Stop Believing in Reserves*†

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Preliminary Draft: July 2023

Abstract

We study the transmission channels of quantitative tightening (QT). We develop a structural model where reducing the size of the Federal Reserve's balance sheet affects the demand for reserves by banks and demand for liquidity by non-banks, and calibrate our model to the data of the current monetary tightening cycle. Rather than the demand for reserves by banks which is typically considered in the existing academic literature, we find that the demand for liquidity by non-banks is the binding constraint for the size of the Federal Reserve's balance sheet. We show that the Federal Reserve can reduce the size of its balance sheet by more if it sets interest rates higher, documenting a novel complimentarity between both monetary policy tools.

Keywords: monetary policy transmission, quantitative tightening, reserves, ON RRP, shadow banks
JEL Classifications: G2, E4, E5

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†We are thankful for comments from Viral Acharya, Gara Afonso, Paola Boel, Benjamin Lester, Wenhao Li, Pedro Gomis-Porqueras, Kinda Hachem, Sebastian Infante, Antoine Martin, Borghan Narajabad, Bernd Schlusche, Zeynep Senyuz, Annette Vissing-Jorgensen; and seminar participants at the Economic Theory Reading Group of the University of Basel (2022); the Macro Brownbag Seminar at the University of California-Irvine (2022); the Summer Workshop of Money, Banking, Payments and Finance (2022); the Midwest Macro Conference (2022); the Swiss Winter Conference on Financial Intermediation (2023), the SFS Cavalcade (2023), the Women in System Economic Research Conference (2023), the Bundesbank (2023), the Federal Reserve Bank of New York (2023) and the Federal Reserve Board (2022).

1 Introduction

How does the demand for liquidity by banks and non-banks change when the Federal Reserve (Fed) tightens monetary policy? Understanding the answer to this question is fundamentally important to policymakers and academics alike because monetary policy tightening has consequential effects on the real economy. When the Fed raises interest rates, the channels of transmission to banks and non-banks are arguably well understood. However, when the Fed tightens monetary policy by reducing the size of its balance sheet, the effect on banks and non-banks, and the money markets they intermediate within, are not well understood. In this paper, we attempt to fill this gap.

The existing literature is well-established for understanding the demand for liquidity by banks and non-banks when the Fed tightens monetary policy using interest rates. Two identified channels are: the "bank deposit channel" and the "non-bank deposit channel." When the Fed tightens monetary policy by raising the federal funds rate, its policy rate, Drechsler et al. (2017) show that this monetary tightening leads to deposits flowing out of the banking system, i.e. the bank deposit channel. At the same time, Xiao (2020) shows that these deposits then flow to non-banks, or money market mutual funds (MMFs), i.e. the non-bank deposit channel. These important channels are well understood when the Fed uses interest rates to change monetary policy.

We ask how the demand for liquidity by banks and non-banks changes when the central bank uses its balance sheet, instead of interest rates, to conduct monetary policy tightening. The Fed has used the size of its balance sheet as an additional monetary policy tool since 2008 when the federal funds rate was lowered to its effective lower bound of zero, and signaled in January 2019 that it would continue to use its balance sheet in this way for the foreseeable future.[1] Since the Fed committed to an "ample reserves framework," meaning that the Fed will continue to use the size of its balance sheet as a monetary policy tool, it is important to understand how these deposit channels of monetary policy transmission change when the Fed uses its balance sheet for monetary policy tightening.

We demonstrate two channels that arise when the Fed reduces the size of its balance sheet to tighten monetary policy. The first channel is the demand for reserves by banks. As the Fed's balance sheet declines, the Fed reduces the amount of reserves available to banks, which reduces bank liquidity and incentivizes banks to pay higher rates for the funding they need. At some level, bank reserve demand should bind the size of the Fed's balance sheet since the Fed needs to maintain an ample reserves framework. Several papers including Acharya et al. (2022), Lopez-Salido and Vissing-Jorgensen (2022), and Afonso et al. (2022) estimate bank reserve demand to determine the optimal size of the Fed's

[1] See the Statement from January 30, 2019.

balance sheet.

However, we show that the second channel, the capacity of the repurchase (repo) market, is more important than the demand for reserves by banks, and binds the effectiveness of the Fed's balance sheet as a monetary tightening tool faster than bank reserve demand. Because the decline in the Fed's balance sheet increases the amount of securities that need to be financed in the repo market, as the size of the Fed's balance sheet declines, increasing demand for financing in the repo market causes repo rates to rise. Then, the intermediation capacity of the repo market, and the demand for liquidity by non-banks, determines how much the Fed can shrink its balance sheet. We show that this liquidity demand by non-nanks matters more for monetary policy transmission via the balance sheet than bank reserve demand.

We develop a tractable theoretical model that captures the flow of deposits between banks and non-banks as the Fed tightens monetary policy using its administered rates— the interest rate on reserve balances (IORB) and the interest rate on the Overnight Reverse Repo Facility (ON RRP)— and by reducing the size of its balance sheet. We then calibrate the model using the moments from the current monetary policy tightening cycle to make predictions of how the demand for liquidity by banks and non-banks changes and, ultimately, the optimal size of the central bank's balance sheet.

A contribution of our model is that we incorporate the role of the ON RRP facility, which the Fed uses to maintain a floor on short-term interest rates. At this facility, non-banks are eligible to lend deposits to the Fed and receive interest. Therefore, the interest received by non-banks is economically identical to the interest received by banks to hold reserves (cash) at the Fed, and can be thought of as the "interest rate for non-bank reserves." We show that when the Fed tightens monetary policy by raising interest rates, lending by non-banks at the ON RRP increases. Non-banks receive inflows but do not have sufficient investment opportunities for this new money, so turn to the ON RRP instead. However, when the Fed tightens monetary policy by reducing the size of its balance sheet, non-banks reduce their lending at the ON RRP and lend more in the repo market instead. Although they receive even more inflows, non-banks are able to lend this money in the repo market since broker-dealers (dealers) need to finance the Treasury securities that the Fed no longer holds on its balance sheet. Importantly, we show that when tightening occurs from interest rates, much of non-banks' increase in deposits is invested at the ON RRP. However, when tightening occurs from the balance sheet, non-banks lend their deposits in the repo market.

We build upon the models of Armenter and Lester (2017) and Xiao (2020). Households have a deposit endowment and can choose whether to invest their deposits into banks (depository institutions) or non-banks (money market mutual funds or MMFs) based on the deposit rates available to them. MMFs have two choices of where they can invest these deposits. They can lend to dealers in the repo market and receive the repo interest rate, or they can lend to the Fed at the ON RRP and receive the ON RRP rate. Banks also have two investment choices for the deposits they receive from households. They can invest either at the Fed and receive IORB, or in loans and receive an interest rate that reflects the return on loans. Dealers hold a portion of the outstanding securities, which they finance by borrowing from MMFs in the repo market.

In the model, we show that when the Fed raises interest rates by raising IORB, households transfer deposits from banks to MMFs since MMFs raise their rates more with IORB, while bank rates lag consistent with Drechsler et al. (2017). MMFs then invest the additional deposits at the ON RRP, rather than in the repo market, because rising interest rates do not change dealers' demand for repo funding, and the ON RRP rate is very close to the repo rate. Repo volumes remain unchanged, but participation at the ON RRP increases, in line with Afonso et al. (2022).

However, when the Fed reduces the size of its balance sheet, which we model by dealers purchasing an exogenous amount of securities that the Fed no longer intends to purchase (and thereby shrinking its balance sheet), dealers' demand for repo borrowing increases to finance these additional security purchases. Therefore, the repo interest rate increases above the ON RRP rate, and MMFs prefer to lend to dealers in the repo market rather than to the ON RRP. MMFs also experience inflows of deposits from households because their yields are higher than banks. Our results show that monetary policy transmission via the Fed's balance sheet occurs through primarily non-banks, and not banks. Further, non-banks increase their lending in private funding markets only when monetary tightening occurs through the balance sheet, and not through interest rates. Our results imply that monetary tightening through interest rates can attract deposits back to the Fed via the ON RRP rather than to private markets.

Next, we calibrate the structural parameters of the model to match moments in the data between September 15, 2021 and December 28, 2022, the period of the Fed's current monetary tightening cycle. The model matches the data quite well, and we have two main results. First, we show that the intermediation capacity of the repo market will bind the equilibrium size of the Fed's balance sheet before bank reserve demand. Since dealers must finance the additional Treasury securities in the repo market that the Fed no longer holds, the amount the Fed can shrink its balance sheet, while maintaining interest rate control and preventing the repo rate from far exceeding the Fed's administered rates, depends on MMFs' willingness to lend in the repo market and their demand for money. Specifically, we show that the Fed can reduce its balance sheet by \$2.2 trillion when IORB is equal to 4.65% before the intermediation capacity of the repo market binds and still maintain its ample reserves framework. Our estimates are in line with results in Lopez-Salido and Vissing-

Jorgensen (2022), who estimate that the Fed can reduce its balance sheet by roughly $2.2 trillion.

Importantly, we show that, in equilibrium, bank reserve demand is less than the capacity of the repo market. If the Fed shrank its balance sheet to the equilibrium level of reserve demand, the size would be smaller than an ample reserves framework and our calibration suggests that repo rates would be considerably above the IORB rate. We show that if the Fed only considered bank reserve demand in determining the size of its balance sheet, and ignored non-bank liquidity demand, the Fed would likely lose interest rate control.

Our second result demonstrates a novel complementarity between interest rate and balance sheet monetary policy. While the two tools are generally thought of as substitutes, we show that the Fed can shrink its balance sheet more if it raises interest rates first. This is because, as the Fed raises rates, households shift deposits from banks to MMFs. When MMFs have more deposits, they have more to lend in the repo market as needed when the Fed shrinks its balance sheet. By expanding the relative size of non-banks versus banks, higher interest rates enable a larger repo market to accommodate a large decline in the Fed's balance sheet.

We contribute to three strands of the literature. First, we provide new insights on the implications of the Fed's new monetary policy implementation framework. In this environment, there are still many outstanding questions, such as the minimum size of the Fed's balance sheet consistent with the ample reserves framework, the determinants of reserve demand, and the implications of the Fed's liability composition, in particular the allocation of reserves versus the ON RRP. Lopez-Salido and Vissing-Jorgensen (2022) find that reserve demand is a function of banks' deposits. In a related paper, Acharya et al. (2022) show how increases in the Fed's balance sheet, and therefore reserves, lead to increases in deposits and other bank liabilities. Our results complement these papers by showing that bank deposits decline with interest rate tightening, but not with balance sheet tightening. Therefore, raising rates before or in conjunction with shrinking the balance sheet could reduce reserve demand, thus allowing for a smaller overall size of the Fed's balance sheet, if desired. Further, we provide evidence that bank demand for reserves is not the only constraint on how much the Fed can shrink its balance sheet. Finally, our results also speak to the composition of reserves and ON RRP, which not only affects the ultimate size of the Fed's balance sheet, but also has implications for the supply of safe assets.[2]

Second, we contribute to the literature on the banking channels of monetary policy

[2] The Fed's current guidance, as laid out in the Plans for Reducing the Size of the Federal Reserve's Balance Sheet (`https://www.federalreserve.gov/newsevents/pressreleases/monetary20220504b.htm`), states that the end of balance sheet runoff is tied to the level of reserves. Therefore, the composition of reserves versus ON RRP may affect the stopping point of runoff and the size of the Fed's balance sheet.

transmission. There is extensive work done on the banking channels of interest rate policy.[3] However, the work on balance sheet policy is more limited. In a paper similar to ours, Diamond et al. (2022) study the expansionary effects of balance sheet policy and show that reserves crowd out bank lending and, to a lesser extent, crowd in deposits. To the best of our knowledge, we are the first to consider a central bank's balance sheet policy in the context of deposit flows between banks and shadow banks. While increasing interest rates and shrinking the size of the balance sheet are both means of tightening monetary policy, we show that they have very different implications for both commercial and shadow banks, as well as money markets more broadly. Further, the existing work in this area mainly focuses on balance sheet accommodation, while we focus on balance sheet tightening. Current evidence, such as D'Amico and King (2013) and Smith and Valcarel (2022), suggests that balance sheet policy is not symmetric so expansions and contractions may have different effects.

Third, our results also shed light on the substitutability of interest rate and balance sheet policy. Interest rate and balance sheet policy both affect the economy through longer-term interest rates. Various studies have quantified the degree of substitution between the two tools using term premium models.[4] However, these tools affect rates differently.[5] In particular, Kiley (2014) suggests that long-term rates are more influenced by expectations of the short-term rate rather than the term premium, and therefore interest rate policy is more effective.[6] We add to this literature by demonstrating an interdependence of the effectiveness of the two tools; that is, the amount of tightening that can occur through balance sheet policy is actually dependent on the stance of interest rate policy. In particular, our results suggest that a central bank can shrink its balance sheet more if it raises interest rates first. Further, we highlight the differing effects of the two tools on the relative size of the shadow bank sector, which has important implications for financial stability.

The paper proceeds as follows. Section 2 provides background information on the Fed's current ample reserve framework. Section 3 presents motivating empirical evidence on the bank and shadow bank deposit channels with both interest rate and balance sheet policies. Section 4 describes the model, while Section 5 presents the calibration. Section 6 discusses the results and Section 7 concludes.

[3] See, among others, Kashyap and Stein (2000), Drechsler et al. (2017), and Xiao (2020).

[4] See, among others, Sims and Wu (2020) and Crawley et al. (2022).

[5] Interest rate policy affects longer-term rates through the expected path of short-term rates, while balance sheet policy affects the term premium embedded in longer-term rates.

[6] Existing studies have also discussed the implications of policy tool uncertainty. Brainard (1967) suggests that diversifying across policy tools is optimal when the effectiveness of different tools is uncertain, while Williams (2013) suggests that the more certain tool should be primary.

2 The Fed's Monetary Policy Framework

2.1 The Ample Reserves Framework

The Fed has traditionally used adjusting its policy rate, the federal funds rate, to conduct monetary policy. The federal funds rate is the interest rate paid by banks to borrow \$1 of reserves, which is money held at the Fed by banks, in the federal funds market. Before the 2008 Global Financial Crisis (GFC), the Fed would adjust the federal funds rate by conducting open market operations to adjust the supply of reserves. This monetary policy framework was, at this time, referred to as a "scarce reserves regime".

During and after the GFC, the Fed considerably expanded its balance sheet, which meant increasing the supply of reserves in the financial system. Since the supply of reserves was so large, the Fed was unable to use open market operations to adjust the federal funds rate because small changes in the level of reserves did not affect rates. At this time, the Fed began using administered policy rates to control the federal funds rate. The administered rates are the interest on reserve balances rate (IORB) and the ON RRP offering rate. To keep a floor on the federal funds rate, the Fed first introduced the interest on reserves in 2008.[7] Banks are able to place money at the Fed, i.e. reserves, and receive IORB. As a result, banks are not incentivized to lend at lower than IORB because they can always lend money to the Fed instead.

However, IORB was not a sufficiently effective floor because, although banks did not lend below IORB, many non-banks would since they are ineligible to hold reserves and earn IORB. This, in turn, put downward pressure on the federal funds rate to trade sometimes below IORB. As a result, the Fed introduced the ON RRP facility in September 2013 to provide a firmer floor to the federal funds rate. At the ON RRP, non-banks, namely MMFs, can lend money to the Fed and receive the ON RRP rate. The ON RRP rate is lower than IORB, providing an effective floor to the federal funds rate.

In January 2019, the Fed officially adopted this new monetary policy framework, which is referred to as an "ample reserves regime".[8] Figure 1 illustrates this framework. As of June 2022, the amount of reserves in the financial system amounted to \$3.3 trillion, denoted by the blue vertical line.

In the ample reserves framework, the Fed can tighten monetary policy in two ways. It can raise IORB and the ON RRP rate, thereby raising the federal funds rate, or it

[7] Initially, the Fed paid interest only on excess reserves (IOER). IOER has since been replaced by IORB because the Fed no longer has reserve requirements for banks, and hence there is no distinction between required and excess reserves.

[8] See Ihrig et al. (2020) for a detailed explanation of the ample reserve regime.

can remove reserves from the financial system. The Fed removes reserves by reducing the size of its balance sheet. The Fed bought Treasury securities and agency mortgage-backed securities (MBS) to create the reserves on its balance sheet during Quantitative Easing. As these securities roll off as they mature, the Fed removes the reserves it initially created. As the Fed lets more securities roll of its balance sheet, the amount of reserves should decline until it reaches a level where the federal funds rate starts responding to changes in reserves, i.e. the amount of reserves is no longer on the flat portion of the reserve demand curve, which is the red line in Figure 1. That level, denoted as $X by the vertical dashed line in the figure, represents the amount of reserves required for the Fed to maintain its ample reserves framework.

3 Aggregate Time Series of Bank Deposits and MMF AUM

Before we present the model, we first show some empirical observations in order to provide some motivation for the setup of the model.

Figure 2 depicts the level of the effective federal funds rate (EFFR) and bank and MMF deposit growth rate over a horizon of 36 years from 1987 to 2023. Panel 2a plots the EFFR (right axis) and bank deposit growth (left axis). Panel 2b plots the EFFR (left axis) and MMF deposit growth (right axis). Consistent with the deposit channel of monetary policy (see Drechsler et al., 2017), we observe a clear negative relationship between monetary policy tightening through interest rate increases and bank deposit growth in Panel 2a. Bank deposits grow less when the policy rate increases. Furthermore, consistent with evidence presented in Xiao (2020), we observe a positive relationship between the policy rate and MMF deposit growth in Panel 2b. MMF deposits grow when policy rates increase.

However, how does monetary policy tightening from the Fed's balance sheet affect flows of funds between bank deposits and MMFs? Figures 3 and 4 plot bank and MMF deposit growth together with changes in the size of the System Open Market Account (SOMA) portfolio before 2008 and after 2008, respectively. After 2008, the balance sheet of the Federal Reserve was much larger and the Fed operated under a different monetary policy framework. Figure 3 shows the growth of the SOMA portfolio (left axis) and bank deposit growth (right axis) in Panel 3a and the growth rate of the SOMA portfolio (left axis) and MMF deposit growth (right axis) in Panel 3b from 1987 to 2008. We observe a positive relationship between SOMA portfolio growth and bank deposits, and a negative relationship between SOMA portfolio growth and MMF deposits.

However, after 2008, the relationship between SOMA portfolio growth, bank deposit growth, and MMF deposit growth changed. Figure 4 Panel 3a shows the growth of the

SOMA portfolio (left axis) and bank deposit growth (right axis). The positive relationship observed before 2008 is no longer present. In addition, in Panel 4b, a positive relationship between SOMA portfolio growth and MMF deposit growth emerged. This figure suggests that MMF deposit growth responds more to monetary tightening via the Fed's balance sheet than bank deposit growth. Based on this novel observation, we construct a structural model that can replicate and provide an explanation for these flow of funds between banks and MMFs when the Fed uses its balance sheet as a monetary tightening tool.[9]

4 The Model

In this section, we describe the theoretical model used to analyze the effects of monetary policy tightening from policy rate increases and balance sheet reductions on banks and shadow banks.

4.1 Environment

The theoretical model is an extension of Armenter and Lester (2017) and builds on Xiao (2020). Consider a two-period economy. The economy is populated by five types of agents: banks, broker-dealers (dealers), money market mutual funds (MMFs), households, and firms. Each type has unit measure. Furthermore, there exists a central bank and a government. Agents do not discount between the two periods.

Figure 5 depicts the timing of events. At the beginning of the period 1, households receive an endowment of m_e units of commodity money from the central bank and an endowment of B units of government bonds. Commodity money is backed by a general good that can be consumed in period 2 and can be produced by the central bank at no cost.[10] Each unit of government bond matures in period 2 and yields one unit of commodity money. At the beginning of the first period, the central bank decides how many units of government bonds b^{CB} to buy from households at price p^g. Dealers purchase the remaining government bonds, denoted b^d. We assume that households cannot hold government bonds across periods, so therefore they are willing to sell these government bonds at any positive price p^g.[11] The total endowment in units of commodity money that households hold after

[9] In Appendix C we provide additional empirical evidence to support our observations discussed here and Appendix E provides a some robustness tests.

[10] In static models, a monetary equilibrium where fiat money has a positive value does not exist. Since we are interested in studying short-term movements of funds between banks and MMF, we focus on a static environment and use commodity money so that a monetary equilibrium is supported. Instead of modelling money as commodity money, we could also introduce money in the utility function to generate a monetary equilibrium.

