Efficient disintermediation with CBDC*

Egemen Eren† Timothy Jackson‡ Giovanni Lombardo§

February 15, 2022

Abstract

We study how CBDC impacts monetary policy and banks in a quantitative macroeconomic model. Financial intermediation by banks and the central bank are both subject to frictions and inefficient. Optimal monetary policy weighs relative inefficiencies of the central bank and banks, and pins down the optimal size and composition of balance sheets. Issuing CBDC generates welfare gains only if reserves issued to fund central bank asset purchases are "excessive" at the margin, that is, they exacerbate financial frictions for banks. We provide diverse, including causal, evidence suggesting this is the case in the United States. Then, CBDC can be designed to reduce deposits and reserves on bank balance sheets, and actually increase bank lending in the long run: *efficient disintermediation*. Optimal CBDC issuance amounts to 14% of GDP when we calibrate the model to the United States. In the short run, the central bank can conduct balance-sheet policies as effectively with CBDC as with reserves.

Keywords: CBDC, optimal monetary policy, reserves, financial frictions

JEL Classification Numbers: E42, E44, E51, E52, G21

*We thank Fernando Alvarez, Raphael Auer, Stijn Claessens, Darrell Duffie, Henry Holden, Ricardo Reis, Philip Wooldridge, and seminar participants at the BIS for helpful comments. Alexandra End provided excellent research assistance. The views in this article are those of the authors and do not necessarily represent those of the BIS. All errors are our own.

†Bank for International Settlements (BIS); Email: `Egemen.Eren@bis.org`

‡University of Liverpool; Email: `Timothy.Jackson2@liverpool.ac.uk`

§Bank for International Settlements (BIS); Email: `Giovanni.Lombardo@bis.org`

1 Introduction

Technological advances in payment technologies and the rise of cryptocurrencies as potential competitors to fiat currencies have led to a renewed interest in central bank digital currency (CBDC). In essence, CBDC allows a broad range of non-bank players, including households, to hold digital and interest-bearing central bank liabilities, which are currently exclusively held by banks and some other select players in the form of reserves. These features make CBDC a closer substitute to bank deposits compared with cash.

The introduction of interest-bearing CBDC has important implications for monetary policy and financial stability. In principle, CBDC would not only allow the central bank to set an additional interest rate in the economy, but also to conduct balance-sheet policies directly non-banks including households. Moreover, if the introduction of CBDC leads to a reduction in bank deposits and disintermediation of banks, it might raise financial stability concerns.

In this paper, we study whether CBDC has a role in the conduct of optimal monetary policy and its implications on the banking system within a quantitative macroeconomic model. In the model, financial intermediation is inefficient: banks face financial frictions and the central bank incurs resource costs arising from its asset holdings and liability issuance. In addition, in the model, household derive liquidity benefits from deposits and CBDC, and they are imperfect substitutes. Optimal monetary policy balances relative inefficiencies of banks and the central bank in financial intermediation, and pins down the optimal size and composition of balance sheets. We characterize the conditions under which issuing CBDC improves welfare. This is the case only if reserves are "excessive," in that they exacerbate financial frictions banks face at the margin. Naturally, optimal volume of CBDC issuance also depends on the optimal size of the central bank balance sheet. Calibrating the model to the United States, we find that the optimal CBDC issuance amounts to 13.7% of GDP in the long run.

Our results have implications for the potential impact of CBDC on financial stability. A particular concern is whether interest-bearing CBDC competes with bank deposits for households' savings and leads to the disintermediation of banks, hindering bank lending. In this paper, we show that this is not necessarily the case. If reserves are "excessive," CBDC can be designed such that disintermediation of banks actually increases bank lending in the long run, if CBDC simultaneously reduces deposits and reserves on bank balance sheets: *efficient disintermediation*. Moreover, in this case the central bank can also conduct balance-sheet policies as effectively with CBDC as with reserves in the short run.

