Bank Regulation and post-2008 US Monetary Policy*

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Abstract

Since U.S. bank capital holdings began rising almost concurrently with the monetary policy change after 2008, we examine the role of capital requirements for monetary policy regimes. While standard models predict that equilibrium determination and responses to aggregate shocks are fundamentally affected at the zero lower bound (ZLB), we show that these effects are absent when bank capital requirements are binding. Estimating a model version with occasionally binding capital requirements, we find that they have been permanently binding after 2008. We further show that capital requirements neither induce monetary non-neutrality nor amplify responses to macroeconomic shocks above the ZLB.

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1. Introduction

In many industrialized countries, the implementation of monetary policy has undergone a structural change. Starting with the global financial crisis (GFC), central banks have reduced policy rates to the zero lower bound (ZLB) and raised money supply via large-scale asset purchase programs (LSAP). According to standard New Keynesian theory, the impact of monetary policy on macroeconomic dynamics is considerably affected when policy rates are at the ZLB, and responses to aggregate shocks are even found to be opposed compared to the off-ZLB case (see Eggertsson, 2011, 2012). The combination of ZLB and LSAP has further led to a change from a monetary policy regime of scarce bank reserves to a regime where reserves are abundant. The US Federal Reserve continued this regime under interest rates above the ZLB via interest payment on reserves (see Figure 1), ensuring that reserve holdings are not costly, such that banks have been willing to accommodate a large central bank balance sheet.

While this monetary policy regime change is well-documented and has been examined in a variety of studies (see e.g. Bianchi and Melosi, 2017; Arce et al., 2020; Sims and Wu, 2021), this paper focuses on a different policy change in the US that occurred almost simultaneously: The gradual implementation of regulatory standards according to Basel II and III after the GFC has led to an increase in total capital holdings of banks (see Walter, 2019). Figure 1 shows that the Tier 1 equity-to-asset ratio steadily increased since the onset of the GFC until the start of the COVID-19 pandemic, where capital requirements were temporarily relaxed. These observations show that US banks have experienced a transition from a regime with scarce reserves to a regime with satiated money demand and tighter capital requirements.

Motivated by these observations, we develop a model that accounts for monetary policy implementation before and after 2008 to examine the role of binding capital requirements under satiated money demand. The paper provides three main novel contributions. *Firstly*, we show that the quantity restriction on financial intermediation induced by binding capital requirements has a fundamental impact on equilibrium determination. Specifically, we show that restrictions on the central bank's interest rate setting that is consistent with locally determined equilibria are much less severe than predicted by New Keynesian models that abstract from money or banking. *Secondly*, we estimate a model version with occasionally binding capital requirements and provide evidence that capital requirements have been binding since the GFC. *Thirdly*, we show that responses to macroeconomic shocks are neither qualitatively affected by policy rates at the ZLB nor amplified above the ZLB when capital requirements bind. Additionally, we show that capital requirements can - in contrast to reserve requirements - not establish monetary non-neutrality, implying that the post-2008 increase in reserves supply did not led to an upward pressure on goods prices.

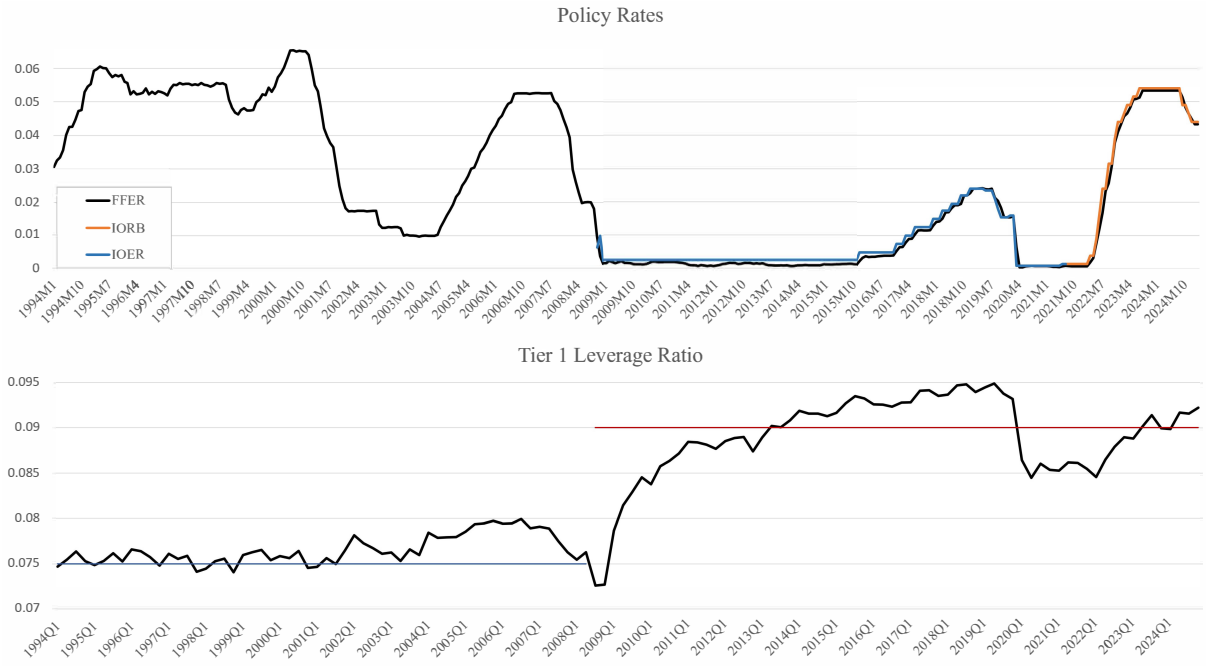

Figure 1: The upper panel depicts the Federal Funds Effective Rate (FFER) (black line) alongside the Interest on Reserve Balances (IORB) (orange line) and the Interest on Excess Reserves (IOER) (blue line). The IOER was discontinued in 2021M7 and replaced by the IORB. The lower panel represents the Tier 1 leverage ratio, defined as Tier 1 capital over total assets. (*Source*: The FRED database.)

Regarding the first main contribution of this paper, we show that a binding capital requirement can fundamentally affect equilibrium properties, in particular when the monetary policy rate is at the ZLB. The reason is that a binding capital requirement imposes a limit on the creation of deposits, similar to a reserve requirement, and relates them to bank assets. Together with an non-explosive supply of nominal public sector liabilities, this restriction acts as an equilibrium selection device, which relates to the case where the central bank controls money supply under a non-satiated money demand (see Chowdhury and Schabert, 2008, or Diba and Loisel, 2021). This property supports local equilibrium determination regardless of whether the monetary policy rates, i.e., the Federal funds rate and IOR, are pegged (e.g., at the ZLB) or follow a state-contingent feedback rule (e.g., a Taylor rule), which we prove analytically for a simplified version of the model. In contrast to a reserve requirement, a binding capital requirement does not induce monetary non-neutrality. The reason is that we account for money supply operations to be conducted as asset swaps, such that changes in bank reserves holding are accompanied by an equally sized inverse change in other bank assets (i.e. treasury bills). As a consequence, the model's predictions are consistent with missing inflation hikes after shifts in reserves supply since the GFC.

As the second main contribution, we provide evidence from macroeconomic data that capital requirements have been binding since the GFC. For this, we allow for the possibility that capital requirements bind occasionally by specifying a regime-switching version of the model, a strategy that relates to Bianchi and Melosi (2017) or Benigno et al. (2025). To account for endogenous

regime switches, we apply endogenous transition probabilities between states where capital requirements are either slack or binding. A Bayesian estimation of the regime-switching model reveals that capital requirements have been permanently binding after 2008. In fact, we find that capital requirements were also binding during the recent pandemic when they were temporarily relaxed. We further estimate two alternative versions of the model with a permanently binding and a permanently slack capital requirement. A formal comparison of all three versions indicates that the model fits the data best when the capital requirement binds permanently. According to our analysis, the incidence of permanently binding capital requirements rather relies on relatively low real interest rates that tend to raise the costs of equity (and thereby the multiplier on the capital requirement) than on the imposition of more severe capital requirements.

As the third main contribution, we show that a binding capital requirement can substantially affect the transmission of macroeconomic shocks under the ZLB regime. We show analytically that negative productivity and positive cost push shocks at the ZLB, which are known to lead to a real expansion in a standard New Keynesian model (see Eggertsson, 2012), induce (conventional) adverse effects on real activity when the capital requirement binds. In fact, the growth rate of agents' shadow value of wealth is not exclusively related to the real interest rate but also to multipliers of constraints on private sector liabilities. As a consequence, a sign reversal of real interest rate responses at the ZLB does not immediately imply a change in consumption/saving responses under binding capital requirements. A quantitative analysis confirms that productivity and cost push shocks lead to output and inflation effects at and above the ZLB that differ quantitatively, but not qualitatively, when capital requirements bind. Relatedly, we find that the fiscal multiplier, which takes extreme values at the ZLB in standard New Keynesian model (see Christiano et al., 2011), is only slightly altered at the ZLB under binding capital requirements. For monetary policy rates above the ZLB, we further find that capital requirements do not per-se lead to a systematic amplification of macroeconomic shocks.

The remainder is structured as follows. Section 2 develops a monetary model with banking. Section 3 provides analytical results on equilibrium determinacy and responses to macroeconomic shocks for a simplified model version. Section 4 presents the results of the model estimation, providing evidence for binding capital requirements since the GFC, and provides impulse responses to macroeconomic shocks for the estimated model. Section 5 concludes.

Related Literature Our paper relates to three strands of the literature: The analysis of equilibrium properties under post-2008 monetary policy regimes is most closely related to Ennis (2018) and Diba and Loisel (2021). Ennis (2018) constructs a flexible price model where banks are constrained by reserve and capital requirements, and the central bank controls IOR and money supply. Like in our paper, the reserve requirement is slack under sufficiently high IOR,

implying that the price level is decoupled from the money supply. He shows that a link between money supply and the price level can be restored when money supply is sufficiently large, such that a bank capital requirement binds. Such a link between money and prices is absent under a binding capital requirement in our paper, where the supply of reserves (via open market operations) is specified as an asset swap, such that the impact of a change in money supply on bank assets is off-set by an equally sized inverse change in other bank assets (typically, t-bills). Our results on equilibrium determinacy at the ZLB are directly related to the findings in Diba and Loisel (2021). They apply a New Keynesian model with a standard money demand, which is not fully satiated, and the central bank controls IOR and money supply, like Ennis (2018). They show that pegging IOR at the ZLB does not lead to indeterminacy and that responses to macroeconomic shocks do not lead to "limit puzzles", which arise in a standard New Keynesian model. While our model shares main properties, our results are derived under a fully satiated money demand due to the equality of IOR and the FFR. Based on the monetary neutrality under binding capital requirements in our model, it does not predict a surge in inflation after an increase in reserves supply, e.g. under QE programs.

Several studies include binding capital requirements in macroeconomic models for various purposes: Arce et al. (2020) compare the conduct of monetary policy under a corridor and a floor system using a macroeconomic model with banking and a non-Walrasian interbank market. Lenel et al. (2019) examine the disconnect between the monetary policy rate and other interest rates in a macroeconomic model where banks face costs of leveraging. Bianchi and Bigio (2022) develop a model with liquidity management of heterogeneous banks, which they apply to describe the pass-through of the monetary policy rate to lending rates and the collapse of bank lending during the GFC. Piazzesi and Schneider (2020) develop a model where central bank digital currency (CBDC) competes with bank deposits and credit lines, and examine welfare effects of CBDC introduction. In a real business cycle model, Malherbe (2020) shows that the optimal capital requirement is countercyclical, being tighter during economic booms than in recessions. Mendicino et al. (2020) and Begenau (2020) show that tighter capital requirements can enhance financial stability and welfare, though at the cost of potential credit reallocation.

None of the above mentioned studies provides direct evidence for binding capital requirements. Our empirical assessment of the relevance of capital requirements relates to studies that apply regime-switching methods for occasionally binding constraints: Guerrieri and Iacoviello (2017) estimate a model with an occasionally binding collateral constraint, solved using a piecewise linear solution method, for the U.S. economy. Benigno et al. (2025) estimate a regime-switching model for Mexico over the period since 1981 and find that it successfully replicates key business cycle dynamics and sudden stop episodes. Bianchi (2013) estimates a New Keynesian model with post-war US data, providing evidence for regime switches between

hawkish and dovish monetary policy stances as well as for the central role of belief formation on future policy regimes. Bianchi and Melosi (2017) provide evidence on a US monetary and fiscal policy regime-switch at the ZLB using a New Keynesian model, which accounts for the lack of deflation in the US. Bjørnland et al. (2018) show that structural macroeconomic shocks and a hawkish monetary policy regime played an important role in mitigating macroeconomic fluctuations during the Great Moderation. Chang et al. (2021) show how underlying structural shocks influence the degree of monetary policy hawkishness, allowing the transition probabilities to depend on macroeconomic conditions.

2. The Model

In this Section, we develop a macroeconomic model with sticky prices, a banking sector as well as a specification of central bank operations and instruments that allows accounting for different monetary policy regimes. Banks intermediate funds between households and firms while being constrained by reserve and capital requirements. The non-financial sectors consist of intermediate goods firms, capital producers, and retailers. The central bank can control the main policy rate (Federal Funds rate), IOR, and the supply of reserves. The government receives central bank transfers, issues bonds, and has access to lump-sum taxes. We introduce several aggregate shocks to facilitate estimating the model (see Section 4).

2.1. Households

There is a continuum of infinitely lived households of mass one. The representative household chooses working hours n_t and real consumption c_t. Let $\mathcal{C}_t = c_t - hc_{t-1}$ be consumption adjusted by a degree of internal habits h. Household instantaneous utility increases with $\mathcal{C}_t$ and decreases n_t. Their lifetime preferences are specified as follows,

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\psi_t^P \frac{(\mathcal{C}_t)^{1-\sigma} - 1}{1-\sigma} - \chi \psi_t^N \frac{n_t^{1+\sigma^n}}{1+\sigma^n} \right], \tag{1}$$

where $\chi > 0, \sigma > 0$, $\sigma^n \geq 0$, ψ_t^P denotes a preference shock, and ψ_t^N denotes a labor supply shock. Households have access to bank deposits, which serve as a means of payment. We account for the fact that households typically hold more deposits than necessary for realized consumption expenditures, which can be motivated by uncertainty with regard to liquidity needs. Specifically, we assume that households are restricted by the following liquidity constraint,

$$P_t c_t \leq \mu D_t, \tag{2}$$

where $\mu \in [0, 1]$ denotes an exogenously determined fraction of deposits used for transaction purposes. Let $w_t = W_t/P_t$ denote the real wage rate, τ_t lump-sum taxes, and div_t dividend

payments, which is the sum of dividends from bankers div_t^B, intermediate goods firms div_t^F, capital producers div_t^{CP}, and retailers div_t^R. The household budget constraint is given by

$$P_t c_t + D_t + P_t \tau_t = W_t n_t + R_{t-1}^D D_{t-1} + P_t div_t. \tag{3}$$

Households maximize (1) subject to the budget constraint (3) and the liquidity constraint (2), leading to the first-order conditions for consumption, deposit, and working hours

$$\begin{aligned} \psi_t^P (\mathcal{C}_t)^{-\sigma} - \beta h \mathbb{E}_t \psi_{t+1}^P (\mathcal{C}_{t+1})^{-\sigma} &= \lambda_t^H + \vartheta_t^H, & (4) \\ \mu \frac{\vartheta_t^H}{\lambda_t^H} + \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_t^D &= 1, & (5) \\ \lambda_t^H w_t &= \chi \psi_t^N n_t^{\sigma^n}, & (6) \end{aligned}$$

where λ_t^H denotes the multiplier on (3), $\vartheta_t^H \geq 0$ the multiplier on (2), and $\Lambda_{t,t+1} = \beta \lambda_{t+1}^H / \lambda_t^H$. Further, the following complementary slackness condition holds

$$\vartheta_t^B \left[\mu D_t - P_t c_t \right] \geq 0. \tag{7}$$

It should be noted that the model properties would be unchanged if we assume that households were able to trade IOUs among each other at an interest rate that is – in contrast to a textbook New Keynesian model – not directly linked to the monetary policy rates.