[11] Alternatively, we could assume that it is costly for households to hold government bonds across periods

the sale of their endowment of government bonds is $m = m_e + p^g B$.

After the central bank has made its asset purchases, a deposit market and a repo market open. In the deposit market, households allocate their endowment m to bank deposits in the amount d^b and MMF deposits in the amount d^m. Bank deposits yield an interest rate i_{d^b} and MMF deposits yield an interest rate i_{d^m} in period 2. In order to deposit some of the endowment at a bank account, households and banks are randomly matched and then bilaterally bargain over the deposit quantity and the deposit rate according to the proportional bargaining solution. After the household and the bank agree on the deposit amount and rate, the remaining funds of households are deposited at MMFs.[12] The market for MMF deposits is assumed to be perfectly competitive and MMFs pay the market clearing interest rate on their deposits.[13] Both banks and MMFs are subject to linear balance sheet costs, k^b and k^m, respectively. The assumption of banks' balance sheet costs is motivated by existing regulation that may limit the size of banks' balance sheets.[14] Balance sheet costs for MMFs are introduced to match the data on MMF deposit rates more accurately.[15]

MMFs can use their deposits obtained from households to lend to dealers in the repo market or invest them at the overnight reverse repo (ON RRP) facility at the central bank. The ON RRP pays an interest rate r. The repo market is assumed to be perfectly competitive and the market clearing interest rate is ρ. Note, by assumption, households cannot lend their funds directly in the repo market. Instead, they deposit their funds at MMFs, which in turn can access the repo market. This is a reasonable assumption since we do not observe households trading directly in the tri-party repo market. We furthermore assume that there exists a record-keeping technology in the repo market, such that repayment is perfectly enforceable. Dealers are the borrowers in the repo market as they need to finance their purchase of government bonds from households.

After the deposit and the repo markets have convened, banks decide how to invest

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and that the cost is large enough such that households have an incentive to sell all government bonds at price p^g. In reality, of course, households are able to hold government bonds as well. In the model and in our calibration, we abstract from this. We discuss how the assumption that all government bonds that are not held by the central bank have to be held by dealers and therefore financed in the repo market affects our results in Section 6.

[12] Since there is no uncertainty in this model, the timing of the bank deposit market relative to the MMF deposit market does not affect the equilibrium. Households would have the same first-order conditions if they first deposited funds at MMFs and then the remaining funds at banks.

[13] We make this assumption that banks have some bargaining power when setting deposits rates because we observe in the data that banks tend to set lower deposit rates relative to MMFs and pass on policy rate increases to a lesser extent. Our results only depend on the idea that bank do not pass-through increases in monetary policy rate one-for-one. Our results would continue to hold with any other theoretical framework that results in a monetary policy pass-through to bank deposit rates that is less than one-for-one.

[14] For instance, the supplementary leverage ratio (SLR) constrains the size of a bank's balance sheet given its capital.

[15] That is, the MMF balance sheet costs create a wedge between the market repo rate and the MMF yield, consistent with fees that MMFs implement, which keep MMF yields somewhat below repo rates.

the funds received from households. Banks can hold either reserves at the central bank, which yield the interest rate on reserve balances (IORB), R, where $R > r$, or they can make loans ℓ and receive an interest rate i_ℓ, where $i_\ell - R$ is assumed to be positive and constant in R. Following Ennis (2018), banks have some costs associated with investing in loans $\chi(\ell)$ that can be motivated by monitoring costs (see for example, Holmstrom and Tirole, 1997). We implicitly assume that the effort of monitoring is sufficient to guarantee repayment of the loan and therefore abstract from default. $\chi(\ell)$ is assumed to be strictly convex. Banks are furthermore subject to regulation that limits their ability to lend out all their deposits. We assume banks have to hold at least a fraction δ of their deposits as reserves. This assumption is motivated by existing bank regulation like the Liquidity Coverage Ratio that incentivizes banks to hold reserves on their balance sheet. δ would also capture banks' liquidity preferences to hold reserves.

To summarize, Figure 6 depicts the t-accounts for the central bank, banks, MMF, households and dealers in period $t = 1$ after the lending market, but before the goods market. The central bank purchases government bonds b^{CB} and holds the general good, x, evaluated at its price P on its asset aside. For its liabilities, it issues reserves m_r to banks and ON RRP balances d^{ONRRP} to MMFs. Next, banks receive funding from households through bank deposits d^b and holds those funds as loans ℓ or as reserves m_r. MMFs receive funding from households as well, denoted d^m and hold these funds either as repo loans z^m or as ON RRP balances d^{ONRRP}. Households have equity as they are endowed with money and government bonds. They hold this equity as bank d^b or MMF d^m deposits. Lastly, dealers hold government bonds b^d on their liabilities side and borrow in the repo market, z^d.[16]

After the lending market convenes, a goods market opens, where firms produce the special good and households purchase and consume the special good. We assume that households and firms are anonymous and cannot commit to honor intertemporal promises. Thus, households need a medium of exchange to acquire the consumption good from firms. We assume furthermore that only bank deposits are accepted as a means of payment by firms, whereas MMF deposits are an investment instrument to save for second period consumption. Thus, households pay firms by transferring some of their bank deposits to the firms' bank deposit account. We assume that firms are identical and are uniformly distributed across banks such that the inflow of firm deposits for each bank is identical. Firms receive the average deposit rate on their deposit balances. Note, since all households and banks are identical, the interest rate on deposits will be identical across household and bank matches and across firms. Households receive utility $u(q)$ from consuming q units of the consumption good. Firms can produce the consumption good at linear cost.

[16]Note both the central bank and banks also have profits and losses, which are not shown. MMF and dealers only operate in perfectly competitive markets, so they have zero-profit conditions.

In period 2, the central bank pays interest on reserves and ON RRP holdings, dealers repay repo loans, MMFs and banks repay deposits, and banks earn their return on loans. The government redeems bonds for commodity money and dealers repay their debt to households. Lastly, the central bank produces the general consumption good x at no cost that can be consumed by all agents in exchange for commodity money.

4.2 Equilibrium

In the following section, we derive the optimal decisions made by banks, MMF, dealers, households, and firms. We solve the model backwards.

The general goods market. In period $t = 2$, the central bank produces the general good x in exchange for commodity money. Denote P the price of the general good. Thus,

$$Px = \Pi^{HH} + \Pi^F + \Pi^B + \Pi^D + \Pi^{MMF}. \tag{1}$$

Denote Π^{HH} and Π^F the commodity money holdings of households and firms in period $t = 2$, respectively. Further, Π^B, Π^D, and Π^{MMF} denote the profits of banks, dealers, and MMFs in period $t = 2$, respectively.

The special goods market. At the end of period $t = 1$, households purchase and consume the special good from firms. Firms play a secondary role in this model. They are used to obtain a demand for bank deposits from households even if $i_{d^b} < i_{d^m}$. The maximization problem for a firm satisfies

$$\max_{q_s} \ -q_s + \phi p q_s (1 + i_{d^b}).$$

Denote ϕ the price of money at the end of period $t = 2$ in terms of the general good, such that $P = 1/\phi$, and p the price of the special good. The first-order condition satisfies

$$\phi p (1 + i_{d^b}) = 1. \tag{2}$$

Equation (2) implies that, in equilibrium, firms are indifferent as to how much to produce if the price of the special good compensates them for the cost of holding bank deposits across periods.

Households can only use bank deposits as a means of payment. Utility maximization implies that households allocate all of their endowment to either bank deposits or MMF deposits. Thus, $m = d^b + d^m$ must hold with equality. The maximization problem of households therefore satisfies

$$\max_q u(q) + \phi(d^b - pq)(1 + i_{d^b}) + \phi(m - d^b)(1 + i_{d^m})$$

$$\text{s.t. } d^b - pq \geq 0.$$

The constraint implies that households cannot spend more bank deposits than they have. It has the Lagrange multiplier λ. The first order condition satisfies

$$u'(q) = \phi p(1 + i_{d^b}) + p\lambda.$$

Thus, the optimal quantity consumed satisfies

$$q = \begin{cases} u'^{-1}(1) & \text{if } d^b - pu'^{-1}(1) > 0, \\ d^b/p, & \text{otherwise.} \end{cases} \tag{3}$$

The bank lending market. After banks obtain deposits from households, they can either allocate these funds in a bank lending market or hold reserves at the central bank. We think of the bank lending market as the sum of all investment options that banks might have. Banks receive a return of $(1 + i_\ell)$ on each unit invested in loans. We assume that $i_\ell - R$ is positive and constant such that banks have an incentive to invest in loans and the marginal return on loans does not depend on the level of the interest rate on reserves. Banks face some costs associated with issuing a loan, denoted $\chi(\ell)$, which is strictly convex. Moreover, banks are subject to linear balance sheet costs, k^b. These balance sheet costs are motivated by existing regulation for banks that make large balance sheets costly for banks, such as the Supplementary Leverage Ratio. Lastly, we assume that banks have to hold at least a fraction δ of deposits as reserves, which are denoted m_r, such that $m_r \geq \delta d^b$ has to hold. The balance sheet identity of banks implies $d^b = \ell + m_r$. Using this identity, the maximization problem of banks can be written as:

$$\max_\ell \phi\ell(i_\ell - R) - \phi\chi(\ell) + \phi d^b(R - k^b - i_{d^b})$$

$$\text{s.t. } (1 - \delta)\phi d^b - \phi\ell - \phi\chi(\ell) \geq 0.$$

The constraint has the Lagrange multiplier λ_r. The first-order condition satisfies:

$$\phi(i_\ell - R - x'(\ell) - \lambda_r(1 + \chi'(\ell))) = 0. \tag{4}$$

Thus, the optimal quantity of loans satisfies:

$$\ell = \begin{cases} \ell^* & \text{if } (1-\delta)d^b - \chi'^{-1}(i_\ell - R) - \chi(\chi'^{-1}(i_\ell - R)) \geq 0, \\ (1-\delta)d^b & \text{otherwise,} \end{cases} \tag{5}$$

where $\ell^* = \chi'^{-1}(i_\ell - R)$. If the constraint on reserve holdings does not bind, banks will choose to lend until the marginal return of lending one more unit of money equals the marginal cost of issuing a loan. If the constraint is binding, banks hold the required quantity of reserves and invest the rest of their funds in bank loans.

The deposit and repo markets. First, we consider the optimal decisions by dealers and MMFs in the repo market. Denote z^d as the quantity borrowed by dealers in the repo market. Dealers have to finance all of their bond holdings in the repo market and thus $z^d = p^g b^d$. Their bond holdings furthermore yield one unit of commodity money in period $t = 2$. Thus, the maximization problem of dealers satisfies

$$\max_{z^d} \phi z^d \left(\frac{1}{p^g} - (1+\rho) \right).$$

The first-order conditions is

$$\frac{1}{p^g} - (1+\rho) = 0. \tag{6}$$

Equation (6) implies that if $1/p^g > 1+\rho$, dealers want to borrow an infinite amount in the repo market. If $1/p^g < 1+\rho$, dealers do not want to borrow in the repo market and would therefore not participate in the economy. If $1/p^g = 1+\rho$, dealers are indifferent as to how much they borrow.

MMFs can use the deposits they receive from households to lend in the repo market or to participate at the ON RRP facility. Their balance sheet constraint implies $d^{ONRRP} + z^m = d^m$, where d^{ONRRP} denotes balances at the ON RRP facility, z^m denotes the quantity lent in the repo market and d^m denotes the deposits received from households. ON RRP balances yield the return r, whereas lending in the repo market yields a return ρ for each unit lent. Lastly, MMFs have to pay the deposit rate i_{d^m} on their deposits and have linear balance sheet costs k^m. Using their balance sheet constraint, the maximization problem of MMFs satisfies

$$\max_{d^m, z^m} z^m(\rho - r) + d^m(r - k^m - i_{d^m})$$

$$\text{s.t. } d^m - z^m \geq 0.$$

The constraint implies that MMFs cannot lend more in the repo market than the amount of deposits they hold and has the Lagrange multiplier λ_M. The first-order conditions satisfy:

$$z^m : \qquad \rho - r - \lambda_M = 0, \tag{7}$$

$$d^m : \qquad r - k^m - i_{d^m} + \lambda_M = 0. \tag{8}$$

If $r - k^m - i_{d^m} > 0$, MMFs are willing to hold an infinite amount of deposits. If $r - k^m - i_{d^m} < 0$, MMFs are not willing to hold any deposits and if $r - k^m - i_{d^m} = 0$, MMFs are indifferent as to how many units of deposits they hold.

Similarly, if the repo rate exceeds the ON RRP rate, $\rho > r$, MMF are willing to lend in the repo market. If, however, the ON RRP rate exceeds the repo rate, $\rho < r$, MMFs prefer to deposit their money at the ON RRP rather than lend in the repo market and if $\rho = r$, MMFs are indifferent between the repo market and the ON RRP facility. Thus, the optimal quantity lent in the repo market satisfies:

$$z^m = \begin{cases} d^m & \text{if } \rho - r > 0, \\ \in [0, d^m] & \text{if } \rho - r = 0, \\ 0, & \text{if } \rho - r < 0. \end{cases} \tag{9}$$

It is straightforward to see that $r > \rho$ cannot be an equilibrium. If the repo rate is below the ON RRP rate, no MMF is willing to lend in the repo market. Thus, the repo rate increases until $\rho = r$. When the repo rate increases to equal the ON RRP rate, MMFs become indifferent between lending in the repo market or depositing at the ON RRP facility. If $\rho > r$, MMFs have an incentive to lend all of their funds in the repo market. Note, it is possible to have equilibria where $\rho > R$; that is, the repo rate exceeds IORB due to the assumption that banks do not participate in the repo market.

Lastly, we consider the decision of households regarding how many units of bank deposits and MMF deposits to hold. Here, we assume that banks and MMFs have different degrees of market power. In particular, we assume that MMFs compete with each other for deposits in a perfectly competitive market. However, in the bank deposit market, we assume that households and banks are randomly matched and then bargain over the deposit quantity and deposit rate according to the proportional bargaining solution.[17] First, we determine the match surplus between a household and a bank. The match surplus for

[17] As we show later, the bargaining power of banks will imply a pass-through of policy rate hikes to bank deposit rates that is smaller than the pass-trough to MMF deposit rates, which is consistent with observations in the data. We use bilateral random matching and proportional bargaining to model this, but many other forms in which banks can exert some market power on bank deposit rates will yield similar results. See Choi and Rocheteau (forthcoming) for a micro-founded approach to explain several empirical observations related to bank deposit and deposit rates.

a household satisfies

$$S_H = u(q) + \phi(d^b - pq)(1 + i_{d^b}) + \phi(m - d^b)(1 + i_{d^m}) - \phi m(1 + i_{d^m}). \tag{10}$$

If the household is not matched with a bank, it can only hold MMF deposits and consequently also not consume the special good.

The match surplus of the bank satisfies

$$S_B = \phi\ell(i_\ell - R) + \phi d^b(R - k^b - i_{d^b}) - \phi\chi(\ell). \tag{11}$$

If a bank is not matched, it does not receive any funds to invest into loans or hold as reserves and thus the value of not being matched is zero. Thus, the match surplus satisfies:

$$S = u(q) + \phi(d^b - pq)(1 + i_{d^b}) - \phi d^b(1 + i_{d^m}) + \phi\ell(i_\ell - R) + \phi d^b(R - k^b - i_{d^b}) - \phi\chi(\ell). \tag{12}$$

Denote θ the constant share of the surplus that the bank receives and consequently $1 - \theta$ the share of the surplus that the household receives. We can interpret θ as the bargaining power of the bank. In reality, households could also use cash as a means of payment as an outside option to bank deposits, which could generate some bargaining power for households. Here, we abstract from cash because empirically we do not observe this pattern in the US.[18] Instead, we interpret $(1 - \theta)$ as a reduced form of the outside options that households have and their resulting bargaining power due to these outside options.

The maximization problem of the bank therefore satisfies:

$$\max_{d^b, i_{d^b}} \phi\ell(i_\ell - R) + \phi d^b(R - k^b - i_{d^b}) - \phi\chi(\ell)$$

$$\text{s.t. } \phi\ell(i_\ell - R) + \phi d^b(R - k^b - i_{d^b}) - \phi\chi(\ell) \geq \frac{\theta}{1-\theta}\left[u(q) + \phi(d^b - pq)(1 + i_{d^b}) - \phi d^b(1 + i_{d^m})\right]$$

The constraint states that the overall match surplus is split proportionally between the household and the bank and has the Lagrange multiplier λ_B. The first-order condition satisfies

$$\begin{aligned} d^b:\ & \phi(R - k^b - i_{d^b}) + \lambda_B\phi(R - k^b - i_{d^b}) - \\ & \lambda_B\frac{\theta}{1-\theta}\left[u'(q)\frac{\partial q}{\partial d^b} + \phi(1 + i_{d^b}) - \phi p\frac{\partial q}{\partial d^b}(1 + i_{d^b}) - \phi(1 + i_{d^m})\right] = 0, \end{aligned} \tag{13}$$

$$i_{d^b}:\ -\phi d^b - \lambda_B\phi d^b - \lambda_B\frac{\theta}{1-\theta}\phi(d^b - pq) = 0. \tag{14}$$

[18] In 2021, 81.5% of US households were fully banked and only 4% of households used cash for all transactions (see FDIC, 2021).

Since we observe in the data that the bank deposit rate is less than the yield on MMFs (i.e., $i_{d^b} < i_{d^m}$), we restrict our analysis to this case. Thus, utility maximization implies that households only hold bank deposits to finance their desired quantity of the special good and invest the remaining funds in MMF deposits. Therefore, $d^b = pq$. From this, Equation (14) implies $\lambda = -1$ and therefore:

$$u'(d^b/p) = \frac{1 + i_{d^m}}{1 + i_{d^b}}. \tag{15}$$

From the constraint, the interest rate for bank deposits satisfies:

$$i_{d^b} = (R - k^b) + \frac{\ell\,(i_\ell - R)}{d^b} - \frac{\chi(\ell)}{d^b} - \frac{\theta}{1-\theta}\left[\frac{u(q)}{\phi d^b} - (1 + i_{d^m})\right]. \tag{16}$$

Lastly, the optimal quantity deposited at MMFs satisfies:

$$d^m = m - pu'^{-1}\left(\frac{1 + i_{d^m}}{1 + i_{d^b}}\right). \tag{17}$$

The zero-profit condition for MMFs in the deposit market yields the interest rate paid on MMF deposits:

$$i_{d^m} = r - k^m + \frac{z^m}{d^m}(\rho - r). \tag{18}$$

4.3 Characterization of Equilibrium

By assumption, the demand for repo borrowing is determined by the central bank, since $z^d = p^g b^d = p^g(B - b^{CB})$. Furthermore, in equilibrium, it must be that the price of government bonds, p^g, satisfies $1/p^g - (1 + \rho) = 0$. Market clearing in the repo market requires

$$z^m = p^g b^d. \tag{19}$$

Proposition 1. *There exist two possible equilibrium regimes in the repo market: An excess liquidity regime where $\rho = r$ and $d^{ONRRP} \geq 0$ and a scarce liquidity regime where $\rho \geq r$ and $d^{ONRRP} = 0$.*

The proof of Proposition 1 can be found in Appendix A.

Since the demand for liquidity in the repo market is fixed, there are two possible regimes in equilibrium. First, there is an excess liquidity regime in which the aggregate supply of liquidity held by MMFs is larger than the demand for liquidity by dealers. In that case, the repo rate is equal to the ON RRP rate and MMFs lend the quantity demanded by dealers in the repo market and deposit the remaining funds at the ON RRP facility. Second, there is a scarce liquidity regime in which the repo rate is above the ON RRP rate. In that case, MMFs lend all of their deposits in the repo market and ON RRP takeup is zero. Consequently, there exits a quantity of bonds held by dealers, $\tilde{b}^d$, such that demand for liquidity by dealers equals the total available supply of liquidity from MMFs and the repo rate equals the ON RRP rate. This critical threshold $\tilde{b}^d$ satisfies $m - d^b = p^g b^d$ at $\rho = r$.

Using Equation (17), the critical threshold $\tilde{b}^d$ at which demand for liquidity in the repo market is equal to the aggregate supply of available liquidity from MMFs (i.e., $z^d = d^m$) satisfies

$$m - pu'^{-1}\left(\frac{1 + i_{d^m}}{1 + i_{d^b}}\right) = p^g \tilde{b}^d$$

when $\rho = r$.