We empirically evaluate potential welfare consequences of the introduction of CBDC through the lens of our model. We focus on the United States due to data availability and quality, but also provide some results for other jurisdictions. Using US bank balance sheet data, we show that while a certain level of reserves can be beneficial for banks, after some point reserves get "excessive:" they become associated with lower profitability and higher CDS spreads after we account for a rich set of control variables. In order to show the causal relationship between reserves and bank profitability, we take an instrumental variables approach, where we instrument the share of reserves in bank balance sheets with the Treasury General Account at the Fed. The results from this approach also agrees with the previous results. In addition, we evaluate a condition on interest rates from our model empirically. It also suggests that CBDC would be a beneficial tool for the conduct of optimal monetary policy in the United States. Applying the same condition on interest rates across several jurisdictions, we show that welfare effects of CBDC vary substantially.

Finally, we study how the economy reacts to several shocks in the short run, when the central bank follows optimal monetary policy or ad-hoc policy rules with or without CBDC in the face of price rigidity, imperfect financial intermediation and the monetary friction leading to a liquidity benefit assigned to deposits and CBDC. We show that in this case conducting monetary policy exclusively through changes of the interest rate cannot achieve the frictionless allocation. Adding an additional instrument, such as asset purchases, allows the central bank to stabilize both inflation and the credit spread: the two sources of inefficiency associated to fluctuations. We show that asset purchases have a similar effect on the real economy regardless of whether these asset purchases are funded through reserves or CBDC.

We introduce CBDC within a model with realistic features of the modern monetary and financial system. Central banks issue reserves to banks and CBDC to households to purchase assets, i.e. long-term bonds or state-contingent securities issued by firms. Banks hold reserves, long-term bonds and state-contingent securities issued by firms. Households hold bank deposits, long-term bonds, and CBDC.

There are two main frictions in the model: financial and monetary. We introduce financial frictions in the form of limited commitment à la Gertler and Karadi (2011).[1] This friction essentially results in the risk-weighted assets of banks to be constrained by their franchise value. Banks hold a diversified portfolio composed of assets differing in their degree of riskiness and social value: private claims on productive firms, long-term bonds (which might include government debt, mortgage-backed securities etc.) and reserves. The financial friction and portfolio diversification jointly result in a limited supply of socially productive capital. This limitation generates an externality manifested through the spreads on the rates on different assets over the rates on banks' liabilities, i.e. deposits. Monetary friction is modeled as transaction cost savings when purchasing goods with money leading to liquidity demand for households. We model deposits and CBDC to be imperfect substitutes.

To correct the externality in the banking sector, the welfare-maximizing central bank uses its own balance sheet to affect the relative net supply of these assets and thus improve on the equilibrium allocations in the long-run. However, central bank assets and liabilities are subject to resource costs, also generating inefficiencies in central bank intermediation.[2] The existence of inefficiencies in both the banking sector and the central bank is at the heart of the trade-off for optimal monetary policy.

Welfare consequences of central bank policies crucially depend on the risk weights of assets for banks and resource costs for the central bank. As long as the marginal risk weight of reserves is lower than

[1]Throughout the paper, we mainly focus on financial frictions, without which issuing CBDC or reserves is irrelevant for the macroeconomic equilibrium in the spirit of the Modigliani-Miller irrelevance theorem. We also model monetary frictions as a way for bank deposits and CBDC to reduce transaction costs as imperfectly substitutable payment instruments, generating a convenience yield. We relegate the results with monetary frictions to the appendix.

[2]These costs might be motivated by the existence of political economy considerations, such as those arising from lending to the real economy or financing the government) or costs arising from operating payment systems or complying with know-your-customer (KYC) or anti-money-laundering (AML) regulations (in the case of CBDC issuance).

that of other assets and central bank resource costs of holding either long-term bonds or private claims is small enough, central bank asset purchases can generate efficiency gains through changing the asset composition of bank balance sheets without decreasing the size of bank balance sheets. If reserves affect banks adversely at the margin (i.e. they have a positive risk weight), funding additional purchases with CBDC further improves welfare as long as resource costs of issuing CBDC are small enough.