2.2. Banks

There is a unit-mass continuum of competitive banks indexed by i. They receive deposits $D_{i,t}$ from households, hold risky assets $L_{i,t}$, and short-term government bonds $B_{i,t}$. They further hold central bank money in the form of reserves $M_{i,t}$ because of their unique ability to settle deposit transactions. Banks are assumed to maximize the present value of dividends $div_{i,t}^B$,

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{0,t} div_t^B, \tag{8}$$

where $\Lambda_{0,t} = \beta^t \lambda_t^H / \lambda_0^H$. We assume that the (primary) bond market opens in the early stage of the period, where new bonds $\tilde{B}_{i,t}$ are purchased. Then, banks enter the asset market where they receive/pay returns on maturing assets/liabilities, i.e. they pay $R_{t-1}^D D_{i,t-1}$ for deposits and earn $R_t^L L_{i,t-1}$ from risky assets. Reserves can be acquired either from the central bank via open market operations or from borrowing $F_{i,t}$ intratemporally in an interbank market. For simplicity, we specify the latter as a frictionless Walrasian market. The central bank supplies money through outright purchases or repurchase agreements, amounting to reserves $I_{i,t}^B$ against eligible assets, i.e., government bonds. The relative price of central bank-supplied money in

open market operations is the repo rate R_t^M,

$$I_{i,t}^B = \Delta B_{i,t}^C / R_t^M, \tag{9}$$

where $\Delta B_{i,t}^C$ denotes securities transferred to the central bank. The asset exchange specification (9) applies not only to regular open market operations, but can also be interpreted as money supply via an asset purchase programme in terms of treasuries at the purchase price $1/R_t^M$. Banks' demand for reserves arises from the need to settle deposit transactions, which are not explicitly modelled. For this, banks hold reserves as a minimum fraction $\varrho > 0$ of deposits, leading to the following liquidity constraint

$$M_{i,t-1} + I_{i,t}^B + F_{i,t} \geq \varrho D_{i,t}. \tag{10}$$

Before the end of the period, banks receive IOR, i.e., interest payments R_t^R on their reserves holdings $M_{i,t-1}+I_{i,t}^B+F_{i,t}$. Then, they settle repurchase agreements and interbank transactions, pay dividends to the household, and choose end-of-period treasury balances $B_{i,t}$ and reserve balances $M_{i,t}$.[1] Precisely, bank i transfers $R_t^M M_{i,t}^R$ to the central bank for purchasing back treasuries $B_{i,t}^R$ and repays $R_t^F F_{i,t}$ to its interbank counterparties, where R_t^F denotes the Federal Funds rate.

We assume that banks face a regulatory capital requirement. This type of regulation can in principle be justified by an uninternalized possibility of bank runs in the form of roll-over crises triggered by risky assets ($L_{i,t}$) and low fire-sale prices, as for example in Gertler and Kiyotaki (2015). The capital requirement is specified as a leverage restriction, which mandates minimum capital holdings $E_{i,t}$ proportional to the end-of-period asset balance, $E_{i,t} \geq \bar{\kappa}_t(L_{i,t}+B_{i,t}+M_{i,t})$, where $\bar{\kappa}_t > 0$ denotes the policy-imposed minimum capital requirement. Further, using a balance sheet identity in terms of the market value of the end-of-period stock of assets/liabilities: $L_{i,t} + B_{i,t} + M_{i,t} = D_{i,t} + E_{i,t}$, the capital requirement can be expressed in terms of a leverage ratio requirement, which relates equity to deposit $E_{i,t} \geq \phi_t D_{i,t}$ or deposits to total assets

$$(1+\phi_t)D_{i,t} \leq L_{i,t} + B_{i,t} + M_{i,t}, \text{ where } \phi_t = \frac{\bar{\kappa}_t}{1-\bar{\kappa}_t}. \tag{11}$$

Notably, an alternative specification where capital requirements are conditioned on risk-weighted assets, for example, on risky assets $L_{i,t}$ with a weight of 100%, $E_{i,t} \geq \widetilde{\kappa}_t L_{i,t}$ with $\widetilde{\kappa}_t > 0$, would imply a similar relation between deposits and bank assets, $D_{i,t} \leq (1-\widetilde{\kappa}_t)L_{i,t} + B_{i,t} + M_{i,t}$. Hence, bank holdings of public sector liabilities $B_{i,t} + M_{i,t}$, which will be crucial for the impact of the capital requirement (see below), enter both versions for the capital requirement in the same way. The reserve requirement (10) and the capital requirement (11) impose two distinct

[1] Hence, reserves can be used for trades in treasury such that end-of-period reserves holdings can be adjusted even after open market operations and interbank transactions are settled.

limits on holdings of deposits. To give a preview, we will show that the former has been slack and the latter has been binding since the GFC. The bank i's flow budget constraint is given by

$$\begin{aligned} P_t div_{i,t}^B = D_{i,t} - R_{t-1}^D D_{i,t-1} - M_{i,t} + R_t^R M_{i,t-1} - (R_t^F - R_t^R) F_{i,t} \\ -B_{i,t} + R_{t-1} B_{i,t-1} - \left(R_t^M - R_t^R\right) I_{i,t}^B - L_{i,t} + (R_t^L - \kappa_L) L_{i,t-1}, \end{aligned} \tag{12}$$

where $\kappa_L > 0$ denotes constant marginal costs of managing loans. The term $(R_t^M - R_t^R) I_{i,t}^B$ measures the costs of reserves acquired in open market operations and $(R_t^F - R_t^R) F_{i,t}$ the costs of interbank borrowing. Maximizing (8) subject to the reserve requirement (10), the capital requirement (11), as well as $M_{i,t} \geq 0$ and $B_{i,t} \geq 0$, leads to the following first-order conditions for money injections, interbank borrowing/lending, bonds, reserves, lending, and deposits

$$\vartheta_t^B = R_t^M - R_t^R, \tag{13}$$

$$\vartheta_t^B = R_t^F - R_t^R, \tag{14}$$

$$\varkappa_t = 1 - \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_t, \tag{15}$$

$$1 = \varkappa_t + \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} \left(R_{t+1}^R + \vartheta_{t+1}^B\right), \tag{16}$$

$$1 = \varkappa_t + \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} \left(R_t^L - \kappa_L\right), \tag{17}$$

$$1 = (1+\phi)\varkappa_t + \rho \vartheta_t^B + \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_t^D, \tag{18}$$

where $\pi_t = P_t / P_{t-1}$ denotes the inflation rate, and to the complementary slackness conditions

$$\vartheta_t^B \left[M_{i,t-1} + I_{i,t}^B + F_{i,t} - \rho D_{i,t}\right] = 0, \tag{19}$$

$$\varkappa_t \left[L_{i,t} + B_{i,t} + M_{i,t} - (1+\phi_t) D_{i,t}\right] = 0, \tag{20}$$

where $\vartheta_t^B \geq 0$ denotes the multiplier on the reserve requirement (10) and $\varkappa_t \geq 0$ the multiplier on the capital requirement (11). Since reserves acquired through open market operations and interbank loans equally serve liquidity purposes (see 10), the Federal Funds rate is identical to the repo rate $R_t^F = R_t^M$ (see 13 and 14). The multiplier ϑ_t^B on the reserve requirement (10) measures banks' costs of reserves. When these costs of acquiring additional reserves are positive, $R_t^M - R_t^R > 0$, banks will not hold reserves in excess of what is required, i.e., the reserve requirement (10) binds. When IOR fully compensates for the costs of reserve acquisition in open market operations and in the interbank market, $R_t^R = R_t^M = R_t^F$, acquiring central bank money incurs no costs. Then, the multiplier ϑ_t^B equals zero, implying that the reserve requirement (10) is slack and that banks are willing to hold excess reserves. As indicated by condition (15), the multiplier on the leverage constraint $\varkappa_t$ tends to be positive under relatively low levels of real interest rates. Precisely, the multiplier on the capital requirement $\varkappa_t$ is positive if the nominal bond rate R_t is lower than the inverse of the private agents' stochastic discount

factor in nominal terms ($\Lambda_{t,t+1}\pi_{t+1}^{-1}$). Then, the build-up of equity gets costly, and banks hold equity at the minimum level imposed by the capital requirement (11). Combining (13) with (16) yields

$$\varkappa_t = 1 - \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_{t+1}^M, \tag{21}$$

indicating that the bond rate equals the expected policy rate up to first order $R_t \approx \mathbb{E}_t R_{t+1}^M$.

2.3. Intermediate goods firms, capital producers, and retailers

Homogeneous intermediate goods firms operate in a competitive market to produce intermediate goods and engage in capital goods transactions with capital producers. Intermediate goods y_t are produced using capital k_{t-1} and labor n_t with a constant-return-to-scale technology,

$$y_t = a_t k_{t-1}^{\alpha} n_t^{1-\alpha}, \tag{22}$$

where a_t denotes a stochastic total factor productivity. At the end of period $t-1$, an intermediate goods firm purchases capital k_{t-1} at the prevailing market price q_{t-1}. After goods are produced in period t, it sells the effective depreciated capital $(1-\delta)\psi_t^K k_{t-1}$ to the capital-producing sector, where the effectiveness of capital might change with the stochastic capital quality ψ_t^K. Acquisition of new capital can be financed through retained earnings and bank funds. For simplicity, we abstract from an endogenous funding decision and assume that a constant fraction ξ of capital purchases are financed with bank funds

$$L_t = \xi q_t k_t, \tag{23}$$

where $\xi \in (0,1)$ consistent with empirical evidence (see Section 4.). Let mc_t denote the price of each goods unit sold to the retail sector. Then, profit maximization of an intermediate goods firm satisfies, $(1-\alpha)\, mc_t \frac{y_t}{n_t} = w_t$, while the return on capital, which equals the return on bank funds, is given by

$$R_t^L \pi_t^{-1} = \frac{\alpha mc_t \frac{y_t}{k_{t-1}} + q_t(1-\delta)\psi_t^K}{q_{t-1}}.$$

At the end of period t, capital producers purchase the depreciated capital from intermediate good firms and repair them using the source of the final output, i.e., investment x_t. New capital is produced following a standard capital accumulation technology, satisfying $k_t = (1-\delta)k_{t-1}\psi_t^K + x_t$, and with adjustment costs $\Psi_t(x_t/x_{t-1})$. Profits of capital producers are

$$div_t^{CP} = q_t k_t - q_t(1-\delta)k_{t-1}\psi_t^K - \left[\Psi\left(\frac{x_t}{x_{t-1}}\right) + 1\right]\frac{x_t}{\psi_t^X}, \quad \text{with } \Psi\left(\frac{x_t}{x_{t-1}}\right) = \frac{\kappa_I}{2}\left(\frac{x_t}{x_{t-1}} - 1\right)^2,$$

where $\kappa_I > 0$ and ψ_t^X denotes an investment technology shock. The capital producer maximizes the present value of dividends, i.e., $\mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{0,t} div_t^{CP}$, such that the optimal choice for

investment x_t satisfies

$$q_t\psi_t^X = 1 + \frac{\kappa_I}{2}\left(\frac{x_t}{x_{t-1}} - 1\right)^2 + \kappa_I\left(\frac{x_t}{x_{t-1}} - 1\right)\frac{x_t}{x_{t-1}} - \beta\kappa_I\mathbb{E}_t\Lambda_{t,t+1}\left(\frac{x_{t+1}}{x_t} - 1\right)\left(\frac{x_{t+1}}{x_t}\right)^2\frac{\psi_t^X}{\psi_{t-1}^X}.$$

Each retailer, indexed by $j \in [0,1]$, purchases intermediate goods from the intermediate goods firm at the price mc_t. They re-package and resell them monopolistically in the final goods market. Final output y_t is a CES composite of retailers' output $y_{j,t}$, $y_t = [\int_0^1 y_{j,t}^{\frac{\eta_t-1}{\eta_t}} dj]^{\frac{\eta_t}{\eta_t-1}}$, where η_t is a stochastic elasticity. Demand for $y_{j,t}$ is given by $y_{j,t} = (P_{j,t}/P_t)^{-\eta_t} y_t$ and the aggregate price satisfies $P_t = [\int_0^1 P_{j,t}^{1-\eta_t} dj]^{\frac{1}{1-\eta_t}}$, where $P_{j,t}$ denotes the price of retail goods $y_{j,t}$. We consider adjustment costs of price setting following Rotemberg (1982) with price indexation at the target/long-run inflation π. Specifically, each period a retailer j maximizes the present value of profits

$$\max_{P_{j,t}} \mathbb{E}_t \sum_{i=1}^{\infty} \Lambda_{t,t+i}\left[\left(\frac{P_{j,t}}{P_t} - mc_{t+i}\right)y_{j,t+i} - \frac{\kappa_p}{2}\left(\frac{P_{j,t}}{\pi P_{j,t-1}} - 1\right)^2 y_{t+i}\right], \tag{24}$$

where κ_p measures the degree of the nominal price rigidity.[2] For $P_{j,t} = P_t$, optimal price setting leads to the following New Keynesian Phillips curve

$$\eta_t - 1 = \eta_t mc_t - \kappa_p\left(\frac{\pi_t}{\pi} - 1\right)\left(\frac{\pi_t}{\pi}\right) + \kappa_p\mathbb{E}_t\Lambda_{t,t+1}\frac{y_{t+1}}{y_t}\left(\frac{\pi_{t+1}}{\pi} - 1\right)\left(\frac{\pi_{t+1}}{\pi}\right). \tag{25}$$

2.4. Public Sector

The central bank supplies reserves to banks in exchange for bank assets, where the asset swap specification given in (9) applies to regular open market operations as well as to larger scale asset purchase programmes in terms of treasuries. At the beginning of each period, central bank holdings of treasuries and the stock of outstanding money are B_{t-1}^C and $M_{t-1} = \int_0^1 M_{i,t-1}di$. The central bank then receives returns on maturing assets and can over-roll bond holdings to $\tilde{B}_t^C$ in the bond market. In open market operations, it receives an amount $\Delta B_t^C = \int_0^1 \Delta B_{i,t}^C di$ of treasuries outright and temporarily under repos in exchange for money at the amount $\Delta B_t^C / R_t^M$. Afterwards, it pays the interest on banks' reserve holdings $R_t^R(M_{t-1} + I_t^B)$ and repurchase agreements are settled, i.e., the central bank sells back $B_t^R = \int_0^1 B_{i,t}^R di$ in return for $R_t^M \int_0^1 M_{i,t}^R di$. At the end of the period, reserves held by banks satisfy $\int_0^1 M_{i,t}di = \int_0^1 (M_{i,t-1} + I_{i,t}^B + F_{i,t} - M_{i,t}^R)di$, and aggregate reserves supply $M_t = M_{t-1} + I_t^B - M_t^R$. The end-of-period stock of treasuries held by the central bank is given by $B_t^C = \tilde{B}_t^C + \Delta B_t^C - B_t^R$, such that the central bank budget constraint can be written as

$$P_t div_t^C = R_{t-1}B_{t-1}^C - B_t^C + M_t - R_t^R M_{t-1} + \left(R_t^M - R_t^R\right) I_t^B. \tag{26}$$

[2] A positive cost-push term ψ_t^η is related to the elasticity η_t by $\eta_t = \eta(\psi_t^\eta)^{-\kappa_p}$.

Related to central bank practice, we assume that remittances $P_t div_t^C$ to the treasury consist of interest earnings from reserve supply as well as from asset holdings net of IOR payments $P_t div_t^C = \left(R_t^M - 1\right) I_t^B + \left(R_{t-1} - 1\right) B_{t-1}^C - \left(R_t^R - 1\right)\left(M_{t-1} + I_t^B\right)$. Substituting out remittances in the central bank budget constraint (26) shows that central bank asset holdings evolve according to $B_t^C - B_{t-1}^C = M_t - M_{t-1}$. Further assuming that initial values satisfy $B_{-1}^C = M_{-1}$, implies for the central bank balance sheet

$$B_t^C = M_t. \tag{27}$$

The central bank has three main instruments at its disposal: the main policy rate R_t^M $(= R_t^F)$, interest on reserves (IOR) R_t^R, and the growth rate of reserves M_t/M_{t-1}. In the subsequent section, we will describe how these main instruments have been controlled by the US Federal Reserve under different monetary policy regimes. The central bank can further decide whether money is supplied in exchange for treasuries via repos or outright. In particular, it controls the ratio of repos to outright purchases of bonds $\Omega_t > 0 : M_t^R = \Omega_t M_t$.

Fiscal policy has access to lump-sum taxes $P_t\tau_t$, which ensure public sector solvency. The government's budget constraint is given by $B_t^T + P_t\tau_t + P_t div_t^{CB} = R_{t-1} B_{t-1}^T$, where B_t^T denotes the total supply of treasuries. Given that treasuries are held by the central bank in exchange for reserves, and banks' bond holdings are relevant for balance sheet restrictions, we consider an explicit supply specification for short-term treasuries. We assume that the total amount of treasuries is supplied at an exogenous growth rate

$$B_t^T = \nu_t^B B_{t-1}^T, \tag{28}$$

where ν_t^B is stochastic with a mean value that is identical to the inflation target, like in Schabert (2015). Notably, this specification implies that inflation can alter the real value of treasuries $b_t^T = B_t^T/P_t$. Below, we will further discuss the role of total bond supply and provide empirical evidence for the specification (28).

