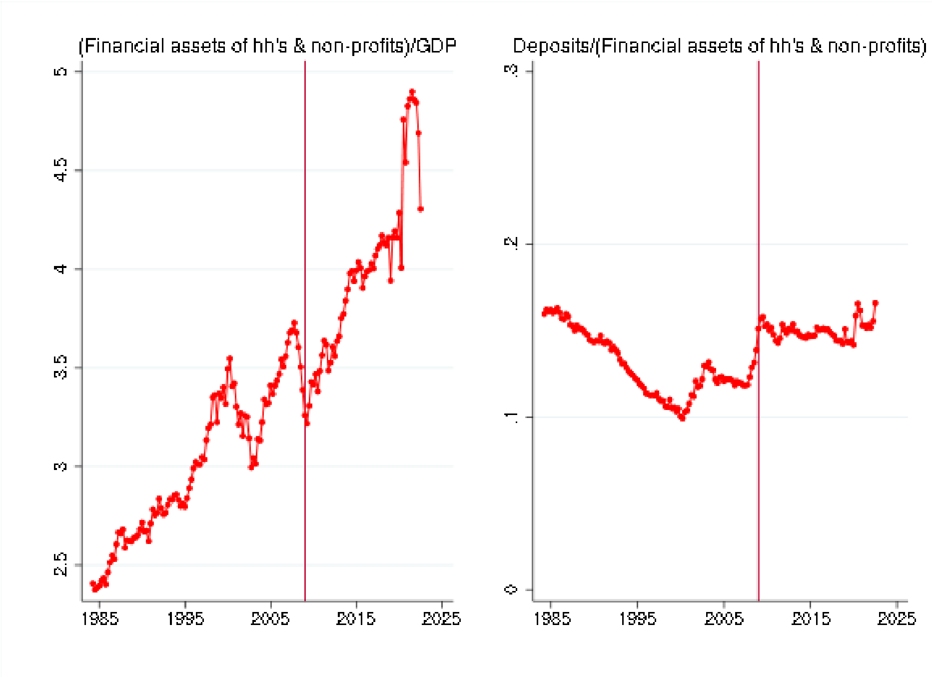


Figure 9. Deposit drivers

Panel A. Financial assets of households and non-profits as a driver of deposits

Values graphed are for the last month of the quarter, 2009Q1-2022Q2.



Panel B. Fit of deposit demand function estimation

Quarterly data (last month of the quarter), 2009Q1-2022Q2. The fitted line is based on the regression in Table 3, Panel B for ln(Deposits).

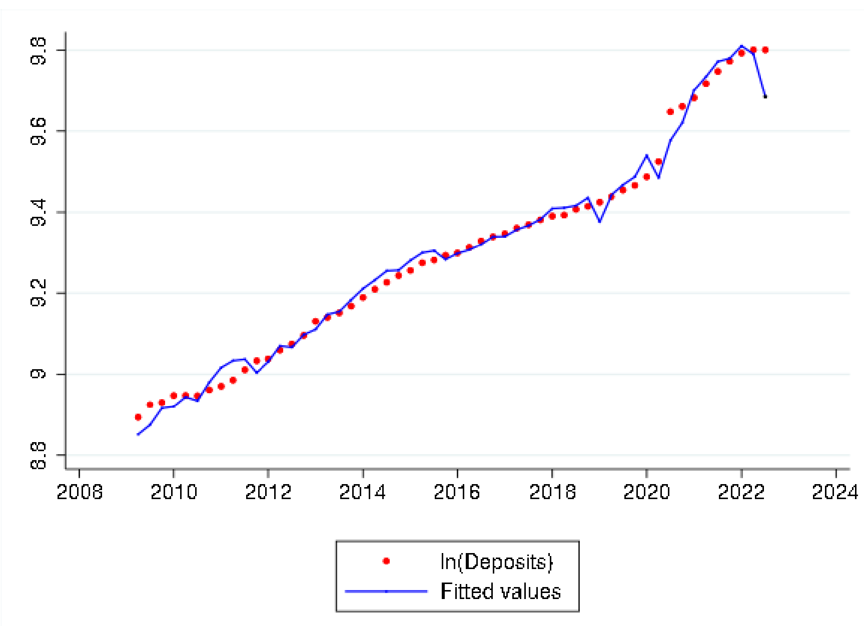


Figure 10. Predicted spread at current deposit level

The figure illustrates the predicted value for the Effective Fed Funds rate-IOR spread as a function of the supply of Reserves+ONRRP. The prediction is based on the estimated version of equation (9)

