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Quantitative easing and quantitative tightening: the money channel

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Abstract

We develop a DSGE model in which commercial banks interact with the central bank through the reserves market, with each other through reserves and interbank markets, and with the real economy through retail loan and deposit markets. Because banks disburse loans through deposit creation, they never face financing risks (being unable to fund new loans), only refinancing risks (being unable to settle net deposit withdrawals in reserves). Permanent quantitative tightening, while reducing the equilibrium real interest rate, has significant negative effects on financial and real variables, by increasing the cost at which reserves-scarce parts of the banking sector create money. Temporary net deposit withdrawals, which affect the funding cost and loan extension of one part of the banking sector at the expense of another part, have highly asymmetric financial and real effects. The quantity and distribution of central bank reserves, and the extent of frictions in the interbank and reserves markets, critically affect the size of these effects, and can matter even in a regime of ample aggregate reserves. Countercyclical reserve injections can help to smooth the business cycle. We find that countercyclical reserve quantity rules can make sizeable contributions to welfare that can reach a similar size to the Taylor rule.

Key words: Quantitative easing, quantitative tightening, monetary policy, central bank reserves, interbank loans, bank deposits, bank loans, money demand, money supply, credit creation.

JEL classification: E51, E52, E58.

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1. Introduction

Since the 2008 Global Financial Crisis (GFC) central banks in advanced economies have relied more frequently on "unconventional" balance-sheet policies. While these policies appear to have been successful, it has remained difficult to disentangle the transmission mechanisms of the new policy tools alongside traditional interest rate tools, including their effects on the business cycle and equally importantly on financial stability. This has been a prominent topic among central banks and international policymakers,[1] as some central banks that have started to reduce their balance sheets have been forced to intervene in financial markets during acute liquidity shortages. A prominent example is the US repo spike in September 2019. Furthermore, central banks are currently considering policy tool combinations that navigate uncharted waters, such as interest rates cuts during periods of falling central bank liquidity.

In the face of these uncertainties about the transmission mechanism, empirical analysis cannot yet provide adequate guidance to policymakers, and more theoretical work on the transmission mechanism is a necessary complement. This is what we attempt in this paper. We put particular emphasis on the liability side of central bank balance sheets, specifically the nature of policy and shock transmission through the reserve and interbank markets. We study the policies that have become known as Quantitative Easing (QE) and Quantitative Tightening (QT), which transmit directly only to the banking system, while their effect on the real economy depends on the response of the banking system, specifically its credit and money creation.[2]

We develop a medium-scale New-Keynesian DSGE model with both a fully specified real sector and a detailed financial sector. Banks interact with the central bank through the reserves market, with each other through reserves and interbank markets, and with the real economy through retail loan and deposit markets. Our model reflects the reality that banks do not face financing risks, only refinancing risks. Banks always finance new loans by creating new deposits, so that there is never a risk of not being able to finance a new loan. But there is a risk of having to refinance lost deposits. We emphasize that this notion of refinancing risk is very different to that in loanable funds models of banking. Specifically, in loanable funds frameworks it is often argued that the two amount to the same, because once a bank makes a new loan and creates the corresponding deposit, it will tend to lose that deposit to another bank and will then need to refinance it. This however is a particularly clear example of a partial equilibrium fallacy. The reason is that all banks continuously make large numbers of new loans, and for a banking system where all banks expand or contract in lockstep, a bank will tend to gain as many deposits as it loses in the above-mentioned manner, and only the small difference remaining after netting deposit inflows and outflows will need to be refinanced, if there is a shortfall, or lent out, if there is a surplus. The average bank will experience neither

[1]See, for example, Schnabel (2023), Logan (2023), Borio (2023) and Bailey (2024).

[2]See Busetto et al. (2022) for a list of potential QE and QT transmission channels.

shortfall nor surplus.[3] Furthermore, this risk is not related to lending per se, but to the preference of depositors for deposits in different banks. For banks that expand or contract in lockstep, the risk is therefore entirely on the liability side of their balance sheets. This risk can be mitigated if there is a higher level of central bank reserves in the system, and the effect of injecting additional reserves is greater the scarcer is the initial level and distribution of reserves.

We calibrate the model to US 2010-2019 data before studying its properties. Our steady state calibration matches characteristics of the real economy, a number of interest rate spreads and balance sheet ratios, and most importantly for this paper the empirically observed relationships between the quantity of reserves and interest rate spreads in reserves and interbank markets.

We first show the effects of different reserve levels on the *steady states* of different variables. When the central bank reduces the stock of aggregate reserves by selling part of the stock of government debt back to private bond investors, thereby increasing the risk premium on government debt, the equilibrium policy rate nevertheless falls because a growing liquidity discount on reserves dominates the increasing risk premium. At the same time, key financial and real variables deteriorate due to an increase in the cost at which especially the reserves-scarce parts of the banking sector can create money. When the central bank reduces the stock of aggregate reserves to match an equal-sized decrease in the aggregate stock of government bonds, we observe qualitatively similar effects for most variables, but with significantly smaller output effects because the risk premium on debt does not increase. Finally, we investigate the model's steady state implications in terms of the so-called iso-market rate curve of Vissing-Jorgensen (2023). That is, we calculate the steady state (real) policy rate necessary to maintain a constant interbank target rate as a function of the supply of reserves. We find that the distribution of central bank reserves, the interbank market structure, and the relative importance of demand and supply schedules of interbank loans are key determinants of the iso-market rate curve's shape.

Next we study *net deposit withdrawals*, specifically changes in deposit demand that result in withdrawals from the reserve-scarce part of the banking sector to to the reserve-abundant part, at given levels of loan demand. These shocks capture modern bank runs where institutional investors, rather than retail depositors, disproportionately flee to large liquidity-rich banks – for evidence see Cipriani, Eisenbach and Kovner (2024). Such shocks have highly nonlinear and asymmetric financial and real effects, by mainly affecting the cost of funding and deposit creation of reserve-scarce banks. The quantity and distribution of central bank reserves, and the extent of frictions in the reserves and interbank markets, critically affect the size of these effects, and can matter even in a regime of ample aggregate reserves. Specifically, we find that a deposit withdrawal shock that shifts deposits equal to 7.5% of GDP between two groups of banks has strong contractionary effects, including a reduction in GDP of 0.7% and a drop in inflation of 45 basis points.

[3] Cipriani, Eisenbach and Kovner (2024) show, using confidential interbank daily US data, that the average bank's net payments are centered around zero, as their payments received and sent tend to cancel each other out.

Relatedly, *asymmetric lending booms*, where an aggressive group of banks expands its lending much faster than the remaining banks, while the share of their deposits that non-banks wish to hold in this group of banks does not change, can have qualitatively similar but quantitatively smaller effects on the distribution of reserves. The reason is that the aggressive group of banks, while it will not lose all of its newly created deposits, will no longer gain as many deposits as it loses, and will thereby lose some reserves. Such shocks are expansionary at the aggregate level, because their loss of reserves merely dampens but does not fully offset the increase in the willingness to create money of the aggressive banks.

A temporary *QT shock*, calibrated to generate a maximum 6 percentage point decline in the reserves-to-GDP ratio through central bank bond sales to non-bank bond investors, leads to a GDP decline of approximately 0.25%, again by reserve scarcity driving up lending rates and the cost of private credit and money creation.

For *all other shocks*, including conventional monetary policy shocks, the model behaves like a conventional New Keynesian model, because such shocks do not significantly affect the distribution of reserves across the banking system.

For each shock we also study the role of *countercyclical reserve rules*, whereby the central bank injects additional reserves when interbank lending spreads deviate from their desired levels. We find that such rules can have very sizeable benefits for economic stability and welfare.

Our model builds on the financing through money creation (FMC) framework first developed in Jakab and Kumhof (2015), where banks interact with the real economy by creating deposits when lending to the private sector.[4] We add to this ex-ante heterogeneity among banks. Specifically, we allow for two groups of banks that have identical steady state net worth and loans levels, but that differ in their deposit holdings and therefore also in their reserve holdings. The first banking group, "B1 banks", has a larger deposit base and also holds larger amounts of central bank reserves, while the second banking group, "B2 banks" has both fewer deposits and fewer reserves. Furthermore, in steady state B1 banks make interbank loans to B2 banks. We allow these bank groups to interact with each other in reserves and interbank markets, which both feature financial frictions. In the reserves market, due to a convex cost of liquidity scarcity, banks with lower reserve levels relative to deposit levels are willing to pay higher interest rates on wholesale deposits, and the interest differential between the two groups increases at an increasing rate in the overall and relative scarcity of reserves. In the interbank market, banks with higher reserve levels are lenders, but due to a convex cost of large counterparty exposures the interest rate on interbank loans increases at an increasing rate in the level of interbank loans, which in turn increase in the overall and relative scarcity of reserves.

[4]For a detailed literature review on the differences between the intermediation of loanable funds (ILF) model and the FMC framework used here, see Jakab and Kumhof (2019). See also Kumhof and Wang (2021).

We model unconventional balance sheet policies (QT or QE) via central bank sales or purchases of bonds to or from non-bank financial institutions (NBFIs), which is close to how central banks have in reality implemented such policies. This is an important and distinctive feature, because under an approach that is commonly used in the literature (see below) the central bank provides direct credit to the real economy, while in our approach an expansion of the central bank's balance sheet has a direct effect only on NBFIs and banks, and only banks interact with the real economy.

The rest of the paper is organized as follows. Section 2 reviews the literature. Section 3 develops the model, and Section 4 presents its calibration. Section 5 performs comparative statics across steady states that differ by the quantity of reserves and the quantity of government bonds. Section 6 studies the effects on real and financial stability of both conventional and unconventional monetary policies by way of impulse responses to selected shocks. Section 7 performs a preliminary welfare analysis based on calibrated parameters and shock standard errors. Section 8 concludes.

2. Literature

Our paper contributes to a growing literature that analyzes the central bank's balance sheet as a monetary policy tool. Within this literature, several studies have investigated the effects of QE policies using modern Dynamic Stochastic General Equilibrium (DSGE) models. Most of these studies have focused primarily on the effects related to the portfolio of assets that the central bank acquires through QE policies, rather than on the liquidity created on the central bank's liability side and its implications for money markets. For example, Chen et al. (2012), building on the approach by Andres, Lopez-Salido and Nelson (2004), introduce bond market segmentation into a standard medium-scale New-Keynesian model with transaction cost frictions to investigate the role of large-scale asset purchases (LSAPs). Their framework does not feature banks or NBFIs that interact with the central bank, monetary policy is limited to a standard interest rate rule, and LSAPs are exogenous shocks to the fiscal authority's supply of long-term bonds. Gertler and Karadi (2012) investigate QE in a loanable funds model where private intermediaries face borrowing constraints. They show that central bank policies that alleviate intermediaries' incentive constraints can have significant macroeconomic effects by affecting the price of capital. QE in their model is akin to a central bank credit policy rather than central bank LSAPs from NBFIs.[5] Sims and Wu (2021) develop a framework in which the central bank conducts QE and other unconventional policies. As in Gertler and Karadi (2012), they define QE policies as open market operations (OMOs) between intermediaries and the central bank, through exchanges of long-term private or public bonds and reserves. They posit a QE policy rule that responds to macro variables such as inflation and output rather than to financial market variables.

[5] Gertler and Karadi (2012) write in footnote 2 of their paper that they believe the term "credit policy" reflects the Fed's policies more accurately than "QE".

In contrast to the main focus of these studies, our main focus is on the liability side of the central bank balance sheet. Under QE the central bank buys assets, principally government securities, from NBFIs, and the latter deposit the proceeds in banks using payment instruments drawn on the central bank. Banks settle these payment instruments with the central bank, and are credited in the form of reserves (see below for more details on the empirical evidence on this point). As a result, commercial bank balance sheets expand.[6]

Two other studies also examine the role of central bank liquidity provision, however they do so using models that do not have a role for commercial banks, and therefore for central bank reserves in interbank settlement. Del Negro et al. (2017) introduce Kiyotaki and Moore (2012) borrowing and resaleability constraints into a DSGE model, and capture unconventional monetary policies as changes in "the composition of liquid and illiquid assets in the hands of the [nonbank] private sector [that] affect the allocation of resources." Cui and Sterk (2021) model QE as affecting household liquidity, held for precautionary motives, under incomplete markets in a tractable Heterogeneous New-Keynesian (HANK) model. Their model features "narrow" rather than commercial banks, as deposits are matched one for one by holdings of central bank reserves. This is equivalent to households directly holding central bank accounts (Benes and Kumhof, 2012).

The growing body of empirical work describing the actual implementation of QE and QT policies strongly favors our modelling choice of capturing unconventional balance-sheet policies as central bank purchases (sales) of bonds from (to) NBFIs that are settled via commercial bank balance sheets. For example, Carpenter et al. (2015) analyze the first rounds of QE in the US between 2008 and 2012 using Flow of Funds data to identify which investors sell government securities to the Fed. They find that a small group of non-banks, including wealthy households/hedge funds, broker-dealers and insurance companies, are the largest sellers. Commercial banks are absent from this list and, as Cui and Sterk (2021) stress, "the Fed could not even have purchased the QE assets exclusively from banks" because of their comparatively small initial holdings. Waller (2024) further decomposes the households/hedge funds category for the most recent US QT period and finds that the changes in government securities holdings are not being driven by hedge funds but rather by actual households and nonprofit organizations.

Smith and Valcarcel (2023) study the financial market effects of the US QT experience between 2017 and 2019 using a combination of time-varying and constant parameter VARs. They find an asymmetry in both the liquidity effects (stronger during QT than QE) and the announcement effects (stronger during QE than QT) such that QT tightens financial conditions under a different transmission mechanism than simply "QE in reverse." Du, Forbes and Luzzetti (2024) provide the

[6] We thereby focus on the QE LSAPs that central banks in advanced economies have conducted since the global financial crisis, where they have bought and, more recently, sold assets from/to NBFIs. This is in contrast to conventional central bank balance sheet policies known as open market operations, where the central bank swaps reserves for government bonds directly with commercial banks.

first cross-country assessment of post-COVID QT, based on data from seven advanced economies,[7] as well as the US 2017-2019 QT episode. They find that nonbank investors are by far the most important (93%) counterparts of central bank balance sheet policies and that they have become even more relevant post-COVID. Because such interventions are settled via commercial bank balance sheets, they also find that during QT the liquidity balances of banking sectors have fallen while spreads between overnight funding rates and central bank interest rates on reserves have increased. Finally, Christensen and Krogstrup (2019) present empirical evidence that is consistent with the money channel of our model. They develop a dynamic term structure model and combine it with an event study approach that exploits the unique set-up of LSAPs by the Swiss National Bank (SNB) in 2011. Because the SNB exclusively bought short term government bonds from NBFIs, the authors are able to disentangle the standard (asset) supply-driven portfolio channel from the effects of reserve injections on long-term interest rates. In a companion paper, Christensen and Krogstrup (2022) develop a simple portfolio model that captures the two necessary frictions for a reserve-induced portfolio balance channel that are also present in our model, namely imperfect asset substitutability and market segmentation, the latter reflecting the fact that NBFIs cannot hold central bank reserves. However, because their framework features homogeneous banks in a non-structural, static, and partial equilibrium model, they do not study the effects of QE/QT on real allocations and financial stability, and the dynamic responses of the economy to monetary and financial shocks, which are at the heart of our paper.

We also contribute to a literature that investigates the monetary transmission mechanism across different operational frameworks. Arce et al. (2020) provide a New Keynesian environment characterized by loanable funds banks and a search and matching interbank set-up. They focus on the influence of the supply of reserves on the interbank market and on the central bank operational framework rather than on the effects of unconventional QE and QT policies. Their central bank therefore interacts exclusively with commercial banks (not with NBFIs) via its deposit and lending facilities, with policies implemented through conventional OMOs – swaps between bonds held by banks and central bank reserves, and driven by bank demand at the posted interest rates. Bianchi and Bigio (2022) develop a granular over-the-counter (OTC) interbank market, also using search and matching frictions, and investigate how central bank balance sheet policies influence commercial banks' lending profits and liquidity risk.