Funding central bank asset purchases by CBDC reduces bank balance sheets through a decline on reserves on the asset side and deposits on the liability side. If reserves are "excessive" at the margin, reducing bank balance sheets alleviates the constraints imposed by the financial frictions on banks, which serves to reduce spreads. This allows banks to invest more in productive assets, for a given net worth, which effectively alleviates the negative externality.

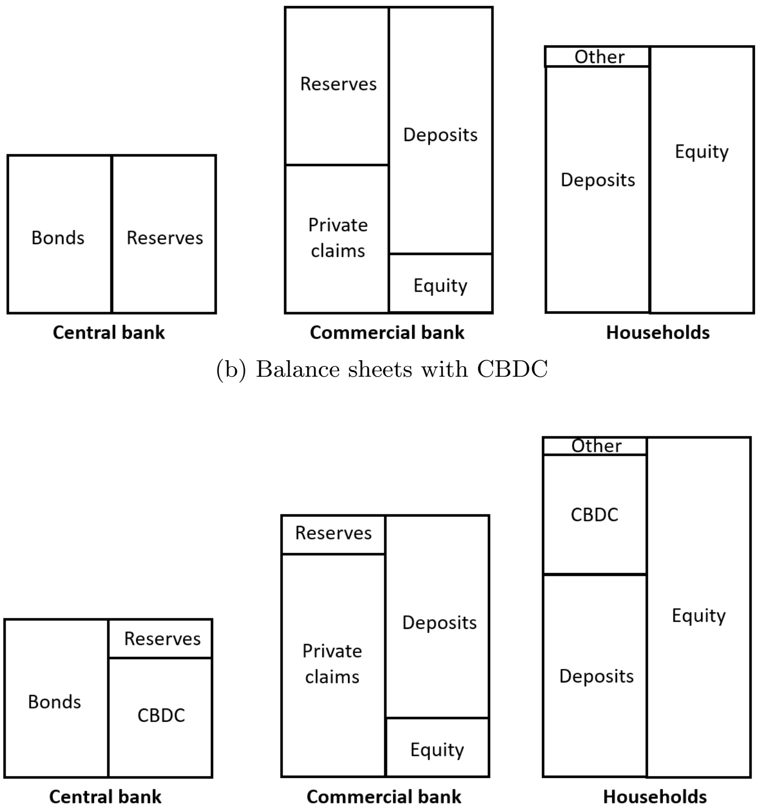
We illustrate the balance sheets of different sectors when disintermediation of banks by the central bank can be efficient in Figure 1. In Panel 1a, for a given amount of bonds outstanding, the central bank issues reserves, banks hold these reserves and purchase private claims, funded by deposits. If a certain amount of reserves are beneficial for banks, but more reserves would exacerbate the financial frictions, Panel 1b shows how the central bank can issue a mix of reserves and CBDC. Since banks do not have to hold reserves to fund the central bank bond purchases, so long as the marginal risk weight of reserves is positive, their incentive compatibility constraints are relaxed and they can purchase more private claims. This results in smaller commercial bank balance sheets, but in which banks lend more to the real economy.

In our model, if the total amount of reserves is "excessive" at the margin, the equilibrium rate on reserves is higher than the equilibrum rate on CBDC. As a result, CBDC also generates an additional benefit in the form of higher central bank revenue and seigniorage. Without CBDC, central banks can only fund assets by issuing reserves. In that scenario, due to market segmentation, banks are the only agents that can invest in reserves. However, with a positive risk weight on reserves at the margin, banks receive a rate on reserves which is higher than the deposit rate and adequately compensates them for tightening their constraint. Empirically, we show that this is the case in the United States, where the interest rate on excess reserves exceeds the average deposit rate estimated from US Call Reports.[3] Since CBDC does not affect bank constraints, in equilibrium the rate on CBDC is lower than the rate on reserves. Therefore, central bank revenue and seigniorage transfers are higher if central bank assets are funded by CBDC rather than reserves.