Consequently, the repo rate satisfies

$$\rho = r \tag{20}$$

if $b^d \leq \tilde{b}^d$ and

$$m - pu'^{-1}\left(\frac{1 + i_{d^m}}{1 + i_{d^b}}\right) = p^g b^d \tag{21}$$

if $b^d > \tilde{b}^d$.

Next, using Equation (18) implies that the interest rate on MMF deposits satisfies

$$i_{d^m} = \rho - k^m. \tag{22}$$

Consequently, the critical threshold $\tilde{b}^d$ satisfies:

$$\frac{1}{p^g}\left[m - pu'^{-1}\left(\frac{1 + r - k^m}{1 + i_{d^b}}\right)\right] = \tilde{b}^d. \tag{23}$$

Proposition 2 (Definition of Equilibrium)**.** *An equilibrium is a policy* (R, r, ϕ, b^{CB}) *and endogenous variables* $(p^g, \rho, i_{d^b}, i_{d^m}, d^b, d^m, z^m, \tilde{b}^d, \ell, x)$ *satisfying Equations (5), (6), (15), (16), (17), (19), (22), (23),*

$$\frac{x}{\phi} = \ell(1 + i_\ell) + m_r(1 + R) + d^{ONRRP}(1 + r) - m(k^b + k^m) + d^b k^m + d^m k^b + b^d, \tag{24}$$

and Equation (20) if $b^d \leq \tilde{b}^d$ *or Equation (21) if* $b^d > \tilde{b}^d$*.*

The proof of Proposition 2 can be found in Appendix C.

4.4 Properties of Equilibrium

Define the spread $s = R - r$, which is the difference between the central bank's administered rates. We can therefore redefine the policy rate $r = R - s$. In what follows, we discuss the effects of interest rate hikes and balance sheet reductions under the assumption that the spread s remains constant when the central bank increases the policy rate.

Transmission of the policy rate to deposit rates. Since $i_{d^m} = \rho - k^m = r - k^m$ in an excess liquidity regime, the interest rate on MMF deposits increases one-for-one with the ON RRP rate due to perfect competition in the market for MMF deposits. Thus, $\mathrm{d}i_{d^m}/\mathrm{d}r = 1$. Since the market for bank deposits is not perfectly competitive, the bank deposit rate may not adjust one-for-one with the policy rate.

Proposition 3. *The pass-through of policy rate increases to bank deposit rates is less than one-for-one if $\theta > \theta_1$, where*

$$\theta_1 = \frac{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \frac{i_{d^m} - i_{d^b}}{1 + i_{d^b}}\frac{1}{u''(q)q}\right)}{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \frac{i_{d^m} - i_{d^b}}{1 + i_{d^b}}\frac{1}{u''(q)q}\right) + \left(\frac{i_{d^b} - i_{d^m}}{1 + i_{d^b}}\right)\left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right) + \frac{u(q)}{q} - 1}. \tag{25}$$

The proof of Proposition 3 is in Appendix A.

Thus, if the bargaining power of the bank is sufficiently large, the deposit rate will increase by less than one-for-one with the policy rate.

Assuming that this condition holds, increasing the policy rate leads to a one-for-one increase in MMF deposit rates but a less than one-for-one increase in bank deposit rates. This implies that MMF deposits become relatively more attractive and thus more money flows to MMFs as the policy rate increases. This result is consistent with the empirical observations presented in Section 3 and with existing literature on the deposit channel of monetary policy (see Drechsler et al., 2017, Xiao, 2020).

Complementarity between policy rate hikes and balance sheet runoff.

Proposition 4. *The critical value* $\tilde{b}^d$ *is increasing in the policy rate* R *if* $\theta > \theta_2$*, where*

$$\theta_2 = \frac{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\frac{1}{u''(q)q}\right) - 1}{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\frac{1}{u''(q)q}\right) - \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right) + \frac{u(q)}{q} - 1}. \tag{26}$$

The proof of Proposition 4 is in Appendix A. Note that both Propositions 3 and 4 imply a lower bound on the share of the surplus that goes to the bank in the bargaining problem with households. For

$$\frac{1+i_{d^m}}{1+i_{d^b}} \geq \frac{1 + \left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(\frac{u'(q)}{u''(q)}\frac{1}{q} - 1\right) - \left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right) - \frac{u(q)}{q}}{\frac{\phi\ell(i_\ell - R)}{u''(q)q^2} - \frac{\phi\chi(\ell)}{u''(q)q^2} - \left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right)}, \tag{27}$$

$\theta_1 \geq \theta_2$. Thus, if the spread between i_{d^m} and i_{d^b} is large enough, the binding condition will be $\theta > \theta_1$. In what follows, we restrict our analysis to cases where both $\theta > \theta_1$ and $\theta > \theta_2$ are satisfied.

Proposition 4 implies that the maximum level of borrowing that the repo market can absorb without repo rates rising above the ON RRP offering rate is increasing with the level of the policy rate. This implies that if the central bank wants to maintain an excess liquidity regime in the repo market, it can maintain a smaller balance sheet when policy rates are higher, suggesting a complimentarity between tightening through the balance sheet and tightening through policy rates.

Excess liquidity in the repo market and excess reserves. In this model, there are two notions of excess liquidity: excess reserves held by banks and excess liquidity in the repo market. As discussed above, banks hold excess reserves, if they are able to invest the optimal quantity ℓ^* into loans and the reserve constraint is non-binding. Once the constraint becomes binding, banks hold a quantity of reserves to satisfy the constraint and invest the remaining funds into loans. We refer to this as a scarce reserve regime. Denote $\tilde{m}_r$ as the minimal level of reserves consistent with the reserve holding constraint. $\tilde{m}_r$ satisfies

$$\tilde{m}_r = \delta d^b. \tag{28}$$

We can redefine the critical threshold derived above, $\tilde{b}^d$ in terms of the minimal size of the central bank's balance sheet that is consistent with excess liquidity in the repo market, denoted $\tilde{b}^{CB}$. $\tilde{b}^{CB}$ satisfies

$$\tilde{b}^{CB} = B - \tilde{b}^d.$$

If a central bank wants to maintain an excess liquidity regime, both the condition for excess reserves and the condition for excess liquidity in the repo market would need to be satisfied. How much a central bank could reduce its balance sheet is determined by understanding which of these constraints bind first. The binding constraint, that is, either the capacity of repo market or the demand for reserves by banks will determine by how much a central bank can reduce its balance sheet while maintaining an excess liquidity regime.

Proposition 5. *There exists a critical value for R, denoted R' for which the level of bank deposits held when $b^{CB} = \tilde{b}^{CB}$ is equal to the level of bank deposits such that $\ell = \ell^*$ and $m_r = \delta d^b$. The critical value satisfies*

$$\frac{1}{\phi(1+i'_{d^b})} u'^{-1}\left(\frac{1+R'-s-k^m}{1+i'_{d^b}}\right) = \frac{\chi'^{-1}(\kappa)}{1-\delta}, \tag{29}$$

where i'_{d^b} is the bank deposit rate at $R = R'$ and $\kappa = i_\ell - R$.

The proof of Proposition 5 is in Appendix A. Proposition 5 implies that for $R < R'$, the capacity of the repo market, which in turn depends on the demand for liquidity by non-banks is the binding constraint for the central bank's balance sheet. When policy rates are lower, the central bank has to consider both the demand for liquidity by non-banks and the demand for reserves when decreasing its balance sheet. If the central bank decreases its balance sheet below $\tilde{b}^{CB}$, banks still hold excess reserves, but the repo rate will increase above the ON RRP offering rate and the repo market will no longer be in an excess liquidity regime for any $R < R'$. Thus, it is possible that the central bank could lose interest rate control in the repo market, where ρ far exceeds R before reaching scarce reserves, $\tilde{m}_r$.[19] However, if $R \geq R'$, the binding constraint for the central bank is the demand for reserves by banks, and thus, the central bank would only need to consider bank reserve demand when reducing the balance sheet.

In summary, the most important remaining question is the level of R'. When we calibrate the model, we will show how these constraints, the capacity of the repo market or bank reserve demand, bind for the central bank that wants to maintain an excess liquidity regime.

[19] The Federal Reserve does not target a repo rate for monetary policy implementation. We assume that if repo rates spike, the federal funds rate will also follow prompting a loss of interest rate control. This occurred during the September 2019 repo shock (see Anbil et al. (2021)).

5 Calibration

In this section, we calibrate the structural parameters of the model to match moments in the data during the Fed's current policy tightening cycle from September 15, 2021 to December 28, 2022. We use this calibration to demonstrate that the model can match the data fairly well, and then use the calibrated model to forecast the level of reserves at the critical thresholds $b^{CB} = \tilde{b}^{CB}$ and the minimum level of reserves demand. We determine which constraint, the capacity of the repo market or bank reserve demand, is more important for the size of the central bank's balance sheet.

5.1 Mapping the model to the data

Identifying agents and trades. Before we calibrate the model, we need to map the model to the data. The decisions and investment options of MMFs in the model best describe the investment decisions of government MMFs. Banks and dealers in the data are mapped to depository institutions and primary dealers, respectively. We map MMF deposits to government MMFs' assets that are invested in repo and at the ON RRP facility, and bank deposits to aggregate bank deposits held by depository institutions. Government bond holdings of the central bank are mapped to the Treasury security holdings of the Federal Reserve. Government bonds held by dealers are mapped to the Treasury security holdings of primary dealers. The bank lending rate is mapped it to the weighted average return of commercial bank loans and securities.

Data. To calibrate the model, we use data from September 15, 2021 to December 28, 2022.[20] We chose September 15, 2021 as the starting date, since reserve holdings at the Federal Reserve peaked at that time and have continuously declined since then. The Fed's pandemic-era net asset purchases ended on March 11, 2022 and March 16, the Fed began increasing its policy rate. On June 1, the Fed began "balance sheet runoff" and allowed maturing Treasury securities and agency MBS to run off the balance sheet up to monthly caps of \$60 and \$35 billion for Treasury securities and agency MBS, respectively, beginning on September 1.

For the calibration, we use the following data sources. The Fed's administered rates—IORB and ON RRP offering rates—are publicly available from the Federal Reserve Bank of New York (FRBNY) website. We use the publicly available weekly H.4.1 dataset for data on the Fed's balance sheet to retrieve the Fed's holdings of Treasury securities and reserve balances held at Federal Reserve Banks. Data on Treasury holdings of broker-dealers are

[20] We exclude December 29 to 31 in our calibration sample to remove year-end dynamics.

from the primary dealer statistics from the FRBNY website.

Further, we use data on the amount of government MMF assets invested in Treasury repo from SEC N-MFP filings, which captures both private market repo and the ON RRP, at a monthly frequency. Next, we use confidential ON RRP take-up data to calculate aggregate daily government MMF take-up at the ON RRP.[21] The interest rate on MMF deposits is the net seven day yield for government MMFs from iMoneyNet at a weekly frequency. Our repo rate is the Tri-party General Collateral Rate (TGCR), publicly available daily from the FRBNY website.

Bank deposits are the sum of all interest-bearing deposits (other than large time deposits) for all commercial banks, publicly available at a monthly frequency on the Fed's website from the H.8 data release of the assets and liabilities of commercial banks in the United States. The interest rate for bank deposits is the average rate on interest-bearing checking accounts from RateWatch, available weekly. The average interest rate on loans is the aggregate weighted average return on loans and securities held, using total amounts outstanding and total interest income values taken from the quarterly FFIEC Call Report.

Targets. IORB, the ON RRP rate, the quantity of bonds held by the central bank as well as the aggregate quantity of bonds held by the central bank and dealers, the interest rate on loans, and the minimum reserve-to-deposit ratio are taken directly from the data. R is set equal to the average IORB and r is set equal to the average ON RRP offering rate. The nominal amount of bonds held by the central bank $p^g b^{CB}$ is set equal to the average nominal quantity of Treasuries held by the Federal Reserve and the nominal quantity of government bonds in the environment $p^g B$ is set to equal the sum of Treasury holdings of the Federal Reserve and dealers. The interest rate on loans is set equal to the weighted average return on loans and security holdings during the calibration period.[22] For the parameter δ that governs the minimal acceptable ratio of reserves-to-deposits for banks, we take the average reserves-to-deposits ratio of banks over the first two weeks of September 2019.[23] A summary of these parameters can be found in Table 1.

For the utility function, we assume $u(q) = 1/(1-\alpha)q^{1-\alpha}$, which implies $q = \left(\frac{1+i_{d^b}}{1+i_{d^m}}\right)^{1/\alpha}$ from Equation (15). For the cost of loan origination, we assume $\chi(\ell) = 0.5\beta\ell^2$, which

[21] Aggregate ON RRP take-up is publicly available on the FRBNY website. ON RRP take-up by counterparty type can also be found on the Office of Financial Research website, which is publicly available with a lag.

[22] The data does not allow us to distinguish between the interest rates on newly issued loans and the interest rate on existing loans. For that reason, we take the weighted average loan rate of newly issued and existing loans during the calibration period.

[23] On September 17, 2019, the Secured Overnight Financing Rate spiked as demand for liquidity increased. Many think that, on this day, the economy was no longer in an ample reserve regime (Anbil et al., 2021). Using an average reserves-to-deposits ratio from the first two weeks of September 2019 allows us to be conservative in our target of δ, because it was likely binding for some banks.

implies $\ell = \frac{i_\ell - R}{\beta}$ from Equation (5), if the constraint is not binding.

With these assumptions, the parameters left to determine are k^b, k^m, θ, α, ϕ, β, and m_e. We calibrate these parameters to match the average TGCR (the repo rate), the average bank deposit rate, the average interest rate on MMF deposits, the average correlation between bank deposit rates and administered rates, the average markdown of bank deposit rates relative to the weighted average return of bank loans and reserves, average aggregate bank deposits, average aggregate reserves held by banks, average aggregate ON RRP take-up, and aggregate bank and MMF deposits less government bond holdings by the central bank and by dealers. The latter target allows us to back out the level of endowment m_e that households receive in order to match aggregate bank deposits. Lastly, in our model, the number of banks, dealers, and MMFs are normalized to one, which is why we divide aggregate bank deposits and loan issuance by the number of banks, denoted n^b, aggregate MMF assets that are invested in the ON RRP or the repo market by the number of MMFs, denoted n^m, and dealer bond positions by the number of dealers, denoted n^d. Recall, in the model, we assume that the spread between the lending rate and IORB, $i_\ell - R$, is constant. Appendix B provides an overview of the equations used to match our targets using the functional forms of the utility function and the cost of loans function.

We calibrate the model by solving for the parameters $(\alpha, \beta, \theta, k^b, k^m, \phi, m_e)$ and the equilibrium variables $(\rho, i_{d^b}, i_{d^m}, d^b, m_r, d^{ONRRP})$ such that the squared distance between the parameters that solve the model and the moments in the data are minimized.

5.2 Results of the Calibration

In this section, we present the results of our calibration. Table 2 shows our calibrated parameters and Table 3 presents how well the calibrated model matches the moments of our data.

From Table 3, we observe that the model matches our moments very well. The repo rate, the interest rate on bank deposits, and the interest rate on MMF deposits are close to the values in the data, with differences of only 2 and 1.3 basis points for the repo rate and the bank deposit rate, and 3 basis points for MMF deposit rate. The model's predictions of bank deposits, and ON RRP take-up are quite close to the data as well, with differences of \$160, and \$3 billion, respectively. We match average aggregate reserves exactly.

Comparing additional implied values from the model to the data within the calibration period, we find that the estimated quantity of issued loans of \$12.80 trillion is relatively close to average total commercial bank loans and securities held by banks at \$12.79 trillion. The calibrated model furthermore predicts a quantity of \$115.07 billion in repo lending by MMFs, which corresponds roughly to average total government MMF investment in

Treasury repo markets of \$113.38 billion. Lastly, total assets of MMFs in the model are estimated to be \$1.67 trillion, which is very close to the average total quantity invested in the ON RRP and repo market by MMFs of \$1.68 trillion.

Model performance after the February 2023 FOMC meeting. To assess the fit of the model, we test how well the model can predict the monetary policy changes during the February 2023 FOMC meeting, which is just after the end of our calibration period. At this meeting, the FOMC decided to increase administered rates by 25 basis points, such that IORB equaled 4.65%. For this test, we adjust the values of IORB R, the ON RRP rate r, and the nominal quantity of Treasury securities held by the Fed, as noted in Table 4. The results are summarized in Table 5. The model matches TGCR and the interest rate on MMF deposits quite well, with a difference of 4 and and 2 basis points, respectively. The level of bank deposits is slightly higher in the model by about \$80 billion. The predicted level of ON RRP take-up and reserves are very close to the data, with a difference of about \$20 billion and \$40 billion, respectively. However, the model significantly overshoots the predicted value of the bank deposit rate relative to the data, at 3.28% relative to 18 basis points in the data. Table 5 illustrates that the model does very well at predicting the targeted moments.[24]

Model performance on September 17, 2019. On September 17, 2019, the Secured Overnight Financing Rate increased unexpectedly from 2.42% to 5.25%. Anbil et al. (2021) discuss that the economy likely switched from an ample reserves framework to a scarce reserves framework on this day. We test whether the model can predict this switch. Table 6 shows the independent parameters we use from the data for this test; we update the administered rates, Fed holdings of Treasury securities relative to the sum of Fed and dealer Treasury holdings, aggregate deposits, and the aggregate endowment of households (the aggregate endowment must be updated because the sum of bank deposits and MMF repo lending and lending at the ON RRP was notably different on September 17, 2019 relative to our calibration period). Table 7 displays the results. First, the model can indeed predict the switch to a scarce liquidity regime with the repo rate far exceeding the ON RRP rate and matches the increase in repo rate exactly. Indeed, the model matches bank deposits, ON RRP take-up, and reserves very closely with differences of only \$20, \$2.3 billion, and \$10 billion, respectively. In summary, the model does an excellent job of predicting the switch from "ample liquidity" to "scarce liquidity."[25]

[24] The model cannot predict the bank deposit rate very well, highlighting that the low pass-through of administered rates to bank interest rates has always been puzzling to academics. A longer time horizon could potentially help us calibrate the bargaining power of banks (θ) more accurately to reflect this low pass-through.

[25] Since we assume that the repo rate is transferred one-to-one to the MMF deposit rate, the model significantly overshoots the MMF deposit rate by 3.18 percentage points. However, given the temporary

Overall, these tests show that the model does quite well in predicting the switch from excess liquidity to scarce liquidity, and can capture the complicated and rich dynamics of these money markets.

6 Discussion

Using our calibrated model, we now discuss the comparative statics of tightening monetary policy through (i) increasing administered rates or (ii) reducing the size of the central bank's balance sheet in equilibrium.

6.1 Interest Rate Policy in the Excess Liquidity Regime

First, we discuss the effects of tightening through policy rate increases. An increase in the policy rate R, keeping the spread $s = R - r$ constant will have the following effect in equilibrium: Figure 7 shows the movement between bank and MMF deposits as the policy rate R increases, keeping the spread s constant. We see that as the policy rate increases, MMF deposits grow and bank deposits decline. Further, from Figure 8, we see that both the bank and the MMF deposit rate respond to an increase in the policy rate. Lastly, Figure 9 plots the spread $i_{d^m} - i_{d^b}$ as function of the policy rate R, highlighting that even though both deposit rates are increasing, the MMF deposit rate increases relatively more thus widening the spread.

In an excess liquidity regime in the repo market, the MMF deposit rate is determined by the ON RRP offering rate. Thus, an increase in the policy rate will lead to a one-for-one increase in the MMF deposit rate, as the ON RRP rate increases with the IORB. However, following Proposition 3, the bank deposit rate will adjust less than-one-for-one if the bargaining power of banks is sufficiently high. This increase in the spread $i_{d^m} - i_{d^b}$ will make bank deposits relative less attractive and as a result, households have an incentive to deposit less money with banks and more with MMF. These results are in line with the evidence presented in Section 3 and with Drechsler et al. (2017) and Xiao (2020). The model can furthermore show the effects of increasing the policy rate on the balance sheet of the central bank. In particular, for a constant size of the central bank's balance sheet, this results in a shift from funds held as reserves to funds held at the ON RRP facility.

nature of the spike, we argue that matching the MMF deposit rate should not be the primary target for this exercise.