Our model of ex-ante heterogeneous banks, which replaces search and matching frictions with liquidity and risk frictions, allows us to develop a parsimonious model of the interbank market. We are thereby able to study the effects of QT and QE policies on the interbank market, but also their general equilibrium propagation to the wider money markets and the real economy. We also note that while the search and matching frameworks of Arce et al. (2020) and Bianchi and Bigio

[7] Their sample includes Australia, Canada, Euro area, New Zealand, Sweden, UK and US.

(2022) have very desirable characteristics, they rely on the assumption that interbank markets are populated by a large set of anonymous actors on both sides of the market. In reality commercial bank participants face a much more limited set of counterparties that are well known to them, and we argue that our interbank market set-up is able to capture this reality.[8]

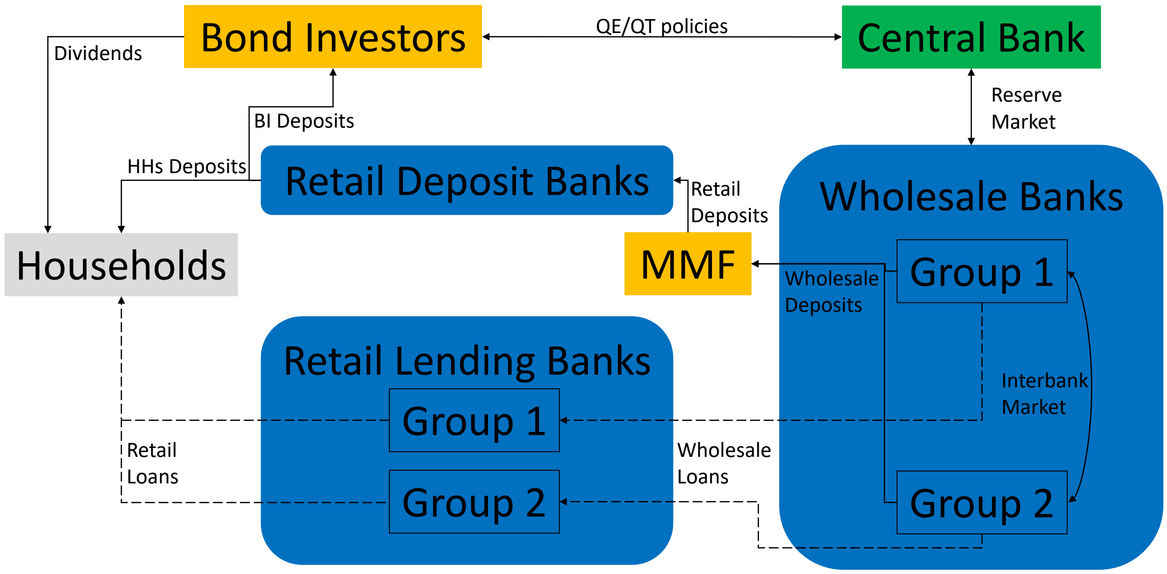
We also contribute to the literature on the interaction of alternative monetary policy tools and their welfare implications. For example, Benigno and Benigno (2022) show that reserves can become an additional tool to control aggregate demand, as output depends not only on real interest rates but also on the supply of liquidity, where in their model reserves directly enter the aggregate supply equation due to a working-capital constraint faced by producers. Similarly, Diba and Loisel (2020, 2021) and Piazzesi, Rogers and Schneider (2021) develop frameworks where central bank liquidity is non-trivial, where in their models there is a decoupling between money-market rates and the relevant rate for household consumption-saving decisions when policy operates on a floor system. Canzoneri, Cumby and Diba (2017) study optimal monetary policy when the Fed has two instruments, and find that the monetary authority can obtain stabilizing welfare effects in cases where the central bank eliminates monetary distortions and has additional macroeconomic goals. Harrison (2017) studies the optimal use of QE and conventional policy in a New Keynesian set-up that incorporates a bond market friction that gives rise to a portfolio balance channel. He finds that at the ZLB the optimal implementation of QE is rapid, while the optimal normalization path is gradual and is characterized by QT taking place before policy rate lift-offs. These frameworks abstract from the role of reserves as an interbank settlement medium, and the resulting effects on financial stability and on bank lending, money creation, and overall economic performance.

3. The Model

The economy is populated by households, manufacturers, unions, banks, money market funds, bond investors, and a government. Figure 1 provides an overview of the model's financial sector. Banks consist of retail deposit banks, wholesale banks, and retail lending banks, where we can think of wholesale banks as the treasury department of the bank that optimizes the overall balance sheet subject to regulations, while treating retail activities as separate profit centers. There are two groups of wholesale and retail lending banks that are identified by subscripts $b1$ and $b2$. Nominal variables are denoted by upper case letters while real variables are denoted by the corresponding lower case letters (L and ℓ for loans). Real normalized (by the price level and productivity) variables are denoted by lower case letters with a check symbol. The growth rate of productivity is constant at $x = T_t/T_{t-1}$, while the growth rate of the CPI price level is $\pi_t^p = P_t/P_{t-1}$.

[8] Salgado-Moreno (2021) analyzes the effects of the change in the US monetary operating framework around the time of the global financial crisis on banks' credit supply to the real economy. He uses a regime-switching model with a parsimonious Federal Funds market, where government-sponsored enterprises (GSEs) are the only interbank lenders.

Figure 1: Overview of the Model



3.1. Households

3.1.1. Preferences

Households have unit mass and are indexed by j. They maximize lifetime utility subject to sequences of intertemporal budget constraints, bank participation constraints, and deposits-in-advance constraints, by choosing plans for consumption $c_t(j)$, hours worked $h_t(j)$, investment $I_t(j)$, capital $k_t(j)$, retail loans $L_{b1,t}(j)$ and $L_{b2,t}(j)$, and retail deposits $D_t^{hh}(j)$. The objective function of household j is

$$Max \quad \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_{hh}^t \left\{ (1-\frac{v}{x}) S_t^c \log(c_t(j) - \nu c_{t-1}) - \psi \frac{h_t(j)^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} \right\} , \tag{1}$$

where S_t^c is a mean 1 first-order autoregressive process with i.i.d. normal error term that represents shocks to consumption preferences, v is the degree of external habit persistence, ψ is the utility weight of hours, and η is the labor supply elasticity. Consumption $c_t(j)$, with corresponding utility-based price index P_t, is a CES aggregate over varieties $c_t(j,z)$, with time-varying elasticity of substitution $\theta_{p,t}$, and therefore with time-varying gross price markups $\theta_{p,t}/(\theta_{p,t}-1) = S_t^{\mu_p}\bar{\mu}_p$, where $S_t^{\mu_p}$ is a mean 1 i.i.d. normal process with error terms that represent price markup shocks.

Household j accumulates the physical capital stock $k_t(j)$, which depreciates at the rate Δ, and with investment subject to adjustment costs $G_{I,t}(j) = S_t^i I_t (\phi_i/2) (I_t(j)/(xI_{t-1}(j)) - 1)^2$. Capital accumulation is therefore given by $k_t(j) = (1-\Delta) k_{t-1}(j) + S_t^i I_t(j) - G_{I,t}(j)$, where S_t^i is a mean 1 first-order autoregressive process with i.i.d. normal error terms that represent shocks to the marginal efficiency of investment. The nominal and real after-tax returns to capital are given by

$Ret_{k,t} = \left[(1-\Delta) Q_t + R^k_t\right]/Q_{t-1}$ and $ret_{k,t} = Ret_{k,t}/(x\pi^p_t) = \left[(1-\Delta) q_t + r^k_t\right]/q_{t-1}$, where R^k_t is the user cost of capital and Q_t is Tobin's q.

3.1.2. Money Demands

Households face a deposits-in-advance constraint for purchases of consumption and investment goods using deposits $D^{hh}_t(j)$,

$$\varkappa D^{hh}_t(j) \geqslant 4 S^{mon}_t P_t \left(c_t(j) + I_t(j)\right) \ , \tag{2}$$

where the factor 4 annualizes quarterly flows, $\varkappa$ determines steady state velocity and thereby the overall size of bank balance sheets, and S^{mon}_t is a mean 1 first-order autoregressive process with i.i.d. normal error terms that represent shocks to money demand. We verify that this constraint always binds in equilibrium. Its multiplier in the household optimization problem is denoted by λ^{dia}_t. In order to satisfy their demand for deposit money, households need to obtain bank loans, and in this they are subject to small but nonzero real adjustment costs $G_{L,b1,t}(j) = \ell_{b1,t}(j)\frac{\phi_\ell}{2}\left(\check{\ell}_{b1,t}(j) - \check{\ell}_{b1,t-1}\right)^2$ and $G_{L,b2,t}(j) = \ell_{b2t}(j)\frac{\phi_\ell}{2}\left(\check{\ell}_{b2,t}(j) - \check{\ell}_{b2,t-1}\right)^2$. We omit cash from the analysis, because in modern economies cash accounts for well under 5% of the broad money supply.

3.1.3. Budget Constraint

The representative household's flow budget constraint, with multiplier $\Lambda^{hh}_t(j)$, is

$$\begin{aligned} & Q_t k_t(j) + D^{hh}_t(j)\left(1 + \phi_f\left(b^{rat}_{bi,t} - \bar{b}^{rat}_{bi}\right)\right) - P_t \Psi^{hh}_t(j) - \Sigma^{b2}_{i=b1} L_{i,t}(j)\left(1 - G_{L,i,t}(j)\right) \\ = \ & Q_{t-1}k_{t-1}(j) Ret_{k,t}\left(1 - \Sigma^{b2}_{i=b1} S^{cred}_{t-1} S^{cred}_{i,t-1}\kappa_i \Gamma^k_{i,t}\right) + i_{d,t-1} D^{hh}_{t-1}(j) \\ & + Q_t S^i_t I_t(j) - Q_t G_{I,t}(j) - P_t I_t(j) - P_t c_t(j) + W^{hh}_t h_t(j) + P_t \Omega_t(j) \ . \end{aligned} \tag{3}$$

Portfolio costs: On the first line of (3), the term $\phi_f\left(b^{rat}_{bi,t} - \bar{b}^{rat}_{bi}\right)$ represents transactions costs related to holding financial assets. The term $b^{rat}_{bi,t} = B^{bi}_t/(4GDP_t)$ is the ratio to GDP of privately held government debt and $\bar{b}^{rat}_{bi}$ is its steady state. This cost is taken as exogenous by households, and $P_t\Psi^{hh}_t(j)$ includes its lump-sum distribution back to households ($P_t\Psi^{hh}_t(j)$ also includes lump-sum redistribution of loan adjustment costs). This allows the model to replicate the small but positive elasticity of US real interest rates with respect to defaultable government debt that has been found in the literature, and that is now also used in IMF debt sustainability analysis (see the section on calibration below). Interest rates on all financial assets are affected in the same fashion, so that a change in the privately held government debt-to-GDP ratio, ceteris paribus, will affect the level of interest rates but not the structure of spreads.

Asset returns: On the second line of (3), households' return to capital excludes returns that serve to repay loans, where $\Gamma^k_{i,t}(j)$ are the endogenous shares of the gross returns of collateral capital that go to bank groups 1 and 2 to service loans, $\kappa_i S^{cred}_{t-1} S^{cred}_{i,t-1}$ are the shares of domestic capital that have been accepted as collateral by these banks, S^{cred}_t is a mean 1 first-order autoregressive process with i.i.d. normal error terms that represent shocks to aggregate credit supply, and $S^{cred}_{i,t}$ are mean 1 first-order autoregressive processes with i.i.d. normal error terms that represent shocks to sectoral credit supply. The nominal interest rate on bank deposits is $i_{d,t}$.

Other income and expenditures: Other than net asset income, households receive net revenue from capital production $Q_t S^i_t I_t(j) - Q_t G_{I,t}(j)$, labor income $W^{hh}_t h_t(j)$, where W^{hh}_t is the wage rate paid by unions, and lump-sum net income $P_t \Omega_t(j)$. The latter includes profits of manufacturers, unions, bond investors, and banks, net fiscal transfers, and all transactions and adjustment costs. Expenditures include consumption and investment purchases $P_t c_t(j)$ and $P_t I_t(j)$.

3.1.4. Participation Constraints

Households also face participation constraints for taking out loans from the two retail lending bank groups, which will be explained below. We have $S^{cred}_t S^{cred}_{i,t} \kappa_i Ret_{k,t+1} Q_t k_t(j) \left(\Gamma^k_{i,t+1}(j) - \xi_i G^k_{i,t+1}(j)\right) - i_{\ell,i,t} L_{i,t}(j)$, with multiplier $\Lambda^{hh}_t(j) \lambda^{part}_{i,t}(j)$, $i \in \{b1, b2\}$. The term $\xi_i G^k_{i,t+1}(j)$ denotes bank group i's endogenous monitoring cost share in gross returns to collateral capital, where ξ_i is the loss-given-default parameter, and $i_{\ell,i,t}$ is the wholesale lending rate charged by wholesale banks to retail lending banks.

3.1.5. Optimality Conditions

Household optimality conditions are shown in full in the Online Appendix. We assume that each household holds identical initial stocks of all physical and financial assets and liabilities, has identical exposures to all investment projects, and receives identical net lump-sum transfers. Because all households face the same market prices, and ex-post set the same prices for their own product varieties, they remain symmetric at all times. The first-order conditions for individual goods varieties and hours are standard. In the first-order conditions for aggregate consumption and investment the *effective purchase price* exceeds the direct purchase price by a mark-up due to monetary frictions, $\tau^{mon}_t = \lambda^{dia}_t 4 S^{mon}_t$, where λ^{dia}_t is decreasing in the quantity of deposits. We will utilize the concept of the effective purchase price in interpreting our simulation results below. The first-order condition for capital has additional terms related to the use of capital as loan collateral. In the Euler equation for deposits, the asset return includes both a gross financial or interest rate yield and a net nonfinancial or convenience yield $\lambda^{dia}_t \varkappa$. The first-order conditions for loans feature loan adjustment cost terms as well as the returns $\lambda^{part}_{b1,t} r_{\ell,b1,t+1}$ and $\lambda^{part}_{b2,t} r_{\ell,b2,t+1}$.

3.2. Manufacturers

Manufacturers have unit mass and are indexed by j, where individual manufacturers differ by the goods variety they produce. Manufacturer j hires labour $h_t(j)$ from unions at the nominal wage rate W_t^{pr}, and capital $k_{t-1}(j)$ from households at the user cost R_t^k, to produce one variety j of the domestic good $y_t(j) = (S_t^a T_t h_t(j))^{1-\alpha} (k_{t-1}(j))^{\alpha}$, where S_t^a is a mean 1 first-order autoregressive process with i.i.d. normal error terms that represent shocks to technology. The labor demanded $h_t(j)$ is a CES aggregate over varieties $h_t(j,z)$, with time-varying elasticity of substitution $\theta_{w,t}$, and therefore with time-varying gross price markups $\theta_{w,t}/(\theta_{w,t}-1) = S_t^{\mu_w}\bar{\mu}_w$, where $S_t^{\mu_w}$ is a mean 1 i.i.d. normal process with error terms that represent wage markup shocks. Manufacturer j sets the price of his variety $P_t(j)$ subject to monopolistic competition and quadratic price adjustment costs $G_{P,t}(j) = (\phi_p/2)\, P_t y_t\, (P_t(j)/P_{t-1}(j) - \bar{\pi})^2$. The first-order conditions for input choice and the New Keynesian Phillips curve are standard.

3.3. Unions

Unions have unit mass and are indexed by j, where individual unions differ by the labour variety they sell. Unions buy homogenous labor from households at a competitively determined nominal household wage rate W_t^{hh}. They set the wage $W_t^{pr}(j)$ of their labor variety $h_t(j)$ subject to monopolistic competition and quadratic wage adjustment costs $G_{W,t}(j) = (\phi_w/2)\, W_t^{pr} h_t \left(W_t^{pr}(j)/W_{t-1}^{pr}(j) - \bar{\pi}x\right)^2$. The wage Phillips curve is standard.