Related literature. Public provision of money and how it interacts with the private money are hardly new ideas. Discussions of the benefits of remunerating cash balances are also not new (e.g. Goodhart, 1993). Gurley and Shaw (1960) introduce the concept of outside money (which is a net asset to the private sector) and inside money (which is an asset and a liability to the private sector at the same time) and argue that changes in the level of these different components of the money stock can have implications for real activity. Proposals of CBDC can be traced to Tobin (1985) who argues that

[3] We also collect data on these rates from other jurisdictions and find a large variation of this spread.

Figure 1: An illustration of efficient disintermediation
(a) Balance sheets without CBDC



central banks could directly transmit monetary policy through allowing broader access by non-banks to central bank issued liabilities. In this context, CBDC can be seen as a technologically feasible way to issue publicly provided and interest-bearing money. Auer et al. (2021) provides a discussion of motives, economic implications and a comprehensive review of the recent literature on CBDC.

A recent and fast-growing literature on CBDC revives ideas of broadening the access to digital central bank liabilities in the context of recent technological developments affecting digital payments. Bech and Garratt (2017) provide a taxonomy of money along the dimensions of whether it is universally accessible, issued by a central bank, electronic, and peer-to-peer. They provide historical examples and place CBDC in context as a type of money having all these characteristics. Chapman and Wilkins (2019) argue that joint trends of innovation in payments and decline of cash present challenges for banks to coexist with public and private providers of digital currencies. Motivations to issue CBDC for central banks together with issues related to the design of CBDC are discussed at length at several publications [see, for example, BIS (2018); Group of Central Banks (2020); BIS (2021) and Duffie et al. (2021)].[4] One key design issue with potential macroeconomic implications is whether households directly hold central liabilities or do so through an intermediary [see, for example, Adrian and Mancini-Griffoli (2019)]. Another key feature

[4] Auer et al. (2020) report the status of ongoing CBDC projects at different jurisdictions and argue how design features fit with different motivations of central banks.

differentiating CBDC from cash is that it is interest bearing and digital. In our paper, we consider CBDC that are direct, interest-bearing and account-based claims on the central bank. While central bank research primarily focus on the introduction of CBDC as a digital means of payment, the introduction of CBDC raises a number of issues related to the conduct of monetary policy, the nature of financial intermediation, financial stability, and welfare implications.

Our main contribution is to the strand of the literature that studies the implications of the introduction of CBDC on the effectiveness and implementation of monetary policy. Piazzesi et al. (2019) compare the transmission of interest-rate policy with CBDC to floor and corridor systems in a New Keynesian model. Barrdear and Kumhof (2016) study CBDC in a New Keynesian setup and derive welfare gains from a reduction in transaction costs. Schilling et al. (2020) consider a model of bank runs in the presence of CBDC and show that central banks face a trade-off between stabilizing bank runs and inflation targeting. We develop a rich quantitative macroeconomic model with standard price rigidities, imperfect financial intermediation due to financial frictions [à la Gertler and Karadi (2011)], and monetary frictions generating a demand for liquid means of payment (in an extension). Ferrari et al. (2020) and Kumhof et al. (2021) study the impact of CBDC and implications for monetary policy in an open economy setting. We find that CBDC can generate efficiency gains in the long run, and the central bank can conduct balance-sheet policies as effectively with CBDC as with reserves in the short-run.

A strand of literature compares bank deposits and CBDC. Faure and Gersbach (2018) and Brunnermeier and Niepelt (2019) are interested in when fractional reserve banking and a system with CBDC are equivalent in terms of allocations. Jackson and Pennacchi (2021) show that CBDC is a more efficient means for the government to create liquidity than providing deposit insurance to private bank deposits. Essentially, the former generates liquidity from scratch while the latter only adds a layer of safety. In our model, CBDC and bank deposits are equally safe. Our results are driven by inefficiencies of intermediation by the central bank and banks rather than household preferences for safety.