6.2 Transitioning from Excess Liquidity to Scarce Liquidity

Next, we study the effects of monetary policy tightening by reducing the balance sheet of the central bank, or in other words QT, while keeping the policy rate constant.

In order to study the impact of QT, we look at the effects on the equilibrium allocation when the central bank decides to purchase a smaller quantity of government bonds. The smaller quantity of government bond held by the central bank implies that dealers hold a larger share of government bonds that they need to refinance in the repo market. If there is excess liquidity in the repo market, this implies that MMF will simply allocate more funds to repo lending and hold less ON RRP balances. Thus for each unit of smaller government bond holdings by the central bank, trading in the repo market increases and MMF move funds from the ON RRP to the repo market. If ON RRP take-up reaches zero, the repo market is no longer in an excess, but rather scarce liquidity regime. If the central bank further reduces the quantity of government bond holdings, dealers need to refinance again a larger share in the repo market. Since ON RRP take-up is zero, MMF can however no longer move funds away from ON RRP to the repo market. In order to meet the increased demand for repo financing, MMF have to attract more funding and therefore, the MMF deposit rate needs to increase. This will incentivze households to move funds from banks to MMFs. MMF then lend all of their funds in the repo market. Since funding costs of MMFs have increased, the repo rate needs to increase as well. Thus, if the central bank decreases its government bond holdings in an equilibrium with scarce liquidity in the repo market, trading activity in the repo market, the repo rate and the MMF deposit rate increase.

These effects are depicted in Figures 10, 11 and 12. Figure 10 presents the repo rate ρ as a function of the nominal size of the Fed's balance sheet ($p^g \times b^{cb}$). Recall, we define $b^{\tilde{CB}}$ as the size of the central banks balance sheet at which the repo market moves from excess to scarce liquidity. The vertical dashed line denotes $\tilde{b}^{CB}$ for the policy rates in our calibration period. If the central bank reduces its government bond holdings in an excess liquidity regime in the repo market, that is to the right of the dashed line, there is no effect on the repo rate as MMF simply move funds between the ON RRP facility and the repo market. Once government bond holdings are below the critical threshold $tildeb^{CB}$, demand for refinancing by dealers increases and the repo rate has to increase for the market to clear. Correspondingly, Figure 11 plots ON RRP take-up as a function of central bank government bond holdings. The dashed line represents again the critical value $\tilde{b}^{CB}$. As discussed above, as the central bank reduces its government bond holdings, MMF reallocate funds between the ON RRP facility and the repo market and thus ON RRP take-up decrease until it reaches zero.

Next, we discuss the effects on deposits. Figure 12 plots MMF deposits and bank deposits, respectively, as a function of government bond holdings by the Fed ($p^g \times b^{cb}$). Looking at the right side of the graph first, as the Fed reduces the size of its balance sheet ($p^g \times b^{cb}$ declines), MMF and bank deposits are not affected at first. As long as $b^{CB} > \tilde{b}^{CB}$, MMFs lend more in repo by depositing less at the ON RRP and, consequently, there is no effect on the repo rate. Once b^{CB} crosses the threshold, MMF have to attract more funding to meet the increasing demand for repo by dealers. Thus, the MMF deposit rate and consequently the repo rate increase and households shift their deposits from banks to MMFs. Correspondingly, Figure 12 shows a decline in bank deposits as $p^g \times b^{cb}$ declines beyond the critical threshold. These results are also consistent with our empirical observations in Section 3. Recall, that we observed a negative relationship between the growth rate of the SOMA portfolio and MMF deposits before 2008 during the scarce reserves regime and no or even slightly positive relationship in an ample or abundant reserve regime. Figure 12 replicates these findings. MMF deposit decline as the central bank increases it's balance sheet until the economy reaches an excess liquidity regime at which point MMF deposit cease to grow and remain uncorrelated to the growth of the SOMA portfolio.[26]

6.3 Interest Rate and Balance Sheet Policy as Complements

Figure 13 plots the critical threshold $\tilde{b}^{CB}$ as a function of the policy rate R, again keeping the spread s constant. We see that the critical threshold is decreasing in the policy rate, which implies that the critical threshold of the size of the central banks balance sheet at which the repo market move from excess to scarce liquidity is decreasing in the policy rate. This suggests that a central bank that wants to maintain an excess liquidity regime can maintain a smaller balance sheet when policy rates are high. The intuition for this result is the following: As the central bank increases the policy rate, the MMF deposit rate increases relatively more than the bank deposit rate, making MMF deposits relatively more attractive. As a result, households deposit more with MMF and less with banks, leading to an inflow of funds for MMFs. On the other hand, if the central bank reduces its government bond holdings, demand for liquidity by dealers increase as they need to refinance a larger share of government bond holdings in the repo market. Putting this together, with higher interest rates, MMFs hold more funds that can be lent to dealers, which means that the demand for liquidity by dealers can be larger without a corresponding increase in the repo rate. In other words, the capacity of the repo market to absorb higher demand for refinancing by dealers is larger, when interest rates are high. Thus, the central bank can reduce its balance sheet by more if interest rates are high, even if it wants to

[26] Note, in the empirical section we observe that bank deposits continue to decline with reductions in the size of the Fed's balance sheet even after 2008. However, since we don't observe a corresponding increase in MMF deposit during that period, there might other drivers behind this movement.

maintain excess liquidity in the repo market. Using our calibration, these results imply that, for example at $R = 4.65\%$, the equilibrium nominal quantity of Treasury securities held by the central bank consistent with rate control ($p^g \times \tilde{b}^{cb}$) is approximately \$3.37 trillion. With roughly \$5.68 trillion of Treasury securities on the Fed's balance sheet at the end of 2022 (see Table 1), this suggests that, if the Fed would have ceased hiking rates in February 2023, the Fed's balance sheet could be reduced by approximately \$2.28 trillion and still remain in the excess liquidity regime. However, if the policy rate R were lower, for example at 1.5%, the Fed's balance sheet could only be reduced by about \$1.59 trillion and remain in the excess liquidity regime. On the other hand, if the Fed increased rates to the median projection for the 2023 federal funds rate in the March 2023 Summary of Economic Projections of 5.1%, the Fed's balance sheet could be reduced further, by about \$2.37 trillion cumulatively, and remain in the excess liquidity regime.

6.4 Stop believing in reserves

Lastly, we discuss how the minimum level of reserves demanded by banks relates to the critical threshold at which the economy moves from excess liquidity to scarce liquidity in the repo market. Importantly, as defined by the Federal Reserve, an ample reserves regime does not just require reserves to be above bank reserve demand, but also requires that short-term rate control is achieved via the setting of the Fed's administered rates (IORB and the ON RRP rate).[27] We show in Proposition 5 that for $R < R'$, the constraint from the repo market is the binding constraint in order to maintain an excess liquidity regime and interest rate control. In our calibration, we find that R' is higher than current prevailing interest rates and therefore the constraint in the repo market binds first, leading to a larger ultimate size of the Fed's balance sheet than implied by reserve demand.

Figure 14 depicts these results. The blue line represents the level of reserves when the level of government bond holdings b^{CB} equals the critical threshold $\tilde{b}^{CB}$. Consequently, the area above the blue line represents the space where there exists excess liquidity in the repo market, thus $\rho = r$ and $d^{ONRRP} \geq 0$. The area below the blue line represents the space where there exists scarce liquidity in the repo market and therefore $\rho > r$ and $d^{ONRRP} = 0$. The red line represents reserves at the critical threshold $\bar{b}^{CB}$, which is defined as the level of government bonds held by the Fed such that $\rho = R$, that is

$$p^g \bar{b}^{CB} = p^g B - p^g \left[m - p u'^{-1} \left(\frac{1 + R - k^m}{1 + i''_{d^b}} \right) \right],$$

where $\bar{b}^{CB}$ denotes the threshold of central bank government bond holdings at which $\rho = R$

[27] See the January 2019 Statement Regarding Monetary Policy Implementation and Balance Sheet Normalization (`https://www.federalreserve.gov/newsevents/pressreleases/monetary20190130c.htm`).

and i''_{d^b} denotes the bank deposit rate when $\rho = R$.

Thus, the area between the blue line and the red line is where there is scarce liquidity in the repo market but the central bank still maintains firm rate control since $R \geq \rho \geq r$. The area below the red line is where the repo rate exceeds IORB, $\rho > R$, and thus the central bank only has weak rate control.[28] Lastly, the orange line represents the level of reserves that are consistent with the minimum level of reserve demand. Consequently, the area above the orange line represents the space where banks hold excess reserves. Note that reserves cannot be lower than the orange line, since the orange line represents the reserve holding constraint from the banks' maximization problem. Thus, if reserves are strictly above the orange line, banks hold excess reserves. If reserves are equal to the orange line, bank hold the minimum quantity of reserves required. Consequently, if reserve holdings are strictly above the orange line, the economy has excess reserves. If reserve holdings are equal to the orange line, the economy has scarce reserves.

Our results imply that the minimum level of reserves demanded by banks is not a sufficient indicator to assess whether the economy is in an excess liquidity regime. In particular, we find that market rates start increasing at a level of reserves that is much higher than the indicated level of minimum reserves. Moreover, the level of reserves at which the repo rate reaches IORB, which recently has been set 10 basis points below the upper bound of the target range of the fed funds rate, is very close to the level of reserves at which repo rates begin to increase and therefore also much higher than the implied minimum level of reserves. Thus, if the central bank wants to maintain interest rate control and remain in an ample liquidity regime, the level of reserves has to be much higher. Our estimates from the calibration imply that, at an IORB equal to 4.65%, reserves would have to be around \$2.9 trillion (the blue line) to be consistent with an ample liquidity regime relative to minimum reserve demand of about \$2.1 trillion (the orange line).[29] Thus, for a central bank that wants to maintain an ample reserves framework, the critical threshold $\tilde{b}^{CB}$ is the effective constraint on the size of the central bank's balance sheet, and not the level of minimum reserve demand.

Our numerical estimates for the level of reserves at $b^{CB} = \tilde{b}^{CB}$ and $b^{CB} = \bar{b}^{CB}$ depend on a series of assumptions. First, we assume that all government bonds held by dealers are financed in repo. Historical FR 2004 data shows that in reality dealers only finance

[28] As noted above, the Federal Reserve targets the effective federal funds rate and not repo rates. The underlying assumption here is that when repo rates increase beyond IORB, the EFFR will follow. Thus, weak interest rate control in the repo market would imply weak interest rate control in the federal funds market.

[29] As noted in Section 6.3, maintaining excess liquidity in the repo market and rate control implies that, if the Fed would have ceased hiking rates in February 2023 at IORB of 4.65%, the Fed's balance sheet could be reduced by approximately \$2.29 trillion and still remain in the excess liquidity regime. However, there is not a direct mapping from the minimum reserve demand to the total size of the Fed's balance sheet since a variety of levels of the ON RRP can be consistent with minimum reserve demand.

about half of their government bond holdings in the repo market. Less reliance by dealers on the repo market would imply that the central bank can shrink its balance sheet further before rate control is threatened, leading to a lower level of reserves. This suggests that our estimates of the level of reserves consistent with an ample liquidity regime are an upper bound.[30] Second, we assume that there are no frictions in the repo market. Frictions such as persistent lending relationships could lead to a slower increase in repo rates when $b^{CB} < \tilde{b}^{CB}$. Furthermore, as mentioned above, the repo rate may also increase slower as the level of government bond holdings of the central bank declines beyond $\tilde{b}^{CB}$ if MMFs can move funds out of alternative investments such as government bills to the repo market, rather than needing to attract new funds from households. This would make the repo rate less sensitive to further declines in the central bank's balance sheet, leading to a lower level of reserves when the repo rate reaches IORB. Lastly, our estimate of the minimum level of reserve demand is based on the ratio of bank deposits and reserves at the end of August 2019. We interpret this constraint as a combination of both regulations that require banks to hold a certain amount of reserves and internal preferences of banks for holding reserves. Any changes in either regulations or preferences of banks to hold reserves may move the estimate for the minimum level of reserve demand in either direction.

7 Conclusion

In this paper, we aim to understand the transmission channels of quantitative tightening through the Fed's balance sheet. In particular, we are address two questions: First, how does balance sheet tightening affect the allocation of funds between banks and non-banks and second, by how much can a central bank reduce its balance sheet while maintaining an excess liquidity regime. Empirically, we observe that when the Fed reduces it's balance sheet, bank deposits grow less similar to monetary policy tightening through interest rate increases. However, we observe that MMF deposits only grow more when the Fed decreases it's balance sheet in a scarce liquidity regime. We build a structural model that can replicate our empirical observations and calibrate it to the current tightening cycle in the US. We find two novel insights. First, we show that there exists some complimentarity between monetary policy tightening through the balance sheet and monetary policy tightening by increasing policy rates, that is the central bank can reduce its balance sheet by more when policy rates are high. Second, we show that, contrary to the traditional focus on bank

[30] A related issue is that we calibrate our model only to the Fed's Treasury securities holdings. In reality, the Fed also holds a substantial amount of agency MBS. If dealers also absorb the agency MBS that the Fed runs off its balance sheet and finances all these securities in the repo market, the implications for total amount that the Fed can shrink its balance sheet are the same. However, agency MBS are also held by other types of institutions and, for the portion held by dealers, are not financed completely in repo to an even greater extent than for Treasuries. Less reliance on the repo market suggests that the Fed could shrink its balance sheet further than the estimates shown here.

reserve demand alone, the repo market's capacity to bear the additional securities that the Fed is running off is actually more likely to constrain the size of the Fed's balance sheet in the current environment. In our calibration, we show that for current levels of policy rates the demand for liquidity by non-banks is the binding constraint for a central bank that wants to maintain an excess liquidity regime. This implies that the Fed's balance sheet will need to be larger than what bank reserve demand alone might suggest and that, within an ample reserves framework, the demand for money by shadow banks also needs to be considered. These findings have significant implications for the Fed's current tightening cycle and the eventual end point of its balance sheet runoff.

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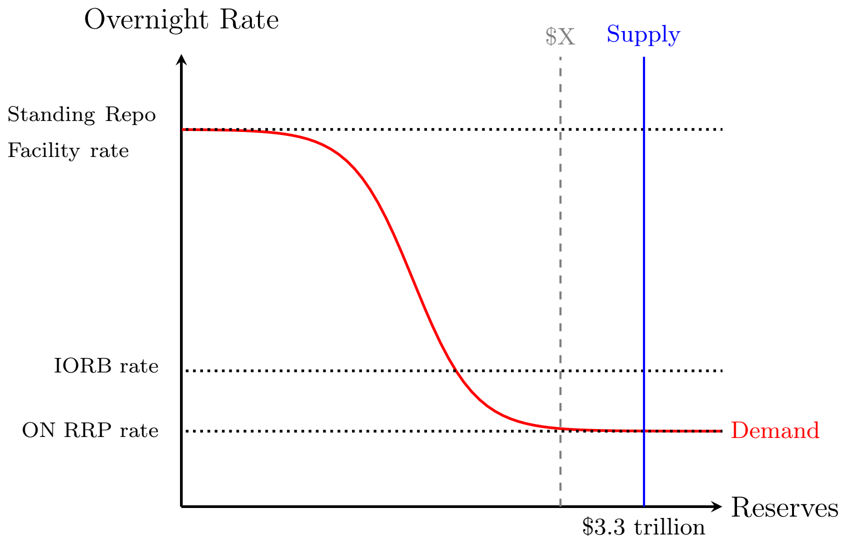
Figures and Tables

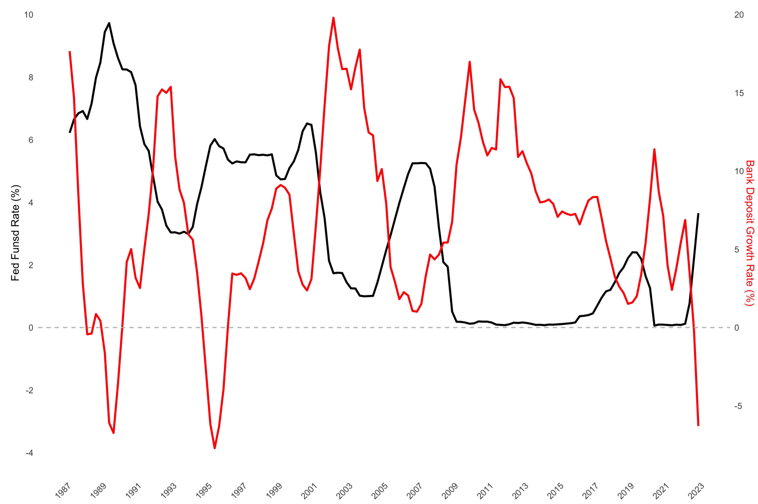
Figure 1: Ample Reserves Framework



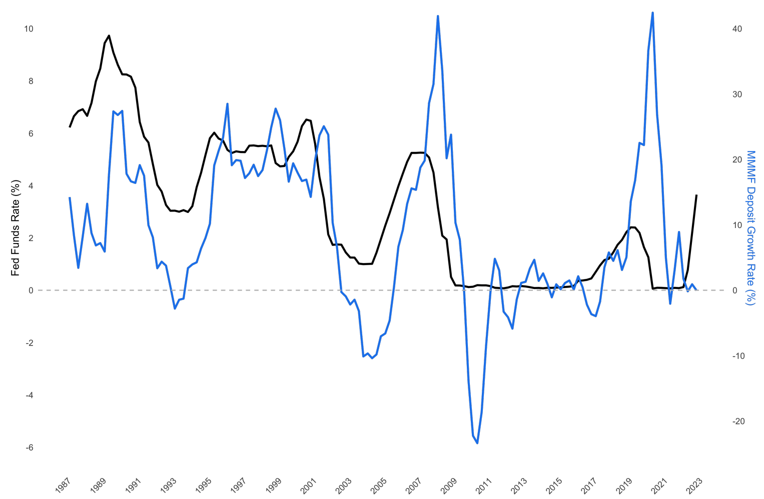
This figure shows the relationship between overnight rates and reserves. The red line denotes reserve demand and the blue line denotes reserve supply. Reserves were $3.3 trillion as of June 2022. $X denotes the minimum level of reserves consistent with an ample reserves environment. IORB rate is the interest rate on reserve balances at which banks can lend to the Fed. ON RRP rate is the offering rate at the Overnight Reverse Repo Facility at which banks and other institutions can lend to the Fed. Standing Repo Facility rate is the rate at which institutions can borrow from the Fed at the Standing Repo Facility.

Figure 2: EFFR, Bank and MMF Deposit Growth

(a) EFFR and Bank Deposit Growth



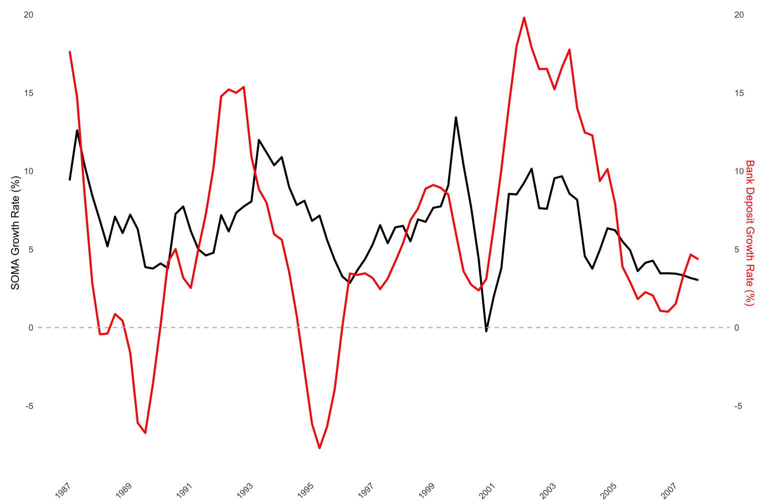
(b) EFFR and MMF Deposit Growth



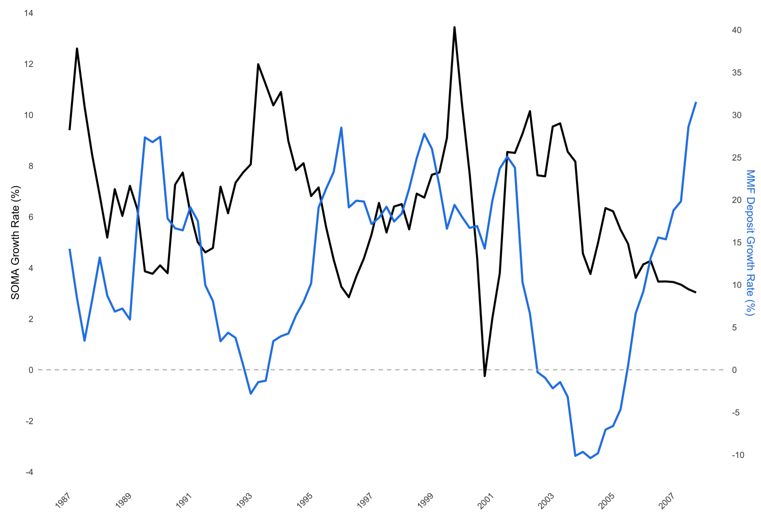
Panel (a) depicts the EFFR (left axis) and bank deposit growth (right axis) from 1987 to 2023. Panel (b) depicts the EFFR (right axis) and MMF deposit growth (left axis) from 1987 to 2023.