$$r(FF) - r(Reserves) = A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits)$$

using the parameter estimates for A, B and C from Table 2, Panel C, and deposits of \$17.753T as of 2022M10. Reserves+ONRRP is varied in increments of \$100B and Reserves+ONRRP graphed ranges from \$100B to \$7,000B. Observed Reserves+ONRRP data for our sample 2009M1-2022M10 range from \$662B to \$5,811B, indicated by grey shading.

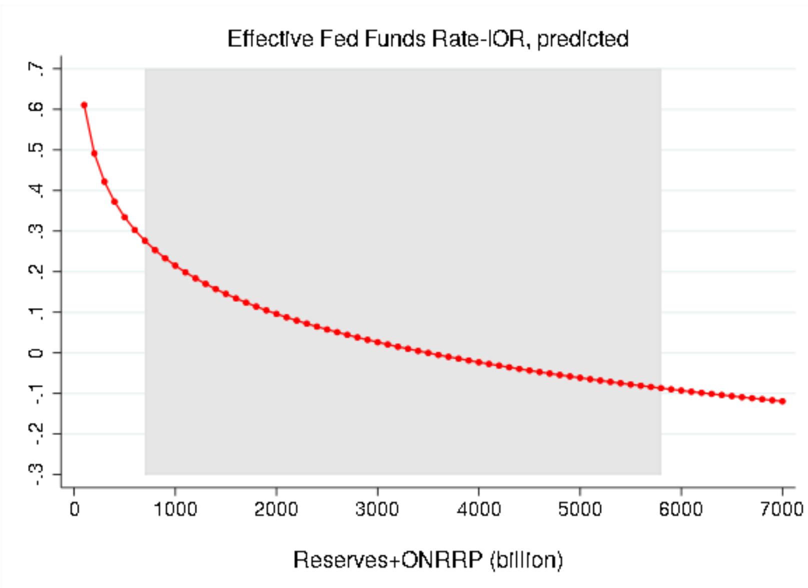


Figure 11. Iso-fed funds curves

The figures show combinations of IOR and Reserves+ONRRP which result in a predicted effective federal funds rate equal to a chosen value (2% in the left figure, 4% in the right figure). A given iso-fed funds curve is constructed from equation (9)

$$r(FF) - r(Reserves) = A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits)$$

which implies that along an iso-fed funds curve with a predicted effective fed funds rate of X:

$$r(Reserves) = X - [A + B * \ln(Reserves + ONRRP) + C * \ln(Deposits)]$$

We implement this using the estimated values for A, B and C from Table 2, Panel C, and deposits of \$17.753T as of 2022M10. Along a given iso-fed funds curve, Reserves+ONRRP is varied in increments of \$100B and Reserves+ONRRP graphed ranges from \$100B to \$7,000B. Observed Reserves+ONRRP data for our sample 2009M1-2022M10 range from \$662B to \$5,811B, indicated by grey shading.