Another strand of the literature that we contribute to studies the implications of the introduction of CBDCs on commercial bank deposits. Keister and Sanches (2019) emphasize complementarity between deposits and lending, and argue that CBDC could weaken this link. In their model, banks offer deposits at low interest rates, which relaxes net worth constraints faced by banks and increases investment. CBDC competition with bank deposits increases interest rates and weakens investment. Piazzesi and Schneider (2020) study this focusing on the complementarity between deposits and credit lines. If the central bank offers CBDC but not credit lines, then it interferes with the complementarity between credit lines and deposits reducing welfare even if the central bank provision of deposits alone is superior to banks. A similar feature between our model and Piazzesi and Schneider (2020) is the effective constraint on the total bank balance sheet. Chiu et al. (2019) show that if banks have market power in the deposit market, CBDC can enhance competition and intermediation capacity, and can ultimately raise output. Andolfatto (2018) studies a model of monopoly banking where the introduction of CBDC reduces rents in the deposit market and increases financial inclusion. He also emphasizes that there need not be a detrimental effect on investment.

Our results support the view that the issuance of CBDC does not necessarily imply an inefficient downsizing of banks. In our model, issuing CBDC can generate efficiency gains in the long run, as commercial banks can disinvest in reserves and focus their activity in more productive private-credit extension. Even in the face of shocks driving funds away from banks, the central bank can stabilize banks' funding by changing the adjusting the supply of CBDC. In that context, our results are also related to Garratt et al. (2015) and McCauley (2021), who discuss costs of holdings reserves in the presence of balance sheet costs.

The rest of the paper is organized as follows. In Section 2 we introduce the model. In Section 3, we apply our model to the United States and in Section 4, we calibrate the model to the US economy. In Section 5, we study optimal monetary policy. In Section 6, we explore some other considerations for the introduction of CBDC and in Section 7, we conclude.

2 Model

The model is based on a closed sticky-price production economy with financial intermediation à la Gertler and Karadi (2011). Our main departure from their framework is to extend the model with a central bank that grants access to its liabilities also to households, which we refer to as CBDC. Households can therefore hold deposits of both banks and the central bank, instead of holding only bank deposits. Holding deposits of either type allows households to save on transaction costs associated with purchases of final goods, adding a monetary friction to the model as in Schmitt-Grohé and Uribe (2010). This friction allows experimentation with the degree of substitutability between commercial and CB deposits, as well as changes in household preferences for either type. Banks use the proceeds from the sales of deposits to and purchase productive claims from firms, hold central bank reserves, and invest in long-term bonds issued by the government, which could include government bonds or mortgage-backed securities guaranteed by the government. Households can also invest in these assets.

2.1 Households

In each period households decide how much to consume (C_t), how many hours of work to supply to firms (H_t) at real wage W_t, how many deposits to purchase from banks (D_t) and from the central bank ($D_{CB,t}$). For calibration purposes, households hold a constant proportion of long-term bonds ($\mathcal{B}_H$) and total capital that is not intermediated by banks (K_H). Household income consists of labor income, revenue from deposits (at gross rate $R_{D,t}$ and $R_{CB,t}$ respectively), return on equities and long-term bonds (at gross rate $R_{K,t}$ and $R_{B,t}$ respectively) and lump-sum transfers (T_t). Lump-sum transfers consist of net profits from capital producers, net worth of exiting private banks net of transfers to start-up banks, and lump-sum taxation ($\mathcal{T}_t$).