2.5. Equilibrium properties

In equilibrium, banks are identical and all markets clear, such that total supply of bank funds equals total demand by intermediate goods firms, $L_t = \int_0^1 L_{i,t} di = \int_0^1 L_{j,t} dj$, aggregate deposit supply by households equals demand from banks, $D_t = \int_0^1 D_{i,t} di$, and interbank market positions satisfy $\int_0^1 F_{i,t} di = 0$. The aggregate stock of reserves is $M_t = \int_0^1 M_{i,t} di$, aggregate capital is $K_t = \int_0^1 K_{i,t} di$, and the total amount of money supplied in open market operation is $I_t^B = \int_0^1 I_{i,t}^B di$. Bond market clearing requires the total amount of treasuries B_t^T to satisfy $B_t^T = B_t^C + B_t$, where B_t denotes aggregate bond holdings of banks $B_t = \int_0^1 B_{i,t} di$. Using that aggregate reserves satisfy $I_t^B = (1 + \Omega_t) M_t - M_{t-1}$, the reserve requirement (10) for a

representative bank can be rewritten as $\varrho D_t \leq (1+\Omega_t)M_t$. Given the central bank balance sheet (27), bond market clearing shows $B_t^T = M_t + B_t$, such that bond supply (28) implies that total public sector liabilities to the private sector defined as $S_t = M_t + B_t$ grow at the rate ν_t^B:

$$S_t = \nu_t^B S_{t-1}. \tag{29}$$

Given that total public sector liabilities are relevant for the capital requirement, we provide evidence for the specific form (29) in Appendix A3, where we consider several alternative specifications. With total public sector liabilities S_t, the capital requirement (11) can be rewritten in aggregate terms as

$$(1+\phi_t)\, D_t \leq L_t + S_t. \tag{30}$$

The full set of conditions for the recursive competitive equilibrium is given in Appendix A. These conditions are specified independently of the prevailing policy regime, which can be distinguished along two main dimensions:

Firstly, regimes can differ with regard to the prevailing monetary policy instrument(s). Specifically, the central bank either controls the policy rates when money demand is well defined or the policy rates and the supply of reserves when money demand is not determined. When there is a positive spread between the main policy rate (i.e., the Federal Funds rate) and the IOR, reserve holdings are costly. Then, the multiplier on the reserve requirement (10) is positive (see 13), and banks' money demand is well-defined by the binding reserve requirement (see 19). In this case, monetary policy accommodates money demand, such that money supply adjusts endogenously. If, however, IOR is set equal to the policy rate, reserve holdings are costless and the reserve requirement (10) is slack, such that the equilibrium level of reserves is determined by money supply.

Secondly, bank operations are constrained by the capital requirement (11). According to (21), monetary policy is decisive for this constraint to be binding or not. In fact, the multiplier on the capital requirement (11) depends on the interest rate level (see 15). Precisely, the multiplier is positive if the risk-free bond rate is lower than the inverse of the stochastic discount factor in nominal terms. If they are identical, such that $\mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_t = 1$, banks are indifferent between paying dividends or retaining profits today, which allows building up equity and investing at the rate R_t. In this case, the multiplier $\varkappa_t$ equals zero, indicating that it is costless for banks to satisfy the capital requirement. If the interest rate is lower, such that the multiplier $\varkappa_t$ is positive (15), building up equity is costly, and the capital requirement binds (see 20). Given that the bond rate, as well as other interest rates, follow the level of the policy rate (see 21), the monetary policy stance decides on the relevance of the capital requirement, particularly in the long run (where the time-index of variables is dropped).

Proposition 1. *If the central bank sets*

1. *the policy rate above (equal to) the IOR, the reserve requirement (10) is binding (slack).*
2. *the long-run real policy rate R^M/π below (equal to) the inverse of the discount factor β, the capital requirement (11) is binding (slack) in the long run.*

Proof. The claim made in part 1 immediately follows from (13) and (19). The claim made in part 2 follows from the steady state version of (21), i.e. $\varkappa = 1 - \beta R^M/\pi$, and (20). ■

The condition for a binding/slack reserve requirement can immediately be assessed for each state/period via observed data on the policy rate and IOR. Yet, the condition for a binding/slack capital requirement cannot as easily be assessed, given that the multiplier depends on various equilibrium objects, specifically, on the stochastic discount factor in nominal terms (see 21). We therefore provide a Bayesian estimation of a model version that allows for an occasionally binding capital requirement (see Section 4).

Further note that the household optimality condition for deposits (5) and the bank optimality condition for deposits (18) imply the following relation between the multiplier ϑ_t^H on the household liquidity constraint (2), the multiplier ϑ_t^B on the reserve requirement (10), and the multiplier $\varkappa_t$ on the capital requirement (11)

$$\mu\vartheta_t^H/\lambda_t = \rho\vartheta_t^B + (1+\phi_t)\varkappa_t. \tag{31}$$

Hence, the liquidity constraint (2) is binding if at least one of the two constraints that banks face binds. Then, banks pass through the costs of the prevailing constraint(s) to the depositors via a lower deposit rate, such that households hold deposits just at the minimum level.

Proposition 2. *The household liquidity constraint (2) binds if the reserve requirement (10) or the capital requirement (11) is binding.*

Proof. The claim made in the proposition immediately follows from (31) and (7). ■

Even though they have a similar impact on household deposit holdings according to Proposition 2, a capital requirement (11) is not equivalent to a reserve requirement (10). Apparently, the two constraints differ with regard to the balance sheet items that limit the creation of deposits. Specifically, the reserve requirement imposes a constraint on deposits exclusively in terms of reserve holdings M_t (see 10). Thereby, a binding reserve requirement constitutes a well-defined money demand relation, providing the basis for monetary non-neutrality. In contrast, a binding capital requirement relates deposits to bank assets, i.e., loans L_t and total public sector liabilities $S_t = M_t + B_t$ (see 30). Therefore, the sum of reserves and treasuries, rather than reserves, alters the relation between deposits and loans, and may thereby exert an impact on the allocation. As reflected by the central bank balance sheet identity $M_t = B_t^C$, an increase

in money supply leads to an increase in bond holdings of the central bank. For an independent total supply of treasuries, $B_t^T = B_t^C + B_t$, as specified in (28), a change in bank reserve holdings therefore leads to an equally-sized decrease in bank bond holdings, $\Delta M_t = -\Delta B_t$, such that the impact of a change in money supply on banks' total assets is neutralized.

Proposition 3. *Suppose that IOR equals the policy rate, such that the reserve requirement (10) is slack. Then, changes in the supply of reserves do neither affect the equilibrium allocation nor prices, regardless of whether the capital requirement (11) is slack or binding.*

Proof. When IOR equals the policy rate, reserves are solely related to decisions and restrictions of the private sector via total public sector liabilities $S_t = M_t + B_t$ entering the potentially binding capital requirement. According to (29), the supply of total public sector liabilities S_t, which – by the central bank balance sheet identity $M_t = B_t^C$ – are equal to B_t^T, is independent of reserves M_t. A change in reserve supply does therefore exclusively affect the composition of S_t by causing an equally-sized opposite change in bank treasuries holdings, $M_t = B_t^T - B_t$. ■

Proposition 3 establishes that monetary neutrality holds under a slack reserve requirement (10), even if the capital requirement (11) is binding. In this case, bank operations are affected by total public sector liabilities S_t, while a change in money supply implies an inverse change in bank bond holdings. Given that the supply of total public sector liabilities S_t is independent of reserves M_t (see 29), changes in money supply exclusively alter the composition of S_t. Proposition 3 implies that an increase in money supply neither affects output nor the inflation rate at the ZLB, where the reserve requirement (10) is slack. Notably, this property is consistent with the lack of inflation hikes in post-2008 US data even under increases in reserves induced by QE.

3. Monetary policy under binding capital requirements

In this section, we examine main properties of the model in an analytical way. It is well-established that the sequence of policy rates followed a Taylor-type feedback rule under pre-GFC monetary policy, while the reserve requirement (10) and thereby the household liquidity constraint (see Proposition 2) were binding due the non-existence of IOR. The performance of this type of New Keynesian model with liquidity-constrained agents is well-established, and its local equilibrium determinacy is known to depend on the Taylor principle (see e.g. Ravenna and Walsh, 2006). Here, we focus on main properties of post-2008 monetary policy where the equality of IOR and FFR has led to a slackening of the reserve requirement (see Proposition 1), while the capital requirement has been binding, as will be confirmed by the estimations in Section 4. We, firstly, derive local equilibrium determinacy properties and, secondly, examine impulse responses to productivity and cost push shocks.

To facilitate the derivation of analytical results, we introduce some simplifying assumptions, mainly by reducing the set of endogenous state variables: Firstly, we ignore households' internal

habit formation $h = 0$, such that the first-order condition (4) simplifies to, $c_t^{-\sigma} = \lambda_t + \vartheta_t^H$. Secondly, we abstract from capital formation and consider a linear production function ($\alpha = 0$), i.e., $y_t = a_t n_t$. As assumed before, external financing is required for funding the costs of production. Given that we abstract from capital formation, we assume that external funds are equal to a constant fraction ξ of production:

$$l_t = \xi y_t. \tag{32}$$

Thirdly, we consider a simple feedback rule for the policy rate, $R_t^M/R^M = (\pi_t/\pi)^{\gamma_{r,\pi}}$, with $\gamma_{r,\pi} \geq 0$. In addition, we restrict parameter values to ensure that the capital requirement establishes an unambiguous relation between the supply of public sector liabilities S_t and real activity. Precisely, the capital requirement is assumed to satisfy $\phi > \mu\xi - 1$. According to our analysis of post-2008 data in Section 4, this parameter restriction is satisfied. Finally, we set those stochastic variables equal to their steady state values, which have solely been introduced to enhance the model's fit to the data.

Assumption 1. *Agents' preferences (1) and the production function (22) satisfy $h = 0$ and $\alpha = 0$, firms' loan demand is given by (32), instead of (23), the policy rate satisfies $R_t^M/R^M = (\pi_t/\pi)^{\gamma_{r,\pi}}$, and the capital requirement $\phi > \mu\xi - 1$, while $\psi_t^P = \psi_t^N = 1$, $\phi_t = \phi$, and $\nu_t^B = \nu^B$.*

Based on the set of equilibrium conditions for the simplified version, we apply a linear approximation of the equilibrium conditions at a steady state of the economy, where the real interest rate is sufficiently low such that the multiplier on the capital requirement is strictly positive (see Proposition 1). According to Proposition 3, money is neutral when $R_t^R = R_t^M$ such that the reserve requirement is slack. We can therefore neglect the sequence of reserves for the analysis in this section. Let variables without a time index denote steady state values and variables with a hat denote percentage deviations from a steady state. In the neighborhood of this steady state, a rational expectations equilibrium (REE) under a slack reserve requirement and a binding capital requirement is a set of sequences $\{\widehat{\pi}_t,\ \widehat{s}_t,\ \widehat{\lambda}_t\}_{t=0}^{\infty}$ that converge to the steady state and satisfy $\widehat{R}_t^M = \gamma_{r,\pi}\widehat{\pi}_t$ (see Appendix A2),

$$\widehat{\pi}_t = \beta\mathbb{E}_t\widehat{\pi}_{t+1} - \Pi_a\widehat{a}_t - \Xi\widehat{\lambda}_t + \Pi_s\widehat{s}_t - \kappa_p^{-1}\widehat{\eta}_t, \tag{33}$$

$$\mathbb{E}_t\widehat{\lambda}_{t+1} - \mathbb{E}_t\widehat{\pi}_{t+1} + \widehat{R}_{t+1}^M = \digamma_\lambda\widehat{\lambda}_t + \digamma_s\widehat{s}_t, \tag{34}$$

$$\widehat{s}_t = -\widehat{\pi}_t + \widehat{s}_{t-1}, \tag{35}$$

where $\Pi_s = \Xi\sigma_n$, $\digamma_\lambda = 1 + \frac{\varkappa}{1-\varkappa}\kappa_\varkappa^{-1} > 1$, $\Pi_a = \Xi\,(1+\sigma_n)$, $\Xi = \frac{\eta-1}{\kappa_p} > 0$, $\digamma_s = \frac{\varkappa}{1-\varkappa}\sigma\kappa_\varkappa^{-1} > 0$, and $\kappa_\varkappa = \varkappa\frac{1+\phi}{\mu}/(1+\varkappa\frac{1+\phi}{\mu}) \in (0,1)$, given $\{\widehat{a}_t, \widehat{\eta}_t\}_{t=0}^{\infty}$. Output and consumption are further determined by $\widehat{y}_t = \widehat{c}_t = \widehat{s}_t$. This set of conditions differs from a basic New Keynesian model by two elements: Firstly, the Euler equation (15) differs from those of a textbook version of the New Keynesian model by the multiplier $\varkappa_t$ on the capital requirement. Secondly, the supply of total

public sector liabilities (see 35) matters in this economy, because they shift the relation between deposits and loans via the capital requirement (see 30). Therefore, $\widehat{s}_t$ enters the aggregate supply constraint (33) and the condition (34), which originates in the Euler equation. As a consequence, local equilibrium determinacy does not rely on the well-known Taylor principle. Given that public sector liabilities are supplied in a way that relates to a constant money growth policy in a New Keynesian model (see Chowdhury and Schabert, 2008), the equilibrium is stable and uniquely determined when the interest rate is pegged $\gamma_{r,\pi} = 0$, for example, at the ZLB.

Proposition 4. *Suppose that Assumption 1 holds. A REE under a slack reserve requirement and a binding capital requirement is uniquely determined if*

$$\gamma_{r,\pi} < 1 + \frac{\digamma_s + (1+\digamma_\lambda)\,\sigma_n}{2} + \frac{(1+\digamma_\lambda)\,(1+\beta)}{\Xi}. \tag{36}$$

Proof. See Appendix A2 ■

According to Proposition 4, equilibrium determinacy is ensured if the inflation feedback does not exceed an upper bound specified by the RHS of inequality (36). This threshold is not restrictive under plausible parameter values, for example, based on the calibration informed by the estimation results in Section 4, the bound is computed to be 28.27.

The set of conditions (33)-(35) reveals that a positive productivity shock $\widehat{a}_t > 0$ and a cost-reducing shock $\widehat{\eta}_t > 0$ have symmetric effects on inflation $\widehat{\pi}_t$, public liabilities $\widehat{s}_t$ and the multiplier $\widehat{\lambda}_t$ due to the property that they exclusively enter (33) with identical signs. Since $\widehat{s}_t = \widehat{c}_t$ and $\widehat{c}_t = \widehat{y}_t$ further hold in equilibrium, the impact of these shocks on output are also symmetric. Hence, to qualitatively assess the effects of productivity and cost push shocks on output and inflation, it suffices to examine only one of them. As for the determinacy analysis, we thereby do not need to examine the regimes at and above the ZLB in a separate way.

Proposition 5. *Suppose that Assumption 1 holds and that (36) is satisfied. Under a slack reserve requirement and a binding capital requirement, a negative productivity shock $\widehat{a}_t < 0$ and a cost-push-shock $\widehat{\eta}_t < 0$ lead to a decline in output and an increase in inflation on impact if*

$$\rho_a > (1-\rho_s)\,\frac{\digamma_\lambda}{\digamma_\lambda - \rho_s} \tag{37}$$

or if $\rho_a < (1-\rho_s)\,\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}$ and $\gamma_{r,\pi} < 1 + \frac{\digamma_s \frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}}{(1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}-\rho_a}$, where $\rho_s \in (0,1)$.

Proof. See Appendix A2 ■

Proposition 5 reveals that the direction of the effects of productivity and cost-push shocks is not affected by an interest rate peg, $\gamma_{r,\pi} = 0$. In fact, a productivity (cost-push) shock leads to an increase (decrease) in output and a decline (increase) in inflation if the autocorrelation coefficient ρ_a is sufficiently high, i.e., if (37) is satisfied. The sign of the output responses to both types of shocks are not opposed between policy rates at or above the ZLB, which is predicted by

the basic new Keynesian model (see Eggertsson, 2011, 2012). When (37) holds, both types of shocks therefore lead to intuitive responses regardless of the ZLB. Using the parameter values based on US data (see Section 4), the RHS of (37) is given by 0.51, whereas the autocorrelation coefficient equals $\rho_a = 0.82$ ($\rho_\eta = 0.85$) and is therefore clearly satisfies (37).[3]

4. Quantitative results

In the first part of this section, we estimate the model for post-2008 US data, indicating that capital requirements have been binding since the GFC. In the second part, we examine the transmission of macroeconomic shocks.