3.4. Bond Investors

Bond investors have unit mass and are indexed by j. They are neither producers nor consumers of physical goods. They are the sole investors in domestic government securities $B_t^{bi}(j)$ that pay the nominal interest rate $i_{b,t}$. Their holdings of wholesale deposits are denoted by $D_t^{bi}(j)$ and pay the wholesale interest rate $i_{w,t}$. Bond investors transfer part of their net interest earnings to households as dividends $\Pi_t^{bi}(j)$ in a lump-sum fashion, subject to dividend smoothing modelled as external habit persistence. The objective function for bond investor j is

$$Max\ \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_{bi}^t \left[S_t^c \left(1 - \frac{\nu}{x}\right) \log\left(\check{\Pi}_t^{bi}(j) - \frac{\nu}{x}\check{\Pi}_{t-1}^{bi}(j)\right) + \varphi \frac{\left(\check{b}_t^{bi}(j)\right)^{1-\vartheta}}{1-\vartheta} \right], \tag{4}$$

where β_{bi} differs from β_{hh}. To represent the highly interest-sensitive nature of wholesale money markets, bonds in the utility function replace the deposits-in-advance friction of households. The interest semi-elasticity of demand for government securities ϵ_b^{bi}, which depends on ϑ, measures the percent increase of bond investors' demand for government bonds in response to a one percentage point increase in the annualized interest rate on government bonds $i_{b,t}$. The nominal budget constraint exhibits the same portfolio costs as households. We omit the optimality conditions.

3.5. Money Market Funds

Money market funds (MMF) represent the Federal Funds market. MMF have unit mass and are indexed by j. They buy wholesale deposit liabilities $D_{b1,t}(j)$ and $D_{b2,t}(j)$ from wholesale banks, in a competitive market and at interest rates $i_{w,b1,t}$ and $i_{w,b2,t}$. Their customers are retail deposit banks, who demand a CES aggregate $D_t^{rdb}(j)$, at interest rate $i_{w,t}$, over $D_{b1,t}(j)$ and $D_{b2,t}(j)$. The interest rate $i_{w,t}$ represents the effective Federal Funds rate (EFFR). The CES aggregate features a (high) elasticity of substitution θ, and a quasi-share parameter bS_t^d, where S_t^d is a mean 1 first-order autoregressive process with i.i.d. normal error terms that represent deposit withdrawal shocks between the two banking groups. The optimality conditions are standard.

3.6. Wholesale Banks

There are two groups of wholesale banks that have identical steady state net worth and loans, but that differ in their position in the deposit market, and therefore also in the markets for reserves and interbank loans. Specifically, bank group 1 represents money center banks that have a larger deposit base, and that therefore also hold larger central bank reserves and are net lenders in the interbank market. Bank group 2 by contrast has fewer deposits and reserves, and is a net borrower in the interbank market. The interest rates on wholesale deposits $i_{w,i,t}$ are determined by each bank group's relative holdings of deposits and reserves, as fewer reserves relative to deposits make the management of the payment system more risky and costly to the bank and lead it to offer a higher wholesale deposit rate in order to attract more reserves. The interest rate on interbank loans, which represents LIBOR and its more recent successors, is determined by the interaction of group 1 supply and group 2 demand, with group 1 demanding a higher rate for larger interbank loans relative to its net worth, as larger loans make the management of counterparty exposures more risky and costly to the bank, and lead it demand higher compensation.

The optimization problems of group 1 and group 2 wholesale banks are very similar, with the only difference being due to the fact that group 1 has the additional problem of managing a costly counterparty exposure in the interbank market. We will therefore describe the optimization problem of group 1, and will refer to differences with group 2 where necessary.

Group 1 wholesale banks are indexed by (j, z), because they are exposed to two different and independently distributed sources of risk. They are ex-ante identical in terms of ratios of assets and liabilities to net worth, while they may differ in terms of the size of net worth. They issue wholesale loans $L_{b1,t}(j, z)$ to retail lending banks and wholesale deposits $D_{b1,t}(j, z)$ to money market funds. They also hold reserves $M_{b1,t}(j, z)$ at the central bank and issue interbank loans $O_{b1,t}(j, z)$. Their net worth equals $N_{b1,t}^b(j, z)$, and their balance sheet is $L_{b1,t}(j, z) + M_{b1,t}(j, z) + O_{b1,t}(j, z) = D_{b1,t}(j, z) + N_{b1,t}(j, z)$.

Along the continuum indexed by j, gross interest-inclusive loans are subject to lognormally distributed idiosyncratic shocks $\omega^b_{b1,t+1}$ with mean 1 and variance $(\sigma^b_{b1})^2$ that represent shocks to banks' non-interest earnings, and that give rise to ex-post differences across banks in terms of violations of minimum capital adequacy rules (MCAR). We denote the pdf and cdf of these shocks by $f^b(\omega^b_{b1,t+1})$ and $F^b(\omega^b_{b1,t+1})$, the cutoff below which MCAR is violated ex-post by $\bar{\omega}^b_{b1,t}$, and we define $f^b_t = f^b(\bar{\omega}^b_{b1,t})$ and $F^b_t = F^b(\bar{\omega}^b_{b1,t})$. Along the continuum indexed by z, current period net worth is subject to lognormally distributed idiosyncratic shocks ω^o_{t+1} with mean 1 and variance $(\sigma_o)^2$ that represent shocks to banks' equity, and that give rise to ex-post differences across banks in terms of the ratio of interbank loans to net worth. We denote the pdf and cdf of these shocks by $f^o(\omega^o_{t+1})$ and $F^o(\omega^o_{t+1})$, the cutoff productivity shocks below which loan default occurs ex-post by $\bar{\omega}^o_t$, and we define $f^o_t = f^o(\bar{\omega}^o_t)$ and $F^o_t = F^o(\bar{\omega}^o_t)$.

Reserve scarcity cost (RSC): Each bank faces a reserve scarcity cost that is proportional to its net worth, increasing in the ratio of deposits to reserves, and dependent on a parameter $\eth$ that indexes the convexity of the cost function, $G_{M,b1,t}(j,z) = (\upsilon/(1+\eth))\, N_{b1,t}(j,z)\,(D_{b1,t}(j,z)/M_{b1,t}(j,z))^{1+\eth}$. The coefficients υ and $\eth$ of the RSC are assumed to be equal across group 1 and group 2 wholesale banks. Note that the functional form of our RSC is the inverse of Vissing-Jorgensen's (2023) so-called "reserves convenience yield function". While our cost function is decreasing in reserves and increasing in deposits, Vissing-Jorgensen's convenience yield function is increasing in reserves and decreasing in deposits. Both specifications capture the liquidity benefits of reserves for banks, such as reductions in transaction costs when faced with deposits outflows.

Minimum capital adequacy rules (MCAR): MCAR limit wholesale banks' ability to create credit and money. Bank (j,z) faces a future penalty of $\chi_{b1,\ell}\,(L_{b1,t}(j,z) + \mathfrak{r}O_{b1,t}(j,z))\,\pi^p_{t+1}$ if next period's net worth falls short of a fraction γ_ℓ of risk-weighted assets. Next period's net worth equals the difference between the gross returns on asset-side and liability-side items, plus the net profits of retail deposit and retail lending banks, minus reserve scarcity costs. The regulatory risk weights on loans to households and banks equal 1 and $\mathfrak{r} < 1$.

Large exposure limit costs (LELC): Bank (j,z) faces a future cost of $(\chi_o/(1+\varpi))\,N_{b1,t}(j,z)\,(O_{b1,t}(j,z)/N_{b1,t}(j,z))^{1+\varpi}\,\pi^p_{t+1}$ if the ratio of interbank loans to current net-loss-adjusted net worth $O_{b1,t}(j,z)/\left(N_{b1,t}(j,z)\omega^o_{t+1}(j,z)\right)$ exceeds γ_o.

In equilibrium each bank faces the same interest rates $r_{\ell,b1,t+1}$, $r_{w,b1,t+1}$, $r_{o,t+1}$, r_{t+1}, and $r_{d,t+1}$, the same parameters $\chi_{b1,\ell}$, γ_ℓ, and χ_o, the same expected risk $F^b_{b1,t+1}$, $f^b_{b1,t+1}$, F^o_{t+1}, f^o_{t+1}, and identical lump-sum distributions from retail lending and deposit banks relative to net worth. This implies that the optimality conditions can be solved for unique loans-to-net-worth, deposits-to-net-worth, reserves-to-net-worth, and interbank-loans-to-net-worth ratios that are identical across banks. We can therefore drop the index (j,z) in our final optimality conditions.

Net worth maximization: There are three first-order conditions with respect to the bank's asset side items, taking interest rates as given. Defining $r_{a,b1,t+1} = r_{w,b1,t+1} + \left(\check{\Pi}^R_{b1,t+1} x / \check{n}_{b1,t}\right) + \left(r_{t+1} - r_{w,b1,t+1}\right)\left(\check{m}_{b1,t}/\check{n}_{b1,t}\right) + \left(r_{o,t+1}\left(1-\gamma_\ell \mathfrak{r}\right) - r_{w,b1,t+1}\right)\left(\check{o}_{b1,t}/\check{n}_{b1,t}\right) - \left(\check{G}_{M,b1,t}/\check{n}_{b1,t}\right)$, the first-order conditions for wholesale loans, reserves and interbank loans are:

$$\mathbb{E}_t r_{w,b1,t+1} = \mathbb{E}_t \left(r_{t+1} + \upsilon \left(\frac{\check{d}_{b1,t}}{\check{m}_{b1,t}}\right)^{\eth} \frac{\check{\ell}_{b1,t}\check{n}_{b1,t} + \check{o}_{b1,t}\check{n}_{b1,t} - \check{n}^2_{b1,t}}{\check{m}^2_{b1,t}} \right), \tag{5}$$

$$\mathbb{E}_t r_{\ell,b1,t+1} = \mathbb{E}_t \left[r_{w,b1,t+1} + \upsilon \left(\frac{\check{d}_{b1,t}}{\check{m}_{b1,t}}\right)^{\eth} \frac{\check{n}_{b1,t}}{\check{m}_{b1,t}} \left(1 + \frac{\chi_{b1,\ell} f^b_{b1,t+1}}{\left(1-\gamma_\ell\right) r_{\ell,b1,t+1}} \left(1 + \mathfrak{r}\frac{\check{o}_{b1,t}}{\check{\ell}_{b1,t}}\right)\right)\right] \tag{6}$$
$$+\mathbb{E}_t \chi_{b1,\ell} \left(F^b_{b1,t+1} + f^b_{b1,t+1}\left(1 + \mathfrak{r}\frac{\check{o}_{b1,t}}{\check{\ell}_{b1,t}}\right)\left(\frac{r_{a,b1,t+1}}{\left(1-\gamma_\ell\right) r_{\ell,b1,t+1}\left(\check{\ell}_{b1,t}/\check{n}_{b1,t}\right)}\right)\right),$$

$$\mathbb{E}_t r_{o,t+1} = \mathbb{E}_t \left(r_{w,b1,t+1} + \upsilon \left(\frac{\check{d}_{b1,t}}{\check{m}_{b1,t}}\right)^{\eth} \left(\frac{\check{n}_{b1,t}}{\check{m}_{b1,t}}\right)\right) / \left(1 - \gamma_\ell \mathfrak{r} + \frac{\gamma_\ell \mathfrak{r}}{\mathfrak{f}_t}\right) \tag{7}$$
$$+\mathbb{E}_t \left(\chi_{b1,\ell}\mathfrak{r} F^b_{t+1} + \chi_o \left(\frac{\check{o}_{b1,t}}{\check{n}_{b1,t}}\right)^{\varpi} \left(F^o_{t+1} + f^o_{t+1}\frac{1}{\left(1+\varpi\right)\gamma_o}\frac{\check{o}_{b1,t}}{\check{n}_{b1,t}}\right)\right) / \left(\left(1 - \gamma_\ell \mathfrak{r} + \frac{\gamma_\ell \mathfrak{r}}{\mathfrak{f}_t}\right)\mathfrak{f}_t\right),$$

$$\mathfrak{f}_t = \left(1 + \frac{\chi_{b1,\ell} f^b_{b1,t+1}}{\left(1-\gamma_\ell\right) r_{\ell,b1,t+1}} \left(1 + \mathfrak{r} S^{rwgt}_t \frac{\check{o}_{b1,t}}{\check{\ell}_{b1,t}}\right)\right). \tag{8}$$

Condition (5) shows that RSC drives a wedge between the wholesale deposit rate and the policy rate ONRRP. The reason is that in order to increase the level of their reserves banks have to offer a higher wholesale deposit rate. Condition (6) shows that both MCAR and RSC drive a wedge between wholesale lending rates and wholesale deposit rates. The reason is that an increase in loans increases the likelihood and thus expected cost of violating capital adquacy rules (MCAR), and increases the scarcity of reserves and thus the bank's wholesale funding costs (RSC). Condition (7) shows that LELC, RSC and MCAR (the latter only if $\mathfrak{r} > 0$) drive a wedge between interbank lending rates and wholesale deposit rates. The reason is that an increase in interbank loans increases the likelihood and expected cost of breaching large exposure limits (LELC), and increases the scarcity of reserves and thus the bank's wholesale funding costs (RSC).

Post-dividend net worth equals net interest earnings, minus MCAR, LELC and RSC costs, and minus dividends that equal a fixed fraction of net worth. The latter are paid out to households in a lump-sum fashion, a specification that can be obtained by applying the "extended family" approach of Gertler and Karadi (2011).

Group 2 wholesale banks, whose interbank borrowings are denoted by $O_{b2,t}(j)$, only exist in the continuum indexed by j, as they do not face interbank lending risks. Their optimality condition for reserves is identical to (5) after replacing $\check{o}_{b1,t}$ with $-\check{o}_{b2,t}$. Their optimality condition for wholesale loans is similar to (6) but with the interbank loans term $\check{o}_{b1,t}$ replaced by zero. Their optimality condition for interbank borrowing takes the same form as the denominator on the first line of (7), with the denominator replaced by one and the second line absent. Group 2 wholesale banks trade off the higher cost of maintaining lower reserves with the higher cost of interbank borrowing.

3.7. Retail Deposit Banks

Retail deposit banks have unit mass and are indexed by j. They place wholesale deposits $D_t^{rdb}(j)$ with money market funds at interest rate $i_{w,t}$, and pay for them by issuing retail deposit varieties indexed by z, $D_t^{hh}(j,z)$ and $D_t^{bi}(j,z)$, to households and bond investors. Retail holders demand CES composites of all deposit varieties. Retail deposit banks are perfectly competitive on the asset side, while on the liability side they are perfectly competitive vis-à-vis bond investors, and monopolistically competitive vis-à-vis households. This implies the pricing rules $i_{d,t}^{bi} = i_{w,t}$ and $i_{d,t}^{hh} = i_{d,t} = s i_{w,t}$, where s is a mark-down term whose size depends on the elasticity of substitution between household deposit varieties.

3.8. Retail Lending Banks

The model of retail lending banks is based on a modified version of Bernanke et al. (1999). Group 1 and 2 retail lending banks obtain wholesale loans from group 1 and 2 wholesale banks, respectively. Inside each group retail lending banks are homogenous, and each bank lends the same amount to a borrower j. The total eligible loan collateral is the gross return to capital $\mathbb{E}_t Ret_{k,t+1} Q_t k_t(j)$, while actual collateral is determined by the fractions $\kappa_i S_t^{cred} S_{i,t}^{cred}$ of this collateral that banks accept. Along the continuum indexed by j, the gross return to capital is subject to log-normally distributed idiosyncratic productivity shocks $\omega_{i,t+1}^k$ with mean 1 and variance $(\sigma_i^k)^2$ that represent shocks to borrowers' real earnings, and that give rise to ex-post differences across borrowers, with a fraction entering bankruptcy. We denote the pdf and cdf of these shocks by $f^k(\omega_{i,t+1}^k)$ and $F^k(\omega_{i,t+1}^k)$, the cutoffs below which bankruptcy occurs ex-post by $\bar{\omega}_{i,t}^k$, and we define $f_{i,t}^k = f^k(\bar{\omega}_{i,t}^k)$ and $F_{i,t}^k = F^k(\bar{\omega}_{i,t}^k)$. Retail lending banks' cost of funding is given by wholesale lending rates $i_{\ell,i,t}$, while their loan contracts stipulate non-contingent retail lending rates $i_{r,i,t}$ that must be paid in full unless borrowers declare bankruptcy, which becomes advantageous when $\omega_{i,t}^k < \bar{\omega}_{i,t}^k$. In case of bankruptcy, because of monitoring costs, the bank can only recover a fraction $1 - \xi_i$ of collateral. In equilibrium each retail lending bank in sector i faces the same $r_{r,i,t+1}$, $r_{\ell,i,t+1}$, $ret_{k,t+1}$, ξ_i, κ_i and q_t. This implies that there are unique loans-to-capital ratios that are identical across borrowers, so that all equilibrium conditions are straightforward to aggregate. The optimality conditions are the participation constraints that are shown in Section 2.1.4. These state that ex-ante net loan losses must equal zero, while ex-post net loan losses are generally different from zero because lending rates are non-contingent.