Figure 3: SOMA Growth, Bank and MMF Deposit Growth from 1987 to 2008

(a) SOMA Growth and Bank Deposit Growth



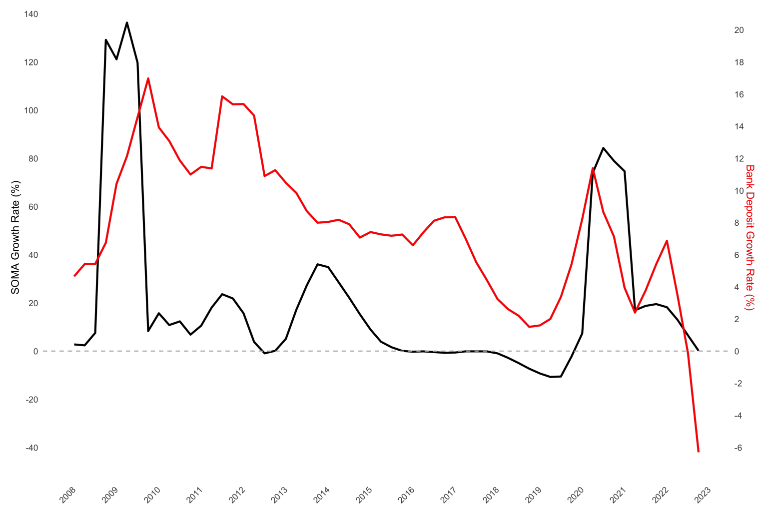
(b) SOMA Growth and MMF Deposit Growth



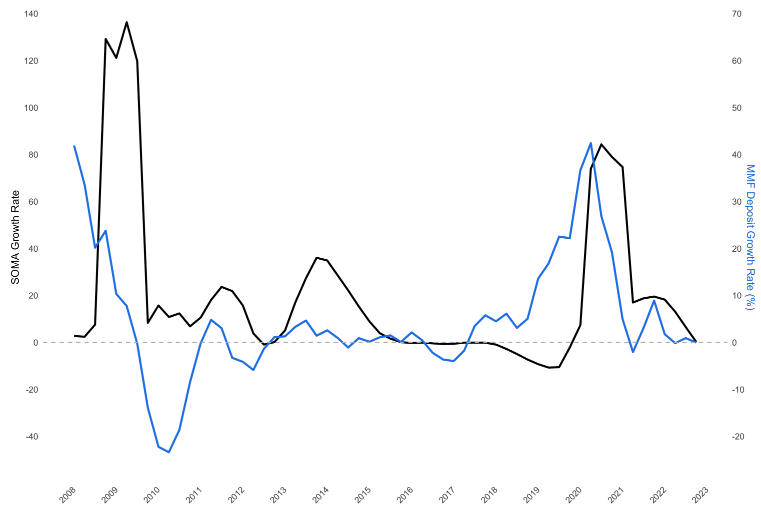
Panel (a) depicts the SOMA growth (left axis) and bank deposit growth (right axis) from 1987 to 2008. Panel (b) depicts the SOMA growth (right axis) and MMF deposit growth (left axis) from 1987 to 2008.

Figure 4: SOMA Growth, Bank and MMF Deposit Growth from 2008 to 2023

(a) SOMA Growth and Bank Deposit Growth

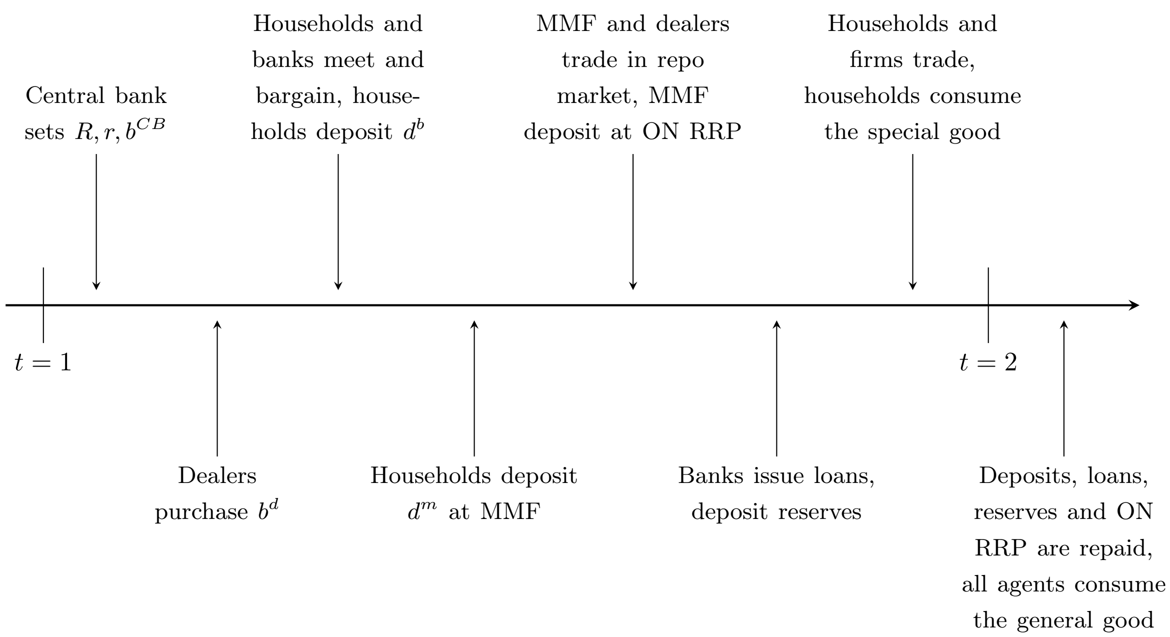


(b) SOMA Growth and MMF Deposit Growth



Panel (a) depicts the SOMA growth (left axis) and bank deposit growth (right axis) from 2008 to 2023. Panel (b) depicts the SOMA growth (right axis) and MMF deposit growth (left axis) from 2008 to 2023.

Figure 5: Timing of events



This figure depicts the timing of events in the model. In period $t = 1$, the central bank sets the IORB, R, the ON RRP rate, r and decides how many government bonds, b^{CB} to purchase. Next, dealers purchase the remaining bonds, b^d from households. Households then meet with banks and bargain over the quantity of bank deposits, d^b and the deposit rate, i_{d^b}. After depositing their bank deposits, households deposit their remaining funds with MMF, d^m. Next, MMF and dealers trade in the repo market and MMF deposit their funds at the ON RRP. Then, banks issue loans ℓ and decide how many reserves, m_r to hold. Finally, in period $t = 2$, reserves, ON RRP balances, deposits and loans are being repaid and all agents consume.

Figure 6: T-Accounts of the Central Bank, Banks, MMFs, Households and Dealers

Central Bank

Bonds b^{CB}	Reserves m_r
General goods Px	ON RRP d^{ONRRP}

Banks

Loans ℓ	Bank deposits d^b
Reserves m_r	

MMF

Repo z^m	MMF deposits d^m
ON RRP d^{ONRRP}	

Households

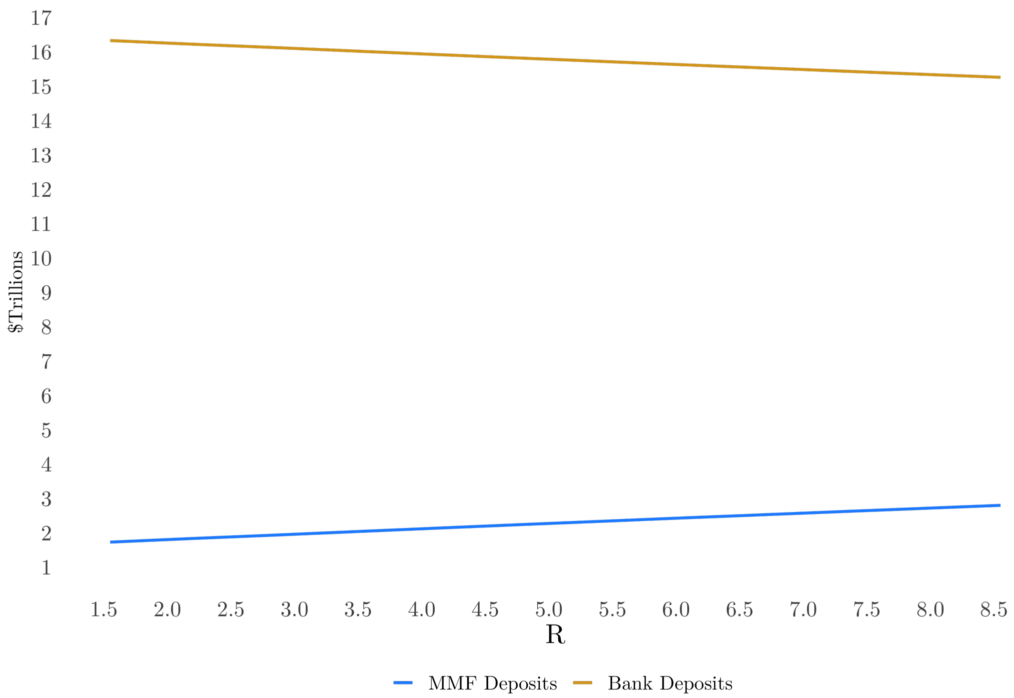
Bank deposits d^b	Equity
MMF deposits d^m	

Dealers

Bonds b^d	Repo z^d

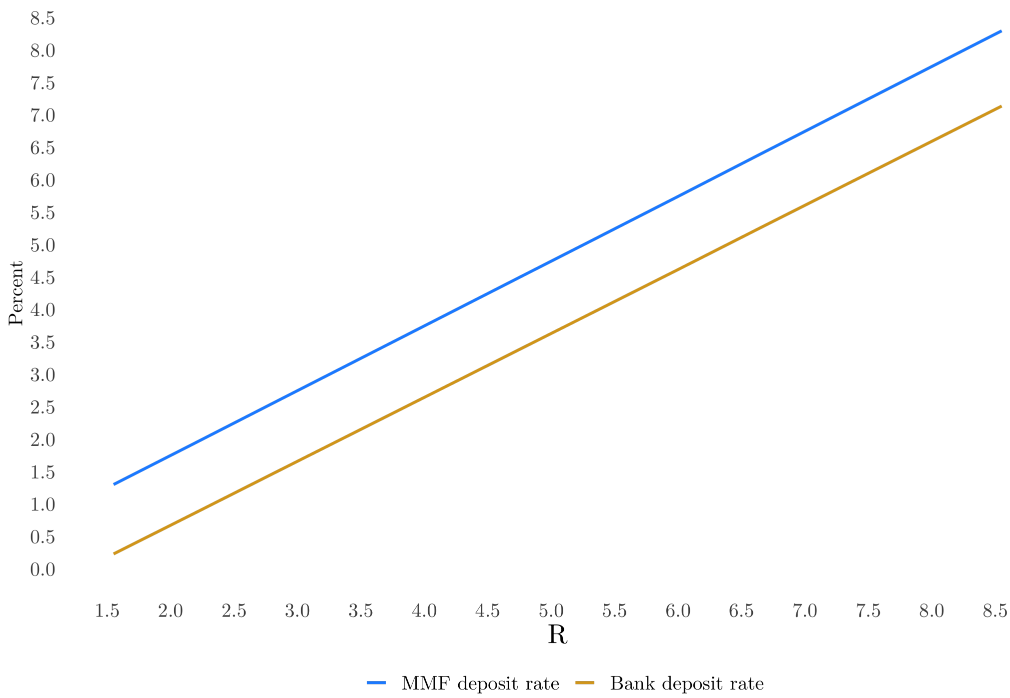
This figure depicts the T-accounts for the central bank, banks, MMFs, households and dealers. The central bank holds government bonds, b^{CB} and the general good Px on its asset side and reserves m_r and ON RRP balances d^{ONRRP} on its liabilities side. Banks hold loans ℓ and reserves m_r on their asset side and bank deposits d^b on their liabilities side. MMFs hold repo lending z^m and ON RRP balances d^{ONRRP} on their asset side and MMF deposits d^m on their liabilities side. Household have equity through their endowment and hold this equity either in bank d^b or MMF d^m deposits. Dealers borrow in the repo market z^d and hold government bonds on their asset side.

Figure 7: Deposit Allocation and the Policy Rate



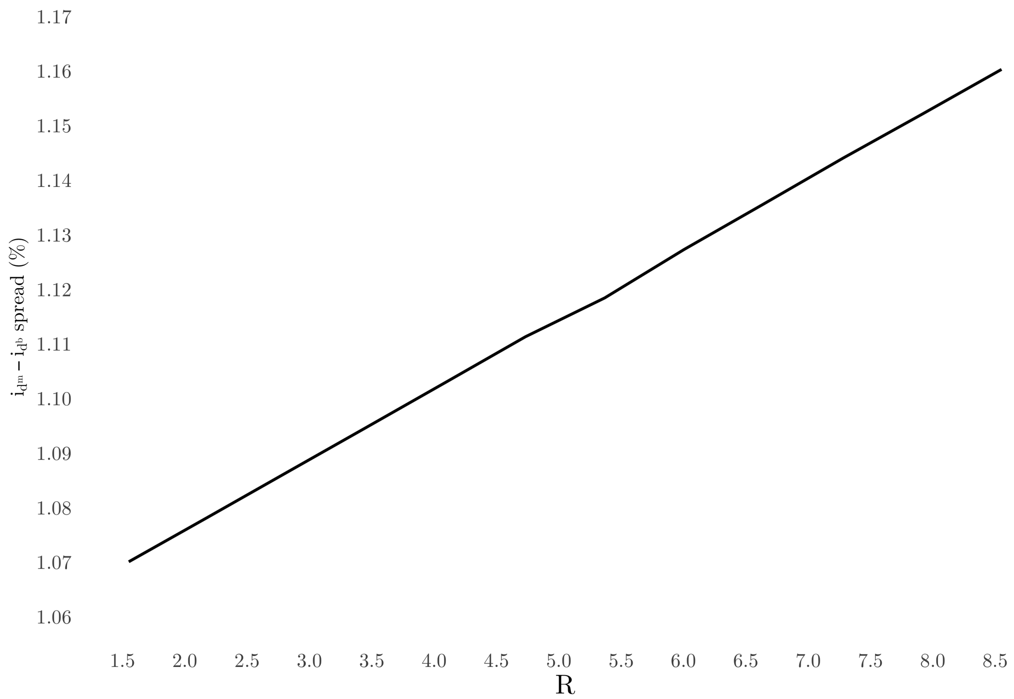
This figure shows how deposits at banks d^b (the orange line) and deposits at MMFs d^m (the blue line) change with the policy rate R. As the policy rate increases, households shift deposits from banks to MMFs.

Figure 8: Deposit Rates and the Policy Rate



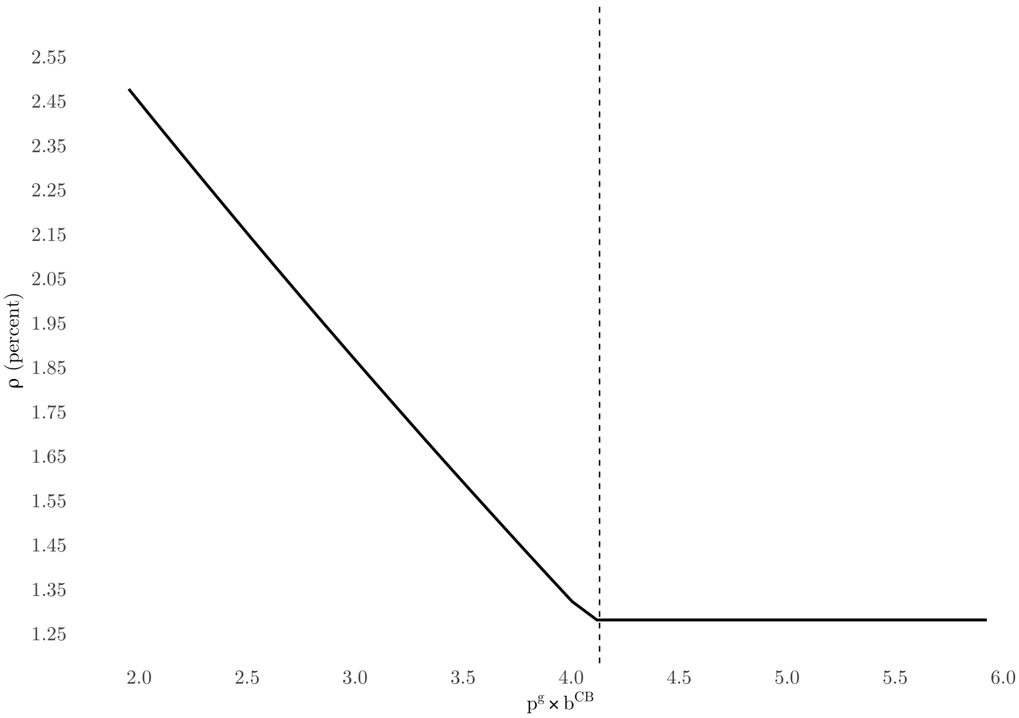
This figure shows how the deposit rate at banks i_{d^b} (the orange line) and the deposit rate at MMFs i_{d^m} (the blue line) change with the policy rate R. As the policy rate increases, both banks and MMFs increase their deposit rate, but MMFs do so at a somewhat faster pace.

Figure 9: The Spread between Deposit Rates



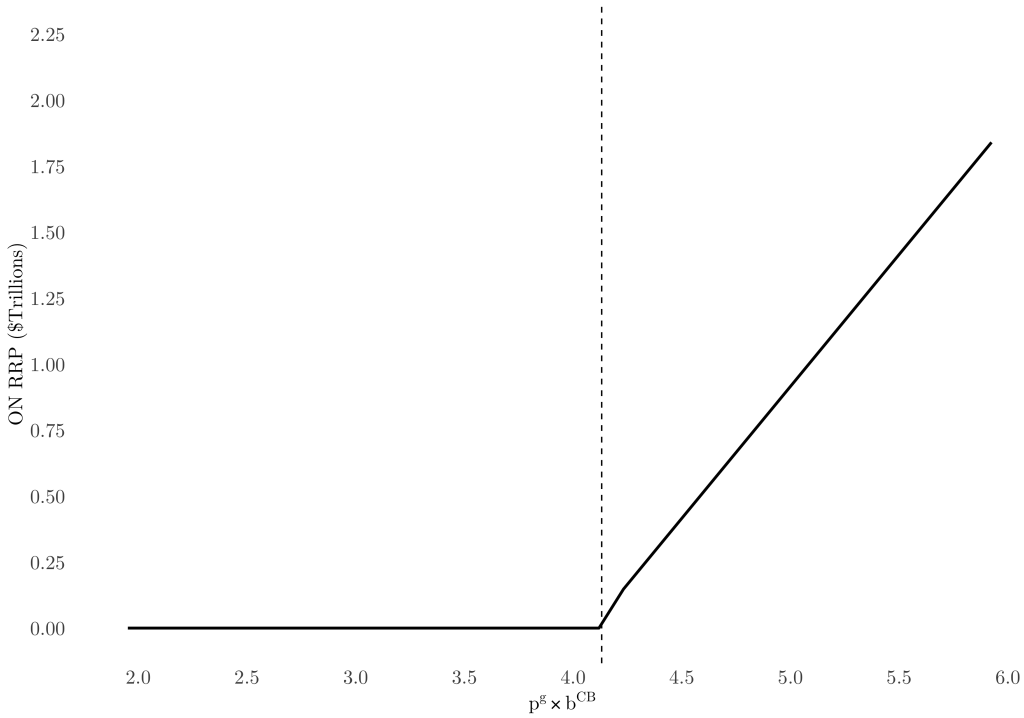
This figure shows the spread between the MMF deposit rate and the bank deposit rate. The positive slope indicates that the pass-through of an increase in the policy rate R is somewhat larger for MMF deposit rates than it is for bank deposit rates.