4.1. Evidence on binding capital requirements

Figure 1 and Proposition 1 indicate that the reserve requirement (10) has been slack since 2008, when the US Federal Reserve set IOR equal to the policy rate $R_t^R = R_t^M$. Figure 1 further shows how the capital-to-asset ratio increased since 2008 and went down in 2020, which relates to the gradual implementation of Basel II and III since the GFC, and the relaxation of capital requirements at the onset of the pandemic. We perceive this pattern as suggestive of capital requirements to be binding since 2008. This can, however, only be validated by assessing the multiplier on the capital requirement and therefore the relation between the real interest rate and the stochastic discount factor (see 21).

To assess the relevance of capital requirements, we allow for occasionally binding capital requirements and re-specify the framework in form of a regime-switching model (like Benigno et al., 2025), where the switch refers to slack or binding capital requirements. To focus on our main novel argument, we thereby abstract from policy regime switches that might have occurred simultaneously. Specifically, we disregard regime switches between a state-contingent feedback rule for the policy rate to a fixed main policy rate at the ZLB. According to Proposition 4, the model is uniquely determined even under a peg, which allows specifying the sequence of policy rates by the realized sequence in the data. For the identification of regime switches, we focus on the information about the multiplier of capital requirement (see Proposition 1). We abstain from imposing pre-specified values for the capital requirement ratio and let the leverage ratio be determined by observed data. The reason for this strategy is that bank regulation has been implemented as a combination of capital requirements related to assets with different risk weights, state-contingent capital buffers, and additional leverage ratio requirements. Moreover, regulatory standards according to Basel II and III, and the Dodd-Frank Wall Street Reform were gradually introduced over time, such that time-invariant capital ratios would be misspecified.

[3]For the computation of the upper bound, we used that the unique stable eigenvalue of the simplified model equals $\rho_s = 0.85$.

4.1.1. A regime-switching specification

In this subsection, we describe a regime-switching re-formulation of the model. We introduce a two-state Markov chain that governs the tightness of the capital requirement, denoted as $\mathcal{S}_t^{lev} = \{S, B\}$ where S indicates that the capital requirement is slack, and B indicates that the capital requirement is binding. Focusing on the post-2008 period, we use that the reserve requirement has been slack. For simplicity, we introduce ad-hoc costs of managing deposits κ^d, which ensures that the household liquidity constraint (2) binds even if both requirements for banks are slack (see also Proposition 1).[4] For the two-state Markov chain $\mathcal{S}_t^{lev}$ governing the relevance of the capital requirement, we introduce the following matrix of transition probabilities,[5]

$$\mathbb{Q}_t^{lev} = \begin{bmatrix} 1 - prob_t^{S,B} & prob_t^{S,B} \\ prob_t^{B,S} & 1 - prob_t^{B,S} \end{bmatrix}$$

where $prob_t^{S,B}$ denotes the probability of transitioning from state S in period t to state B in period $t+1$, with $1 - prob_t^{S,B}$ denoting the probability of remaining in state S. The terms $prob_t^{B,S}$ and $1 - prob_t^{B,S}$ are defined analogously. These probabilities are specified as logistic functions, ensuring that they are bounded between 0 and 1. Let $\bar{\varkappa}$ be the steady-state value of the multiplier under a binding capital requirement, i.e., $\bar{\varkappa} = 1 - \beta R^M(B)/\pi > 0$, and $\widetilde{\varkappa}_t$ be the distance of the multiplier $\varkappa_t$ from this steady state value, $\widetilde{\varkappa}_t = \varkappa_t - \bar{\varkappa}$. The endogenous transition probabilities are assumed to satisfy

$$prob_t^{S,B} = \frac{1}{1 + \mathcal{O}_{s,b} \exp(-\theta_{s,b} \varkappa_t)}, \tag{38}$$

$$prob_t^{B,S} = \frac{1}{1 + \mathcal{O}_{b,s} \exp(\theta_{b,s} \widetilde{\varkappa}_t)}, \tag{39}$$

where $\mathcal{O}_{s,b}$ and $\mathcal{O}_{b,s}$ are scaling parameters for the transition probabilities and the parameters $\theta_{s,b}$ and $\theta_{b,s}$ measure the sensitivity of switches. Equation (38) implies that the probability of transitioning from a slack to a binding capital requirement increases with the multiplier $\varkappa_t$. Likewise, equation (39) implies that the probability of transitioning to a slack capital requirement increases when the multiplier $\varkappa_t$ falls below the steady state value $\bar{\varkappa}$ such that $\widetilde{\varkappa}_t$ gets negative, indicating that the constraint imposed by the capital requirement is less tight. To formalize regime-specific conditions, the complementary slackness condition (20) is re-specified by introducing a regime-switching indicator $\mathbf{z}(\mathcal{S}_t^{lev})$, which takes the values $\mathbf{z}(S) = 1$

[4] The banks' first-order conditions for deposits is then given by $1 = (1+\phi)\varkappa_t + \kappa^d + \mathbb{E}_t \Lambda_{t,t+1} \pi_{t+1}^{-1} R_t^D$ instead of (18), while the multiplier ϑ_t^H on the household liquidity constraint (2), $\mu \vartheta_t^H / \lambda_t = \kappa^d + (1+\phi)\varkappa_t > 0$.

[5] We adopt regime-dependent steady states as perturbation points, following Binning and Maih (2017) and Barthélemy and Marx (2017), which naturally impose a non-negative Lagrange multiplier, offering a useful approximation for analyzing capital regulation.

and $\mathbf{z}(B) = 0$,

$$\mathbf{z}(\mathcal{S}_t^{lev})\varkappa_t + \left(1 - \mathbf{z}(\mathcal{S}_t^{lev})\right)(\epsilon_t - \phi_t) = 0, \tag{40}$$

where ϵ_t denotes the observed capital-to-deposit ratio $\epsilon_t = e_t/d_t$. For state S, the first term in (40) implies that the multiplier $\varkappa_t$ is equal to zero. For state B, the second term in (40) demands the endogenous capital-to-deposit ratio ϵ_t to be equal to the policy-imposed capital-to-deposit ratio ϕ_t. Hence, the policy-imposed leverage requirement ratio ϕ_t will be determined as an outcome of the model estimation.

To capture the heightened macroeconomic uncertainty observed during the GFC and the COVID-19 pandemic, we follow a standard approach (e.g., Liu et al., 2011; Benigno et al., 2025) and allow for heteroskedasticity in the standard deviations of all structural shocks. Specifically, we allow for regime-dependent standard deviations for the structural shocks. For this, we define two regimes $\mathcal{S}_t^{vol} = \{L, H\}$ with the transition matrix

$$\mathbb{Q}^{vol} = \begin{bmatrix} 1 - prob^{L,H} & prob^{L,H} \\ prob^{H,L} & 1 - prob^{H,L} \end{bmatrix},$$

where $prob^{L,H}$ ($prob^{H,L}$) is the exogenous probability of transitioning from a low (high) volatility state L (H) to a high (low) volatility state H (L)[6]. Hence, our model comprises four regimes denoted by $\mathcal{S}_t = \mathcal{S}_t^{lev} \times \mathcal{S}_t^{vol}$, which are governed by a combined transition matrix $\mathbb{Q}_{t,t+1} = \mathbb{Q}_t^{lev} \otimes \mathbb{Q}^{vol}$. Finally, the model incorporates the following shocks expressed as AR(1) processes: TFP a_t, consumption preference ψ_t^P, IST ψ_t^X, labor supply ψ_t^N, capital quality ψ_t^K, cost-push ψ_t^η, equity-to-deposit ratio ϕ_t, and a stochastic process of public sector liabilities supply ν_t^B. The set of equilibrium conditions is provided in Appendix A4.

4.1.2. Estimation results

The first-order perturbation solution is obtained using the functional iteration method proposed by Chang et al. (2021), which accommodates nonlinear regime-switching models with multiple steady states and endogenous transition matrices. Posterior mode maximization and posterior simulation are implemented via the RISE toolbox. Bayesian estimation is conducted using U.S. quarterly data spanning from 2008Q4 to 2024Q3. Observed quantities are seasonally adjusted for population growth and expressed in terms of growth rates. We consider an exogenous balanced growth path *bgp*, which will be identified by the estimation. For the estimation, we use time series for the nominal FFR $R_{t,data}^M$, CPI inflation $\pi_{t,data}$, the Tier-1 capital-to-deposit ratio $\epsilon_{t,data}$, per capita real GDP growth $\Delta \log y_{t,data}$, non-durable goods real consumption growth

[6]For identification purposes, we impose a restriction $\varsigma_{i,(L)} < \varsigma_{i,(H)}$, $i \in \{a, b, k, x, n, p\}$ with the ordering consistent with the sequence of shocks introduced above, ensuring that the standard deviation of shock i in the low-volatility regime is strictly smaller than in the high-volatility regime.

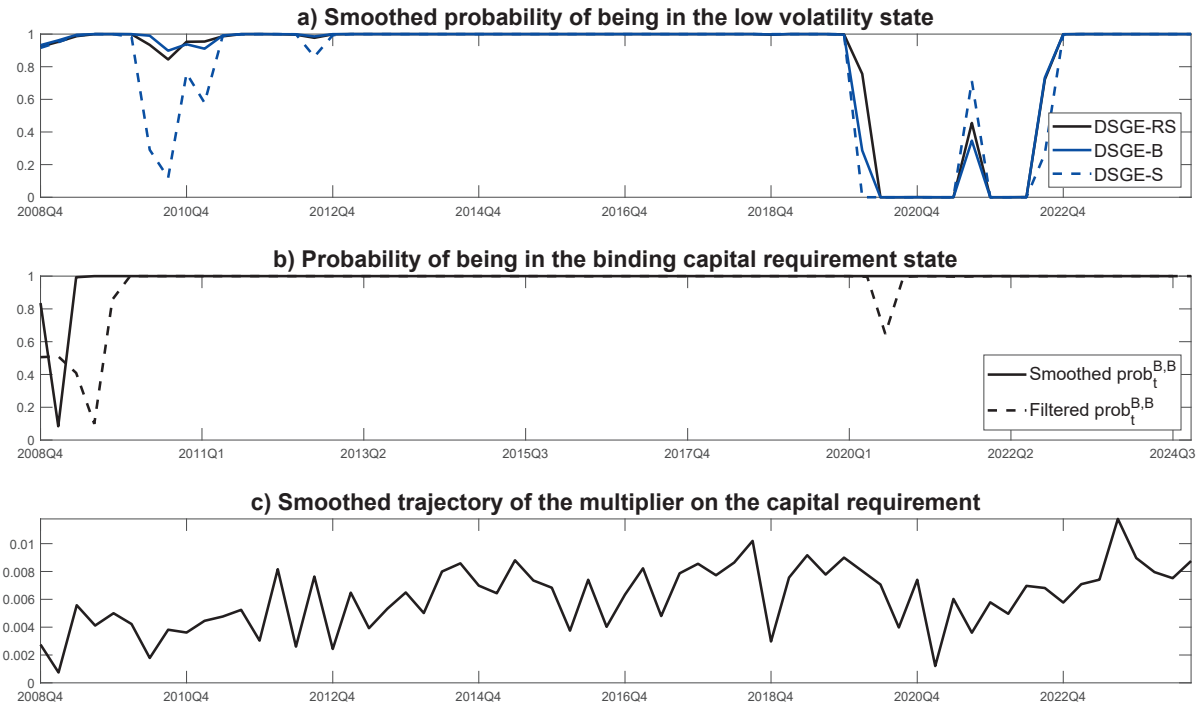

Figure 2: The black line in the top panel represents the probability of being in a low-volatility regime. In the middle panel, the black line represents the smoothed probability of being in a binding capital requirement regime, while the dashed line plots the filtered probabilities using information only up to time t. The black line in the bottom panel depicts the expected trajectory of the capital requirement multiplier. The initial point of the filtering procedure is set to the ergodic mean.

$\Delta \log c_{t,data}$, real fixed capital investment growth$\Delta \log x_{t,data}$, and real wage growth $\Delta \log w_{t,data}$.

A subset of parameters is calibrated, using empirical means or information from other studies.[7] The discount factor is set to $\beta = 0.99682$, which equals average ratio of inflation to the Federal Funds rate based on pre-2008 data (1994Q1–2008Q3). The (annual) inflation target is set at 2% and the steady-state Federal Funds rate at 1.1%, reflecting the post-2008Q4 sample mean. For the utility function, we set $\sigma = 1$, while the weight $\chi = 2.95$ is calibrated such that steady-state labor supply equals one-third of available time in state S. The steady-state consumption-to-deposit ratio is set at $\mu = 0.22$, based on the sample mean of nondurable consumption relative to broad money (M3). The marginal cost of deposits, $\kappa_d = 0.12\%$, is calibrated to match a 0.5% annual deposit–bond spread, consistent with Ulate (2021). The steady state equity-to-deposit ratio is set at $\epsilon = 9.9\%$, which equals the average after 2009Q3. The marginal monitoring cost $\kappa_L = 0.625\%$ matches the sample mean of the spread between the prime loan rate and the Federal Funds rate. The share of firms' external finance, $\xi = 0.2$, equals the sample mean of the ratio of non-financial firms' debt to net worth. Capital depreciates at $\delta = 0.025$ quarterly. Finally, the parameters $\theta_{b,s}$ and $\theta_{s,b}$ in (38) and (39) are set at 2000 (see e.g. Binning and Maih, 2017).

[7]We use the following data sources (from FRED database): non-durable goods consumption (PCEND), M3 monetary aggregate (MABMM301USM189S), total non-financial firms' loans (NCBLL), and net worth (TNWMVBSNNCB).

Table 1: Model comparison

	DSGE-B	DSGE-RS	DSGE-S
Log MDD (Laplace)	1232.47	1225.60	1196.84
Schwarz Information Criteria	-2477.59	-2444.97	-2437.31

The remaining parameters are estimated under weakly informative priors. Following Bjørnland et al. (2018), we use 90 percent quantile intervals, allowing the data to primarily shape the posterior distributions.[8] For the scaling parameters $\mathcal{O}_{s,b}$ and $\mathcal{O}_{b,s}$ of the transition probabilities (38) and (39), we choose an identical and loose distribution, capturing the uncertainty about the switch between binding or slack capital requirements. We find that the data provides informative signals for a large majority of the estimated parameters (for the full set of priors and posteriors see Table A3 in Appendix). For the parameters governing the heteroskedasticity, we find clear differences between high- and low-volatility states. The model further accounts for the transitory nature of the disruptions caused by the COVID-19 pandemic, as reflected in the first panel of Figure 2 and the relatively high transition probability of $prob^{H,L} = 9.56\%$, which is three times as high as the probability of moving from low to high volatility regime. The posterior modes of the scaling parameters $\mathcal{O}_{s,b}$ and $\mathcal{O}_{b,s}$ are estimated at 26.58 and 27.86, which imply steady-state transition probabilities of 3.63% from state S to state B and 3.47% for the opposite direction.

The second panel of Figure 2 displays the model-implied smoothed probability of being in state B, which measures the ex-post estimated likelihood that the capital requirement is binding, conditional on the full sample of observed data. The result indicates that the capital requirement starts to be permanently binding shortly after the onset of the GFC (2009Q2), including the pandemic period. The third panel of Figure 2, which shows the expected smoothed trajectory of the multiplier $\varkappa_t$ on the capital requirement, confirms this finding. The multiplier fluctuates in the positive domain, confirming a permanently binding capital requirement. At the onset of the GFC and the COVID-19 pandemic periods – when regulatory capital requirements were temporarily relaxed – the multiplier is relative low, indicating a reduction of equity creation costs in these episodes.

To further assess the validity of our model, we estimate two alternative model specifications: one where the capital requirement is always binding (DSGE-B), and another where it is always slack (DSGE-S). Table A3 presents posterior estimates for these specifications. The fit of the three model versions is formally assessed by the comparison of the marginal data density (MDD) at the posterior mode, reported in Table 1, and computed by Laplace approximation. While

[8]The posterior mode is searched using the stochastic global optimizer, "bee_gate", available in the RISE toolbox (see Chang et al., 2021). While it helps avoid getting trapped in local maxima, it comes at the cost of longer computational time relative to derivative-based alternatives.

the regime-switching specification with an occasionally binding capital requirement, DSGE-RS, provides information for the probability of binding capital requirements, it does not achieve the highest MDD (1225.60) and falls short of the value for the DSGE-B specification (1232.47). This outcome is influenced by the implicit penalty for model complexity, particularly in terms of parameter dimensionality and structural flexibility. The markedly lower MDD value (1196.98) for the specification DSGE-S reveals a less plausible data-generating process and thus misspecification of the model with slack capital requirements. The relative performance of the alternative model versions in fitting the data remains unchanged when evaluated using the Schwarz Information Criterion (SIC), a similar criterion that penalizes additional parameters in posterior densities (see discussion in Liu et al., 2011).[9] In particular, this information criterion confirms that the DSGE-B version fits the data best.