3.9. Government

The Taylor rule for ONRRP, the interest rate on central bank reserves i_t, is a conventional inflation forecast-based rule, with a steady state $\bar{\imath}$, interest rate smoothing with coefficient i_i, a countercyclical response to deviations of one-quarter-ahead (as in Christiano et al. (2014)) inflation from the inflation target $\bar{\pi}$ with coefficient i_π, and monetary policy shocks to S_t^{int}, a mean 1 process with i.i.d. normal error terms:

$$i_t = (i_{t-1})^{i_i} \, \bar{\imath}^{(1-i_i)} \mathbb{E}_t \left(\frac{\pi_{t+1}^p}{\bar{\pi}} \right)^{(1-i_i)i_\pi} S_t^{int} \quad . \tag{9}$$

A second rule, for the ratio to GDP of the quantity of reserves $m_t^{rat} = \left(\check{m}_t / \left(4 * gd\check{p}_t \right) \right)$, ensures that the spread of the LIBOR interbank rate $i_{o,t}$ over the ONRRP rate i_t does not increase too much relative to its steady state. We assume a steady state reserve ratio $\bar{m}^{rat}$, a countercyclical response to deviations of the interbank rate spread with coefficient m_o, and reserve policy shocks to S_t^r, a mean 1 first-order autoregressive process with i.i.d. normal error terms. The rule is

$$\check{m}_t^{rat} = \bar{m}^{rat} \left(\frac{i_{o,t}/i_t}{\bar{\imath}_{o,t}/\bar{\imath}_t} \right)^{4m_o} S_t^r \quad . \tag{10}$$

On the central bank balance sheet, reserves are backed one-to-one by government securities, $B_t^{cb} = M_t$. This implies that any central bank profits are transferred directly to the government budget and are not retained as equity.

Real government spending is given by $g_t = s_g \overline{gdp} S_t^g$, where S_t^g is a mean 1 first-order autoregressive process with i.i.d. normal error terms. The government adjusts lump-sum taxes to ensure that government debt remains constant relative to trend, $\check{b}_t = \bar{b}$.

3.10. Market Clearing

The market clearing conditions for government bonds and reserves are $B_t = B_t^{cb} + B_t^{bi}$ and $M_t = M_{b1,t} + M_{b2,t}$. The market clearing conditions for retail and wholesale deposits are $D_t^{rdb} = D_t^{hh} + D_t^{bi}$ and $D_t^{whs} = D_{b1,t} + D_{b2,t}$. The interbank market clears at $O_{b1,t} = O_{b2,t}$. Finally, the goods market clearing condition is $y_t = c_t + I_t + g_t = gdp_t$.

4. Calibration

Our calibration is for the US. Calibration of the steady state is based on the literature and on sample averages, where available, over the period 2010Q1-2019Q4. For some interest rates we had to use a shorter sample as they are not available over the full decade.

4.1. Real Sector

Trend productivity growth x is calibrated at 2% in annual terms. The CPI inflation target $\bar{\pi}$ and the (pre-CBDC) equilibrium real interest rate $\bar{r}$ are set to 2% and 3% in annualized terms, respectively, the latter by adjusting the discount factor of bond investors β_{bi}. For preferences of households, following the estimates in Cesa-Bianchi et al. (2023), we fix the habit persistence parameter v at 0.77, and the elasticity of labour supply η at 1.54. We normalize steady state labour supply to 1 by adjusting the preference weight ψ. For preferences of bond investors, we set the opportunity cost semi-elasticity of demand for government bonds at a high $\epsilon_b^{bi} = 300$, by adjusting the parameter ϑ. This ensures that for bond investors very large changes in relative holdings of wholesale deposits and government securities require only very small changes, measured in a few basis points, in the spread between the wholesale deposit rate and the rate on government securities.

For technologies, steady state gross markups are fixed at $\bar{\mu}_p = \bar{\mu}_w = 1.1$, in line with much of the literature. To match BLS sample averages for the US business sector, we set the steady state labor income share to 59.4% by adjusting the share parameter α. We set the ratio of investment to GDP to its sample average of 17.3% by adjusting the depreciation rate Δ. We calibrate the ratio of the value of capital $Q_t k_t$ to GDP, which according to Fed and NIPA data equals around 240%, by adjusting the willingness-to-lend parameter κ_{b1}.

4.2. Fiscal Sector

The steady state total government debt-to-GDP ratio is set to its sample average of 98% by adjusting $\bar{b}^{rat}$. The steady state reserves-to-GDP ratio is set to its sample average of 11.5% by adjusting $\bar{m}^{rat}$. As a result, the steady state ratio of privately held government debt to GDP $\bar{b}_{bi}^{rat}$ equals 86.5%. The steady state share of government spending in real GDP is set to its sample average of 19% by adjusting s_g. We set the steady state spread between the interest rates on reserves and on government securities to 20 basis points, equal to the sample average of the difference between the Federal Funds rate and the 3-month treasury bill rate, by adjusting the bonds-in-the-utility function parameter φ. The elasticity of the real interest rate on government securities with respect to changes in the government debt-to-GDP ratio is the subject of Laubach (2009), Engen and Hubbard (2004), and Gale and Orszag (2004), who report, for the US, that each percentage point increase in the debt ratio increases the real interest rate by between 1 and 6 basis points. The IMF's revised Debt Sustainability Framework (International Monetary Fund (2021, 2022)) now makes explicit reference to a "Laubach (2009) Rule", putting the value of that elasticity at 4 basis points. Our calibration is more conservative at 2 basis points, which requires setting $\phi_f = 0.00005$.

4.3. Financial Sector

The first subset of financial sector calibration targets relates to bank capital ratios. The steady state capital adequacy ratio γ_ℓ is set to 10.5% which is the sum of the 8.0% Basel III total capital ratio and the 2.5% capital conservation buffer (see Basel Committee on Banking Supervision (2017)). We omit the countercyclical and GSIB buffers, and the additional supervisory requirements, as these do not apply to all banks and/or at all times. As shown in Federal Reserve Bank of New York (2018), banks hold capital considerably above the regulatory minimum. In our model they do so to self-insure against the risk of violating the MCAR. Based on the data in Federal Reserve Bank of New York (2018), we therefore set the actual steady state capital ratio to 15.5%, for an endogenous capital buffer of 5.0%, by adjusting banks' dividend payout parameters δ_{b1} and δ_{b2}. We set the risk weight on interbank loans to $\mathfrak{r} = 0.2$.

The second subset of financial sector calibration targets relates to regulatory non-compliance rates of banks and bankruptcy rates of their borrowers. The cumulative shares of banks that violate the Basel minimum in any quarter are F^b_{b1} and F^b_{b2}. We set these shares to 2.5% in steady state, close to the approximate historical frequency of systemic banking crises in Jorda et al. (2011), by adjusting the bank riskiness parameters σ^b_{b1} and σ^b_{b2}. Borrower bankruptcy rates F^k_{b1} and F^k_{b2} are set to 1.5% by adjusting the loss-given-default parameters ξ_{b1} and ξ_{b2}. This matches delinquency rates on corporate loans reported in the FRED database.

The third subset of financial sector calibration targets relates to steady state spreads outside the interbank market. To calibrate the wholesale lending spread over the policy rate, we use a 2000-2016 data set produced by Anderson and Cesa-Bianchi (2020) of "maturity-adjusted credit spreads" (MACS) for listed non-financial US firms. These are spreads between the cost of borrowing for a given firm and an equal-maturity risk-free interest rate. We recall that in the model the wholesale lending rate corresponds to the interest rate that would be charged to a notional zero-risk corporate borrower. A model-consistent calibration for the wholesale lending spread is therefore the spread between the average commercial paper rate paid by the safest blue-chip (AAA) non-bank corporates and the treasury bill rate (not the policy rate, which is on average 20 basis points higher than the treasury bill rate) at matching maturities of 3 months. Over the sample period this spread equals 66 basis points, and we therefore calibrate the steady state wholesale lending rates $\bar{r}_{\ell,b1}$ and $\bar{r}_{\ell,b2}$ to 3.46% by adjusting the MCAR parameters $\chi_{b1,\ell}$ and $\chi_{b2,\ell}$. The steady state retail lending rates $\bar{r}_{r,b1}$ and $\bar{r}_{r,b2}$ are calibrated by adjusting the borrower riskiness parameters σ^k_{b1} and σ^k_{b2}. For their data counterpart we use the difference between Moody's seasoned Baa corporate bond yield and the market yield on U.S. treasury securities at 10-year constant maturity. Over the sample period this spread equals 189 basis points. This yields retail lending rates of 5.35%. The steady-state spread between the policy rate and the retail deposit rate is calibrated by adjusting the spread parameter s. Pre-GFC average spreads between the US policy rate and the effective interest rate on household checking accounts (from FDIC data) equalled around 300 basis points.[9] However, in our model deposits include a much wider range of financial sector liabilities, including deposits which attract rates much closer to the policy rate. To approximate the average convenience yield of total financial sector liabilities to households, we therefore calibrate this spread at 150 basis points. This is similar to Ashcraft and Steindel (2008), who compute, for the single year 2006, a spread of 134 basis points between the average rate of US commercial banks' portfolio of treasury and agency securities on the one hand and the average rate on their complete portfolio of liabilities on the other hand.

The fourth subset of parameters determines the steady state size and composition of balance sheets. Based on US Flow of Funds data for the sample period, retail loans are calibrated at 135% of GDP, spread equally between the two bank groups, by adjusting the discount factor of households β_{hh} and the willingness-to-lend parameter κ_{b2}. The steady state retail deposits to GDP ratio is calibrated at 65% based on the average value over the sample in BIS data, by adjusting the velocity parameter $\varkappa$. Together with the steady state net worth implied by the calibration of bank capital ratios, and the steady state reserve and interbank ratios discussed below, this leaves the bond investor wholesale deposits to GDP ratio as a residual, at 79% of GDP.

The fifth subset of parameters determines the size of the interbank market. Based on Allen et al. (2020), Table 1, we set the steady state interbank loans to net worth ratio of group 1 wholesale banks to 25%, which implies a steady state interbank loans to total assets ratio of 3.3%, by adjusting the quasi share coefficient of the deposits aggregate b.[10] We set the interbank loans to net worth ratio beyond which penalties start to apply to 35% by adjusting the parameter γ_o. The fraction of banks that exceed that ratio in each quarter F^o is set to 20% by adjusting the parameter σ_o.

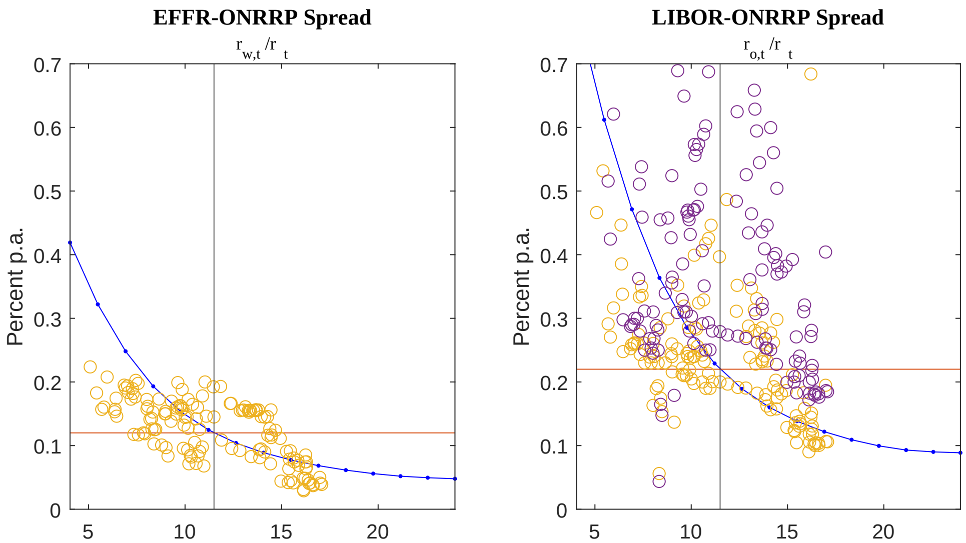
The sixth subset of parameters determines interest rates in the interbank market, with i_t representing the ONRRP rate, $i_{w,t}$ the EFFR, and $i_{o,t}$ LIBOR. Figure 1 shows the empirical relationships between reserves and interest rate spreads in the data (circles) and the model (lines).

We first match the empirical relationship between the quantity of reserves and the EFFR-ONRRP spread, which is shown on the left-hand-side of Figure 1. Between 2013m10, when the ONRRP was created, and 2019m12, the average spread between EFFR and ONRRP has averaged 12 basis points. We therefore calibrate the steady state level of the real wholesale deposit rate at 3.12%, by adjusting the scale parameter of reserve scarcity costs υ. To match the slope of the relationship, we set the elasticity of substitution between the two deposit types to a fairly high $\theta = 5$, and then adjust the curvature parameter of reserve scarcity costs $\eth$ to obtain a 9 basis points increase in $i_{w,b2,t}$ for every 1 percentage point of GDP reduction in group 2 banks' reserves, approximately in line with the data.

[9]This spread has been significantly compressed during the ZLB period, but we do not consider this period to be representative of normal conditions in the banking sector.

[10]The 3.3% US value is considerably lower than the approximately 30% values reported for France and Germany.

Figure 2: Interbank Market Spreads as a Function of Reserves



(horizontal axis = reserves in percent of GDP)
(line = model fit, circles = monthly data)
(r.h.s. circles: orange/violet = 1-month/3-month LIBOR)

Next we match the empirical relationship between the quantity of reserves and the LIBOR-ONRRP spread. Figure 2 shows both 1-month and 3-month LIBOR, but our calibration is based on the former. Over the same period 2013m10 - 2019m12, the average spread between 1-month LIBOR and EFFR has averaged 10 basis points. We therefore calibrate the steady state level of the real interbank lending rate at 3.22%, by adjusting the LELC coefficient χ_o. To match the slope of the relationship, we set the LELC curvature coefficient to $\varpi = 2$.

4.4. Adjustment Costs, Shock Persistence, and Policy Rules

We have used the estimation results of the related models (without interbank market) in Cesa-Bianchi et al. (2023) and Kumhof et al. (2023) to allow us to perform preliminary welfare analysis. We calibrate the price and wage adjustment cost parameters at $\phi_p = \phi_w = 300$, the investment adjustment cost parameter at $\phi_i = 0.78$, and the loan adjustment cost parameter at $\phi_\ell = 0.0005$. The autocorrelation coefficients are $\rho_a = 0.96$, $\rho_c = 0.57$, $\rho_{cred} = 0.95$, $\rho_d = 0.5$, $\rho_g = 0.94$, $\rho_i = 0.87$ and $\rho_{mon} = 0.89$.

In our simulations, the interest rate policy rule parameters are set to $i_i = 0.5$ and $i_i = 2.0$. For the QE policy rule we will experiment with different values for m_o, with a baseline of $m_o = 0$. We set the standard errors of shocks to approximately reproduce the standard errors and autocorrelation coefficients of GDP, consumption, investment, government spending, policy rates, inflation, credit, and risky spreads over our sample.

5. Steady State Effects of the Quantity of Reserves

5.1. Pure Monetary QE/QT

Figure 3 studies the effects on 20 key model variables of permanently changing the quantity of central bank reserves by varying the parameter $\bar{m}^{rat}$ while leaving all other parameters unchanged, including the overall quantity of government debt. The horizontal axis is the total reserves to GDP ratio. This is a pure monetary policy without any coordination with debt issuance policy.