The representative household has GHH preferences (Greenwood et al. (1988)) and solves the following problem: The representative household solves the following problem:

$$\max_{C_t,H_t,M_t,D_t,D_{CB,t}} E_t \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\sigma}\left(\bar{U} + C_t - \frac{\chi H_t^{1+\psi}}{1+\psi}\right)^{1-\sigma}, \tag{2.1}$$

subject to the budget constraint

$$\begin{aligned}&(1+s(v_t))\,C_t + D_t + D_{CB,t} + P_{B,t}\mathcal{B}_H + Q_t K_H \\ &= W_t H_t + \frac{R_{D,t-1}}{\pi_t} D_{t-1} + \frac{R_{CB,t-1}}{\pi_t} D_{CB,t-1} + \frac{R_{B,t}}{\pi_t} P_{B,t-1}\mathcal{B}_H + R_{K,t} Q_{t-1} K_H + T_t,\end{aligned} \tag{2.2}$$

where $\bar{U}$ is a scaling parameter to ensure that welfare lies on the real axis and lump-sum transfers are defined as

$$T_t = Q_t\, I_t - I_t\left(1 + \frac{\eta}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right) + (1-\theta)\ N_{i,t} - \delta_T K_{F,t-1} - \mathcal{T}_t, \tag{2.3}$$

and $s(v_t)$ denotes a transactions cost incurred in purchasing consumption. Households particularly value the money-ness features of bank deposits (D_t) and CBDCs ($D_{CB,t}$) because these assets can be used to transact. Define money holdings M_t as a CES aggregate of deposits and CBDCs:

$$M_t = \left[\mu_m D_t^{\frac{\eta_m-1}{\eta_m}} + (1-\mu_m)\, D_{CB,t}^{\frac{\eta_m-1}{\eta_m}}\right]^{\frac{\eta_m}{\eta_m-1}}, \tag{2.4}$$

where $\eta_m \in (0,\infty)$ captures the degree of substitutability between these money-like assets. Further, let the velocity of money be $v_t \equiv C_t/M_t$.[5] We choose a transactions cost function, $s(v_t)$ which satisfies the following properties. Define $\underline{v} = \{\underline{v} \in \mathbb{R}^+ | s(\underline{v}) = 0\}$, then have that $\underline{v} = \sqrt{\frac{B}{A}}$ and that $s'(\underline{v}) = 0$. The general assumptions about $s(v)$ are (Schmitt-Grohé and Uribe, 2010, p 6):

a) $s(v) \geq 0$

b) $s(\underline{v}) = s'(\underline{v}) = 0$ (demand for money can be finite even at zero nominal rate)

c) $(v - \underline{v})s'(v) > 0$ for $v \neq \underline{v}$ (money velocity always greater or equal the satiation level)

d) $2s'(v) + vs'' > 0\ \forall\ v \geq \underline{v}$ (demand for money decreasing function of the interest rate [differential])

Specifically, the transactions cost function takes the form:[6]

$$s(v_t) = \chi_M \frac{(v_t - A)^2}{2}. \tag{2.5}$$

Denote by λ_t the Lagrange multiplier on the budget constraint; φ_t the Lagrange multiplier on the monetary aggregator and $Q_{m,t} \equiv \frac{\varphi_t}{\lambda_t}$ is the 'Money Q'.

The FOCs are

$$C_t: \qquad u_{C,t} = \lambda_t(1 + s(v_t) + s'(v_t)v_t), \tag{2.6}$$

$$H_t: \qquad \lambda_t W_t = \chi H_t^{\varphi} u_{C,t} \tag{2.7}$$

[5]This implies Lucas timing. Svensson (1985) timing would instead define $v_t \equiv C_t/M_{t-1}$.

[6]Alternatively, we can define the transaction cost à la Schmitt-Grohé and Uribe (2010): $s(v_t) = Av + \frac{B}{v} - 2\sqrt{AB}$.

$$M_t: \quad Q_{m,t} = s'(v_t)v_t^2, \tag{2.8}$$

$$D_t: \quad E_t\Lambda_{t+1|t}\frac{R_{D,t}}{\pi_{t+1}} + Q_{m,t}M_t^{\frac{1}{\eta_m}}\mu_m D_t^{\frac{-1}{\eta_m}} = 1, \tag{2.9}$$

$$D_{CB,t}: \quad E_t\Lambda_{t+1|t}\frac{R_{CB,t}}{\pi_{t+1}} + Q_{m,t}M_t^{\frac{1}{\eta_m}}\left(1-\mu_m\right)D_{CB,t}^{\frac{-1}{\eta_m}} = 1, \tag{2.10}$$

where $u_{C,t} \equiv \left(\bar{U} + C_t - \frac{\chi H_t^{1+\psi}}{1+\psi}\right)^{-\sigma}$ is the marginal utility of consumption and stochastic discount factor is $\Lambda_{t+1|t} \equiv \beta u_{C,t+1}/u_{C,t}$.