4.2. Transmission of macroeconomic shocks

In this section, we present impulse responses of the estimated model to macroeconomic shocks. We firstly assess responses to supply side shocks, i.e., productivity and cost push shocks, at and above the ZLB, confirming the findings presented in Proposition 5. We secondly examine the transmission of fiscal shocks, which shows that a binding capital requirement causes fiscal multiplier not be substantially affected by policy rates at the ZLB. Different versions of the model will be appreviated with three letters, where the first informs about whether the reserve requirement is slack (S) or binding (B), the second about the capital requirement, and the third about the policy rate being at the ZLB (Z) or above (N). For example, the pre-2008 regime will be abbreviated with "BS-N" and ZLB regime after 2008 with "SB-Z". For the counterfactual policy regime where both requirements are slack we will use "NKM".

4.2.1. Supply side shocks

Figure 3 shows impulse responses to productivity and cost-push shocks for the estimated model at the ZLB. The black solid line shows impulse responses for our benchmark model (SB-Z), where the central bank sets IOR equal to the policy rate such that the reserve requirement is slack and the relatively low real interest rate induces the capital requirement to be binding. The first two rows show responses to a productivity shock, and the last two rows show responses to a cost-push shock. Consistent with conventional expectations, productivity (cost-push) shocks raise (reduce) aggregate output and reduce (raise) inflation. Consumption and investment increase as well as bank funding.

The blue solid line refers to a counterfactual model version at the ZLB, where the reserve and

[9] Unlike the Laplace approximation, which accounts for the curvature of the posterior density via the Hessian matrix, SIC penalizes model complexity based on the dimension of parameters and sample, tied to the maximized likelihood.

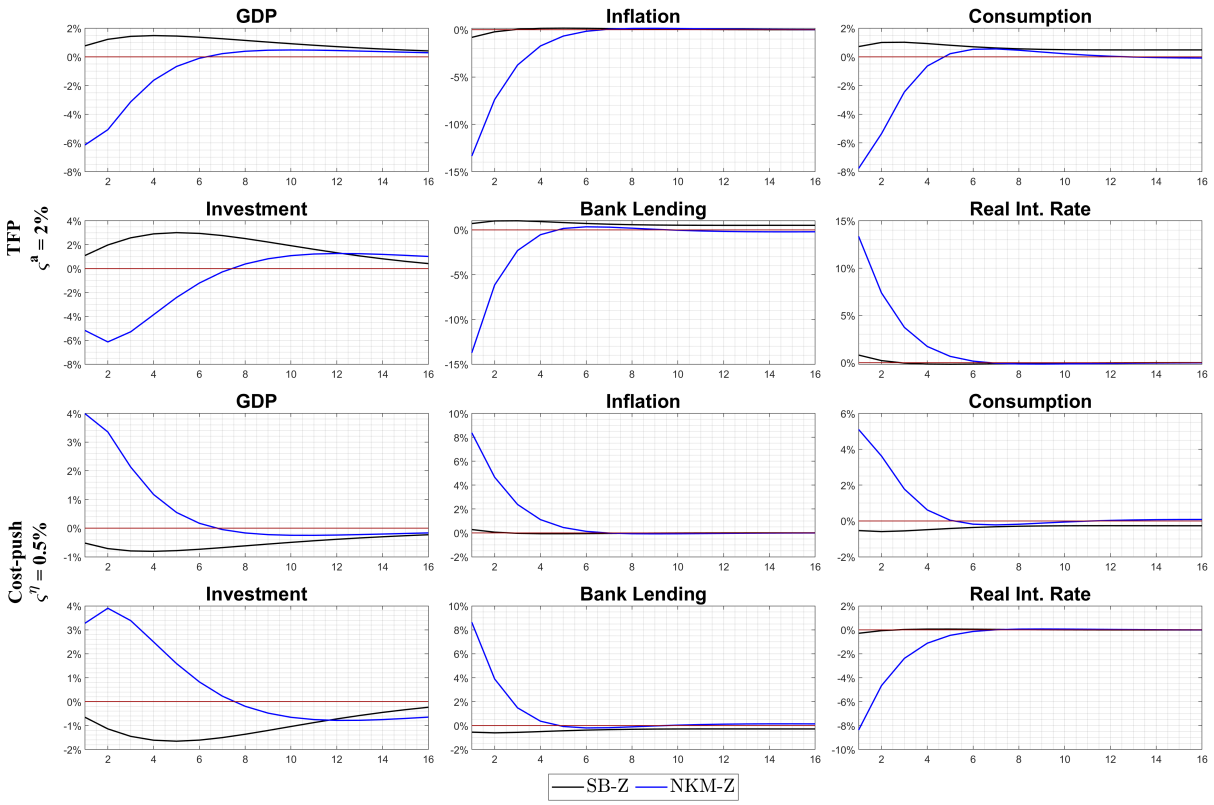

Figure 3: Impulse responses to a 2% TFP shock and a cost-push shock (modelled as a 20% reduction in the elasticity of substitution), comparing the benchmark model (SB-Z: black solid line) and a NK-type specification (NKM-Z: blue solid line) under the ZLB. The vertical axis reports percentage deviations from the steady state.

the capital requirement are assumed to be slack (NKM-Z). Given that the reserve requirement is also slack, neither reserves nor total public sector liabilities are relevant for the allocation. This version thus relates to a standard New Keynesian model. In contrast to the benchmark model, which is locally determined under a peg (see Proposition 4), a New Keynesian model is known to be locally indetermined under a peg. A typical strategy to ensure equilibrium uniqueness is to apply an interest rate rule that satisfies the Taylor-principle and to introduce an adverse shock, which is sufficiently large to induce that the central bank sets the interest rate at the ZLB. To keep the analysis as transparent as possible and to abstract from the impact of expected duration at the ZLB, we abstain from this strategy and assume that the policy rate is pegged at zero, while we apply the minimum state variable solution for NKM.

Apparently, the counterfactual model predicts that output falls (increases) at the ZLB in response to a productivity (cost-push) shock. These well-established counterintuitive predictions of the New Keynesian model (see Eggertsson, 2011, 2012) are based on the property that the real interest rate increases (falls) in response to a productivity (cost-push) shock, raising agents' willingness to save more (less). This impact of the monetary policy rate on aggregate demand dominates the impact of the shock on the supply side. In the benchmark model with a binding capital requirement, the impact of the real policy rate on agents' intertemporal choices is muted by the multiplier on the capital requirement (see 21), such that the supply side effects dominate

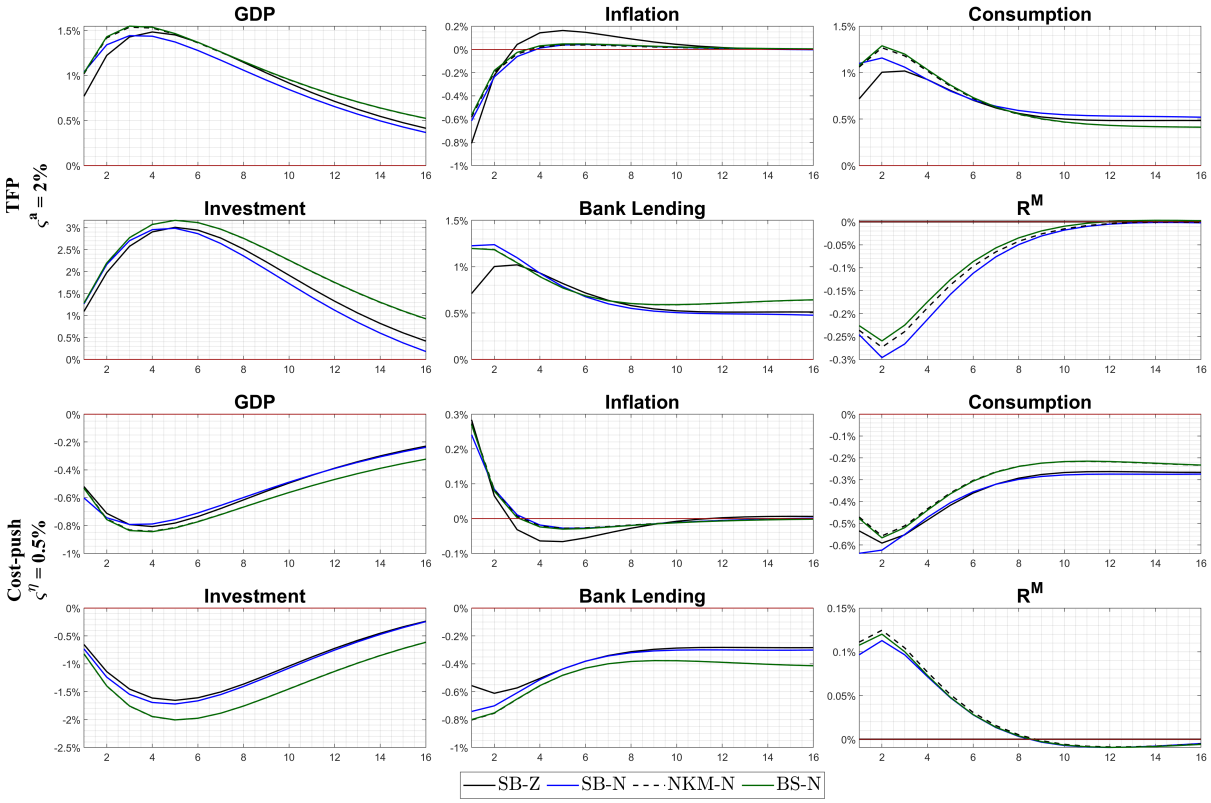

Figure 4: Impulse responses to a 2% TFP shock and a cost-push shock (modelled as a 20% reduction in the elasticity of substitution) in the benchmark models (SB-Z: black solid line; SB-N: blue solid line), a NK-type specification (NKM-N: black dashed line), and a model version with a binding reserve requirement (BS-N: green solid line). The vertical axis reports percentage deviations from the steady state.

and intuitive effects of both shocks prevail.

Figure 4 displays impulse responses to productivity and cost-push shocks for four model versions: the benchmark model at the ZLB and above the ZLB (SB-Z and SB-N), the New-Keynesian-type model (NKM-N), and a specification with a binding reserve requirement and slack capital requirement (BS-N). Given that we consider the policy rate is to be set above the ZLB, we assume that the main policy rate follows a standard Taylor rule,

$$R_t^M/R^M = \left(R_{t-1}^M/R^M\right)^{\rho_r} \left[(\pi_t/\pi)^{\gamma^{r,\pi}} (y_t/y_t^*)^{\gamma^{r,y}}\right]^{1-\rho_r}, \tag{41}$$

where $\gamma^{r,\pi} \geq 0$ and $\gamma^{r,y} \geq 0$ denote the feedback coefficients to changes in inflation and in the output gap, which is measured by output deviation from its flexible price level y_t^*. Values for the coefficients in (41) are taken from Smets and Wouters (2007): $\rho_r = 0.81$, $\gamma_{r,\pi} = 2.03$ and $\gamma_{r,y} = 0.08$. A comparison of the four versions shows that they lead to similar impulse responses under both types of supply side shocks. Overall, these results suggest that the ZLB (or, more generally, interest rate pegs) do not substantially affect the transmission of supply side shocks under binding capital requirements. In fact, the versions with slack capital requirements (NKM-N and BS-N) exhibit broadly similar, though slightly more pronounced, output responses. These findings indicate that binding capital requirements have no systematic amplification effects of

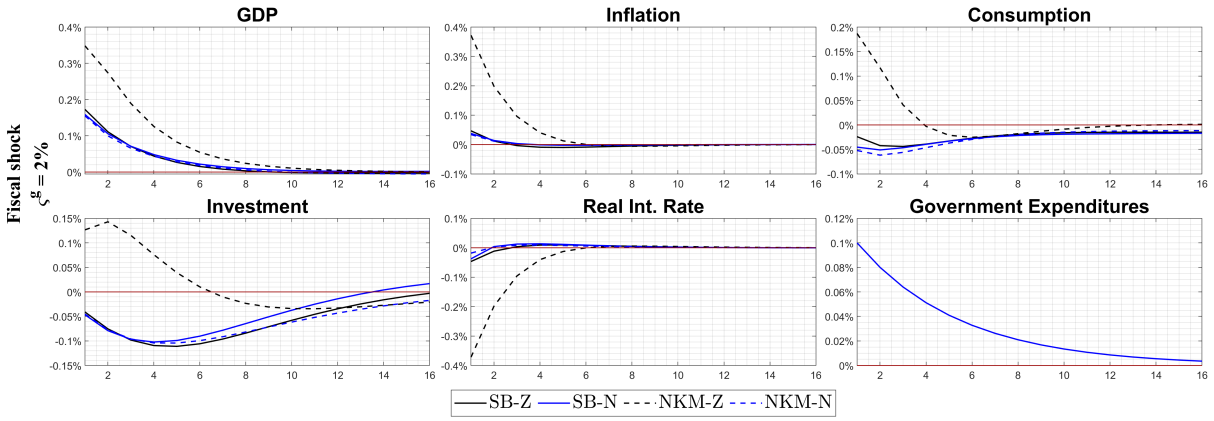

Figure 5: Impulse responses to a 2% increase in government expenditures with autocorrelation $\gamma_g = 0.8$ in the benchmark models (SB-Z: black solid line; SB-N: blue solid line) and in two NK-type specifications (NKM-Z: black dashed line; NKM-N: blue dashed line). The vertical axis reports percentage deviations from the steady state, while the response of government expenditures is adjusted by the steady-state ratio g/y.

supply side shocks above the ZLB. Notably, this property differs from the predictions of models where leverage constraints endogenously arise due to the presence of financial frictions (see e.g. Gertler and Karadi, 2011), which have been omitted in our analysis to isolate the effects of the capital requirement.

4.2.2. Government spending shocks

To demonstrate that capital requirements are also relevant for demand shocks, we further introduce government expenditures g_t, which are assumed to be financed through lump-sum taxation, for convenience. Government expenditures follow an AR(1) process: $g_t/g = (g_{t-1}/g)^{\gamma_g} \exp(\varsigma^g \epsilon_t^g)$.[10] Figure 5 presents the impulse responses to a positive government expenditure shock for four specifications of the model (SB-Z, NKM-Z, SB-N, and NKM-N).

According to a basic New Keynesian model, government spending tends to raise inflation and to partially crowd-out consumption and investment, such that the fiscal multiplier is less than one. This is confirmed by the blue dashed lines (NKM-N), where the fiscal multiplier equals the relation of the output and the government expenditure responses. The overall pattern of the NKM-N responses are closely related to the impulse responses for the versions with a binding capital requirement above and at the ZLB (SB-Z and SB-N). When the capital requirement is slack, the responses are however markedly different at the ZLB, revealing an impact multiplier clearly above one. This outcome is well-established (see e.g., Christiano et al., 2011) and relies on the inflationary impact of the fiscal shock, which implies a reduction of the real interest rate at the ZLB. Like for the supply side shocks, the real interest rate is decisive for aggregate demand under a slack capital requirement, such that consumption and also investment are crowded-in. Under a binding capital requirement, the real interest rate effect is muted, such

[10] Gíven that the model has been estimated without government expenditures, we apply a relatively small value (5%) for the steady-state output share g/y.

that the impact multiplier rather takes normal than extreme values, as reported for standard New Keynesian models (see e.g., Christiano et al., 2011).

5. Conclusion

Our paper presents a medium-scale macroeconomic model with banks that incorporates key features of U.S. monetary policy before and after the GFC. The model allows the central bank to control the federal funds rate, IOR, and the supply of reserves. It captures the transition from a pre-2008 regime characterized by binding reserve requirements and zero IOR to a post-2008 environment with satiated money demand and positive IOR. In addition, the model introduces a regulatory capital requirement that constrains bank deposit creation.

We estimate the model using a regime-switching structure that allows for the capital requirement to bind occasionally. The estimation reveals that the capital requirement has been permanently binding after 2008, even during the COVID-19 pandemic, despite temporary regulatory relaxation. We find that this result is rather driven by relatively low real interest rates, which increase the cost of equity creation, than by stricter regulatory standards introduced after the GFC. We further show that a binding capital requirement can fundamentally affect macroeconomic dynamics, especially at the ZLB. We show analytically that local equilibrium determinacy is not threatened by interest rate pegs when standard New Keynesian models predict indeterminacy. Notably, binding capital requirements do not restore monetary non-neutrality at the ZLB, which is consistent with missing inflation hikes after increased reserve supply since the GFC. Unlike standard models, a monetary policy regime under binding capital requirements is associated with conventional output and inflation responses to productivity and cost-push shocks at the ZLB. An assessment of the transmission of macroeconomic shocks shows that an accommodative monetary policy at the ZLB does not reverse the responses of output relative to an active interest rate policy. Above the ZLB, binding capital requirements do not systematically amplify responses to macroeconomic shocks.