We begin by discussing the balance sheet mechanics, and for concreteness we will discuss QT, which moves towards the left from the black vertical line that indicates the initial steady state. With QT, the central bank sells bonds to bond investors, and bond investors pay by transferring wholesale deposits to the central bank. Banks settle the central bank's wholesale deposit claims in reserves, which decline one-for-one with the decrease in central bank bond holdings. Retail deposits of households remain constant relative to GDP and therefore decline in line with GDP. The reason is that the deposits-in-advance constraint implies that retail deposits move one-for-one with the sum of consumption and investment, while the government spending rule implies that government spending moves one-for-one with the sum of consumption and investment.

The initial reserve positions of bank groups B1 and B2 are approximately 9.5% and 2.0% of GDP. Accordingly, most of the drop in reserves is absorbed by B1 banks, even though at the margin the effect of QT on the reserve scarcity of B2 banks is more severe. We observe this in the behavior of the wholesale deposit rate spread over ONRRP, which is around six times larger for the reserves-scarce B2 banks. Because retail loans are priced directly off wholesale deposit rates, this means that the loans of B2 banks become relatively more expensive, and therefore drop by significantly more than those of B1 banks. B2 banks, in addition to paying a significantly higher interest rate on their wholesale deposits, are also willing to pay significantly more to attract interbank loans, with their interbank loan spread increasing by a very similar magnitude to their wholesale deposit rate spread. At the left margins of Figure 3, total central bank reserves have decreased by 7% of GDP, and B2 banks have compensated for this by paying 70-75 basis points more on their wholesale deposits and interbank loans, and thereby attracting interbank loans equal to 4% of GDP. However, due to more expensive lending rates, their loans decrease by 1% of GDP, and those of their B1 competitors by another 0.4% of GDP. The resulting contraction in deposits has significant effects on economic activity, with GDP lower by around 0.4%, and investment by 1.0%, for the largest QT policies shown in Figure 3.

The effects of QT on equilibrium real interest rates are driven by two effects that are both present at all points on the curve, but whose relative strength varies along the curve. To see this, note that bond investor and wholesale bank optimality conditions for wholesale deposit rates are

$$\bar{r}_w = \frac{x}{\beta_{bi}} \left(1 + \phi_f(\bar{b}_{bi}^{rat} - \bar{b}_{bi,ss}^{rat})\right), \tag{11}$$

$$\bar{r}_w = \left(\frac{\bar{d}^{whs}}{\bar{d}^{rdb}}\right) \bar{r} + \left(\frac{\bar{d}_{b1}}{\bar{d}^{rdb}}\right) \overline{RSC}_{b1}^{m} + \left(\frac{\bar{d}_{b2}}{\bar{d}^{rdb}}\right) \overline{RSC}_{b2}^{m}, \tag{12}$$

where $(\bar{b}_{bi}^{rat} - \bar{b}_{bi,ss}^{rat})$ captures the deviations of bond investor's government bond holdings from the initial (calibrated) steady state, and where

$$\overline{RSC}_i^m = \upsilon \left(\frac{\bar{d}_i}{\bar{m}_i}\right)^{\eth} \left(\frac{\bar{n}_i}{\bar{m}_i}\right) \left(\frac{\bar{d}_i - \bar{m}_i}{\bar{m}_i}\right),$$

for $i \in (b1, b2)$, are the derivatives of reserves scarcity costs with respect to reserves. We can combine (11) and (12) to yield

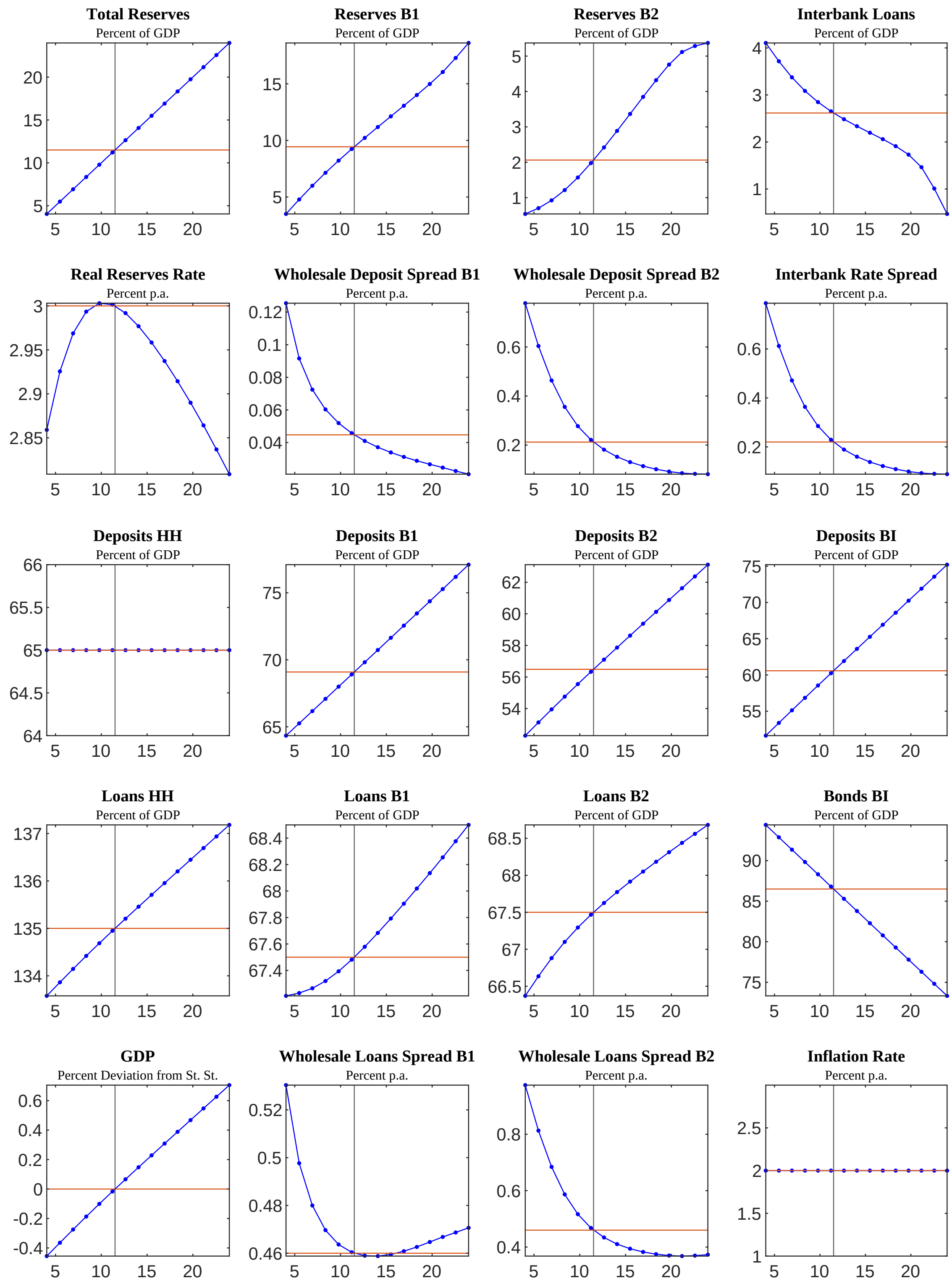
$$\bar{r} = \left(\frac{\bar{d}^{rdb}}{\bar{d}^{whs}}\right) \frac{x}{\beta_{bi}} \left(1 + \phi_f(\bar{b}_{bi}^{rat} - \bar{b}_{bi,ss}^{rat})\right) - \left(\frac{\bar{d}_{b1}}{\bar{d}^{whs}}\right) \overline{RSC}_{b1}^{m} - \left(\frac{\bar{d}_{b2}}{\bar{d}^{whs}}\right) \overline{RSC}_{b2}^{m}. \tag{13}$$

The first effect of QT on the steady state or neutral policy rate can be seen in the first term on the right hand side of (13). This is that, for a constant level of total government debt, a reduction in central bank reserves and therefore in central bank holdings of government debt leads to an increase in bond investor holdings of government debt. As the stock of government debt in private hands increases, all interest rates, including the policy rate, increase.[11] This effect is approximately linear in privately-held government debt and therefore in reserves. As shown in Figure 3, it dominates at reserves-to-GDP ratios above 10%.

The second effect of QT on the steady state policy rate can be seen in the second and third terms on the right hand side of (13). This is that, as the scarcity or convenience yield of reserves increases, banks are willing to pay a higher wholesale deposit rate relative to the rate on reserves in order to not lose reserves to other banks, and this pushes up the spread between the two rates. In other words, *ceteris paribus*, QT reduces the rate that the central bank needs to pay on reserves, because reserves have become so valuable to banks. This effect is highly nonlinear in reserves, because reserve scarcity costs increase at an increasing rate as reserves approach zero. As shown in Figure 3, this effect dominates at reserves-to-GDP ratios below 10%, and can account for liquidity discounts of 20 basis points or more over the range shown. This has important implications for monetary policy.

[11] See the discussion of portfolio costs following equation (3) and of the IMF's "Laubach rule"in Section 4.2.

Figure 3: Steady States - Monetary QE/QT



(horizontal axis = reserves in percent of GDP)
(vertical black line = level of reserves in calibrated st. st.)
(horizontal orange line = value of variable in calibrated st. st.)

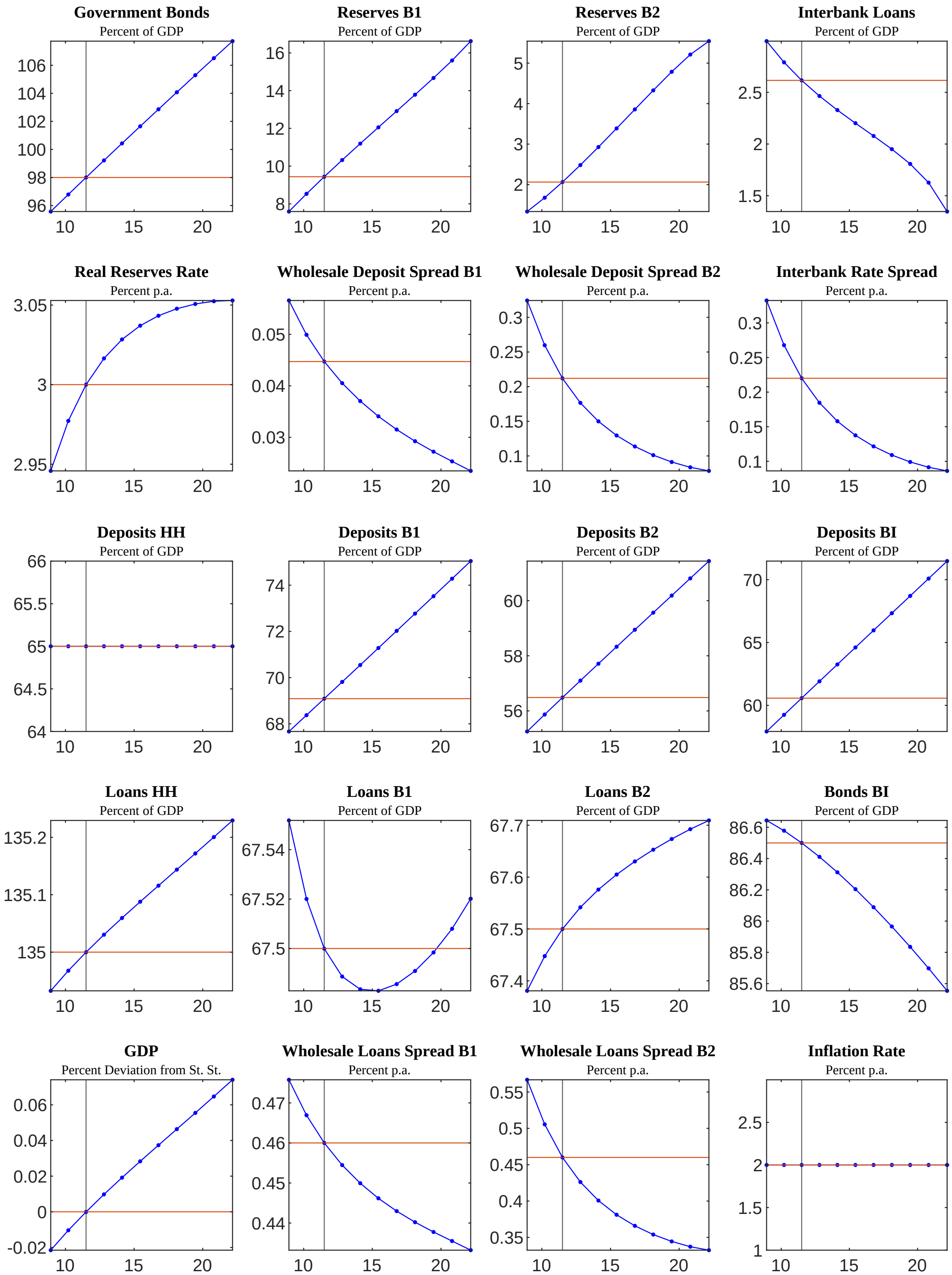
5.2. Fiscal-Monetary QE/QT

Figures 4 and 5 study the steady state effects of changes in the quantity of government bonds that are allowed to be partially or fully absorbed by changes in the quantity of reserves. While these simulations exogenously change the total government debt to GDP ratio, for ease of comparison with figure 3, the horizontal axis remains the total reserves to GDP ratio.

The motivation behind these exercises is that the response to the COVID shock across advanced economies has included very significant increases in both government debt and central bank reserves. For example, between 2020Q1 and 2020Q2 the US ratio of government debt to GDP rose by 26 percentage points and the amount of Fed reserves rose by 7 percentage points. These simultaneous expansions in bonds and reserves have proven very persistent. Hence, in this section we simulate a permanent increase in the government bonds-to-GDP ratio assuming two distinct responses from the central bank that are shown in Figures 4 and 5.