Equation (2.8) gives the money demand:[7]

$$M_t = C_t\sqrt{\frac{s'\left(v_t\right)}{Q_{m,t}}} \tag{2.11}$$

By combining equations (2.9) and (2.10) can write

$$\frac{1 - E_t\Lambda_{t+1|t}\frac{R_{D,t}}{\pi_{t+1}}}{1 - E_t\Lambda_{t+1|t}\frac{R_{CB,t}}{\pi_{t+1}}} = \left(\frac{\mu_m}{1-\mu_m}\right)\left(\frac{D_{CB,t}}{D_t}\right)^{\frac{1}{\eta_m}}, \tag{2.12}$$

Moreover, using the FOCs in the CES aggregator, one obtains

$$Q_{m,t} = \left(\mu_m^{\eta_m}\left(1 - \Lambda_{t+1|t}\frac{R_{D,t}}{\pi_{t+1}}\right)^{1-\eta_m} + \left(1-\mu_m\right)^{\eta_m}\left(1 - \Lambda_{t+1|t}\frac{R_{CB,t}}{\pi_{t+1}}\right)^{1-\eta_m}\right)^{\frac{1}{1-\eta_m}} \tag{2.13}$$

Note that $Q_{m,t} > 0$ only if at least one rate is sufficiently smaller than the "unconstrained" rate $\left(E_t\Lambda_{t+1|t}/\pi_{t+1}\right)^{-1}$. Since deposits and CBDC offer additional services, their return should be smaller that that of a security that does not alleviate the monetary transaction cost.

If deposits and CBDC are perfectly substitutable, for example in the absence of monetary frictions ($\chi_M = 0$), we have:

$$E_t\Lambda_{t+1|t}\frac{R_{D,t}}{\pi_{t+1}} = E_t\Lambda_{t+1|t}\frac{R_{CB,t}}{\pi_{t+1}} = 1. \tag{2.14}$$

2.2 Banks

There is an infinite number of identical banks (financial intermediaries) indexed by the subscript i. Banks sell deposits to households and use them, together with own net-worth ($N_{i,t}$), to purchase: claims on private capital from firms ($Q_tK_{i,F,t}$); long-term bonds ($P_{B,t}\mathcal{B}_{i,B,t}$); and central bank reserves ($B_{i,F,t}$). Banks face a limited commitment problem as in Gertler and Karadi (2011) which leads to an incentive compatibility constraint that aligns the incentives of the banks and the depositors.

The representative bank's optimal value is

$$J_{i,t} = \max_{\left[Q_tK_{i,F,t},P_{B,t}\mathcal{B}_{i,B,t},B_{i,F,t},D_{i,t}\right]} E_t\Lambda_{t+1|t}\left[(1-\theta)N_{i,t+1} + \theta J_{i,t+1}\right], \tag{2.15}$$

[7]Under Svennson timing, this equation alone is replaced by $M_t = E_t\left[C_{t+1}\sqrt{\Lambda_{t+1|t}s'\left(v_{t+1}\right)Q_{m,t}}\right]$.