Figure 10: The Repo Rate and the Fed's Balance Sheet



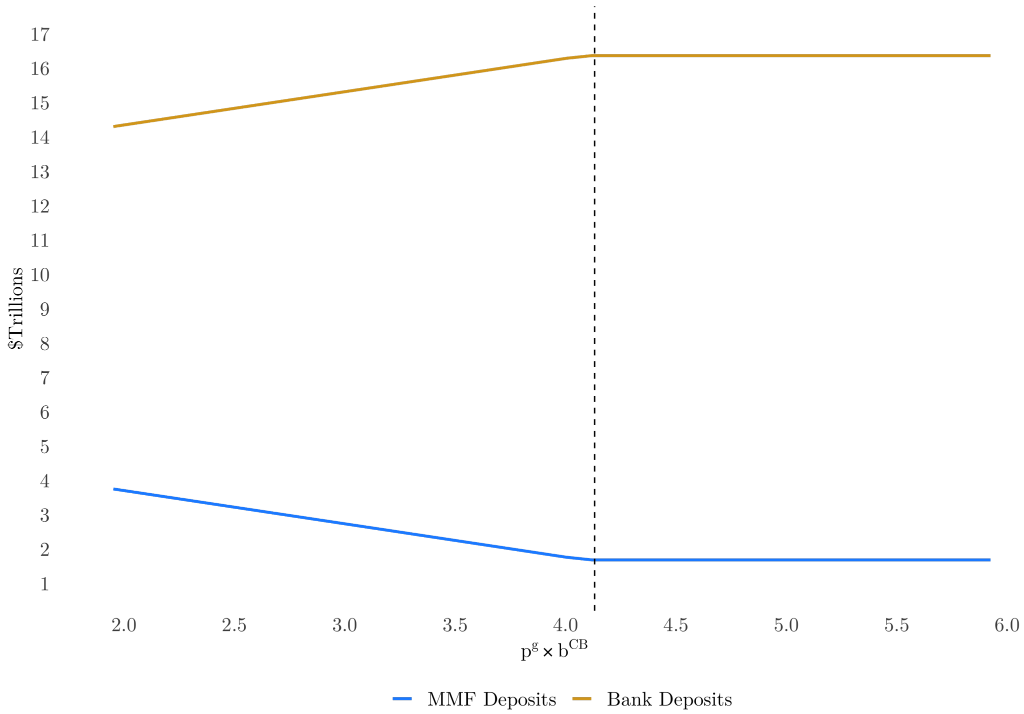
This figure shows how the repo rate ρ changes with the size of the Fed's balance sheet b^{cb}. The dashed line represents $\tilde{b}^{cb}$, the point at which there is a shift from ample liquidity in the repo market (right of the line) to scarce liquidity in the repo market (left of the line). In the ample regime, the repo rate is at the ON RRP rate, whereas in the scarce regime, the repo rate increases as the size of the Fed's balance sheet decreases.

Figure 11: ON RRP Take-up and the Fed's Balance Sheet



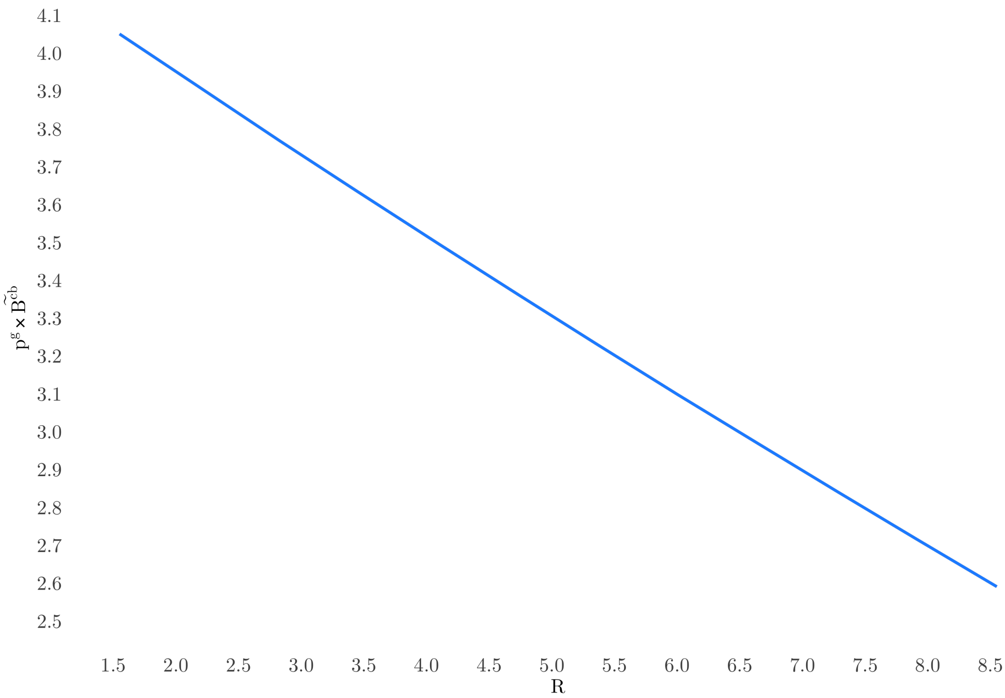
This figure shows how ON RRP take-up changes with the size of the Fed's balance sheet, b^{cb}. The dashed line represents $\tilde{b}^{cb}$, the point at which there is a shift from ample liquidity in the repo market (right of the line) to scarce liquidity in the repo market (left of the line). In the ample regime, ON RRP take-up falls with the size of the balance sheet until it reaches zero, whereas in the scarce regime, ON RRP take-up is constant at zero.

Figure 12: Deposits and the Fed's Balance Sheet



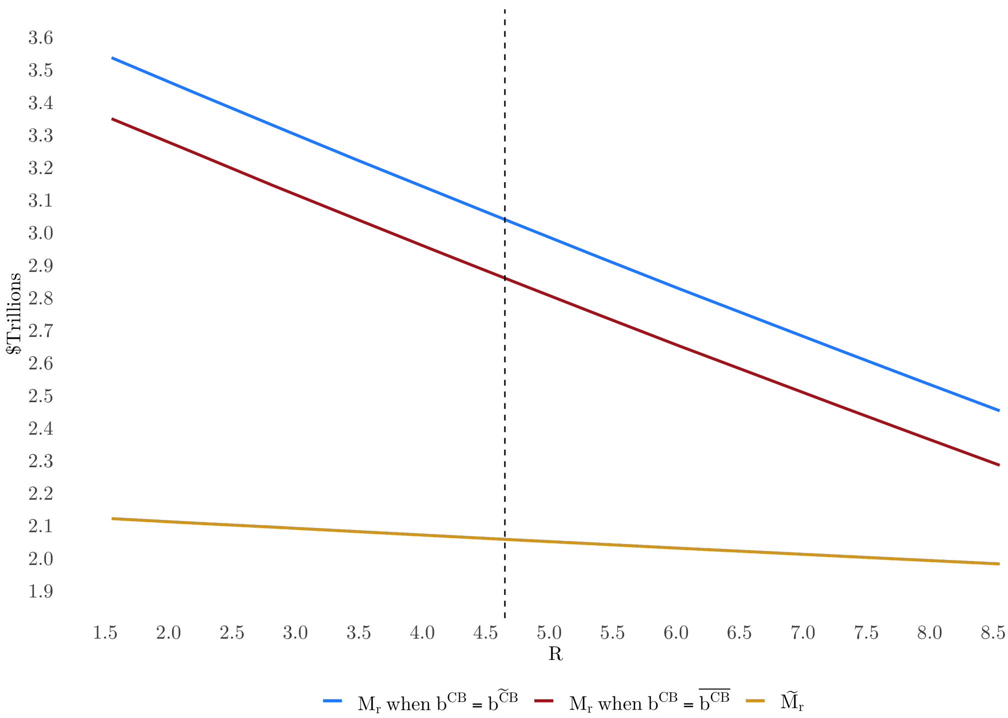
This figure shows how deposit allocation changes with the size of the Fed's balance sheet b^{cb}. The dashed line represents $\tilde{b}^{cb}$, the point at which there is a shift from ample liquidity in the repo market (right of the line) to scarce liquidity in the repo market (left of the line). In the ample regime, deposits are unchanged with the size of the Fed's balance sheet, whereas in the scarce regime, bank deposits decrease and MMF deposits increase as the Fed's balance sheet decreases given the higher rates that MMFs offer relative to bank deposit rates.

Figure 13: The Threshold on Repo Market Liquidity and the Policy Rate



This figure shows how the critical threshold of government bond holdings of the Fed $\tilde{b}^{cb}$ changes with the policy rate R. As the policy rate increases, the critical threshold of the Fed's government bond holdings decreases. If the Fed's government bond holdings are above the blue line, there is ample liquidity in the repo market and if the Fed's government bond holdings are below the line, there is scarce liquidity in the repo market.

Figure 14: Reserves



This figure shows the level of reserves when reserves are equal to the minimum level of reserve demand (orange line), reserves when the Fed's government bond holdings are equal to $\tilde{b}^{CB}$ (blue line), and reserves when the Fed's government bond holdings are equal to $\bar{b}^{CB}$ (red line). This figure shows that there exist four different regimes in equilibrium when the policy rate $R \in [1.5\%, 8.5\%]$. First, if the Fed's government bond holdings are larger than the critical threshold $\tilde{b}^{CB}$, there exists excess liquidity in the repo market and excess reserves (above the blue line). As the Fed reduces its balance sheet beyond $\tilde{b}^{CB}$, the repo rate starts to increase, but banks still hold excess reserves (between the blue line and the red line). If the Fed reduces its balance sheet beyond $\bar{b}^{CB}$, the repo rate increases beyond IORB, $\rho > R$, but banks continue to hold excess reserves (between the red line and the orange line). Lastly, if the Fed reduces its balance sheet further, such that the reserve constraint for banks becomes binding (below the orange line), there exists both scarce liquidity in the repo market and scarce reserves as banks only hold the minimum level of reserve demand.

Table 1: Independent Parameters

Parameter	Description	Value	Source
R	IORB	1.38%	Data
r	ON RRP offering rate	1.28%	Data
i_ℓ	Average interest rate on banks' outside investments	2.71%	Data
$p^g b^{CB}$	Nominal quantity of Treasury securities held by the Fed	\$5.65T	Data
$p^g B$	Nominal quantity bonds in the economy	\$5.77T	Data
δ	Minimal reserve-to-deposit ratio	0.13	Data

Source: FRED, FFIEC Call Reports, Federal Reserve Board H.4.1., Federal Reserve Bank of New York, Federal Reserve Board H.8.

This table shows the independent parameters of the model that are used to calibrate the model.

Table 2: Jointly Calibrated Parameters

Parameter	Description	Data	Model
θ	Bargaining power of banks	-	0.17
k^b	Balance sheet costs of banks	-	0.0019%
k^m	Balance sheet costs of MMF	-	0.15%
α	Relative risk aversion	-	0.08
β	Loan cost function	-	4.48
ϕ	Price level in $t = 2$	-	231.03
M_e	Money endowment to households	-	\$12.28T

This table shows the calibrated parameters.

Table 3: Targeted Moments

Parameter	Description	Data	Model	Error
ρ	TGCR	1.26%	1.28%	$+(0.02)$
i_{d^m}	Interest rate on MMF deposits	1.10%	1.13%	$+(0.03)$
i_{d^b}	Interest rate on bank deposits	0.077%	0.064%	$-(0.013)$
D^b	Bank Deposits	\$16.53T	\$16.37T	$-(0.16)$
D^{ONRRP}	Aggregate ON RRP take-up	\$1.53T	\$1.56T	$+(0.03)$
M_r	Aggregate reserves	\$3.58T	\$3.58T	(0)

Source: Federal Reserve Bank of New York, iMoneyNet, Inc., RateWatch - S&P Global Market Intelligence, Federal Reserve Board H.8., U.S. Money Market Fund Monitor - Office of Financial Research, Federal Reserve Board H.4.1.

This table shows the moments that were targeted in the calibration for both the results from the model and the value in the data. The last column displays the difference between the moment from the model and the moment in the data.

Table 4: Parameters for February 2023

Parameter	Description	Value
R	IORB	4.65%
r	ON RRP offering rate	4.55%
$p^g b^{CB}$	Nominal quantity of Treasury securities held by the Fed	\$5.36T

Source: FRED, FFIEC Call Reports, Federal Reserve Board H.4.1.

This table shows the values of IORB, the ON RRP offering rate, and the quantity of Treasury securities held by the Fed in February 2023.

Table 5: Post February 2023 FOMC Test

Parameter	Description	Data	Model	Error
ρ	TGCR	4.51%	4.55%	$+(0.04)$
i_{d^m}	Interest rate on MMF deposits	4.38%	4.40%	$+(0.02)$
i_{d^b}	Interest rate on bank deposits	0.18%	3.28%	$+(3.10)$
D^b	Bank Deposits	\$15.76T	\$15.84T	$+(0.08)$
D^{ONRRP}	Aggregate ON RRP take-up	\$1.82T	\$1.80T	$-(0.02)$
M_r	Aggregate reserves	\$3.00T	\$3.04T	$+(0.04)$

Source: Federal Reserve Bank of New York, iMoneyNet, Inc., RateWatch - S&P Global Market Intelligence, Federal Reserve Board H.8., U.S. Money Market Fund Monitor - Office of Financial Research, Federal Reserve Board H.4.1.

This table shows the results of running the calibrated model with values for IORB, the ON RRP offering rate, and the quantity of Treasury securities held by the Fed in February 2023.

Table 6: Parameters for September 2019

Parameter	Description	Value
R	IORB	2.1%
r	ON RRP offering rate	2.0%
$p^g b^{CB}$	Treasury securities holdings of the Fed	\$2.10T
$p^g B$	Aggregate Treasury securities holdings of the Fed and dealers	\$2.20T
M	Aggregate Endowment to Households	\$11.34T

Source: FRED, FFIEC Call Reports, Federal Reserve Board H.4.1., Federal Reserve Bank of New York.

This table shows the values of IORB, the ON RRP offering rate, the quantity of Treasury securities held by the Fed, and the aggregate quantity of Treasury securities held by the Fed and dealers at the end of August 2019.

Table 7: September 2019 Test

Parameter	Description	Data	Model	Error
ρ	TGCR	5.25%	5.25%	(0)
i_{d^m}	Interest rate on MMF deposits	1.92%	5.10%	+(3.18)
i_{d^b}	Interest rate on bank deposits	0.14%	0.85%	+(0.71)
D^b	Bank Deposits	\$11.23T	\$11.25T	+(0.02)
D^{ONRRP}	Aggregate ON RRP take-up	\$0.0023T	\$0T	−(0.0023)
M_r	Aggregate reserves	\$1.47T	\$1.46T	−(0.01)

Source: Federal Reserve Bank of New York, iMoneyNet, Inc., RateWatch - S&P Global Market Intelligence, Federal Reserve Board H.8., U.S. Money Market Fund Monitor - Office of Financial Research, Federal Reserve Board H.4.1.

This table shows the results of the calibrated model using values of IORB, the ON RRP offering rate, the quantity of Treasury securities held by the Fed, and the aggregate quantity of Treasury securities held by the Fed and dealers at the end of August 2019.

Appendix

A Proofs

Proof of Proposition 1. Suppose there exists an equilibrium where $\rho > r$ and $d^{ONRRP} > 0$. In that case, MMF have an incentive to move funds out of the ON RRP and lend them in the repo market. The inflow of funds will lead to a decrease in the repo rate ρ such that either $\rho = r$ and MMF are indifferent between the ON RRP facility and the repo market and in that case $d^{ONRRP} \geq 0$ or the repo rate remains above the ON RRP rate $\rho > r$ and MMF move all available funds out of the ON RRP facility to the repo market, such that $d^{ONRRP} = 0$. ■

Proof of Proposition 2. Equations (16), (22), (15), (17), (19), (23), (6) as well as Equations (20) and (21) follow from the derivations given in the main text. It remains to derive Equation (24). First, if households are constrained, they spend all their bank deposit holdings in the goods market. Thus, the money holdings in the beginning of period $t = 2$ satisfy $d^m(1 + i_{d^m})$. Conversely, the money holdings of firms satisfy $d^b(1 + i_{d^b})$, since in equilibrium $pq_s = d^b$.

In period $t = 2$, MMF hold

$$\Pi^{MMF} = z^m(1 + \rho) + (d^m - z^m)(1 + r) - d^m(1 + i_{d^m} - k^m).$$

The liquidity holdings of dealers in period $t = 2$ satisfy

$$\Pi^D = b^d - z^d(1 + \rho)$$

Dealers borrow z^d and use it to purchase bonds. In period $t = 2$, dealers repay their loans and receive the return on government bonds.

Lastly, banks earn a return $(1 + i_\ell)$ on their loans and a return $(1 + R)$ on their reserve holdings. They pay the interest rate i_{d^b} on bank deposits. Their profits therefore satisfy

$$\Pi^B = \ell(1 + i_\ell) + m_r(1 + R) - d^b(R - i_{d^b} - k^b).$$

Adding the money holdings of all agents up and rearranging yields the market clearing condition in $t = 2$,

$$\frac{x}{\phi} = \ell(1 + i_\ell) + m_r(1 + R) + (d^m - z^m)(1 + r) - m(k^b + k^m) + d^b k^m + d^m k^b, \qquad \text{(A.1)}$$

which is Equation (24). $\blacksquare$

Proof of Proposition 3. Totally differentiating Equation (16) yields

$$\mathrm{d}i_{d^b} = dR + \frac{\mathrm{d}\ell(i_\ell - R)}{d^b} - \frac{\ell(i_\ell - R)}{(d^b)^2}\mathrm{d}d^b - \frac{\chi'(\ell)\mathrm{d}\ell}{d^b} + \frac{\chi(\ell)}{(d^b)^2} - \frac{\theta}{1-\theta}\frac{u'(q)}{d^b}\mathrm{d}q + \frac{\theta}{1-\theta}\frac{u(q)}{(d^b)^2}\mathrm{d}d^b + \frac{\theta}{1-\theta}\mathrm{d}i_{d^m}. \tag{A.2}$$

Note, $\mathrm{d}\ell = 0$, since the spread $i_\ell - R$ is assumed to be constant across R. Furthermore, $\mathrm{d}i_{d^m} = dr$, since $i_{d^m} = r$ in an excess liquidity equilibrium. Lastly, since we assume that s is constant, $\mathrm{dR} = \mathrm{dr}$. Next, totally differentiating Equation (2) and rearranging yields

$$\mathrm{d}p = -\mathrm{d}i_{d^b}\frac{p}{1+i_{d^b}}. \tag{A.3}$$

And totally differentiating Equation (15) and rearranging yields

$$\mathrm{d}q = \frac{1}{u''(q)}\left[\frac{1}{1+i_{d^b}}\mathrm{d}r - \frac{1+r}{(1+i_{d^b})^2}\mathrm{d}\mathrm{d}i_{d^b}\right]. \tag{A.4}$$

Using, $d^b + pq$ and plugging Equations (A.3) and (A.4) into Equation (A.2) yields

$$\frac{\mathrm{d}i_{d^b}}{\mathrm{d}r} = \frac{\frac{1}{1-\theta} - (\omega_1 - \omega_2 + \omega_3 - \omega_4)}{1 - \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)(\omega_1 - \omega_2 + \omega_3 - \omega_4) + \omega_5 - \omega_6 + \omega_7}, \tag{A.5}$$

where $\omega_1 = \frac{\theta}{1-\theta}\frac{u'(q)}{u''(q)}\frac{1}{q}$, $\omega_2 = \frac{\theta}{1-\theta}\frac{u(q)}{u''(q)}\frac{1}{q^2}$ and $\omega_3 = \frac{\phi\ell(i_\ell-R)}{u''(q)q^2}$, $\omega_4 = \frac{\phi\chi(\ell)}{u''(q)q^2}$, $\omega_5 = \frac{\theta}{1-\theta}\frac{u(q)}{q}$ $\omega_6 = \frac{\phi(\ell i_\ell - R)}{q}$ and $\omega_7 = \frac{\phi\chi(\ell)}{q}$.