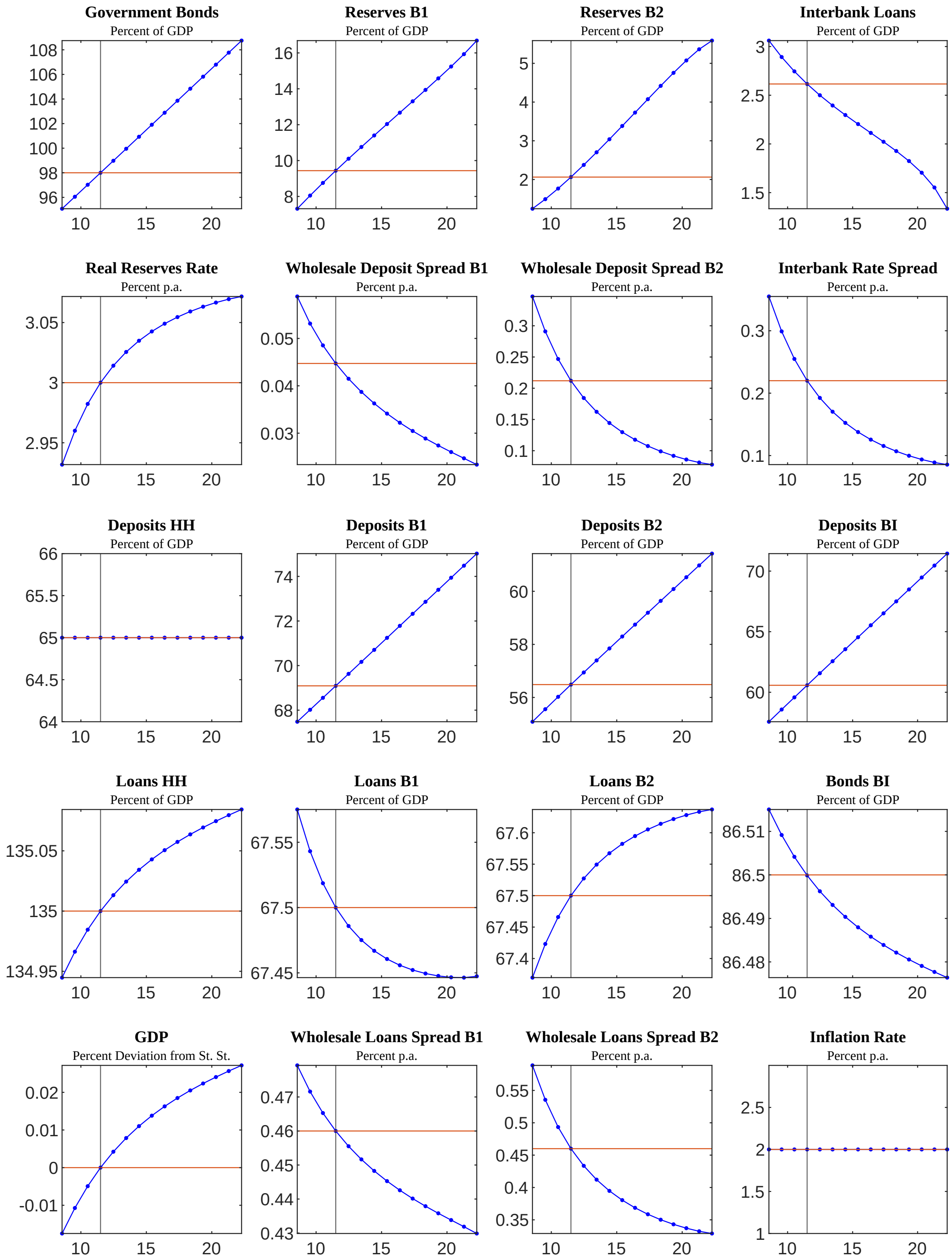
Figure 4 studies the effects of permanently changing the quantity of total government bonds while allowing the supply of central bank reserves, and thus government bonds held by the central bank, to be endogenously determined by commercial bank demand for reserves. This is akin to a "demand-driven" monetary operational framework with abundant reserves that central banks like the Bank of England and the ECB are aiming to maintain in the foreseeable future, after the current cycle of QT comes to an end (see Schnabel (2023) and Bailey (2024)).
We focus our description on the case of an increase in government bonds – the section to the right of the black vertical line. On impact the entire bond issuance is absorbed by bond investors, who immediately sell slightly more than 100% of the additional issuance to banks in exchange for wholesale deposits, so that their bond holdings drop slightly relative to GDP. Banks immediately exchange these bonds for reserves at the central bank, and the central bank accommodates their higher demand. The higher level of reserves affects the interbank market by pushing down both interbank lending and the interbank rate spread. However, the effect on other lending rates is small because the interest rate on reserves increases. The reason is that the much more abundant supply of reserves reduces the scarcity premium or liquidity discount of reserves, while the risk premium is barely affected due to the very small change in government debt held by bond investors. On the balance sheets of commercial banks, the increase in reserve holdings is matched by an increase in wholesale deposits held by bond investors. There is little change in lending because of the small effects on overall lending rates. Finally, the small drop in the opportunity cost of holding money, the spread between lending and deposit rates, causes a small increase in real GDP.

Figure 4: Steady States - Fiscal-Monetary QE/QT - Endogenous Reserves



(horizontal axis = reserves in percent of GDP)
(vertical black line = level of reserves in steady state)
(horizontal orange line = value of variable or of deviation in steady state)

Figure 5: Steady States - Fiscal-Monetary QE/QT - Exogenous Reserves



(horizontal axis = reserves in percent of GDP)
(vertical black line = level of reserves in steady state)
(horizontal orange line = value of variable or of deviation in steady state)

Figure 5 studies the effects of permanently changing the quantity of total government bonds while having the central bank absorb the entire change, $\Delta M = \Delta B^{cb} = \Delta B$. Bonds held by bond investors are constant although their ratio to GDP decreases very slightly due to a small increase in GDP. The effect on GDP in this case is even smaller because the effect on the opportunity cost of money is smaller. This is because bond investors hold on to an unchanged stock of government debt rather than being net sellers, which implies that the interest rate on reserves increases by more in the virtual absence of any Laubach effect, while the interest rate spread on deposits drops by less because reserves increase by less. But other than this small difference the evolution of balance sheets and spreads is qualitatively very similar to Figure 4.

The lesson from both experiments is that if the central bank buys a substantial portion of newly issued government debt by issuing reserves, the result is an increase in the policy rate but a decrease in spreads relative to the policy rate, with a small but beneficial net effect on opportunity costs and real activity. This is accompanied by an increase in financial stability, as the size of banks' balance sheets increases approximately by the quantity of reserves, matched by an increase in wholesale deposits held by bond investors, with very small effects on lending.

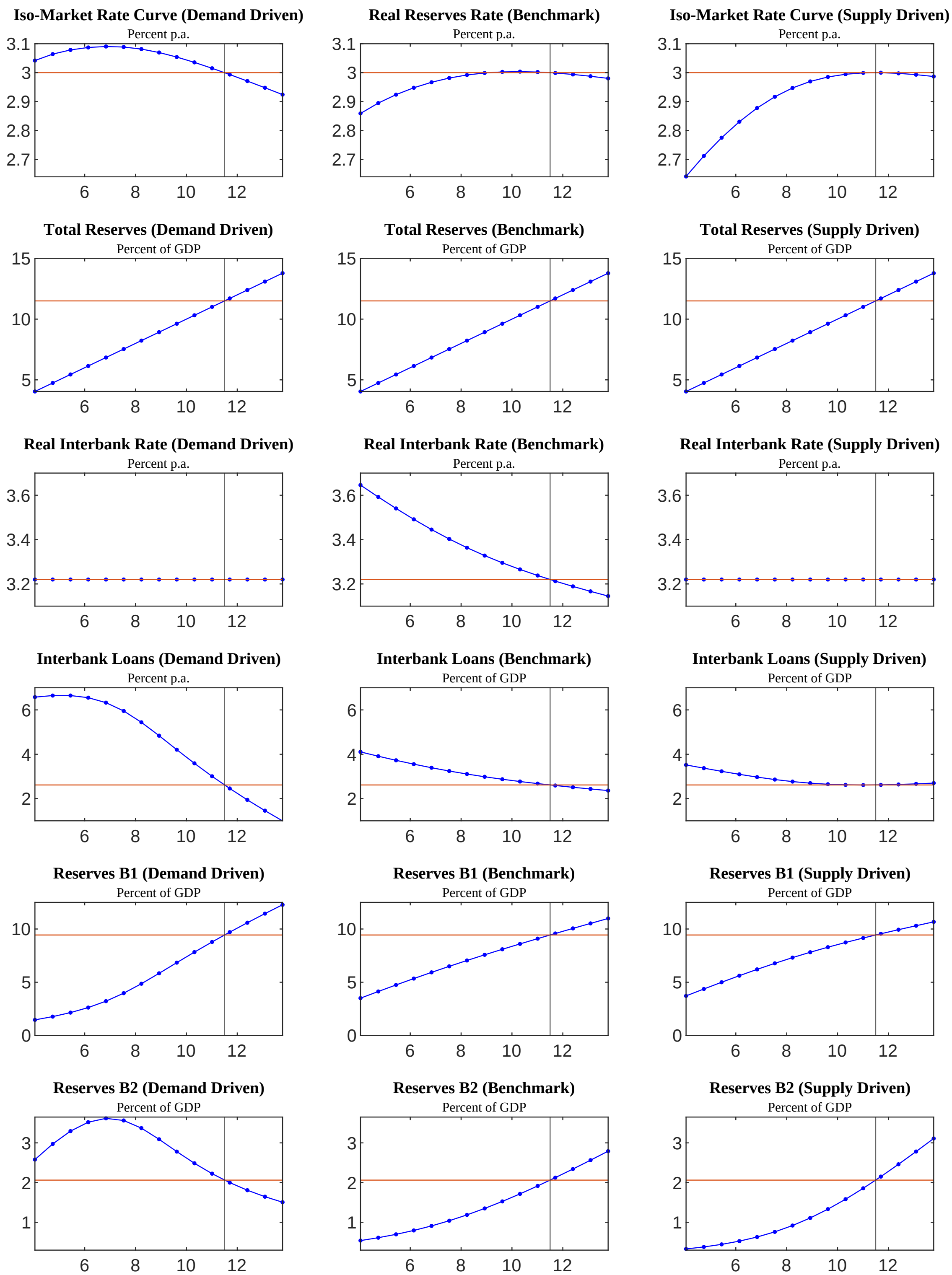
5.3. Iso-Market Rate Curve

Vissing-Jorgensen (2023) introduced the concept of the short-term iso-market rate curve, which she defines as the schedule with "all possible combinations of reserve supply and the interest rate on reserves which achieve the same [interbank] target." Our theoretical model allows us to obtain an iso-market rate curve.

Figure 6 depicts our model's short-term iso-market rate curve for the initial steady state interbank rate. We simulate two cases because in order to fix a central bank interbank rate target, we need to drop one of two possible steady state equations. The first possibility is to drop the interbank loans supply schedule of group 1 banks to obtain a "demand driven" scenario, which is illustrated in the left column of Figure 6. The second possibility is to drop the interbank loans demand schedule of group 2 banks to obtain a "supply driven" scenario, which is illustrated in the right column of Figure 6. The center column shows our benchmark QT/QE simulation where both demand and supply schedules determine the interbank rate simultaneously. All variables share a common x-axis, the reserves-to-GDP ratio, and each row has similar y-axes for ease of comparison.

Under a *demand driven* interbank market, the iso-market rate curve increases to the left of the black vertical line that marks our initial steady state, in other words under QT. At the same time, interbank loans increase substantially more than under our benchmark case, as reserve-scarce banks' demand for relatively cheap interbank funding is fully accommodated by reserve-abundant banks, who absorb more than 100% of the total decline in reserves while reserve-scarce banks increase their reserve levels.

Figure 6: Steady States - Iso-Market Rate Curves



(horizontal axis: Reserves in Percent of GDP)
(vertical black line = level of reserves in steady state)
(horizontal orange line = value of variable or of deviation in steady state)

Under a *supply driven* interbank market, the iso-market rate curve decreases to the left of our initial steady state. Because reserve-abundant banks are not compensated for additional interbank lending with a higher interest rate, the increase in interbank loans is much smaller, and the decline in reserves of reserve-scarce banks is much larger. The resulting steep increase in their interest rate liquidity discount is the main reason behind the decline in the iso-market rate curve, which at the left margin is substantially larger, by 20bps, than in the benchmark case.

These results emphasize the importance of both the distribution of reserves and the interbank market structure for the success of central bank balance-sheet normalization policies. The latter matters because under a demand driven interbank market permanent QT is reflected primarily in quantities, while under a supply driven interbank market QT requires a stronger drop in the real rate paid on reserves to obtain the same interbank rate target.

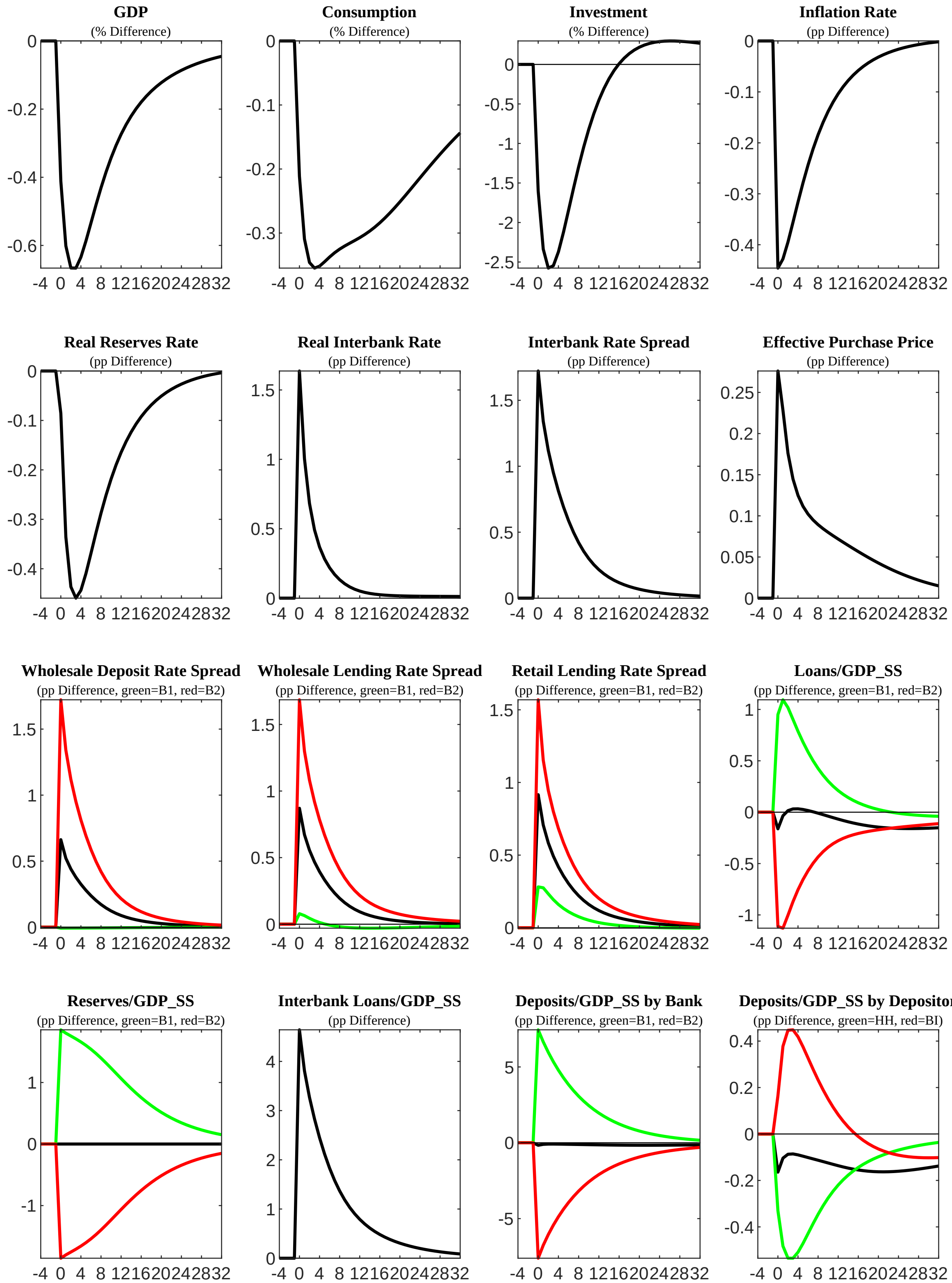
6. Economic Shocks and the Interbank Market

6.1. Deposit Withdrawal Shocks

As mentioned in the introduction, our model reflects the reality that banks never face financing risks, they only face refinancing risks. Banks always finance new loans by creating new deposits, so that there is never a risk of not being able to finance a new loan. But there is a risk of having to refinance a lost deposit, and this is the risk we study in this section. To make the magnitudes of balance sheet changes easier to interpret, we express all balance sheet variables in percent of GDP. Furthermore, to avoid confounding the separate effects of changes in balance sheets and in GDP on these ratios we use steady state GDP rather than actual GDP for scaling.