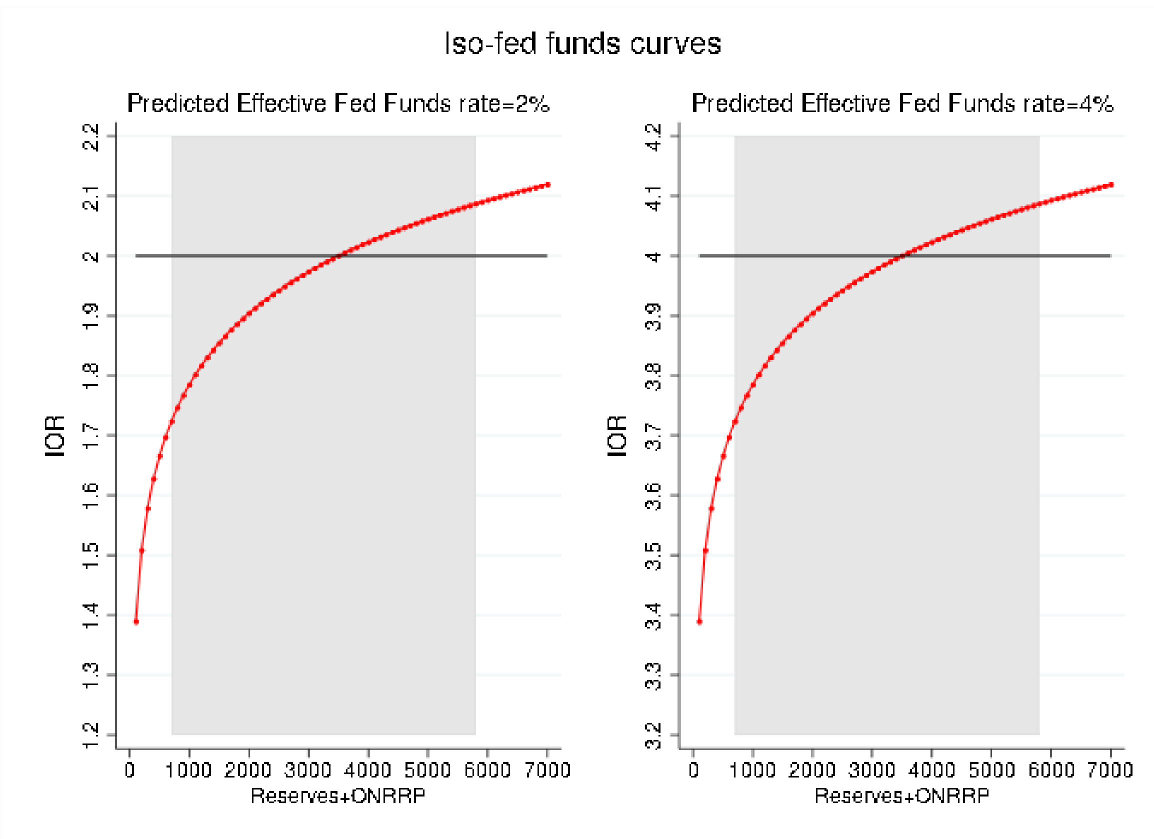


Figure 12. Balance sheet runoff counterfactuals

Panel A repeats Figure 10, focusing on the range of observed data and adding vertical lines for various values of Reserves+ONRRP: \$1,806B (7% of GDP), \$2,840 (same predicted value as in 2019M9), \$3,495B (predicted value of zero), and \$5,274 (the current value as of 2022M10).
Panel B repeats the exercise from Panel A but uses (Reserves+ONRRP)/GDP on the horizontal axis. Predicted values are still calculated as for Panel A. The vertical lines are at 0.07, 0.110 (same predicted value as in 2019M9), 0.135 (predicted value of zero), and 0.204 (the current value as of 2022M10).