For the pass-through of policy rates to be less than one-for-one, $\mathrm{d}i_{d^b}/\mathrm{d}r < 1$ has to hold. Rearranging Equation (A.5) and solving for θ yields

$$\theta > \frac{\left(\frac{\phi\ell(i_\ell-R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \frac{i_{d^m}-i_{d^b}}{1+i_{d^b}}\frac{1}{u''(q)q}\right)}{\left(\frac{\phi\ell(i_\ell-R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \frac{i_{d^m}-i_{d^b}}{1+i_{d^b}}\frac{1}{u''(q)q}\right) + \left(\frac{i_{d^b}-i_{d^m}}{1+i_{d^b}}\right)\left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right) + \frac{u(q)}{q} - 1} \equiv \theta_1. \tag{A.6}$$

Thus, the pass-through of policy rate increases to bank deposit rates is less than one-for-one if $\theta > \theta_1$. $\blacksquare$

Proof of Proposition 4. Recall, $\tilde{b}$ is defined as

$$p^g\tilde{b} = m - d^b.$$

Totally differentiating this equation and rearranging yields

$$\mathrm{d}\tilde{b}^b = \frac{1}{p^g}\left[\mathrm{d}m - \mathrm{d}d^b - \mathrm{d}p^g\tilde{b}\right] \tag{A.7}$$

Recall that $1/p^g = 1+\rho$. Thus, at $b^d = \tilde{b}^d$, $1/p^g = 1+r$. Using this and rearranging, we obtain

$$\frac{\mathrm{d}\tilde{b}}{\mathrm{d}r} = (1+r)\left[\frac{\mathrm{d}m}{\mathrm{d}r} - \frac{\mathrm{d}d^b}{\mathrm{d}r} + \frac{1}{(1+r)^2}\tilde{b}\right]. \tag{A.8}$$

If the central bank only changes its policy rates, then $\mathrm{d}m/\mathrm{d}r = 0$. Thus, to show that $\tilde{b}$ is increasing in the policy rates, it suffices to show that $\mathrm{d}d^b/\mathrm{d}r$ is decreasing in the policy rates.

Totally differentiating $d^b = pq$ yields

$$\mathrm{d}d^b = \mathrm{d}pq + p\mathrm{d}q. \tag{A.9}$$

Plugging Equations (A.3) and (A.4) into Equation (A.9) and rearranging yields

$$\frac{\mathrm{d}d^b}{\mathrm{d}r} = \frac{1}{u''(q)}\frac{p}{(1+i_{d^b})} - \frac{\mathrm{d}i_{d^b}}{\mathrm{d}r}\left[\frac{pq}{1+i_{d^b}} + \frac{p}{u''(q)}\frac{1+r}{(1+i_{d^b})^2}\right]. \tag{A.10}$$

Combining Equations (A.5) and (A.10) and rearranging yields yields

$$\begin{aligned}\frac{\mathrm{d}d^b}{\mathrm{d}r} = {} & \frac{1}{u''(q)}\frac{p}{1+i_{d^b}}\left[1 - \frac{\frac{qu''(q)}{1-\theta} - qu''(q)(\omega_1-\omega_2+\omega_3-\omega_4)}{1 - \frac{1+i_{d^m}}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4) + \omega_5 - \omega_6 + \omega_7}\right] \\ & - \frac{1}{u''(q)}\frac{p}{1+i_{d^b}}\left[\frac{\frac{1}{1-\theta}\frac{1+i_{d^m}}{1+i_{d^b}} - \frac{1+r}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4)}{1 - \frac{1+i_{d^m}}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4) + \omega_5 - \omega_6 + \omega_7}\right]\end{aligned} \tag{A.11}$$

Note, the term $(1/u''(q))(p/(1+i_{d^b}))$ is negative, since $u''(q) < 0$. Thus, $\mathrm{d}d^b/\mathrm{d}r < 0$, if

$$1 - \frac{\frac{qu''(q)}{1-\theta} - qu''(q)(\omega_1-\omega_2+\omega_3-\omega_4)}{1 - \frac{1+i_{d^m}}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4) + \omega_5 - \omega_6 + \omega_7} - \frac{\frac{1}{1-\theta}\frac{1+i_{d^m}}{1+i_{d^b}} - \frac{1+r}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4)}{1 - \frac{1+i_{d^m}}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4) + \omega_5 - \omega_6 + \omega_7} > 0. \tag{A.12}$$

Using the expressions for ω_j for $j = 1,2,3,4,5,6,7$ in Equation (A.12) and rearranging yields

$$\frac{1 - \frac{qu''(q)}{1-\theta} + \frac{\theta}{1-\theta}u'(q) - \frac{1}{1-\theta}\frac{1+i_{d^m}}{1+i_{d^b}}}{1 - \frac{1+i_{d^m}}{1+i_{d^b}}(\omega_1-\omega_2+\omega_3-\omega_4) + \omega_5 - \omega_6 + \omega_7} > 0. \tag{A.13}$$

Note, the numerator of Equation (A.13) is positive. To see that, we can rearrange the numerator and solve for θ, which yields

$$\frac{1 - \frac{1+i_{d^m}}{1+i_{d^b}} - qu''(q)}{1 - u'(q)} \geq \theta. \tag{A.14}$$

Recall that $u'(q) = \frac{1+i_{d^m}}{1+i_{d^b}}$. Using this and rearranging, We can show that Equation (A.14) always holds, since

$$-qu''(q) > 0.$$

Therefore, the numerator of Equation (A.13) is positive. Thus, for $\mathrm{d}d^b/\mathrm{d}r < 0$ to hold, the denominator needs to positive as well. Thus,

$$1 - \frac{1+i_{d^m}}{1+i_{d^b}} (\omega_1 - \omega_2 + \omega_3 - \omega_4) + \omega_5 - \omega_6 + \omega_7 > 0$$

must hold. Rearranging the denominator, using the expressions for ω_j for $j = 1, 2, 3, 4, 5, 6, 7$ and solving for θ yields

$$\theta > \theta_2 = \frac{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\frac{1}{u''(q)q}\right) - 1}{\left(\frac{\phi\ell(i_\ell - R)}{q} - \frac{\phi\chi(\ell)}{q}\right)\left(1 + \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\frac{1}{u''(q)q}\right) - \left(\frac{1+i_{d^m}}{1+i_{d^b}}\right)\left(\frac{u'(q)}{u''(q)}\frac{1}{q} - \frac{u(q)}{u''(q)}\frac{1}{q^2}\right) + \frac{u(q)}{q} - 1}. \tag{A.15}$$

Thus, the critical threshold $\tilde{b}^d$ is increasing in policy rates R, r if $\theta > \theta_2$. ∎

Proof of Proposition 5. In order to show that there exists a critical threshold, R' for which reserves held when $b^{CB} = \tilde{b}^{CB}$ are equal to the minimal reserves held by banks, that is $\ell = \ell^*$ and $m_r = \tilde{m}_r$ it suffices to show that there is a level of R' for bank deposits satisfy these conditions. This is due to our assumption that $i_\ell - R$ is constant across R, which implies that bank lending is constant across R as well. Bank deposit when $b^{CB} = \tilde{b}^{CB}$ satisfy

$$d^b = pq = \frac{1}{\phi(1+i_{d^b})} u'^{-1}\left(\frac{1+R-s}{1+i_{d^b}}\right).$$

Recall $r = R - s$. Bank deposits when $\ell = \ell^*$ and $m_r = \tilde{m}_r$ satisfy

$$d^b = \delta d^b + \ell^* = \delta \frac{1}{\phi(1+i_{d^b})} u'^{-1}\left(\frac{1+R-s-k^m}{1+i_{d^b}}\right) + \chi'^{-1}(\kappa),$$

where $\kappa = i_\ell - R$. If there exists a policy rate R' for which bank deposits when $b^{CB} = \tilde{b}^{CB}$ are equal to bank deposits when $m_r = \tilde{m}_r$, then

$$\frac{1}{\phi(1+i'_{d^b})} u'^{-1}\left(\frac{1+R'-s-k^m}{1+i'_{d^b}}\right) = \delta d^b + \ell^* = \delta \frac{1}{\phi(1+i_{d^b})} u'^{-1}\left(\frac{1+R'-s-k^m}{1+i'_{d^b}}\right) + \chi'^{-1}(\kappa),$$

must hold from some R, where i'_{d^b} denotes the bank deposit rate when $R = R'$. Rearranging yields

$$\frac{1}{\phi(1+i'_{d^b})}u'^{-1}\left(\frac{1+R'-s-k^m}{1+i'_{d^b}}\right)=\frac{\chi'^{-1}(\kappa)}{1-\delta}.$$

Note, from Proposition 4, the left-hand side is decreasing in R. The right-hand side is constant in R by assumption. Thus, there exist a unique R' that satisfies this constraint.

■

B Equations for the calibration

In what follows, we derive the equations used to calibrate our parameters. First, since our calibration period corresponds to a period of more than ample reserves, the repo rate satisfies

$$\rho = r.$$

Further, in an ample reserves framework, the constraint on reserve demand should not be binding and thus $\ell = (i_\ell - R)/\beta$. Under these assumptions, the interest rate on bank deposits satisfies

$$i_{d^b} = (R - k^b) + \frac{(i_\ell - R)^2}{\beta}\frac{1}{2}\left[\frac{\phi(1+i_{d^m})^{1/\alpha}}{(1+i_{d^b})^{(1/\alpha)-1}}\right] - \frac{\theta}{1-\theta}\frac{\alpha}{1-\alpha}(1+i_{d^m}).$$

The MMF deposit rate satisfies

$$i_d^m = r + k^m.$$

The correlation of bank deposit rates and the policy rate is given by totally differentiating Equations (16), (2), and (15) and satisfies

$$\frac{di_{d^b}}{dr} = \frac{\frac{1}{1-\theta} + \frac{\theta}{1-\theta}\frac{1}{\alpha} - \frac{\theta}{1-\theta}\frac{1}{\alpha(1-\alpha)} + \frac{1}{2}\frac{\phi(i_\ell-R)^2}{\alpha\beta}\left(\frac{1+i_{d^b}}{1+i_{d^m}}\right)^{1-(1/\alpha)}}{1 + \frac{1+i_d^m}{1+i_{d^b}}\left(\frac{\theta}{1-\theta}\frac{1}{\alpha} - \frac{\theta}{1-\theta}\frac{1}{\alpha(1-\alpha)} + \frac{\theta}{1-\theta}\frac{1}{1-\alpha} + \frac{1}{2}\frac{\phi(i_\ell-R)^2}{\alpha\beta}\left(\frac{1+i_{d^b}}{1+i_{d^m}}\right)^{1-(1/\alpha)}\right) - \frac{1}{2}\frac{\phi(i_\ell-R)^2}{\beta}\left(\frac{1+i_{d^b}}{1+i_{d^m}}\right)^{-1/\alpha}}.$$

Following Aruoba et al. (2011), we define the markup μ as price over marginal costs. In a perfectly competitive market, $\mu = 0$, such that $1 + \mu = p/MC = 1$. In our deposit market, perfect competition would imply that the bank deposit rate is set such that banks do not make any profits. We proxy this hypothetical deposit rate by the weighted average return on bank loans and reserves. In our model with the assumptions for the utility function, the markup therefore satisfies

$$1 + \mu = \frac{(R - k^b) + \frac{(i_\ell-R)^2}{\beta}\frac{1}{2}\left[\frac{\phi(1+i_{d^m})^{1/\alpha}}{(1+i_{d^b})^{(1/\alpha)-1}}\right] - \frac{\theta}{1-\theta}\frac{\alpha}{1-\alpha}(1+i_{d^m})}{(R - k^b) + \frac{(i_\ell-R)^2}{\beta}\frac{1}{2}\left[\frac{\phi(1+i_{d^m})^{1/\alpha}}{(1+i_{d^b})^{(1/\alpha)-1}}\right]}.$$

Note that the markup in this setup is technically a markdown, as deposit rates tend to be lower relative to a perfectly competitive market. We think of the markup in the deposit market as a negative markup. We argue that the relevant variable in the data for the markup of bank deposit rates is the weighted average return on banks' assets. As banks would not make any profits in a perfectly competitive market, the deposit rate would be equal to the weighted average return on assets.

Further, aggregate average bank deposits satisfy

$$n^b d^b = n^b \left(\frac{1}{\phi} \frac{(1+i_{d^b})^{1/\alpha - 1}}{(1+i_{d^m})^{1/\alpha}} \right),$$

Denote reserve holdings m_r. Aggregate average reserve holdings satisfy

$$n^b m_r = n^b \left(d^b - \frac{i_\ell - R}{\beta} \right)$$

Aggregate average ON RRP take-up is defined as the difference between MMF deposits and repo lending by MMFs and can be rearranged such that

$$n^m d^{ONRRP} = n^m d^m - \left(\frac{1}{1+\rho} (B - b^{CB}) \right).$$

Finally, the initial endowment of commodity money m_e is the difference between the aggregate endowment of households, which can be allocated to either bank or MMF deposits, $d^m + d^b$, and the endowment that stems from the sale of government bonds, $p^g B$. Thus, the initial endowment of commodity money satisfies

$$m_e = n^m d^m + n^b d^b - \frac{1}{1+\rho} B.$$

As mentioned above, we calibrate the model by solving for the parameters $\mathcal{P} = \{\alpha, \beta, \theta, k^b, k^m, \phi, m_e\}$ and the equilibrium variables $\mathcal{X} = (\rho, i_{d^b}, i_{d^m}, d^b, m_r, d^{ONRRP})$, such that the squared distance between the parameters that solve the model and the moments in the data are minimized.

$$\min_{X;\mathcal{P}} (\mathcal{S}_{model}(\mathcal{X};\mathcal{P}) - \mathcal{S}_{data})^2$$
$$\text{s.t. } EC(\mathcal{X};\mathcal{P}) = 0.$$

C Empirical Evidence to Motivate the Model

Before we introduce our model, which illustrates the effects of the Fed reducing the size of its balance sheet, we first provide empirical evidence that motivates the set up of our model. Our model starts with households deciding where to place their money, either with banks or non-banks, as the Fed tightens monetary policy. Banks are the only financial intermediary that can hold reserves at the Fed and receive IORB on those balances. Non-banks, namely MMFs, are the main users of the ON RRP facility. Indeed, the vast majority of ON RRP participation amounting to over \$2 trillion a day on average in 2022 is from MMFs. Banks and MMFs are the two types of financial intermediaries that directly experience the effects of the Fed reducing the size of its balance sheet, so it is important to understand how these two types of entities respond to tightening monetary policy.

C.1 Empirical Specification

Using simple reduced form regressions, we show how bank and MMF deposits change in response to the Fed's two monetary policy tools: increasing its policy rate or reducing the size of its balance sheet. We estimate the following time-series specification quarterly between 1992:Q1 and 2021:Q4, following closely the estimation strategy in Xiao (2020):

$$
\begin{aligned}
\textit{Growth Rate}_t = \alpha &+ \beta \cdot \sum_{t=-12}^{0} \Delta \text{EFFR}_t + \eta \cdot \left[-1 \cdot \sum_{t=-12}^{0} \Delta \log \left(\text{SOMA}\right)_t \right] \\
&+ \theta \cdot \left\{ \sum_{t=-12}^{0} \Delta \text{EFFR}_t \times \left[-1 \cdot \sum_{t=-12}^{0} \Delta \log \left(\text{SOMA}\right)_t \right] \right\} \\
&+ \sum_{c=1}^{4} \gamma_c X_{c,t} + \lambda t + \varepsilon_t
\end{aligned}
\tag{C.1}
$$

where we regress either the quarterly year-over-year commercial bank deposit growth rate or the quarterly year-over-year MMF deposit growth rate (also known as assets under management or AUM) on the three-year cumulative change in the effective federal funds rate ($\Delta \mathit{EFFR}$), the three-year cumulative change in the logged portfolio value of the System Open Market Account ($-\Delta \log(\mathit{SOMA})$), and their interaction ($\Delta \mathit{EFFR} \times -\Delta \log(\mathit{SOMA})$).[31] We also include four control variables: GDP growth, CPI, the TED spread, and the personal savings rate, in addition to a linear time trend. We have transformed the cumulative

[31] EFFR is the volume-weighted median rate of overnight federal funds transactions. The System Open Market Account (SOMA) is where the Fed holds its securities. Its value is equivalent to the amount of securities held outright on the Fed's balance sheet.

change in (log) SOMA by a factor of -1 so that the coefficient estimates on EFFR, SOMA, and their interaction can be read directly as the effects of monetary tightening.

C.2 Data Sources

We make use of the following data sources accordingly.

Deposits. We use quarterly aggregate data on commercial bank deposits and MMF deposits, or assets under management, from 1992:Q1 to 2021:Q4. For commercial banks, we use the sum of interest-bearing savings and transaction deposits booked in domestic banks from the FFIEC Call Reports. For MMFs, we use the total assets under management series from FRED.[32] Growth rates are year-over-year, computed as the percent change from the previous year.

Monetary Policy. For the federal funds rate, we use the publicly available EFFR data from FRED, which is the daily volume-weighted median of overnight federal funds transactions. For the balance sheet, we retrieve daily data on the total size of the SOMA portfolio of the Federal Reserve.[33] For our deposit growth results, we take quarterly averages of the data for the years 1992 to 2021.

Control Variables. We include contemporaneous quarterly measures of GDP growth, CPI inflation, the TED spread, and the personal savings rate, as controls in our estimation. Using data from FRED, we calculate quarterly GDP growth as the percent change in real GDP from one year ago. Similarly, for CPI inflation, we use the standard index measure from FRED where quarterly inflation is the percent change from one year ago. Finally, quarterly data for both the TED spread and the personal savings rate are again from FRED.

C.3 Deposit Growth Results

Table C.1 presents the results from estimating Equation (C.1) at a quarterly frequency from 1992:Q1 to 2021:Q4. Column 1 shows the results for the bank deposit growth rate while Column 2 shows the results for the MMF deposit growth rate. The direction of the coefficient on $\Delta EFFR$ in both columns confirm the results in Drechsler et al. (2017) and Xiao (2020). That is, when EFFR increased, commercial banks experienced an outflow of deposits while MMFs experienced an inflow of deposits.

[32] For the exact series name and description of all data series obtained from FRED that we use, please see the FRED data dictionary in Appendix B.

[33] While we use internal Federal Reserve System data that gives us SOMA sizes at a daily frequency, a weekly value is made publicly available through the H.4.1 data release. For the public series information, see the FRED data dictionary in Appendix D.

Table C.1: Quarterly Deposit Growth, 1992 to 2021

	(1) CB(YoY)	(2) MMF(YoY)
ΔEFFR	-1.559***	2.520***
	(0.400)	(0.400)
$\big[-1 \cdot \Delta \log(\text{SOMA})\big]$	-2.878*	8.848***
	(1.550)	(1.969)
$\Delta\text{EFFR} \times \big[-1 \cdot \Delta \log(\text{SOMA})\big]$	-0.954	0.885
	(0.711)	(0.988)
GDP growth	-0.556	-1.400**
	(0.414)	(0.662)
CPI	-0.291	1.488
	(0.626)	(1.120)
TED Spread	-1.095	12.01***
	(2.640)	(4.272)
Personal Savings Rate	0.181	1.429***
	(0.351)	(0.392)
Observations	119	119
Adjusted R-squared	0.508	0.643
Linear Time Trend	Yes	Yes

Source: FFIEC Call Reports, FRED, Federal Reserve Bank of New York, Federal Reserve Board H.4.1.

This table shows the time series regressions of commercial bank and MMF deposit growth rates on conventional (EFFR) and unconventional (SOMA) monetary policy. Following Xiao (2020), changes in the federal funds rate and changes in SOMA are measured as three-year cumulative changes. The data frequency is quarterly from 1992 to 2021. Standard errors in parentheses are computed with Newey-West standard errors with 12 lags. Significance representations are $^*p < 0.10$,$^{**}p < 0.05$, $^{***}p < 0.01$.