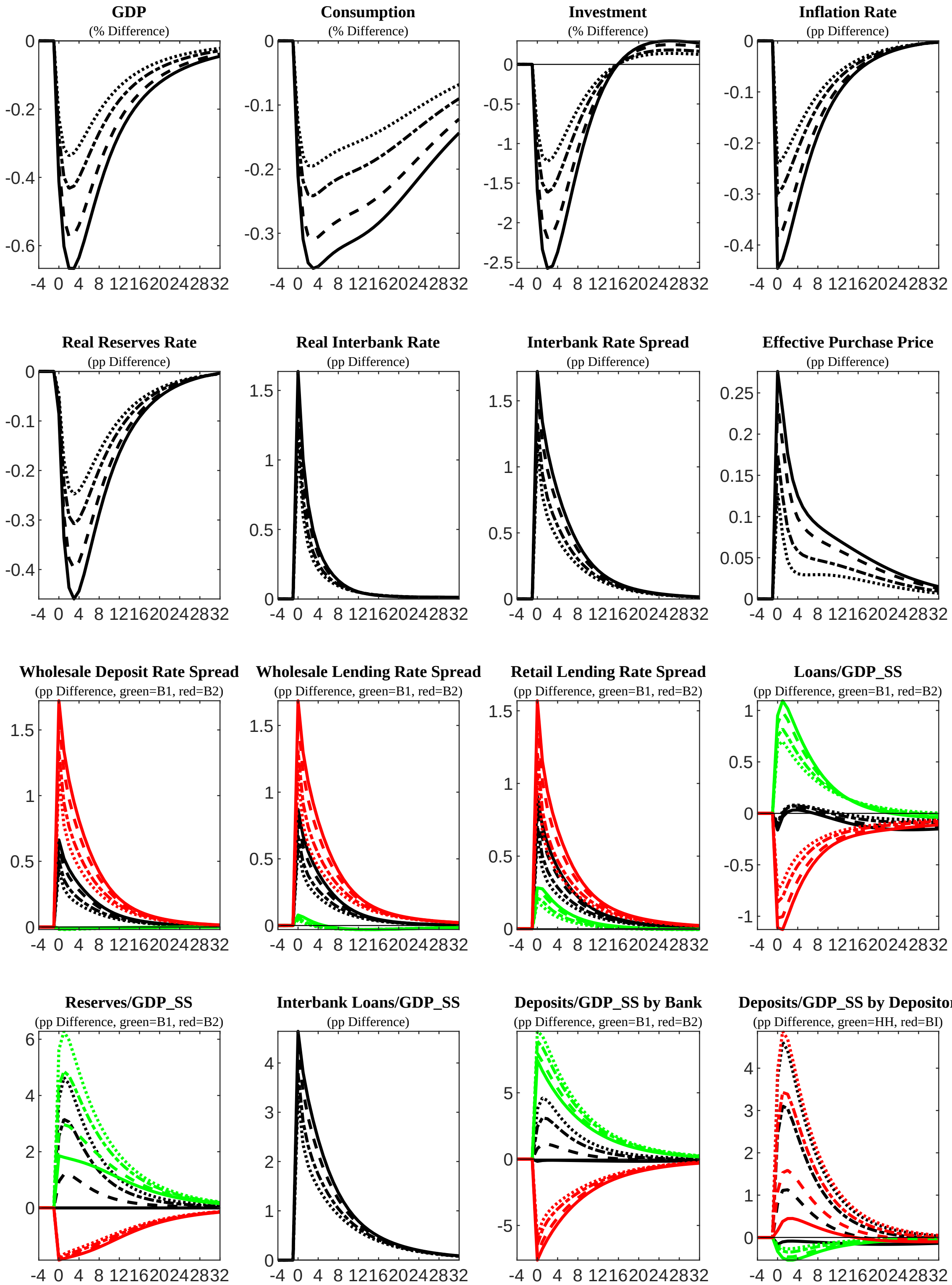
If a bank, after netting, experiences deposit outflows, this captures the notion of a modern bank run. Such runs however are not a runs on the entire banking system by retail depositors, but rather runs from one part of the banking system to another by large institutional depositors. We emphasize the banks-to-banks nature of modern bank runs because deposits are never withdrawn to "eat" them (as in Diamond-Dybvig (1983) runs), but only to deposit them in safer alternatives. The empirical evidence (see Cipriani, Eisenbach and Kovner (2024)) shows that in the 2023 US bank run episodes this alternative has not been cash but the largest US banks, who are perceived to be safer because they benefit from explicit or implicit deposit guarantees. Our model allows us to study this in the simplest possible form, by examining the effects of withdrawals from reserve-scarce bank group B2 to reserve-abundant bank group B1, with no first-round effects on the aggregate quantity of deposits. We emphasize the wholesale nature of modern bank runs because in the 2023 US bank run episodes the key actors have been large wholesale depositors withdrawing very large funds. Our model of money market funds allows us to study this through a negative shock S_t^d to the quasi-share of B2 deposits in their deposits aggregate. This captures the notion of wholesale money markets "getting nervous" about certain sectors of the banking system.

Figure 7: Deposit Withdrawal Shock



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)

Figure 8: Deposit Withdrawal Shock for Different Reserves Rules



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)
(solid line: $m_0 = 0$, dashed/dash-dotted/dotted lines: $m_0 = 10/30/50$)

In Figure 7, black lines indicate aggregate variables, including aggregates over B1 and B2 banks, green lines indicate B1 banks, and red lines indicate B2 banks. The shock is very large, it amounts to a withdrawal of deposits equal to 7.5% of steady state GDP from B2 banks to B1 banks. Ceteris paribus this exceeds the initial reserves of B2 banks, who therefore respond by offering much higher wholesale deposit spreads and interbank loan spreads, which both increase by almost 170 basis points. Wholesale deposit rates of B1 banks are almost unaffected. The result of higher interbank loan spreads is that B2 banks are able to refinance deposit losses of more than 4.5% of steady state GDP in the interbank market. The remaining shortfall of 3.5% of GDP is reflected in roughly equal reserve losses of B2 banks and reserve gains of B1 banks.

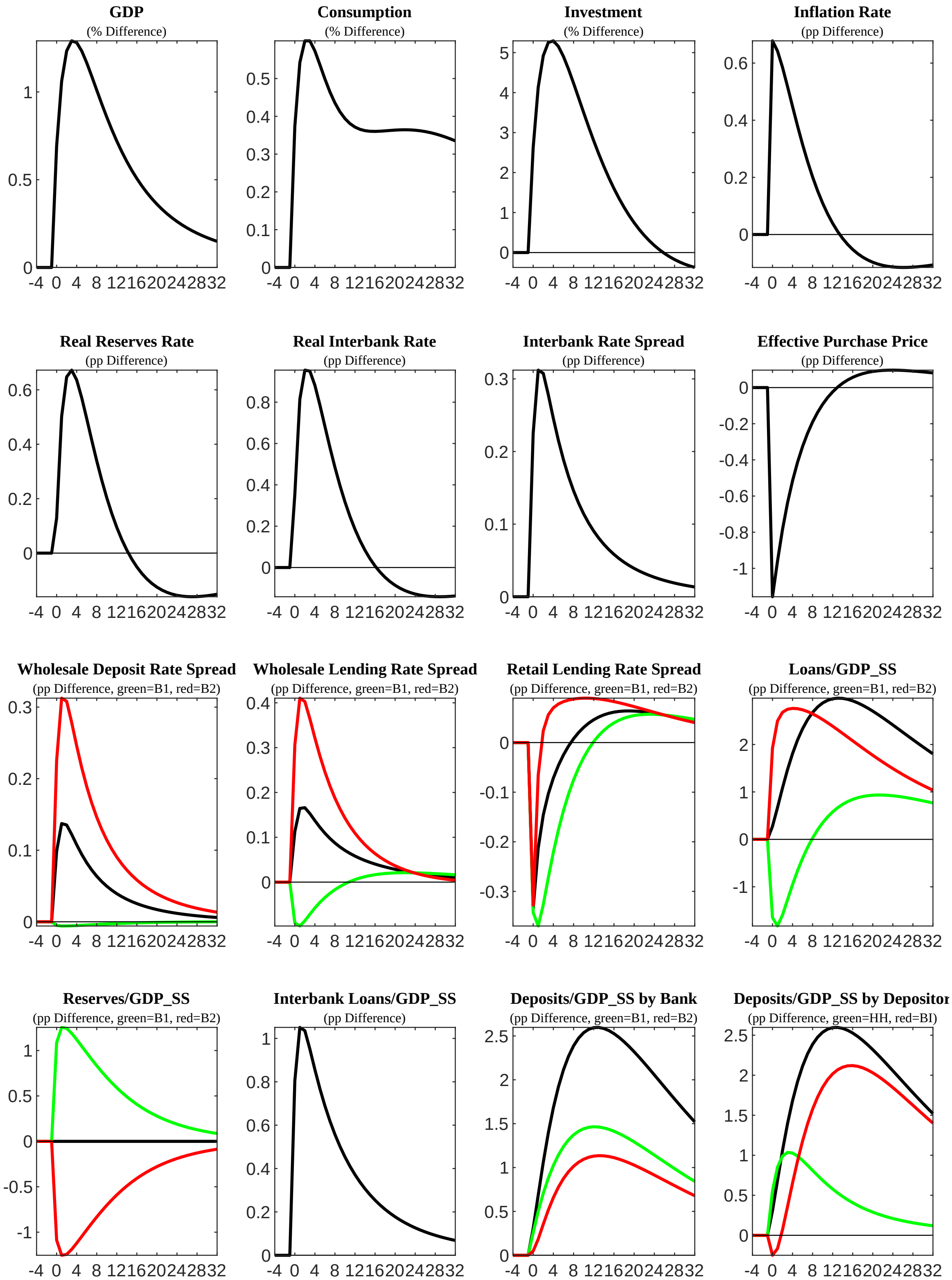
While the shock is purely financial, its effect on the wholesale deposit rate of B2 banks has large real economic effects because it increases the cost at which reserves-scarce parts of the banking sector can create money. For B2 banks their funding rate increase is passed through to wholesale and retail lending rates, so that their lending drops by more than 1% of steady state GDP. For households the resulting increase in spreads between borrowing costs and deposit rates (see the third row in the figure) and the associated increase in the effective purchase price lead to a reduction in retail deposit holdings, see the green line in the bottom right subplot. As a result, GDP drops by 0.65% and inflation by 45 basis points, with the policy rate dropping to partly offset the effects of higher lending spreads.

The maintained assumption in Figure 7 is that the overall level of reserves is kept constant, in other words that $m_o = 0$ and reserves do not respond to deviations of the interbank spread from its steady state level. Figure 8 explores alternatives whereby the central bank injects additional reserves when the interbank spread increases. For the most aggressive reserves rule, aggregate reserves increase by more than 4.5% of GDP. As a result, interbank interest rates increase by around half a percentage point less, and the quantity of interbank borrowing increases by around a percentage point of steady state GDP less. The drops in GDP and inflation are halved in size. A central bank policy that prevents shortages of reserves during banking sector distress can therefore have significant real economic benefits.

6.2. Asymmetric Lending Boom Shocks

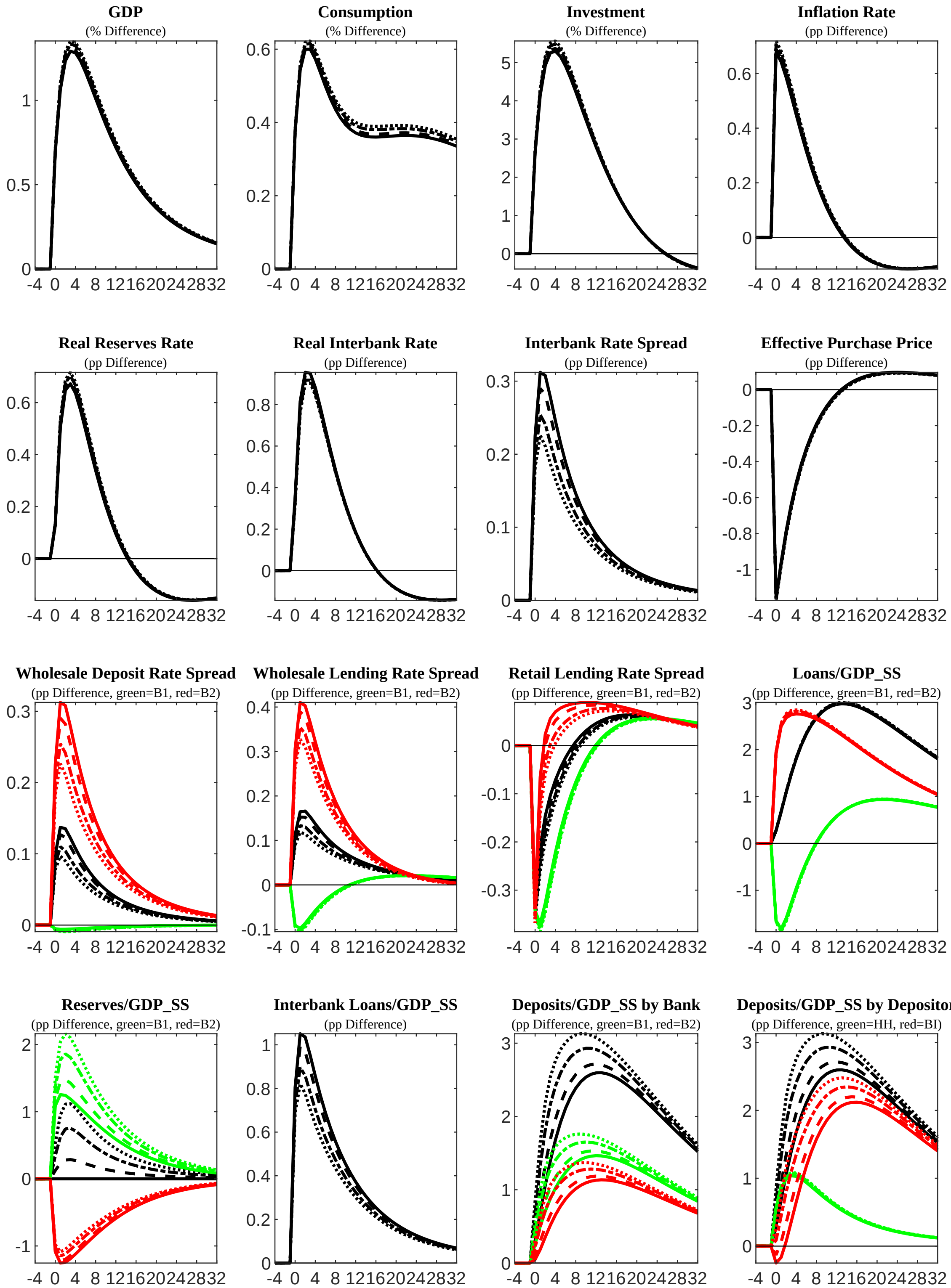
As discussed above, when banks expand and contract in lockstep, the need for deposit refinancing typically does not arise, and if it does it is due to run shocks on the liability side, not due to excessive lending. However, these assumptions are no longer satisfied when bank lending does not expand in lockstep. In Figure 9, we therefore explore a scenario where reserve-scarce B2 banks significantly increase their willingness to lend while B1 banks do not. The specific shock is a persistent increase in the credit supply parameter κ_{b2}.

Figure 9: Asymmetric Lending Boom Shock



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)

Figure 10: Asymmetric Lending Boom Shock for Different Reserves Rules



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)
(solid line: $m_0 = 0$, dashed/dash-dotted/dotted lines: $m_0 = 10/30/50$)

As a result of the shock, B2 banks increase their loans by around 2.7% of steady state GDP. However, their ability to retain deposits remains unchanged, so that their deposits only increase by around 0.4% of steady state GDP over the first year (and just over 1% of steady state GDP at the maximum after two to three years). The difference of around 2.3% of GDP on impact is partly made up by borrowing of around 1.1% of steady state GDP in the interbank market, at a spread that increases by 30 basis points. The remainder, at 1.2% of steady state GDP, represents a loss of reserves to B1 banks. The increase in their funding costs in the interbank and wholesale deposit markets partly offsets their greater willingness to lend, with their retail lending rates dropping by less than those of their competitors, B1 banks. Overall this shock is expansionary because it increases credit and money creation by the banking system, with GDP increasing by 1.25% and inflation by 70 basis points.

Figure 10 once more studies the role of countercyclical reserves rules. The effects are qualitatively similar to, but quantitatively smaller than, Figure 8. The reason is that the increase in the interbank rate spread is much smaller, and therefore triggers a more modest reserve injection.