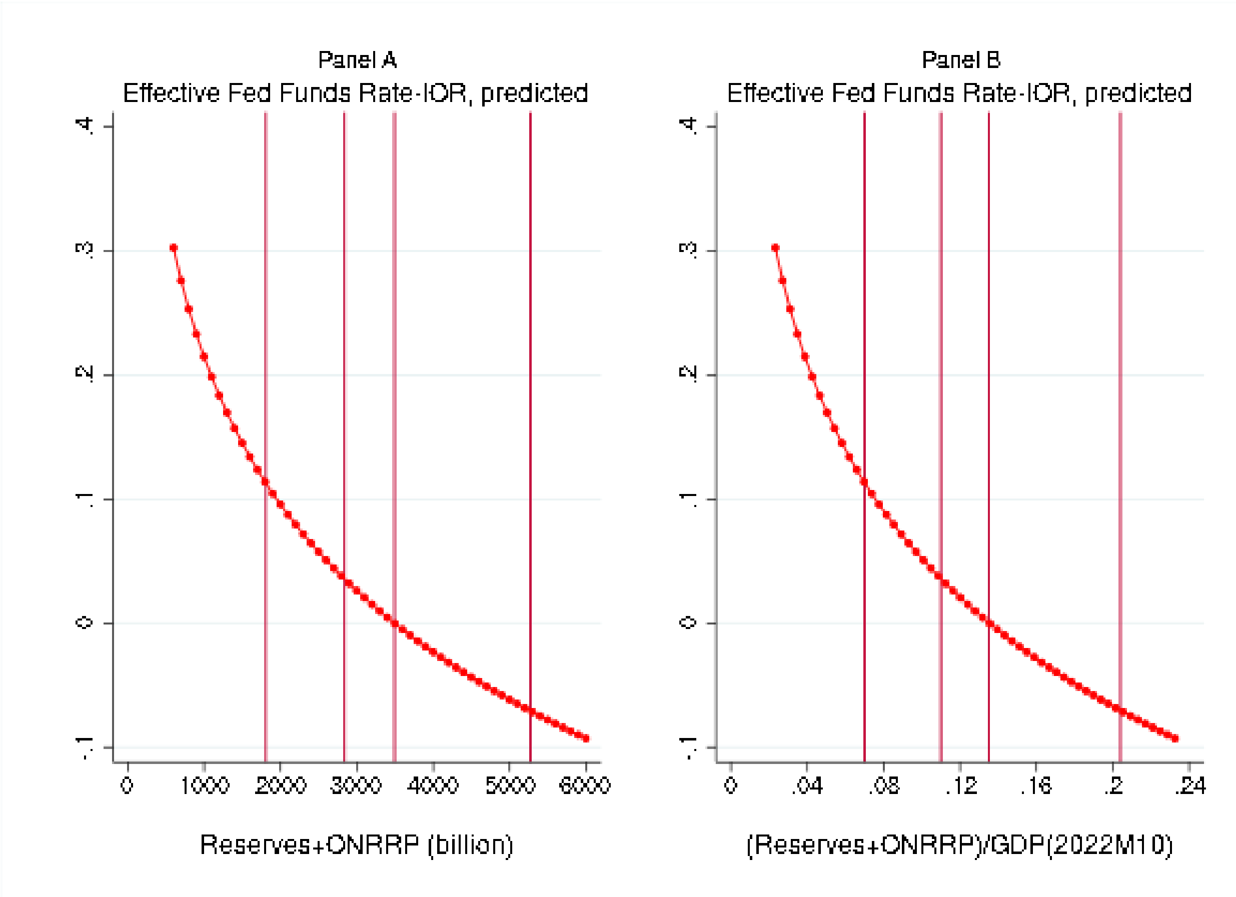


Figure 13. Counterfactual: Predicted (Effective Federal Funds Rate)-IOR spread for Reserves/GDP=0.07 in 2022M10