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A Appendix

A1 Rational expectations equilibrium

A REE is a set of sequences of quantities $\{y_t,\, c_t,\, x_t,\, n_t,\, k_t,\, d_t,\, l_t,\, b_t,\, b_t^T,\, m_t,\, m_t^R,\, i_t^B\}$ and prices $\{w_t,\, mc_t,\, \eta_t,\, q_t,\, \pi_t,\, \lambda_t^H,\, \vartheta_t^H,\, \vartheta_t^B,\, \varkappa_t,\, \Lambda_{t,t+1},\, R_t^L,\, R_t^D,\, R_t^M,\, R_t^R,\, R_t^F,\, R_t\}$ satisfying the following conditions,

$$\psi_t^P(\mathcal{C}_t)^{-\sigma^c} - \beta h \mathbb{E}_t \psi_{t+1}^P(\mathcal{C}_{t+1})^{-\sigma^c} = \lambda_t^H + \vartheta_t^H, \tag{A1}$$

$$\lambda_t^H w_t = \chi \psi_t^N n_t^{\sigma^n}, \tag{A2}$$

$$\mu\vartheta_t^H/\lambda_t^H + \mathbb{E}_t\Lambda_{t,t+1}\pi_{t+1}^{-1}R_t^D = 1, \tag{A3}$$

$$\mu d_t \geq c_t, \quad \text{if } \vartheta_t^B = 0, \quad \text{or} \quad \mu d_t = c_t, \quad \text{if } \vartheta_t^B > 0, \tag{A4}$$

$$\Lambda_{t,t+1} = \beta\lambda_{t+1}^H/\lambda_t^H, \tag{A5}$$

$$\vartheta_t^B = R_t^M - R_t^R, \tag{A6}$$

$$\vartheta_t^B = R_t^F - R_t^R, \tag{A7}$$

$$\varkappa_t = 1 - \mathbb{E}_t\Lambda_{t,t+1}\pi_{t+1}^{-1}R_t, \tag{A8}$$

$$1 = \varkappa_t + \mathbb{E}_t\Lambda_{t,t+1}\pi_{t+1}^{-1}R_{t+1}^M, \tag{A9}$$

$$1 = \varkappa_t + \mathbb{E}_t\Lambda_{t,t+1}\pi_{t+1}^{-1}\left(R_{t+1}^L - \kappa_L\right), \tag{A10}$$

$$1 = (1+\phi_t)\varkappa_t + \varrho\vartheta_t^B + \mathbb{E}_t\Lambda_{t,t+1}\pi_{t+1}^{-1}R_t^D, \tag{A11}$$

$$m_{t-1}\pi_t^{-1} + i_t^B - \varrho d_t \geq 0, \quad \text{if } \vartheta_t^B = 0, \quad \text{or} \quad m_{t-1}\pi_t^{-1} + i_t^B - \varrho d_t = 0, \quad \text{if } \vartheta_t^B > 0, \tag{A12}$$

$$l_t + b_t + m_t - (1+\phi_t)d_t \geq 0, \quad \text{if } \varkappa_t = 0, \quad \text{or} \quad l_t + b_t + m_t - (1+\phi_t)d_t = 0, \quad \text{if } \varkappa_t > 0, \tag{A13}$$

$$l_t = \xi q_t k_t, \tag{A14}$$

$$k_t = (1-\delta)\,\psi_t^K k_{t-1} + x_t, \tag{A15}$$

$$y_t = a_t k_{t-1}^{\alpha} n_t^{1-\alpha}, \tag{A16}$$

$$(1-\alpha)\,mc_t y_t = w_t n_t, \tag{A17}$$

$$R_t^L\pi_t^{-1} = \left[\alpha mc_t y_t/k_{t-1} + q_t(1-\delta)\psi_t^K\right]/q_{t-1}, \tag{A18}$$

$$q_t\psi_t^X = 1 + \frac{\kappa_I}{2}\left(\frac{x_t}{x_{t-1}} - 1\right)^2 + \kappa_I\left(\frac{x_t}{x_{t-1}} - 1\right)\frac{x_t}{x_{t-1}} - \kappa_I\mathbb{E}_t\Lambda_{t,t+1}\left(\frac{x_{t+1}}{x_t} - 1\right)\left(\frac{x_{t+1}}{x_t}\right)^2\frac{\psi_t^X}{\psi_{t+1}^X}, \tag{A19}$$

$$\eta_t - 1 = \eta_t mc_t - \kappa_p\left(\frac{\pi_t}{\pi} - 1\right)\left(\frac{\pi_t}{\pi}\right) + \kappa_p\mathbb{E}_t\Lambda_{t,t+1}\frac{y_{t+1}}{y_t}\left(\frac{\pi_{t+1}}{\pi} - 1\right)\left(\frac{\pi_{t+1}}{\pi}\right), \tag{A20}$$

$$\eta_t = \eta(\psi_t^{\eta})^{-\kappa_p}, \tag{A21}$$

$$c_t + \left[\Psi\left(\frac{x_t}{x_{t-1}}\right) + 1\right]\frac{x_t}{\psi_t^X} + \frac{\kappa_p}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 y_t = y_t, \tag{A22}$$

$$m_t = m_{t-1}\pi_t^{-1} + i_t^B - m_t^R, \tag{A23}$$

$$m_t^R = \Omega_t m_t, \tag{A24}$$

$$b_t^T = m_t + b_t, \tag{A25}$$

$$b_t^T / b_{t-1}^T = \pi/\pi_t, \tag{A26}$$

$$m_t/m_{t-1} = \pi/\pi_t, \tag{A27}$$

$$R_t^M/R^M = \left(R_{t-1}^M/R^M\right)^{\rho_r} \left[(\pi_t/\pi)^{\gamma^{r,\pi}} (y_t/y_t^*)^{\gamma^{r,y}}\right]^{1-\rho_r}, \quad \text{if } R_t^M > 0, \quad \text{or} \quad R_t^M = 1, \tag{A28}$$

the transversality conditions, given exogenous sequences $\{a_t, \psi_t^P, \psi_t^X, \psi_t^N, \psi_t^K, \psi_t^\eta, \phi_t, \Omega_t\}$, $b_{-1} > 0$, $b_{-1}^T > 0$, and $m_{-1} > 0$. For the specifications NKM-N and NKM-Z used in Section 4.2, the reserve requirement (A12) and the capital requirement (A13) are slack, and money-related conditions (A23–A27) are omitted.

A2 Appendix to Section 3.

Suppose that Assumption 1 holds. Then, the resource constraint reduces to

$$c_t = \Phi_t y_t, \text{ where } \Phi_t = 1 - \frac{\kappa_p}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2, \tag{A29}$$

where Φ_t is an inefficiency wedge between consumption and inflation. Using aggregate production, $y_t = a_t n_t$, and (A29), to substitute out working time in (6), gives

$$\lambda_t = \chi c_t^{\sigma_n} a_t^{-\sigma_n} \Phi_t^{-\sigma_n} w_t^{-1}. \tag{A30}$$

Consider $\vartheta_t^B = 0$ and $\varkappa_t > 0$, such that reserve requirement is slack and the capital requirement binds, $(1+\phi)\, d_t = l_t + s_t$. According to Proposition 2, the household liquidity constraint is then also binding, $c_t = \mu d_t$. Further, using loan demand (32) and the resource constraint (A29), the binding capital requirement implies

$$c_t = \mu_t^{lev} s_t, \tag{A31}$$

where $\mu_t^{lev} = 1/\left(\frac{1+\phi}{\mu} - \frac{\xi'}{\Phi_t}\right) > 0$. Under Assumption 1, the household optimality condition (4) simplifies to $c_t^{-\sigma} = \lambda_t^H + \vartheta_t^H$. Substituting out the multiplier ϑ_t^H with (31) for $\vartheta_t^B = 0$, yields

$$c_t^{-\sigma} = \lambda_t \left(1 + \varkappa_t \frac{(1+\phi)}{\mu}\right). \tag{A32}$$

Further, labor demand (A17) simplifies to $w_t/a_t = mc_t$. Using the latter and $\widehat{\Phi}_t = 0$, we log-linearize (15), (25), (29), (A30), (A31), (A32) at the steady state, leading to

$$\mathbb{E}_t \widehat{\lambda}_{t+1} - E_t \widehat{\pi}_{t+1} - \widehat{\lambda}_t + \widehat{R}_t = -\frac{\varkappa}{1-\varkappa}\widehat{\varkappa}_t, \tag{A33}$$

$$\widehat{\pi}_t = \beta \mathbb{E}_t \widehat{\pi}_{t+1} + \Xi(\widehat{w}_t - \widehat{a}_t) - \widehat{\eta}_t/\kappa_p, \tag{A34}$$

$$\widehat{s}_t = \widehat{s}_{t-1} - \widehat{\pi}_t, \tag{A35}$$

$$\widehat{\lambda}_t = \sigma_n \widehat{c}_t - \sigma_n \widehat{a}_t - \widehat{w}_t, \tag{A36}$$

$$\widehat{c}_t = \widehat{s}_t, \tag{A37}$$

$$-\sigma \widehat{c}_t = \widehat{\lambda}_t + \kappa_\varkappa \widehat{\varkappa}_t, \tag{A38}$$

where $\Xi = \frac{\eta - 1}{\kappa_p}$ and $\kappa_\varkappa = \frac{\varkappa^{\frac{1+\phi}{\mu}}}{1+\varkappa^{\frac{(1+\phi)}{\mu}}} \in (0,1)$. Substituting out $\widehat{w}_t$ with (A36), and $\widehat{c}_t$ with (A37) in (A34), gives

$$\widehat{\pi}_t = \beta \mathbb{E}_t \widehat{\pi}_{t+1} + \Pi_s \widehat{s}_t - \Xi \widehat{\lambda}_t - \Pi_a \widehat{a}_t - \widehat{\eta}_t / \kappa_p. \tag{A39}$$

Combining (A37) and (A38) to $-\sigma \widehat{s}_t = \widehat{\lambda}_t + \kappa_\varkappa \widehat{\varkappa}_t$, and using the latter to substitute out $\widehat{\varkappa}_t$ in (A33), gives

$$\mathbb{E}_t \widehat{\lambda}_{t+1} - \mathbb{E}_t \widehat{\pi}_{t+1} + \widehat{R}_t = \digamma_s \widehat{s}_t + \digamma_\lambda \widehat{\lambda}_t, \tag{A40}$$

where $\Pi_a = \Xi(1+\sigma_n) > 0$, $\Pi_s = \Xi \sigma_n > 0$, $\digamma_s = \frac{\varkappa}{1-\varkappa} \kappa_\varkappa^{-1} \sigma > 0$ and $\digamma_\lambda = 1 + \frac{\varkappa}{1-\varkappa} \kappa_\varkappa^{-1} > 1$. Hence, (A35), (A39), and (A40) constitute a 3x3 system in $\{\widehat{\pi}_t\ \widehat{s}_t,\ \widehat{\lambda}_t\}$ for a sequence for $\widehat{R}_t$ given by monetary policy.

Proof of Proposition 4. Since there is one predetermined state variable $\{\widehat{s}_t\}$ and two non-predetermined variables $\{\widehat{\lambda}, \widehat{\pi}_t\}$, the REE is stable and locally determined if and only if there are two unstable and one stable eigenvalue. Substituting out $\widehat{R}_t^M$ with $\widehat{R}_t^M = \gamma_{r,\pi} \widehat{\pi}_t$ and summarizing the system (33)-(35) by

$$\begin{pmatrix} \beta & 0 & \Pi_s \\ 0 & 0 & 1 \\ \gamma_{r,\pi} - 1 & 1 & -\digamma_s \end{pmatrix} \begin{pmatrix} \widehat{\pi}_{t+1} \\ \widehat{\lambda}_{t+1} \\ \widehat{s}_t \end{pmatrix} = \begin{pmatrix} 1 & \Xi & 0 \\ -1 & 0 & 1 \\ 0 & \digamma_\lambda & 0 \end{pmatrix} \begin{pmatrix} \widehat{\pi}_t \\ \widehat{\lambda}_t \\ \widehat{s}_{t-1} \end{pmatrix} + \begin{pmatrix} \Pi_a \\ 1/\kappa_p \\ 0 \end{pmatrix} \begin{pmatrix} \widehat{a}_t \\ \widehat{\eta}_t \\ 0 \end{pmatrix},$$

we define the matrix $\mathbb{A}$ as

$$\mathbb{A} = \begin{pmatrix} \beta & 0 & \Pi_s \\ 0 & 0 & 1 \\ \gamma_{r,\pi} - 1 & 1 & -\digamma_s \end{pmatrix}^{-1} \begin{pmatrix} 1 & \Xi & 0 \\ -1 & 0 & 1 \\ 0 & \digamma_\lambda & 0 \end{pmatrix}.$$

Characteristic polynomial of $\mathbb{A}$ is given by $G(X) = X^3 - \frac{\beta + \Xi + \Pi_s - \Xi \gamma_{r,\pi} + \beta \digamma_\lambda + 1}{\beta} X^2 + \frac{\Xi + \digamma_\lambda - \Xi \gamma_{r,\pi} + \Xi \digamma_s + \beta \digamma_\lambda + \Pi_s \digamma_\lambda + 1}{\beta} X - \frac{\digamma_\lambda}{\beta}$ with

$$G(0) = -\frac{\digamma_\lambda}{\beta} < -1, \quad G(1) = \frac{\Xi \digamma_s + \Pi_s (\digamma_\lambda - 1)}{\beta} > 0,$$
$$G(-1) = -\frac{\Xi \digamma_s + (1 + \digamma_\lambda)(2(1+\beta) + \Pi_s) + 2\Xi(1 - \rho_\pi)}{\beta}.$$

Hence, $G(-1)$ is negative for $\gamma_{r,\pi} < 1 + \frac{\Xi \digamma_s + (1+\digamma_\lambda)(2(1+\beta)+\Pi_s)}{2\Xi}$, or using $\Pi_s = \Xi \sigma_n$,

$$\gamma_{r,\pi} < 1 + \frac{\digamma_s + (1 + \digamma_\lambda)\sigma_n}{2} + \frac{(1 + \digamma_\lambda)(1+\beta)}{\Xi}. \tag{A41}$$

Given that $G(0) = -\digamma_\lambda/\beta < -1$, there exists at least one unstable eigenvalue. Further, $G(1) > 0$ implies that there is at least one stable eigenvalue between zero and one. For $G(-1) < 0$, the third eigenvalue is unstable. Hence, the system is locally stable and uniquely determined iff (A41) is satisfied. ■

Proof of Proposition 5. Suppose that (36) is satisfied and productivity $\widehat{a}_t$ follows an AR(1) process, $\widehat{a}_t = \rho_a \widehat{a}_{t-1} + \varepsilon_{a,t}$ with $\rho_a \in (0,1)$. Further neglecting cost push shocks $\widehat{\eta}_t = 0$, the fundamental solution to the system (33)-(35) with $\widehat{R}_t^M = \gamma_{r,\pi}\widehat{\pi}_t$ can be written as

$$\widehat{\pi}_t = \delta_{\pi,s}\widehat{s}_{t-1} + \delta_{\pi,a}\widehat{a}_t, \tag{A42}$$

$$\widehat{\lambda}_t = \delta_{\lambda,s}\widehat{s}_{t-1} + \delta_{\lambda,a}\widehat{a}_t, \tag{A43}$$

$$\widehat{s}_t = \rho_s \widehat{s}_{t-1} + \delta_{s,a}\widehat{a}_t, \tag{A44}$$

where we know that $\rho_s \in (0,1)$, since the unique stable root of the system (33)-(35) lies between one and zero. To identify the six unknown coefficients in (A42)-(A44), replace the endogenous variables with the fundamental solutions. Substituting out $\mathbb{E}_t\widehat{\pi}_{t+1}$, $\widehat{\pi}_t$, $\mathbb{E}_t\widehat{\lambda}_{t+1}$, $\widehat{\lambda}_t$ and $\widehat{s}_t$ with the fundamental solutions (A42)-(A44) in (33), and using $\mathbb{E}_t\varepsilon_{a,t+1} = 0$, yields

$$\left[(\delta_{\pi,s} + \Xi\delta_{\lambda,s}) - \beta\delta_{\pi,s}\rho_s - \Pi_s\rho_s\right]\widehat{s}_{t-1} = \left[\beta\delta_{\pi,s}\delta_{s,a} + \beta\delta_{\pi,a}\rho_a + \Pi_s\delta_{s,a} - (\delta_{\pi,a} + \Xi\delta_{\lambda,a} + \Pi_a)\right]\widehat{a}_t,$$

which can only be satisfied if the following equalities hold

$$\begin{aligned} &i.) \quad (1-\beta\rho_s)\,\delta_{\pi,s} = \Pi_s\rho_s - \Xi\delta_{\lambda,x}, \\ &ii.) \quad (\beta\delta_{\pi,s} + \Pi_s)\,\delta_{s,a} = (1-\beta\rho_a)\,\delta_{\pi,a} + \Xi\delta_{\lambda,a} + \Pi_a. \end{aligned}$$