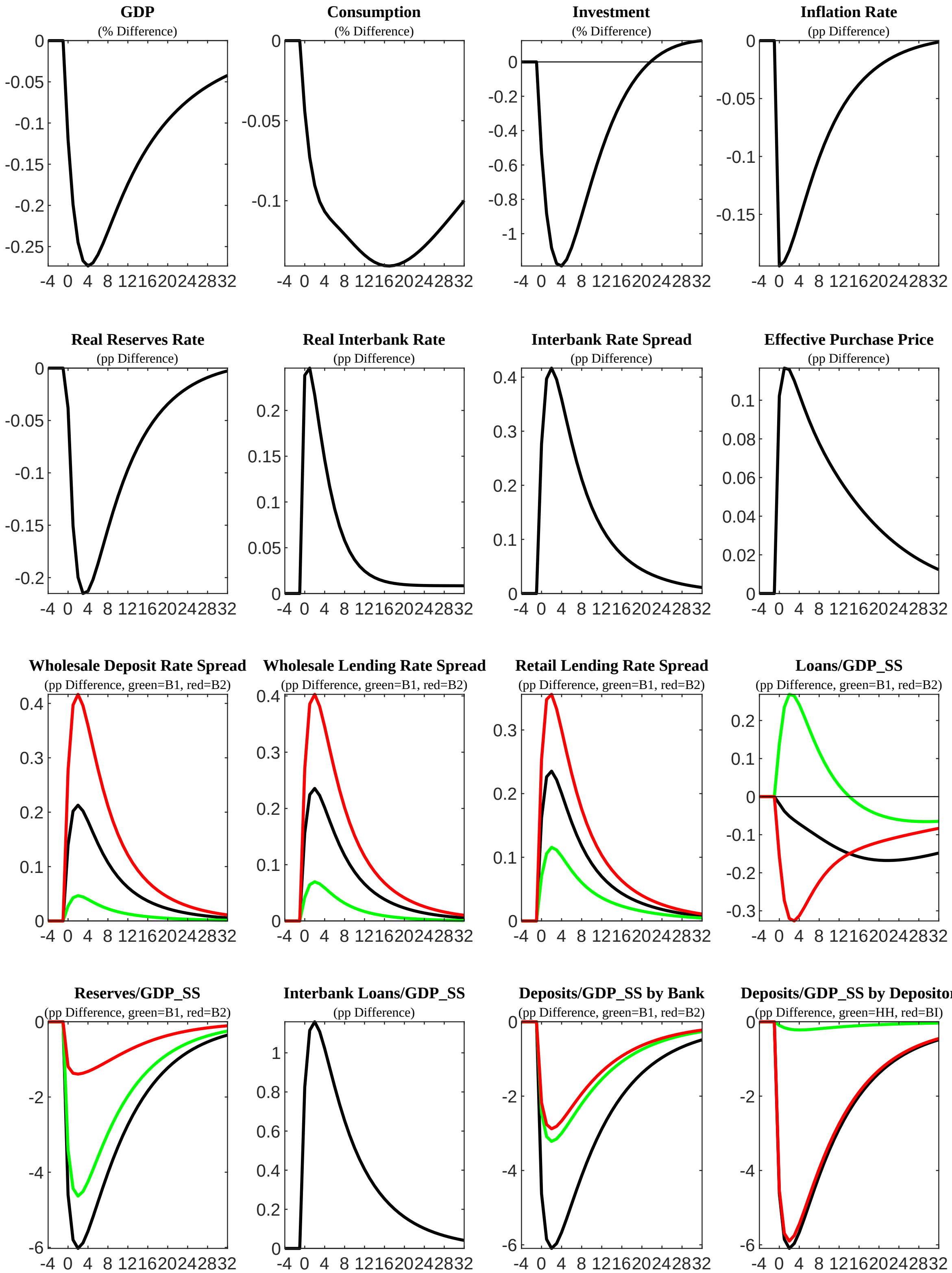
6.3. Reserves Shocks

Figure 11 studies the effects of a large, temporary and persistent reduction in the quantity of reserves, or QT, from 11.5% of GDP in steady state to around 5.5%. Because of the asymmetric deposit and reserve positions of the two banking groups, most of the reserve loss is absorbed by B1 banks. But despite this it is B2 banks that experience the strongest effects, with their wholesale deposit spread increasing by 40 basis points, compared to 5 basis points for B1 banks. This is passed on to loan pricing, with the result that B2 loans decrease, B1 loans increase, and overall loans decrease. The overall effect of the increase in funding costs is a decrease in GDP of almost 0.3% and a decrease in inflation by around 20 basis points. In other words, as we have already seen in Figures 3, 4 and 5 for permanent QT, QT affects real economic activity through the cost of credit and money creation, and affects banks that have weak deposit bases disproportionately.

6.4. Monetary Policy Shocks

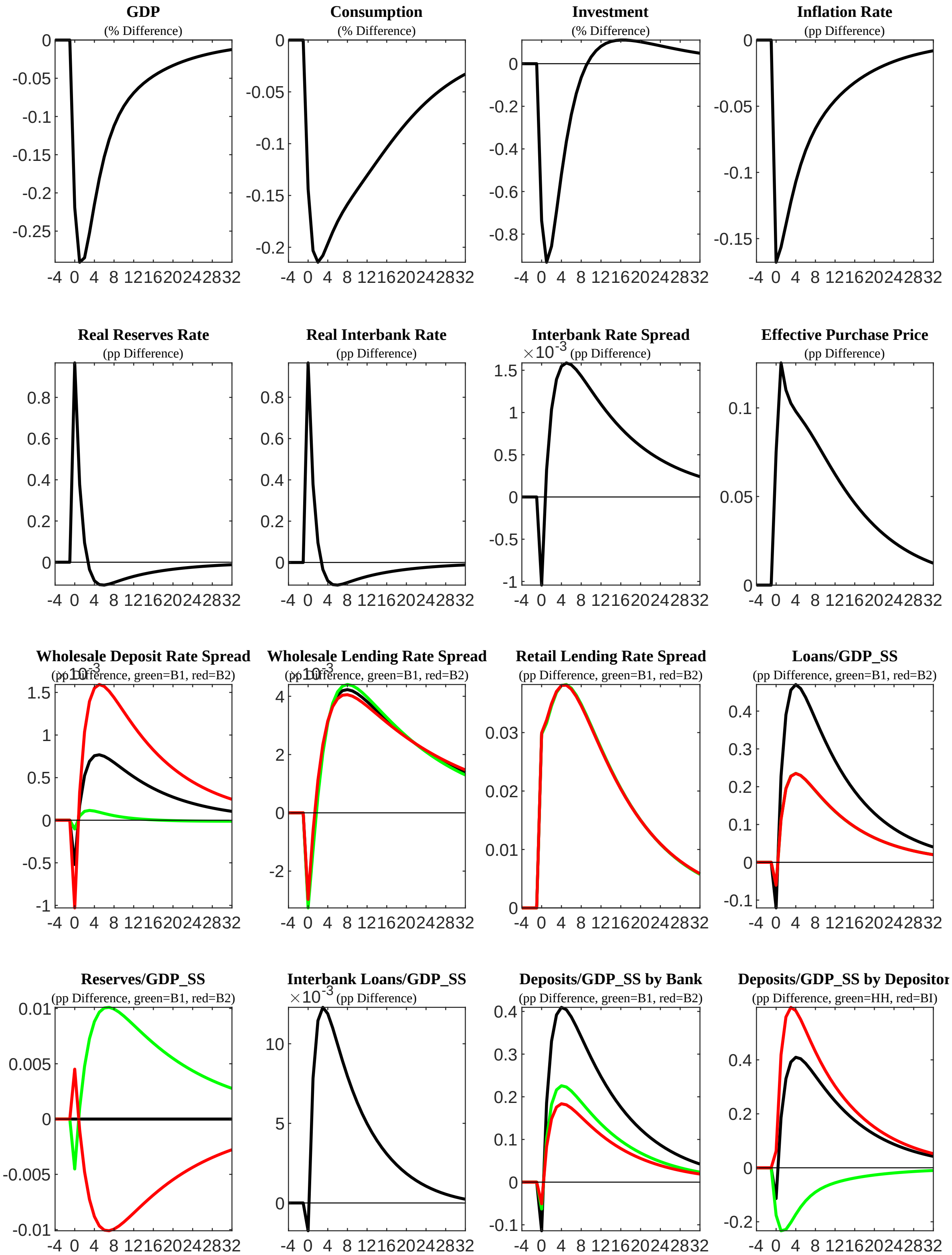
Figure 12 studies the effects of a 100 basis points shock to the interest rate reaction function. Because interest rate smoothing is modest at $i_i = 0.5$, the effects of this shock are highly temporary. The main observation is that there are almost no significant effects through the interbank market, while the effects on inflation and real variables are standard. This result carries over to all other real business cycle and aggregate financial sector shocks. The main shocks for which the interbank market plays an important role are therefore shocks to the quantity of reserves and shocks to the relative quantities of deposits and/or loans between different parts of the banking system.

Figure 11: Reserves Shock



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)

Figure 12: Monetary Policy Shock



(black line = aggregates or B1/B2 averages)
(green line = B1 banks, red line = B2 banks)

7. Welfare

We have seen that a policy of injecting additional central bank reserves during periods of stress in interbank markets is beneficial in that it helps to smooth wholesale deposit rates, and thereby lending rates, credit creation, and money creation. The effects on real activity can be substantial. Figure 13 attempts to quantify this by performing welfare evaluations of both policy rules, the Taylor for the ONRRP rate and the reserves rule for the quantity of reserves. We perform a second-order approximation of both the welfare criterion and the equilibrium equations of the model over a grid of policy rule parameterizations. The zero-welfare baseline for the grid sets $i_\pi = 1.5$ and $m_o = 0$. The upper limits of our search are $i_\pi = 3.00$ (as in Schmitt-Grohe and Uribe (2004)) and $m_o = 100$. Of course the results in Figure 13 depend on the calibrated standard errors of the model's shocks, including reserves shocks and net deposit withdrawal shocks.

Under our baseline calibration, we find that around our highest welfare point welfare is nearly flat in the two smoothing coefficients, except at very high interest rate smoothing where welfare is decreasing. The highest welfare is achieved when both smoothing coefficients are at zero and both feedback coefficients are at their upper limits, where welfare is very flat in i_π but less flat in m_o. The overall welfare gain, relative to the baseline, equals a 0.16% compensating consumption variation, roughly equally shared between the Taylor rule and the reserves rule. An active reserves policy can therefore make a substantial contribution to smoothing the business cycle and thereby improving welfare. This result is dependent on a significant role for reserves shocks and deposit withdrawal shocks in our calibration.

8. Conclusion

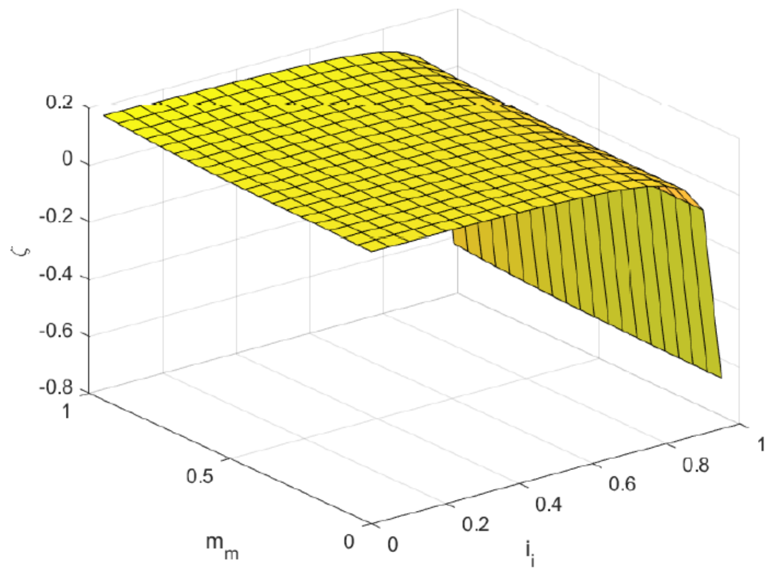
This paper aims to shed light on the macroeconomic and financial stability implications of central bank balance sheet policies. Much of the early theoretical literature on QE focused on the asset side of central bank balance sheets, most importantly on the effect of asset purchases on interest rates and term premia of different assets, while treating the liability side as simply a short-term asset held by households or investors. By contrast, our focus is on the liability side of central bank balance sheets, and the fact that the principal central bank liability is reserves, which have a very specific function in the financial system and thereby the economy. Most importantly, we focus on the effects of reserve creation (QE) or destruction (QT) on interbank rates and ultimately bank lending rates, and through these on credit creation, money creation, and economic activity.

The framework that we have developed has two other important advantages. First, it takes account of the fact that banks never face financing risks when making loans, they only face refinancing risks when losing deposits after netting, where on average such post-netting deposit losses will equal zero over the cycle. Second, the framework lends itself to ready incorporation into standard

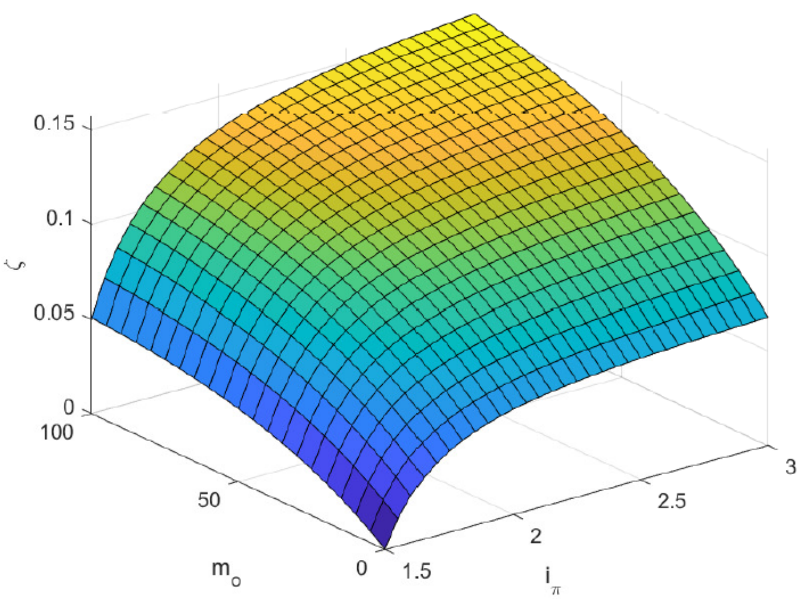
New Keynesian DSGE frameworks, with a fully developed real as well as financial sector, as all financial-to-real linkages are explicitly modeled without reliance on reduced-form model elements.

Figure 13: Policy Rules and Welfare

Smoothing Parameters



Feedback Parameters



Our results show that the effects of central bank balance sheet operations through the reserves market can be sizeable. Intuitively, a larger central bank balance sheet reduces interbank frictions, and this reduces the opportunity cost of credit and money for households and firms. This in turn boosts economic activity. Also, the incremental effects of injecting reserves are much larger at lower reserve levels. Both of these statements are supported by the data – see Figure 2.

At low reserve levels the equilibrium real interest rate (r-star) is significantly (in our example by up to around 20 basis points) reduced by a liquidity discount due to a scarcity premium for reserves, while the output effects of increasing reserve levels are very sizeable. Given these beneficial (albeit at a decreasing rate) effects of higher reserve levels, it is not surprising that a policy rule of actively injecting additional reserves into the interbank market in response to financial disturbances can make a sizeable contribution to financial and real stability. One such financial disturbance that we have identified is a shock whereby deposits are withdrawn from one part of the financial system and deposited in another part. This can lead to highly asymmetric effects on the two parts of the banking system, with the part experiencing withdrawals experiencing large increases in funding costs while the other part sees almost no change. This asymmetry can imply large effects on the real economy. Another financial disturbance is an asymmetric lending boom, whereby one part of the financial sector expands lending by far more than the other, and as a result will tend to lose some deposits and therefore reserves even after netting.

For most real business cycle and aggregate financial shocks, the reserves and interbank markets and thus the liability sides of central banks' balance sheets play only a negligible role, so that the conclusions and policy recommendations of existing models remain nearly unchanged. These markets do matter when shocks are to the quantity of reserves themselves, or when shocks are asymmetric across different parts of the financial system. Because such asymmetric shocks are clearly now a concern of policymakers, and because our model can represent them in a very parsimonious way, this should make this framework interesting for policymakers.

Bayesian estimation of this model is part of our future research agenda. But there is one other important topic for future research. In our model, a QT operation takes the form of the central bank buying government bonds from bond investors and getting paid in wholesale deposits, which are then settled by banks in the form of reserves. The central bank never becomes a lender to the real economy. This reserves-against-government-bonds modus operandi of QT (and QE) corresponds closely to the institutional reality in the US and the UK.[12] However, in some jurisdictions such as the eurozone the central bank follows a reserves-against-private-securities model. This would require modifications to our model.

[12] In the UK there are also some purchases and sales of high-quality corporate securities, but their size is very small compared to purchases and sales of government securities.

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