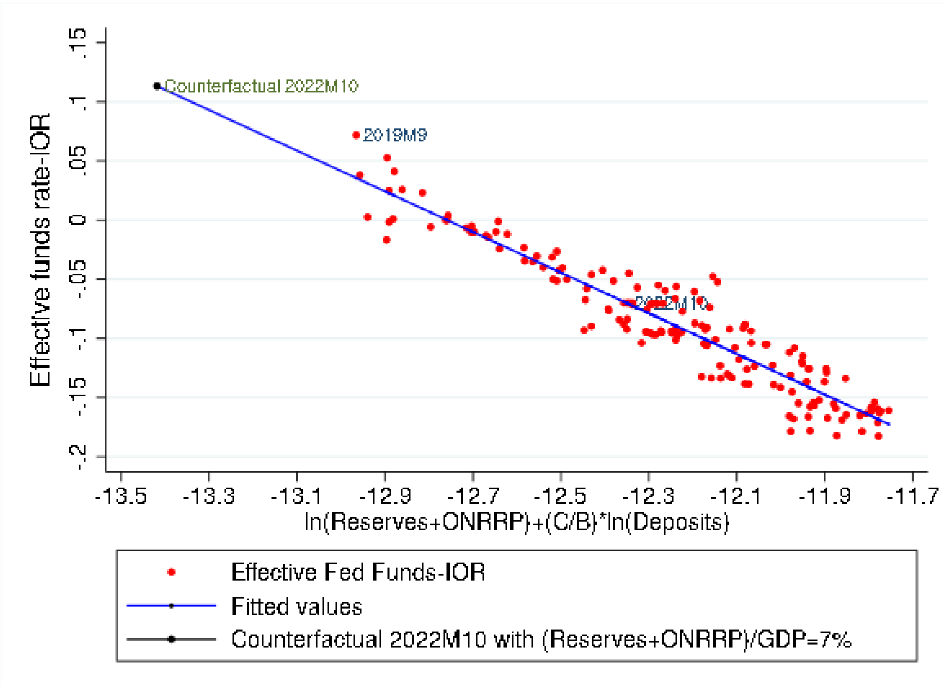


Figure 14. ONRRP take-up as a guide to feasible Reserve+ONRRP reduction

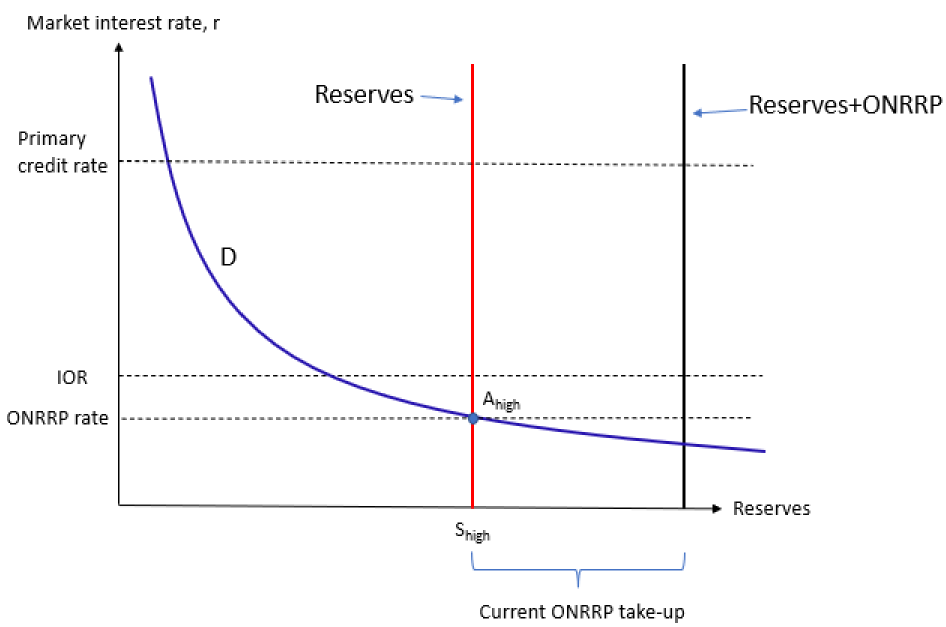
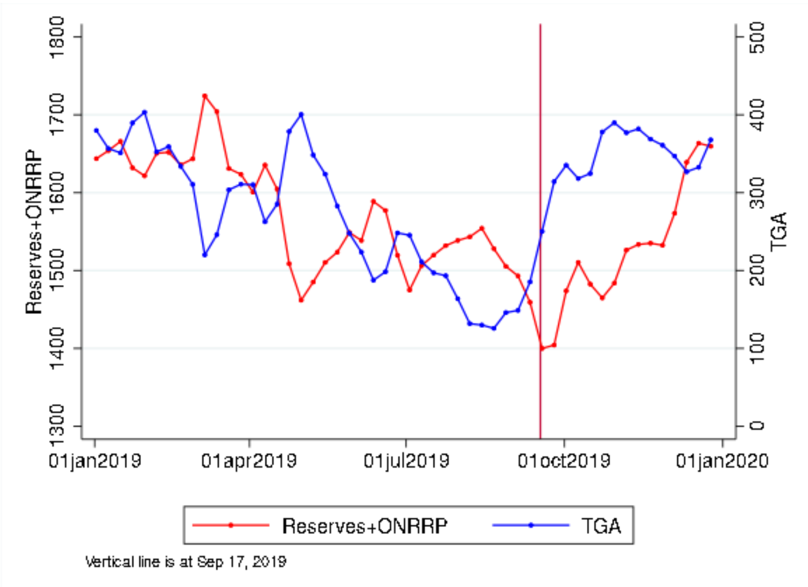


Figure 15. Reserves+ONRRP and the TGA around the September 17, 2019, yield spike

Amounts are in billions of dollars.