Substituting out $\widehat{\pi}_t$ and $\widehat{s}_t$ with the fundamental solutions (A42)-(A44) in (35), yields $(\delta_{s,a} + \delta_{\pi,a})\,\widehat{a}_t = (1 - \rho_s - \delta_{\pi,s})\,\widehat{s}_{t-1}$, which can only be satisfied if the following equalities hold

$$\begin{aligned} &iii.) \quad \delta_{\pi,s} = (1-\rho_s) > 0, \\ &iv.) \quad -\delta_{\pi,a} = \delta_{s,a}. \end{aligned}$$

Substituting out $\mathbb{E}_t\widehat{\pi}_{t+1}$, $\widehat{\pi}_t$, $\mathbb{E}_t\widehat{\lambda}_{t+1}$, $\widehat{\lambda}_t$ and $\widehat{s}_t$ with the fundamental solutions (A42)-(A44) in (34) and using $\mathbb{E}_t\varepsilon_{a,t+1} = 0$, yields

$$\begin{aligned} 0 = \; & (\delta_{\lambda,s}\rho_s - (1-\gamma_{r,\pi})\,\delta_{\pi,s}\rho_s - \digamma_s\rho_s - \digamma_\lambda\delta_{\lambda,s})\,\widehat{s}_{t-1} \\ & + (\delta_{\lambda,s}\delta_{s,a} + \delta_{\lambda,a}\rho_a - (1-\gamma_{r,\pi})\,\delta_{\pi,s}\delta_{s,a} - (1-\gamma_{r,\pi})\,\delta_{\pi,a}\rho_a - \digamma_s\delta_{s,a} - \digamma_\lambda\delta_{\lambda,a})\,\widehat{a}_t, \end{aligned}$$

which can only be satisfied if the following equalities hold

$$\begin{aligned} &v.) \quad \delta_{\lambda,s} = -\frac{\rho_s}{\digamma_\lambda - \rho_s}\left((1-\gamma_{r,\pi})\,\delta_{\pi,s} + \digamma_s\right) < 0, \\ &vi.) \quad (\delta_{\lambda,s} - (1-\gamma_{r,\pi})\,\delta_{\pi,s} - \digamma_s)\,\delta_{s,a} = (\digamma_\lambda - \rho_a)\,\delta_{\lambda,a} + (1-\rho_\pi)\,\delta_{\pi,a}\rho_a. \end{aligned}$$

The unknown coefficients in (A42)-(A44) can be determined by the equations $i.) - vi.)$. Substituting out $\delta_{\pi,s} = (1-\rho_s)$ and $\delta_{s,a}$ with $iii.)$ and $iv.)$ in $ii.)$, yields

$$\delta_{\pi,a} = -\frac{\Xi}{(\beta(1-\rho_s)+\Pi_s)+(1-\beta\rho_a)}\delta_{\lambda,a} - \frac{\Pi_a}{(\beta(1-\rho_s)+\Pi_s)+(1-\beta\rho_a)}. \tag{A45}$$

Substituting out $\delta_{\pi,s}$, $\delta_{s,a}$ and $\delta_{\lambda,s}$ with $iii.)$, $iv.)$ and $v.)$ in $vi.)$, further yields

$$\delta_{\pi,a} = \frac{(\digamma_\lambda - \rho_a)}{(1-\gamma_{r,\pi})\left((1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s} - \rho_a\right) + \digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}}\delta_{\lambda,a}. \tag{A46}$$

Hence, the coefficients $\delta_{\pi,a}$ and $\delta_{\lambda,a}$ have the same sign if

$$\digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s} > (1-\gamma_{r,\pi})\left(\rho_a - (1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}\right). \tag{A47}$$

For $\rho_a < (1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}$, the inequality (A47) is satisfied if

$$\gamma_{r,\pi} < 1 + \frac{\digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}}{(1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s} - \rho_a}. \tag{A48}$$

For $\rho_a > (1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}$, the inequality (A47) requires $\gamma_{r,\pi} > 1 - \digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}/(\rho_a-(1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s})$, which is satisfied for $\gamma_{r,\pi} \geq 0$, $\rho_a \in (0,1)$, and $\rho_s \in (0,1)$, given that the second term on the RHS is larger than one. To see this, use that

$$\digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}\Big/\left(\rho_a - (1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}\right) > 1 \;\Leftrightarrow\; H(\rho_s) > \rho_a,$$

where $H(\rho_s) = \digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s} + (1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}$ and $H'(\rho_s) = \digamma_\lambda\frac{\digamma_s-\digamma_\lambda+1}{(\digamma_\lambda-\rho_s)^2} > 0$, such that $H(\rho_s) > H(0) = \digamma_s + 1$. Finally, substitute out $\delta_{\pi,a}$ in (A45) with (A46), yielding

$$\begin{aligned}\delta_{\lambda,a} \;=\; & -\left[\frac{(\digamma_\lambda-\rho_a)}{(1-\gamma_{r,\pi})\left((1-\rho_s)\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}-\rho_a\right)+\digamma_s\frac{\digamma_\lambda}{\digamma_\lambda-\rho_s}} + \frac{\Xi}{(\beta(1-\rho_x)+\Pi_s)+(1-\beta\rho_a)}\right]^{-1} \\ & \cdot\frac{\Pi_a}{(\beta(1-\rho_s)+\Pi_s)+(1-\beta\rho_a)}.\end{aligned}$$

The term in the square brackets is positive if (A48) is satisfied. Then, $\delta_{\lambda,a}$ as well as $\delta_{\pi,a}$ (see A46) are negative, such that $\delta_{s,a}$ is positive according to $iv.)$. ■

A3 Supply of public sector liabilities

In this appendix, we provide evidence for the supply of public sector liabilities (29). Firstly, we provide a description of the data used in the regression analysis for the specification of public sector liabilities $S_t = M_t + B_t$. In particular, for Specification (1), S_t is defined as reserves (WRESBAL) plus bills issued by the public sector (from the Fiscal database), excluding holdings

Table A1: Regression Results

	Specification (1)		Specification (2)		Specification (3)	
	OLS	2SLS	OLS	2SLS	OLS	2SLS
$\widehat{\nu}^B_{t-1}$	0.008	-0.774	0.055	-0.405	0.137	0.106
	(0.102)	(2.091)	(0.109)	(0.981)	(0.110)	(0.596)
$\widehat{m}_t$	0.096	0.174	0.050	0.046	0.087	-0.025
	(0.058)	(0.341)	(0.033)	(0.107)	(0.069)	(0.174)
$\widehat{\pi}_t$	-2.463	-13.86	-1.687*	-6.287	-2.278	-6.980
	(1.590)	(18.12)	(0.900)	(5.156)	(1.841)	(6.786)
$\widehat{y}_t$	-0.153	-0.567	-0.198	-0.419	-0.007	0.091
	(0.379)	(1.990)	(0.216)	(0.628)	(0.439)	(0.703)
$\mathcal{D}_t$	0.314***	0.434*	0.130***	0.141	0.318***	0.444***
	(0.473)	(1.147)	(0.032)	(0.117)	(0.067)	(0.131)
R^2	0.450		0.378		0.410	
p-value (J-stat)		0.404		0.578		0.266

Notes: *** Indicates that the t-values of coefficients (standard error in parentheses) are significant at the 1% level; ** at the 5% level; and * at the 10% level. Instrument variables used in 2SLS are $\widehat{\nu}^B_{t-2}$, $\widehat{m}_{t-1}$, $\widehat{\pi}_{t-1}$, $\widehat{y}_{t-1}$, the shadow rate, and the log-deviation of per capita nominal government expenditure growth.

by the central bank (BOGZ1FL713061113Q), foreigners (BOGZ1FL263061110Q), and the non-financial sector (BOGZ1FL143061113Q). For Specification (2), S_t is defined as total treasury securities held by the domestic financial sector (FBTSAAQ027S) minus holdings of the central bank (BOGZ1FL713061103Q) plus reserve balances. For Specification (3), S_t is defined as short-term securities held by the domestic financial sector (BOGZ1FL794022415Q) minus open market papers (FBOMPAQ027S) and holdings of the central bank (BOGZ1FL713061113Q), plus reserve balances.

The data span from 2009Q1 to 2024Q3, which is consistent with the sample for the permanently binding capital requirement in Section 4. To examine the supply of public sector liabilities, we consider a specification for the growth rate which allows for various contingencies:

$$\hat{\nu}^B_t = a_1\hat{\nu}^B_{t-1} + a_2\hat{m}_t + a_3\hat{\pi}_t + a_4\hat{y}_t + a_5\mathcal{D}_t + \varepsilon_t, \tag{A49}$$

where $\hat{\nu}^B_t$ and $\hat{m}_t$ denote the log-deviations of ν^B_t and m_t from the respective sample average (denoted by a bar), i.e., $\hat{\nu}^B_t = \log(\nu^B_t/\bar{\nu}^B)$ and $\hat{m}_t = \log(m_t/\bar{m})$. Inflation deviations from the target value are given by $\hat{\pi}_t = \log(\pi_t/\pi)$, while the output gap is defined as deviations of real GDP from its potential level (GDPPOT): $\hat{y}_t = \log(y_t/y^*_t)$. The dummy variable $\mathcal{D}_t$ accounts for the initial phase of the COVID-19 pandemic.[11]

Table A1 presents sets of regression results based on the three specifications for the growth rate of S_t, which indicate that the coefficients with respect to reserve balances, inflation, and the

[11]Specifically, we set $\mathcal{D}_t$ to 1 at 2020Q1-Q2, ensuring that the estimation results reflect structural relationships rather than short-term fluctuations driven by disruptions at the onset of the COVID-19 pandemic.

Table A2: Regression Results

	Specification (1)		Specification (2)		Specification (3)	
	OLS	2SLS	OLS	2SLS	OLS	2SLS
$\log \nu_{t-1}^B$	-0.020	0.317	0.033	0.200	0.112	0.134
	(0.101)	(0.306)	(0.111)	(0.340)	(0.111)	(0.307)
$\widehat{m}_t$	0.079	-0.082	0.044	-0.047	0.074	-0.110
	(0.058)	(0.110)	(0.033)	(0.054)	(0.069)	(0.110)
$\log \pi_t$	-1.154	2.167	-1.189	-0.679	-1.112	-0.732
	(1.720)	(5.829)	(0.967)	(2.730)	(2.019)	(5.598)
$\widehat{y}_t$	-0.634	-0.547	-0.386	-0.452	-0.415	-0.699
	(0.457)	(1.041)	(0.266)	(0.515)	(0.538)	(0.973)
$\mathcal{D}_t$	0.324^{***}	0.625^{***}	0.134^{***}	0.224^{***}	0.329^{***}	0.516^{***}
	(0.056)	(0.157)	(0.032)	(0.071)	(0.067)	(0.138)
$\mathtt{b}_0$	0.010	-0.026	0.021^{**}	0.011	0.008	-0.004
	(0.017)	(0.049)	(0.010)	(0.024)	(0.020)	(0.048)
R^2	0.479		0.393		0.425	
p-value (J-stat)		0.817		0.664		0.910

Notes: *** Indicates that the t-values of coefficients (in parentheses) are significant at the 1% level; ** at the 5% level; and * at the 10% level. Instrument variables used in 2SLS are $\log \nu_{t-2}^B$, $\widehat{m}_{t-1}$, $\log \pi_{t-1}$, $\widehat{y}_{t-1}$, the shadow rate, the log-deviation of per capita nominal government expenditure growth, and a constant term.

output gap are not statistically significant. The significant coefficient on the dummy variable captures exceptional effects at the start point of COVID-19. To address a potential endogeneity, particularly the possibility that output gap and reserve balance may be affected by public sector liabilities, we conduct robustness analyses using two-stage least squares (2SLS) estimations. For the instrument selection, in addition to the first lag of endogenous variables, we include the shadow rate (Wu and Xia, 2016) and the growth of government expenditures. The Hansen J-statistic shows that the instruments are valid and the model is well specified. Overall, the results remain qualitatively unchanged, showing that $\hat{\nu}_t^B$ remains insignificantly related to reserves and macroeconomic conditions.

$$\log \nu_t^B = \mathtt{b}_0 + \mathtt{b}_1 \log \nu_{t-1}^B + \mathtt{b}_2 \hat{m}_t + \mathtt{b}_3 \log \pi_t + \mathtt{b}_4 \hat{y}_t + \mathtt{b}_5 \mathcal{D}_t + \varepsilon_t. \tag{A50}$$

We next consider an alternative regression specification (A50) in which both ν_t^B and inflation are expressed in logs rather than in deviations from average (target value for inflation). We further include a constant term in all regressions to ensure unbiased estimations. Table A2 presents the estimation results using the same three specifications for ν_t^B. Consistent with the findings above, the growth rate of public sector liabilities is not significantly influenced by reserve supply, inflation, or the output gap. We therefore apply an exogenous growth rate of S_t as specified in (29).

A4 Appendix to the regime switching model

A REE of the regime-switching model is a set of sequences of quantities $\{y_t,\ c_t,\ x_t,\ n_t,\ k_t,\ d_t,\ l_t,\ s_t,\ \epsilon_t,\ e_t\}$ and prices $\{w_t,\ mc_t,\ \eta_t,\ q_t,\ \pi_t,\ \lambda_t^H,\ \vartheta_t^H,\ \varkappa_t,\ \Lambda_{t,t+1},\ R_t^L\}$, given the exogenous sequences $\{a_t,\ \psi_t^P,\psi_t^X,\psi_t^N,\psi_t^K,\psi_t^\eta,\ \phi_t,\ R_t^M,\ \nu_t^B\}$ satisfing (A1), (A2), (A4), (A5), (A9), (A10), (A14)-(A22),

$$\mu\vartheta_t^H/\lambda_t^H = \kappa_d + (1+\phi_t)\,\varkappa_t,\ \ \mathbf{z}(\mathcal{S}_t^{lev})\varkappa_t + \left(1-\mathbf{z}(\mathcal{S}_t^{lev})\right)(\epsilon_t-\phi_t) = 0,$$

$$\epsilon_t = e_t/d_t,\ \ e_t = l_t + s_t - d_t,\ \ R_t^M/R^M = \exp\left(\varsigma_r\epsilon_t^R\right),\ \ s_t/s_{t-1} = \nu_t^B/\pi_t,$$

$$\widetilde{\varkappa} = \varkappa_t - \bar{\varkappa},\ \ prob_t^{S,B} = [1+\mathcal{O}_{s,b}\exp(-\theta_{s,b}\varkappa_t)]^{-1},\quad prob_t^{B,S} = [1+\mathcal{O}_{b,s}\exp(\theta_{b,s}\widetilde{\varkappa}_t)]^{-1},$$

$$\nu_t^B/\nu^B = \exp\left(\varsigma^b(\mathcal{S}_t^{vol})\epsilon_t^B\right),\ \ a_t = (a_{t-1})^{\rho_a}\exp\left(\varsigma^a(\mathcal{S}_t^{vol})\epsilon_t^A\right),$$

$$\psi_t^P = (\psi_{t-1}^P)^{\rho_p}\exp\left(\varsigma^p(\mathcal{S}_t^{vol})\epsilon_t^P\right),\ \ \psi_t^X = (\psi_{t-1}^X)^{\rho_x}\exp\left(\varsigma^x(\mathcal{S}_t^{vol})\epsilon_t^X\right),$$

$$\psi_t^N = (\psi_{t-1}^N)^{\rho_n}\exp\left(\varsigma^n(\mathcal{S}_t^{vol})\epsilon_t^N\right),\ \ \psi_t^K = (\psi_{t-1}^K)^{\rho_k}\exp\left(\varsigma^k(\mathcal{S}_t^{vol})\epsilon_t^K\right),$$

$$\psi_t^\eta = (\psi_{t-1}^\eta)^{\rho_\eta}\exp\left(\varsigma^\eta(\mathcal{S}_t^{vol})\epsilon_t^\eta\right),\ \ \phi_t/\phi = (\phi_{t-1}/\phi)^{\rho_\phi}\exp(\varsigma^\phi\epsilon_t^\phi).$$

Steady-state of the regime switching model To solve for the steady-state of the model, we proceed by imposing that all variables are constant over time. The steady-state values of the shocks are normalized such that $a_t = \psi_t^P = \psi_t^X = \psi_t^N = \psi_t^K = \psi_t^\eta = 1$. Taking the inflation target π and the nominal interest rate in state B $R^M(B)$ as given, the regime-dependent steady-state value of R^M is determined by,

$$R^M = \mathbf{z}(\mathcal{S}^{lev})\pi/\beta + (1-\mathbf{z}(\mathcal{S}^{lev}))R^M(B).$$