Our contribution is the magnitudes and directions of the coefficients on $-\Delta \log(SOMA)$ and $\Delta EFFR \times -\Delta \log(SOMA)$. We observe that a one unit decrease in the SOMA portfolio induces both an outflow of banks deposits from commercial banks, and a significantly larger inflow in MMF deposits. Indeed, the coefficient on $-\Delta \log(SOMA)$ is much higher than $\Delta EFFR$ for both commercial banks and shadow banks, suggesting that monetary tightening through the balance sheet has larger effects on commercial bank deposit outflows and MMF deposit inflows than increasing the policy rate. The interaction term, however, shows that when the Fed tightens monetary policy through its balance sheet and interest rates at the same time, the effects on commercial bank deposit outflows and MMF deposit inflows are only marginally magnified.[34]

[34] These results are robust to a host of alternative specifications. In particular, our results hold (a) when considering alternative horizon changers in monetary policy (i.e. at the 1-year, 2-year, and 3-year horizons), (b) when using exogenous monetary policy shocks à la Romer and Romer (2004) instead of the effective federal funds rate, (c) when considering only pre-2008 values, and (d) when using the $EFFR-IOR$ spread as our right-hand-side variable. For further notes, see Appendix E.

Given the fact that Table C.1 shows that, while bank deposit growth does respond to monetary tightening through the Fed's balance sheet, the effect on MMF deposits inflows is significantly more pronounced, this suggests that banks are not the main financial intermediary through which transmission of this monetary policy tool occurs. Indeed, Table C.1 suggests that the marginal financial intermediary is MMFs. There has been a lot of research on the effect of expanding the Fed's balance sheet, i.e. quantitative easing, on bank lending. However, there has been no research on the effect of the Fed's balance sheet on non-bank investment activity. We fill that gap with this paper, and this is motivated by Table C.1 that shows that MMFs receive significant inflows when the Fed shrinks its balance sheet.

C.4 Where do MMFs invest their inflows?

We have shown preliminary empirical evidence that MMFs receive inflows (deposits) when the Fed tightens monetary policy by shrinking its balance sheet. What do they do with that new money? To motivate a main mechanism of our model, we next provide some empirical evidence that when MMFs receive that extra money, they place that money in short-term funding markets, specifically the repurchase (repo) market. A repo is a short-term, often overnight, collateralized loan between a borrower and lender. Alternative investments could include placing the money at the ON RRP or investing the money in Treasury bills. In this section, we provide some empirical evidence of this.

Our data are from the monthly snapshots of the composition of MMF portfolio holdings from the Securities and Exchange Commission filings (Form N-MFP) from 2010 to 2021. These mandated monthly reports provide fund-level data on total assets and holdings broken down into detailed asset categories.[35] We keep only those funds which participate in Treasury repo markets and the ON RRP. Because multiple funds comprise a MMF complex, we sum up to the MMF complex level by summing total assets and each of the holdings categories by month to get monthly complex-level aggregate measures of total assets and total holdings by type.

We estimate the following panel regression monthly between 2010 and 2021 for a given MMF complex c who invests in product p at time t. MMF complex c is comprised of a universe of individual funds f that comprise universe F, a subset of which $S \subseteq F$ are

[35] In particular, these are: Treasuries, Treasury repo, asset-backed commercial paper, commercial paper, certificates of deposit, government agency debt, and government agency repo.

eligible to use the ON RPP facility.

$$
\begin{aligned}
\Delta Share_{c,p,t} = \alpha &+ \beta \cdot \Delta \text{EFFR}_{t-1} + \eta \cdot \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \\
&+ \theta \cdot \Big\{\Delta \text{EFFR}_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big]\Big\} \\
&+ \log(\text{AUM}_{c,t}) + \log(\text{Bills Outsanding}_t) + \lambda t + \mu_c + \delta_t + \varepsilon_{c,p,t}
\end{aligned}
\tag{C.2}
$$

Share is defined as the total investment in product p at time t for MMF complex c divided by the sum of total assets under management for MMF complex c at time t.

Formally, *Share* is defined as follows:

$$
Share_{c,p,t} = \frac{\sum_{f \in S} \text{Investment}_{f,c,p,t}}{\sum_{f \in S} \text{Assets}_{f,c,t}}
$$

$$
\text{where } S = \Big\{ f \in F : \ \exists\, t \in T \text{ where } (\text{ON RRP}_{f,c,t} > 0) \Big\} \subseteq F
$$

where p is either the dollar amount of MMF complex c lending in the repo market backed by Treasury collateral, or the dollar amount of take-up at the ON RRP facility on day t.

We regress the monthly change in *Share* on the lagged one month change in EFFR, the lagged one month change in (log) SOMA, and their interaction. We also include several control variables: the total AUM of MMF complex c, the total supply of Treasury bills outstanding, a linear time trend, MMF complex fixed effects, and year $\times$ quarter time fixed effects. As above, we similarly transform the one month change in (log) SOMA by a factor of -1 so that the coefficient estimates on EFFR, SOMA, and their interaction can be read directly as the effects of monetary tightening.

Given, as just shown above, that when monetary tightening is achieved through either rate policy, balance sheet policy, or both, MMFs experience an inflow of deposits, an important following question is naturally what do MMFs do with their increased assets under management? One might expect that, when the policy rate increases, all else equal, because MMFs are endowed with more deposits but the demand in the repo market has remained unchanged, MMFs substitute proportionally away from private repo and into the ON RRP. Conversely, one might expect that, when the balance sheet is reduced, all else equal, the increase in MMF deposits is met with a commensurate increase in demand in the repo market, MMFs substitute proportionally away from the ON RRP and towards the private repo market.

Table C.2 presents the results from estimating Equation (C.2). Column 1 shows the results for when p is MMF lending in Treasury repo and Column 2 shows the results for when p is the amount of MMF take-up at the ON RRP facility. We observe that ON RRP take-up increased when the Fed tightened monetary policy by raising policy rates.

This result makes sense because from Table C.1 we observed that MMFs receive inflows when the Fed raises interest rates. However, when the Fed tightens monetary policy by reducing the size of its balance sheet, we observe from the coefficients on $-\Delta\log(SOMA)$ and $\Delta EFFR \times -\Delta\log(SOMA)$ that MMFs shift away from the ON RRP and lend more in the private Treasury repo market. The mechanism that we show in the model is that when the Fed rolls off Treasury securities from its balance sheet, the U.S. Treasury must continue to finance that debt and sell more Treasuries to the private market, namely primary dealers. Those dealers then need to finance that extra inventory in the Treasury repo market, thereby putting upward pressure on repo rates. MMFs then shift to lend more in the Treasury repo market instead of placing their money at the ON RRP to meet that heightened demand because the rates are more attractive. The results of Table C.2 provide evidence of this mechanism in our model.

Table C.2: Eligible MMF Complex Holdings, Jan. 2014 to Dec. 2019

	(1) Δ (Private Repo Share)	(2) Δ (ON RRP Share)
ΔEFFR_{t-1}	-0.0669	0.305***
	(0.0398)	(0.0559)
$\big[-1 \cdot \Delta\log(\text{SOMA})_{t-1}\big]$	1.866	-6.501***
	(1.349)	(1.308)
$\Delta\text{EFFR}_{t-1} \times \big[-1 \cdot \Delta\log(\text{SOMA})_{t-1}\big]$	15.55***	-22.56***
	(4.358)	(4.736)
log(AUM)	0.000376	-0.00205
	(0.000993)	(0.00148)
log(Bills Outstanding)	0.0103	-0.0833*
	(0.0296)	(0.0491)
Observations	2167	2167
Number of Clusters	33	33
Adjusted R-squared	0.0860	0.272
Adjusted Within R-Squared	0.0998	0.277
Year-Quarter Fixed Effects	Yes	Yes
MMF Complex Fixed Effects	Yes	Yes
Time Trend	Yes	Yes

Source: SEC N-MFP, Federal Reserve Bank of New York, Federal Reserve Board H.4.1., US Treasury Department.

This table shows the panel regressions of MMF portfolio allocation on conventional (EFFR) and unconventional (SOMA) monetary policy. The data frequency is monthly from 2014 to 2019. In particular, using the sub-sample of ON RRP eligible MMFs, we regress a MMF's investment share in either private repo or at the ON RRP facility on the one quarter lag in the change in EFFR, the one quarter lag in the change in SOMA, and their interaction. Standard errors in parentheses are clustered at the MMF Complex level. Significance representations are $^{*}p < 0.10$,$^{**}p < 0.05$, $^{***}p < 0.01$.

D FRED Data Dictionary

Variable	Frequency	Series Name	Series Description
MMF AUM	Quarterly	`MMMFFAQ027S`	Total Financial Assets Under management for Money Market Mutual Funds in millions, not seasonally adjusted
EFFR	Monthly & Quarterly	`EFFR`	Effective federal funds rate in percent, not seasonally adjusted
SOMA	Monthly & Quarterly	`WALCL`	Total assets of the Federal Reserve System Open Market Account, Wednesday level.
GDP Growth	Quarterly	`GDPC1_PC1`	Real Gross Domestic Product, percent change from one year ago
TED Spread	Quarterly	`TEDRATE`	Spread between 3-month LIBOR and 3-month Treasury Bill, percent
Personal Savings Rate	Quarterly	`PSAVERT`	The ratio of personal savings to disposable personal income.

E Robustness Checks

E.1 Longer Horizon Policy Changes on Deposit Growth

As a robustness check, we estimate specifications at a variety of horizons on the quarter-to-quarter deposit growth rates - in particular, the one, two, and three year changes in EFFR, SOMA, and their interaction. That is to say concretely, for the time horizons of one, two, and three years at quarterly observation intervals we estimate $\forall h \in \{4, 8, 12\}$

$$\begin{aligned} \textit{Growth Rate}_t = \alpha + \beta \cdot \Delta_{t-h}\mathrm{EFFR}_{t-1} + \eta \cdot \big[-1 \cdot \Delta_{t-h}\log(\mathrm{SOMA})_{t-1}\big] \\ + \theta \cdot \Big\{\Delta_{t-h}\mathrm{EFFR}_{t-1} \times \big[-1 \cdot \Delta_{t-h}\log(\mathrm{SOMA})_{t-1}\big]\Big\} \\ + \sum_{c=1}^{3} \gamma_c X_{c,t} + \lambda t + \varepsilon_t \end{aligned} \tag{E.1}$$

The results from estimating Equation (E.1) are presented in Table E.1, where panels one, two, and three, display the results from the one, two, and three year time horizons respectively. As can be well seen, the results in table E.1 accord well with our main results in table C.1. In particular, at all longer time horizons, it is always the case that conventional monetary tightening achieved by increasing the federal funds rate is associated with a decline in commercial bank deposit growth and with an increase in MMF deposit growth. Moreover, at all longer time horizons, it is always the case that unconventional monetary tightening (i.e. reducing the balance sheet) induces MMF deposit inflows larger in magnitude than the deposit growth effect of conventional monetary tightening.

Table E.1: Quarterly Deposit Growth, Long Horizon Policy Changes, 1990-2021

	(1) CB(QtQ)	(2) MMF(QtQ)
Panel 1 - One Year Horizon		
$\Delta_{t-4}\text{EFFR}_{t-1}$	-0.552***	0.924***
	(0.165)	(0.226)
$\big[-1 \cdot \Delta_{t-4}\log(\text{SOMA})_{t-1}\big]$	-0.438	6.924***
	(0.492)	(1.411)
$\Delta_{t-4}\text{EFFR}_{t-1} \times \big[-1 \cdot \Delta_{t-4}\log(\text{SOMA})_{t-1}\big]$	0.0104	3.072***
	(0.546)	(0.868)
Observations	127	127
Adjusted R-squared	0.324	0.286
Linear Time Trend	Yes	Yes
Panel 2 - Two Year Horizon		
$\Delta_{t-8}\text{EFFR}_{t-1}$	-0.265***	0.956***
	(0.0898)	(0.122)
$\big[-1 \cdot \Delta_{t-8}\log(\text{SOMA})_{t-1}\big]$	-0.102	1.996
	(0.583)	(1.800)
$\Delta_{t-8}\text{EFFR}_{t-1} \times \big[-1 \cdot \Delta_{t-8}\log(\text{SOMA})_{t-1}\big]$	0.219	1.070
	(0.269)	(0.995)
Observations	123	123
Adjusted R-squared	0.307	0.318
Linear Time Trend	Yes	Yes
Panel 3 - Three Year Horizon		
$\Delta_{t-12}\text{EFFR}_{t-1}$	-0.211***	1.027***
	(0.0708)	(0.122)
$\big[-1 \cdot \Delta_{t-12}\log(\text{SOMA})_{t-1}\big]$	-0.149	2.912**
	(0.473)	(1.127)
$\Delta_{t-12}\text{EFFR}_{t-1} \times \big[-1 \cdot \Delta_{t-12}\log(\text{SOMA})_{t-1}\big]$	0.0186	1.108***
	(0.133)	(0.385)
Observations	119	119
Adjusted R-squared	0.267	0.372
Linear Time Trend	Yes	Yes

Standard errors in parentheses are Newey-West with 12 lags.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

E.2 Romer-Romer Policy Shocks

As a robustness check we re-estimate our quarterly deposit growth rate results using the exogenous monetary shock measure presented by Romer and Romer (2004), instead of using raw changes in the federal funds rate. Following Romer and Romer (2004) and the methodology outlined in Breitenlechner (2018), we extend the Romer-Romer exogenous monetary policy shock series through to Q4 2016 - that is, using the latest publicly available Tealbook (formerly Greenbook) data. Figure E.1 plots the original and extended Romer-Romer policy shock series.

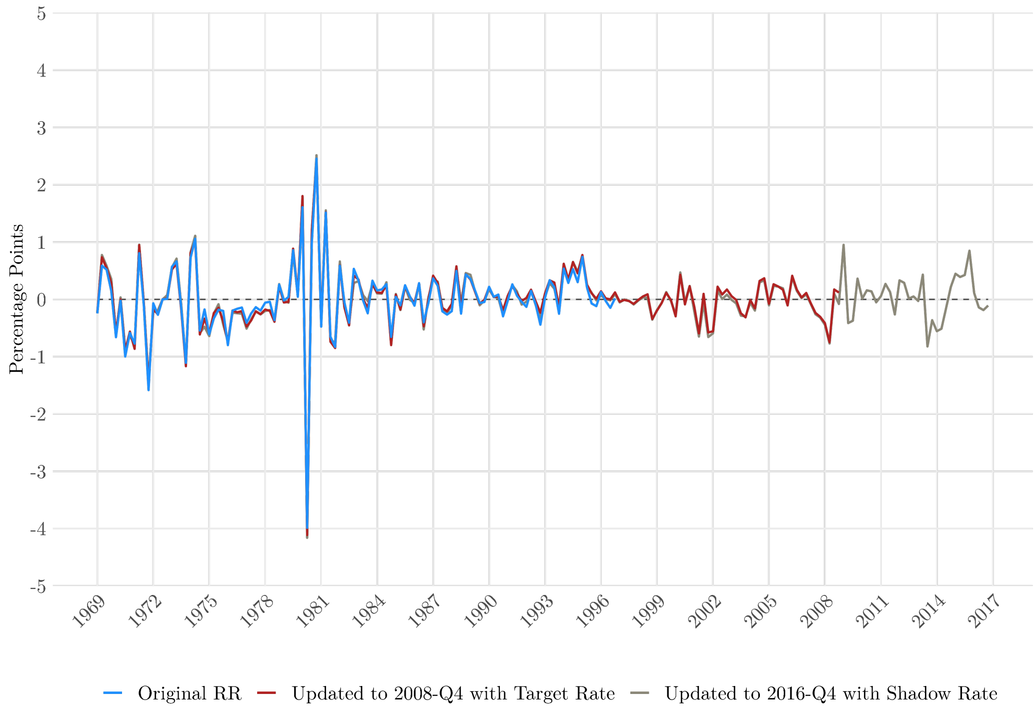


Figure E.1: Original and Extended Romer and Romer (2004) Monetary Policy Shock Series

Specifically, we regress the quarter-to-quarter growth rate of deposits on the one period lag of the monetary policy shock, the one period lag of the change in (log) SOMA, and their interaction, as well as our usual control variables:

$$\begin{aligned} \textit{Growth Rate}_t = \alpha &+ \beta \cdot (\text{RR MP Shock})_{t-1} + \eta \cdot \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \\ &+ \theta \cdot \Big\{ (\text{RR MP Shock})_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \Big\} \\ &+ \sum_{c=1}^{3} \gamma_c X_{c,t} + \lambda t + \varepsilon_t \end{aligned} \tag{E.2}$$

The results from Equation (E.2) are displayed in table E.2.

Table E.2: Quarterly Deposit Growth, Romer-Romer Shocks, 1990Q1-2016Q4

	(1) CB(QtQ)	(2) MMF(QtQ)
RR MP Shock$_{t-1}$	-1.678*	2.067*
	(0.901)	(1.061)
$\left[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\right]$	1.905	20.94***
	(2.536)	(6.995)
RR MP Shock$_{t-1}$ $\times \left[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\right]$	2.693	39.34***
	(5.743)	(8.715)
GDP growth	-0.372***	0.127
	(0.0871)	(0.258)
CPI	-0.319*	0.0766
	(0.189)	(0.209)
TED Spread	-0.660	5.713***
	(0.527)	(1.052)
Observations	108	108
Adjusted R-squared	0.223	0.332
Linear Time Trend	Yes	Yes

Standard errors in parentheses are Newey-West with 12 lags.
$^{*}p < 0.10$,$^{**}p < 0.05$, $^{***}p < 0.01$

E.3 EFFR spread to IOR

Here, we consider the case when using the EFFR spread to IOR (the interest on reserve balances) as our right-hand-side variable. In particular, we use the following specification regressing the quarter-to-quarter growth rate of deposits on the one period lag of the EFFR to IOR spread, the one period lag in the (log) SOMA, and their interaction, as well as our usual control variables:

$$\begin{aligned} \textit{Growth Rate}_t = \alpha &+ \beta \cdot (\text{EFFR} - \text{IOR})_{t-1} + \eta \cdot \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \\ &+ \theta \cdot \Big\{ (\text{EFFR} - \text{IOR})_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \Big\} \\ &+ \sum_{c=1}^{3} \gamma_c X_{c,t} + \lambda t + \varepsilon_t \end{aligned} \tag{E.3}$$

The results from Equation (E.3) are displayed in table E.3.

Table E.3: Quarterly Deposit Growth with EFFR-IOR Spread, 2008 Q4 - 2021 Q4

	(1) CB(QtQ)	(2) MMF(QtQ)
$(\text{EFFR} - \text{IOR})_{t-1}$	-0.430	27.88***
	(2.182)	(8.917)
$\big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big]$	0.719	29.22***
	(4.003)	(10.03)
$(\text{EFFR} - \text{IOR})_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big]$	15.14	137.8
	(32.44)	(154.8)
GDP growth	-0.597***	-0.290**
	(0.204)	(0.111)
CPI	0.586***	-0.0368
	(0.189)	(0.231)
TED Spread	0.0681	0.822
	(2.103)	(4.580)
Observations	52	52
Adjusted R-squared	0.336	0.360
Linear Time Trend	Yes	Yes

Standard errors in parentheses are Newey-West with 12 lags.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

E.4 Pre-2008

Here, we consider only pre-2008 data, and regress the quarter-to-quarter growth rate of deposits on the one period lag in the change in EFFR, the one period lag in the change in (log) SOMA, and their interaction, as well as our usual control variables:

$$\begin{aligned} \textit{Growth Rate}_t = \alpha &+ \beta \cdot (\Delta\text{EFFR})_{t-1} + \eta \cdot \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \\ &+ \theta \cdot \Big\{ (\Delta\text{EFFR})_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big] \Big\} \\ &+ \sum_{c=1}^{3} \gamma_c X_{c,t} + \lambda t + \varepsilon_t \end{aligned} \tag{E.4}$$

The results from Equation (E.4) are displayed in table E.4.

Table E.4: Pre-2008 Quarterly Deposit Growth, 1990-2007

	(1) CB(QtQ)	(2) MMF(QtQ)
ΔEFFR_{t-1}	-2.126**	6.014***
	(0.843)	(1.160)
$\big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big]$	-12.63	87.59**
	(22.55)	(34.25)
$\Delta\text{EFFR}_{t-1} \times \big[-1 \cdot \Delta \log(\text{SOMA})_{t-1}\big]$	48.03*	220.9***
	(27.57)	(46.93)
GDP growth	0.0985	-0.974***
	(0.160)	(0.359)
CPI	0.0190	-0.971***
	(0.281)	(0.306)
TED Spread	-0.526	8.735***
	(0.837)	(1.214)
Observations	72	72
Adjusted R-squared	0.486	0.338
Linear Time Trend	Yes	Yes

Standard errors in parentheses are Newey-West with 12 lags.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$