Appendix Table 1. Drivers of deposits, monthly data, 2009M1-2022M6

Monthly data for 2009M1-2022M6. Liquid deposits are defined as demand deposits plus other liquid deposits (H6 release). Household financial assets (including assets of non-profits) are from the Financial Accounts of the United States. IOR is the interest rate paid on reserves. In Panel B, Δ denotes a one-year change relative to the same month the prior year. t-statistics in parenthesis (based on 12 Newey-West lags). *** p<0.01, ** p<0.05, * p<0.1.

Panel A. Regressions in levels

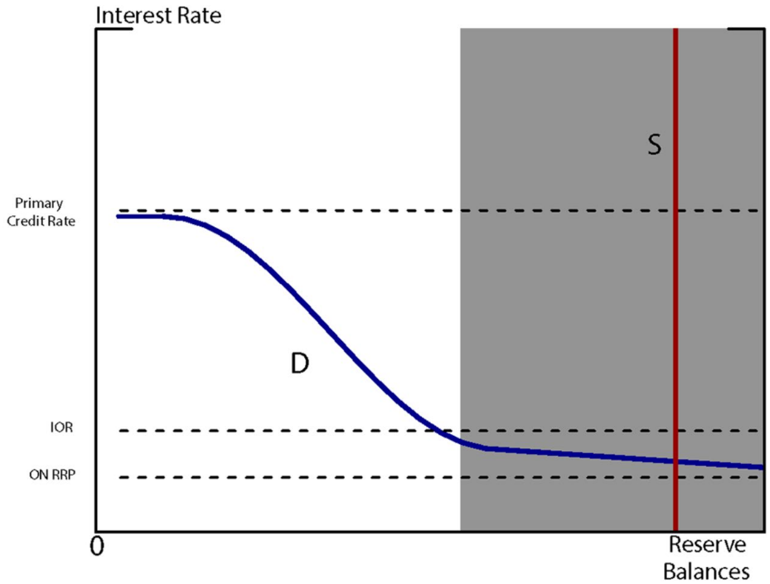
	Dependent variable					
	ln(Deposits)			ln(Liquid deposits)		
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Reserves)	0.50***		-0.045*	0.70***		0.088***
	(7.14)		(-1.75)	(8.95)		(2.50)
ln(Household financial assets)		1.03***	1.10***		1.39***	1.25***
		(42.71)	(29.63)		(37.68)	(20.91)
IOR		-0.025***	-0.036***		-0.036***	-0.014
		(-5.40)	(-4.71)		(-3.76)	(-1.59)
Constant	5.50***	-2.26***	-2.69***	3.85***	-6.34***	-5.50***
	(10.56)	(-8.35)	(-10.08)	(6.60)	(-15.33)	(-12.33)
N (months)	162	162	162	162	162	162
R^2	0.659	0.987	0.988	0.721	0.985	0.988

Panel B. Regressions in changes

	Dependent variable					
	Δln(Deposits)			Δln(Liquid deposits)		
	(1)	(2)	(3)	(4)	(5)	(6)
Δln(Reserves)	0.11***		0.033	0.17***		-0.0006
	(5.78)		(1.27)	(3.73)		(-0.01)
Δln(Household financial assets)		0.38***	0.31***		0.53***	0.33*
		(4.80)	(4.19)		(4.00)	(2.36)
ΔIOR		-0.047***	-0.036***		-0.067***	-0.066***
		(-13.15)	(-4.87)		(-11.35)	(-5.58)
Lagged levels of explanatory variables and dependent variable included as regressors	Yes	Yes	Yes	Yes	Yes	Yes
Constant term included	Yes	Yes	Yes	Yes	Yes	Yes
N (months)	150	150	150	150	150	150
R^2	0.854	0.870	0.898	0.639	0.833	0.870

Appendix Figure 1. Reserve demand as a function of the market interest rate

Framework of Ihrig, Senyuz and Weinbach (2020)



Appendix Figure 2. Fit when instrumenting for both reserves and deposits

The fitted line is based on the regression in Table 3, Panel C.