Banks' optimality conditions and the definition of distance $\widetilde{\varkappa}$ ($\Lambda=\beta$), imply $\varkappa = 1-\beta R^M\pi^{-1}$, $\bar{\varkappa} = 1-\beta R^M(B)\pi^{-1}$, $\widetilde{\varkappa} = \varkappa - \bar{\varkappa}$. Firms' optimality conditions and production imply,

$$mc = \frac{\eta-1}{\eta},\qquad \frac{y}{k} = \frac{R^L\pi^{-1}-(1-\delta)q}{\alpha mc},\qquad \frac{k}{n} = \left(\frac{y}{k}\right)^{\frac{1}{\alpha-1}},\qquad \frac{y}{n} = \left(\frac{k}{n}\right)^{\alpha},$$

where $q=1$. Capital accumulation and market-clearing further imply,

$$\frac{x}{n} = \delta\frac{k}{n},\quad \frac{l}{n} = \xi\frac{k}{n},\quad w = (1-\alpha)\,mc\frac{y}{n},\quad \frac{c}{n} = \frac{y}{n} - \frac{x}{n}. \tag{A51}$$

Combining the first-order conditions for deposits of households and banks, yields

$$\frac{\vartheta^H}{\lambda^H} = \frac{\kappa_d + (1+\phi)\varkappa}{\mu}. \tag{A52}$$

We set the parameter χ such that the steady-state level of labor supply corresponds to a normalized 8-hour workday in the state S, $n(S) = 0.33$. Then, $c(S)$ and $w(S)$ follow from the

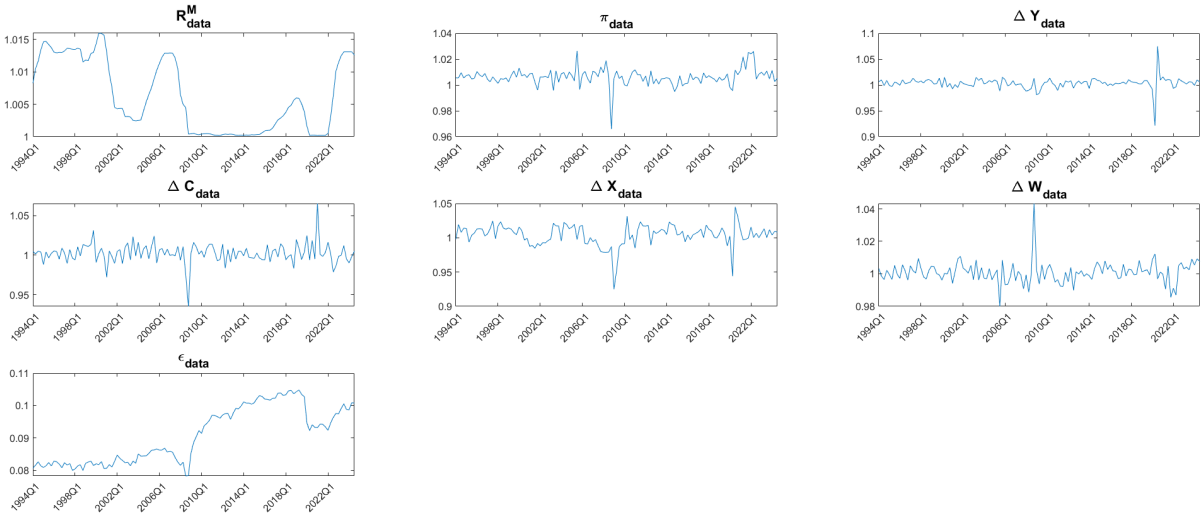

Figure A1: Data used in the model estimation

ratios in (A51). The household's optimality conditions imply

$$\lambda^H(S) = \left[(1-\beta h)\left((1-c(S))^{-\sigma}\right)\right](1+\kappa_d/\mu)^{-1}, \quad \chi = \lambda^H(S)w(S)n(S)^{-\sigma_n}.$$

The regime-dependent steady-state value of labor is identified accordingly:

$$n = \left[\frac{w\,(1-\beta h)\left((1-h)\frac{c}{n}\right)^{-\sigma}}{\chi\,(1+(\kappa_d+(1+\phi)\varkappa)/\mu)}\right]^{\frac{1}{(\sigma^n+\sigma)}} \tag{A53}$$

The regime-dependent steady-state values of $\{c,\ y,\ x,\ l,\ k,\ w,\ \vartheta^H,\ \lambda^H\}$ are determined by repeating (A51)- (A52) using (A53). Finally, the steady state values for deposits, public sector liabilities, and equity are determined by $d = \mu^{-1}c$, $s = (1+\epsilon)d - l$, $e = l + s - d$.

A5 Appendix to the model estimation

The empirical analysis draws primarily on macroeconomic data from the Federal Reserve Economic Data (FRED) database for the U.S. economy. The observed sequences for the nominal interest rate and inflation used in the Bayesian estimation corresponds to the nominal effective federal funds rate (FEDFUNDS) and the quarter-over-quarter change in the consumer price index (CPIAUCSL). The codes in parentheses refer to the corresponding identifiers in the FRED database and are consistently used throughout this section. Per capita data are derived by adjusting raw values with the population level (POPTHM). Non-seasonally adjusted raw data are processed using the X-12 seasonal adjustment method conducted in Eviews12. Consumption corresponds to personal non-durable goods consumption expenditures (PCEND), and the final output is measured by gross domestic product (GDP). The real growth rate of wages is calculated using hourly earnings (USAHOUREAQISMEI), adjusted for CPI inflation. The leverage ratio is constructed using the Tier 1 leverage ratio, which is defined as Tier 1 Capital (QBPB-

Table A3: Prior and Posterior Distribution of Parameters

Parameters	Prior		Posterior (DSGE-RS)				Posterior (DSGE-B)				Posterior (DSGE-S)			
	initial	distribution	mode	mean	5%	95%	mode	mean	5%	95%	mode	mean	5%	95%
bgp	$1.015^{\frac{1}{4}}$	G(1,1.02)	$1.013^{\frac{1}{4}}$	$1.014^{\frac{1}{4}}$	$1.009^{\frac{1}{4}}$	$1.018^{\frac{1}{4}}$	$1.010^{\frac{1}{4}}$	$1.008^{\frac{1}{4}}$	$1.002^{\frac{1}{4}}$	$1.014^{\frac{1}{4}}$	$1.009^{\frac{1}{4}}$	$1.008^{\frac{1}{4}}$	$1.000^{\frac{1}{4}}$	$1.014^{\frac{1}{4}}$
h	0.75	B(0.55,0.95)	0.31	0.29	0.18	0.39	0.29	0.31	0.20	0.43	0.30	0.30	0.22	0.40
σ^n	0.276	B(0.22,0.32)	0.23	0.21	0.17	0.26	0.23	0.21	0.18	0.24	0.17	0.16	0.15	0.18
α	0.333	B(0.2,0.4)	0.42	0.43	0.39	0.46	0.44	0.44	0.40	0.47	0.53	0.53	0.51	0.54
κ_I	5	N(3,8)	3.55	3.62	2.52	4.77	2.92	3.23	2.25	4.22	3.41	3.33	2.96	3.73
ϖ	0.6	B(0.5,0.7)	0.66	0.67	0.60	0.73	0.65	0.67	0.61	0.73	0.73	0.73	0.66	0.78
η	6	N(4,8)	7.63	7.63	6.90	9.18	7.68	7.65	5.96	9.16	7.34	7.55	7.20	7.92
ρ_a	0.75	B(0.6,0.9)	0.79	0.77	0.69	0.85	0.81	0.82	0.70	0.92	0.93	0.95	0.88	0.98
ρ_η	0.75	B(0.6,0.9)	0.85	0.83	0.76	0.90	0.86	0.85	0.79	0.91	0.89	0.89	0.87	0.91
ρ_x	0.5	B(0.2,0.8)	0.46	0.43	0.34	0.53	0.50	0.47	0.33	0.58	0.57	0.55	0.50	0.60
ρ_n	0.5	B(0.2,0.8)	0.90	0.89	0.85	0.93	0.21	0.33	0.09	0.56	0.93	0.91	0.87	0.94
ρ_k	0.5	B(0.2,0.8)	0.14	0.15	0.06	0.24	0.10	0.16	0.03	0.31	0.10	0.11	0.04	0.17
ρ_p	0.5	B(0.2,0.8)	0.29	0.31	0.13	0.47	0.92	0.93	0.89	0.96	0.98	0.98	0.97	0.98
ρ_ϕ	0.5	B(0.2,0.8)	0.87	0.85	0.78	0.92	0.87	0.87	0.80	0.94				
$100\varsigma_{a,L}$	2	G(0.5,5)	0.32	0.47	0.14	0.79	0.34	0.53	0.09	0.99	0.63	0.73	0.57	0.91
$100\varsigma_{a,H}$	2	G(0.5,5)	1.12	1.40	0.51	2.32	1.22	1.84	0.45	3.20	2.51	2.34	1.84	2.95
$100\varsigma_{b,L}$	2	G(0.5,5)	0.69	0.73	0.58	0.89	0.65	0.70	0.53	0.87	0.19	0.19	0.10	0.28
$100\varsigma_{b,H}$	2	G(0.5,5)	4.37	4.74	3.02	6.30	4.12	4.68	3.36	6.15	1.87	2.12	1.68	2.55
$100\varsigma_{\eta,L}$	2	G(0.5,5)	0.42	0.41	0.30	0.53	0.44	0.40	0.26	0.55	0.28	0.30	0.19	0.42
$100\varsigma_{\eta,H}$	2	G(0.5,5)	1.33	1.54	0.79	2.13	1.40	1.16	0.81	1.61	1.28	1.22	0.76	1.63
$100\varsigma_{k,L}$	5	G(1,10)	1.95	1.65	1.36	2.54	1.87	1.86	1.37	2.34	1.19	1.26	0.99	1.57
$100\varsigma_{k,H}$	5	G(1,10)	7.06	7.63	4.76	10.40	6.79	7.25	4.64	9.79	6.66	6.62	6.06	7.31
$100\varsigma_{x,L}$	5	G(1,10)	2.06	2.12	1.67	2.55	1.82	1.96	1.43	2.46	1.30	1.36	1.16	1.57
$100\varsigma_{x,H}$	5	G(1,10)	6.99	7.38	4.40	10.35	6.79	6.85	4.71	8.96	5.07	5.05	4.77	5.29
$100\varsigma_{n,L}$	2	G(0.5,5)	0.86	0.89	0.64	1.14	0.84	0.92	0.66	1.19	0.28	0.32	0.24	0.41
$100\varsigma_{n,H}$	2	G(0.5,5)	3.66	3.99	2.58	5.35	1.24	2.22	0.92	3.45	2.23	2.47	1.87	3.13
$100\varsigma_{p,L}$	2	G(0.5,5)	1.95	2.19	1.24	2.89	0.64	0.69	0.27	1.07	1.62	1.62	1.29	1.93
$100\varsigma_{p,H}$	2	G(0.5,5)	1.96	3.11	1.60	4.62	4.22	3.49	1.97	4.95	3.05	3.05	2.56	3.59
$100\varsigma_\phi$	2	G(1,10)	1.53	1.51	1.29	1.75	1.53	1.55	1.33	1.72				
$100\varsigma_r$	0.1	IG(0.01,0.5)	0.40	0.40	0.35	0.46	0.42	0.42	0.36	0.48	0.42	0.42	0.36	0.48
$prob^{L,H}$	0.05	B(0.02,0.08)	3.66%	3.76%	3.15%	4.59%	3.47%	2.33%	1.48%	3.29%	4.27%	4.30%	4.06%	4.57%
$prob^{H,L}$	0.10	B(0.05,0.15)	9.56%	9.88%	7.46%	12.2%	9.24%	9.69%	8.74%	10.6%	10.6%	10.7%	10.3%	11.1%
$\mathcal{O}_{s,b}$	26	N(20,32)	26.58	26.93	26.17	27.66								
$\mathcal{O}_{b,s}$	26	N(20,32)	27.87	26.12	24.09	28.00								
Log MDD (Laplace)			1225.60				1232.47				1196.98			

Note: Abbreviations for prior distributions include B (Beta), N (Normal), G (Gamma), and IG (Inverse Gamma). Values in parentheses indicate the lower and upper bounds of the 90% confidence interval for the quantile prior. The log marginal data density is computed using the Laplace approximation. Given that $\kappa_p = (\eta-1)\varpi/(1-\varpi)/(1-\beta\varpi)$ under first order approximation, we estimate the Calvo parameter ϖ as a proxy.

SLEVK) divided by Total Assets (QBPBSTAS) for FDIC-regulated banks. The raw investment data is sourced from the OECD database, which is represented by gross fixed capital formation for the total economy. The processed data are presented in Figure A1.

The connection between model variables and observed data is established via the following measurement equations.

$$\begin{bmatrix} \log R^M_{t,data} \\ \log \pi_{t,data} \\ \log \epsilon_{t,data} \\ \Delta \log y_{t,data} \\ \Delta \log c_{t,data} \\ \Delta \log x_{t,data} \\ \Delta \log w_{t,data} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \log bgp \\ \log bgp \\ \log bgp \\ \log bgp \end{bmatrix} + \begin{bmatrix} \log R^M_t \\ \log \pi_t \\ \log \epsilon_t \\ \log y_t - \log y_{t-1} \\ \log c_t - \log c_{t-1} \\ \log x_t - \log x_{t-1} \\ \log w_t - \log w_{t-1} \end{bmatrix} \tag{A54}$$

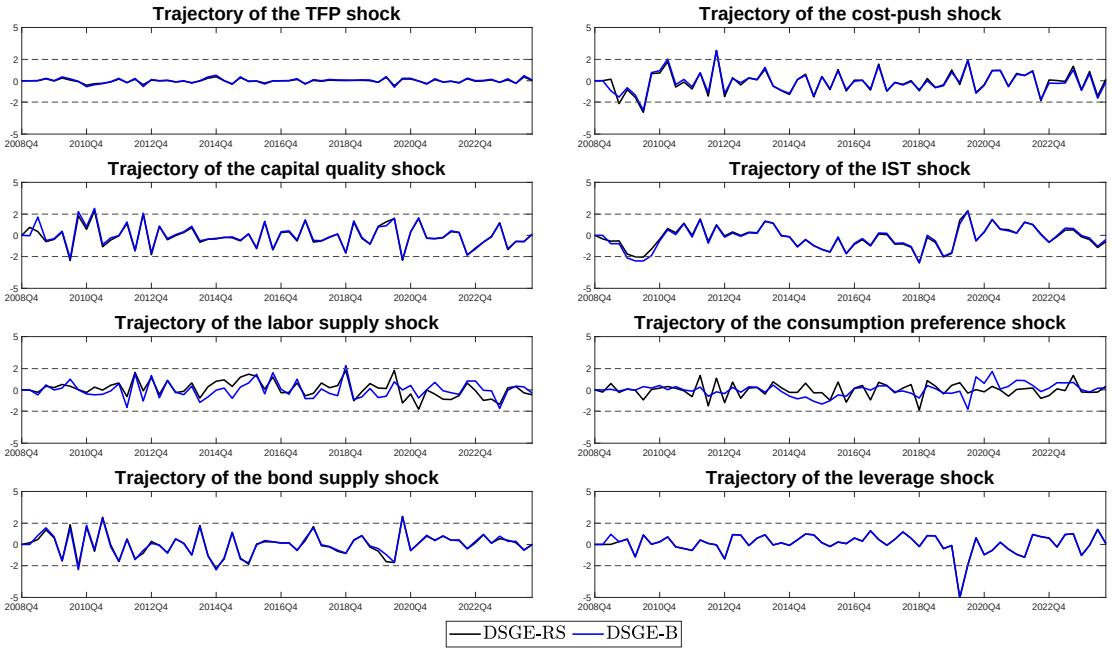

Figure A2: Estimated model implied shocks. The figure plots the smoothed trajectories of model-implied shocks, along with a two-standard-deviation band (black dashed lines).

Table A3 presents the full set of prior and posterior distributions for the estimated parameters across three model specifications, each initialized with identical starting values to ensure comparability. The initial values for mode maximization are selected to align with commonly used values in the literature. Multiple runs of the global optimizer are conducted to ensure stability in locating a high-density region, from which the mode with the highest density is chosen as the starting point for posterior simulation. Posterior statistics are carried out via the random walk Metropolis-Hastings algorithm, where we run two parallel Markov chains with 100,000 draws each, adjusting the scale parameters such that acceptance rates of approximately 0.3 are realized.

Figure A2 plots the model-implied structural shocks together with a two-standard-deviation band. The trajectories fluctuate predominantly within this band, indicating that the regime-switching structure of heteroscedasticity provides a well-behaved representation of out-sized movements in the data during the pandemic period without systematically relying on excessive volatility.