where $(1-\theta)$ is the probability of exiting the banking industry and bank net worth evolves according to

$$N_{i,t} = R_{K,t}Q_{t-1}K_{i,F,t-1} + \frac{R_{B,t}}{\pi_t}P_{B,t-1}\mathcal{B}_{i,B,t-1} + \frac{R_{F,t-1}}{\pi_t}B_{i,F,t-1} - \frac{R_{D,t-1}}{\pi_t}D_{i,t-1}, \tag{2.16}$$

subject to the balance sheet

$$N_{i,t} + D_{i,t} = Q_tK_{i,F,t} + P_{B,t}\mathcal{B}_{i,B,t} + B_{i,F,t}, \tag{2.17}$$

and an incentive compatibility constraint (ICC) that a bank's net-worth must be greater than its risk-weighted assets ($\mathcal{A}_t$):

$$J_{i,t} \geq \mathcal{A}_t, \tag{2.18}$$

where $\mathcal{A}_t$ is:

$$\mathcal{A}_t := \kappa\left(Q_tK_{i,F,t}, P_{B,t}\mathcal{B}_{i,B,t}, B_{i,F,t}\right), \tag{2.19}$$

where $\kappa(\cdot)$ captures the riskiness of capital, long-term bonds and reserves. The ICC thus depends on *both the size and composition* of bank assets.

Using equation (2.17) to replace $D_{i,t}$ in equation (2.16) yields

$$N_{i,t+1} = \left(R_{K,t+1} - \frac{R_{D,t}}{\pi_{t+1}}\right)Q_tK_{i,F,t} + \left(\frac{R_{B,t+1}}{\pi_{t+1}} - \frac{R_{D,t}}{\pi_{t+1}}\right)P_{B,t}\mathcal{B}_{i,B,t} + \left(\frac{R_{F,t}}{\pi_{t+1}} - \frac{R_{D,t}}{\pi_{t+1}}\right)B_{i,F,t} + \frac{R_{D,t}}{\pi_{t+1}}N_{i,t}. \tag{2.20}$$

Aggregating across banks yields

$$N_{t+1} \equiv \theta \int N_{i,t+1}di + \delta_T K_{F,t}, \tag{2.21}$$

where $\delta_T K_{F,t}$ denotes start-up capital transferred to new banks from households.

The first order conditions for an individual bank are

$$Q_tK_{i,F,t}: \qquad E_t\Omega_{t+1|t}\left(R_{K,t+1} - \frac{R_{D,t}}{\pi_{t+1}}\right) = \kappa_{K_F,t}\gamma_t, \tag{2.22}$$

$$P_{B,t}\mathcal{B}_{i,B,t}: \qquad E_t\Omega_{t+1|t}\left(\frac{R_{B,t+1} - R_{D,t}}{\pi_{t+1}}\right) = \kappa_{\mathcal{B}_B,t}\gamma_t, \tag{2.23}$$

$$B_{i,F,t}: \qquad E_t\Omega_{t+1|t}\left(\frac{R_{F,t} - R_{D,t}}{\pi_{t+1}}\right) = \kappa_{B_F,t}\gamma_t, \tag{2.24}$$

where $\kappa_{i,t}$ with $i \in \{K_F, \mathcal{B}_B, B_F\}$ denote the marginal effects of bank assets on the ICC constraint and $\Omega_{t|t-1} \equiv \Lambda_{t|t-1}\left[(1-\theta) + \theta J'_{i,t}\right]$ is the discount factor of the bank and $J'_{i,t}$ is the bank's marginal value.[8]

It will be convenient to refer to the excess returns to bank asset holdings, so we define:

$$Rx_{K,t} = R_{K,t+1} - \frac{R_{D,t}}{\pi_{t+1}}, \tag{2.25}$$

$$Rx_{F,t} = \frac{R_{B,t+1} - R_{D,t}}{\pi_{t+1}}, \tag{2.26}$$

[8] Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) show that under the assumption underlying the bank problem, the value function J_t is linear in net-worth. This allows aggregation across agents and implies that $J_{i,t} = J'_{i,t}N_{i,t}$.

$$Rx_{B,t} = \frac{R_{F,t} - R_{D,t}}{\pi_{t+1}}. \tag{2.27}$$

The envelope condition is

$$N_{i,t}: \qquad J'_{i,t}(1-\gamma_t) = E_t \Omega_{t+1|t} \frac{R_{D,t}}{\pi_{t+1}}, \tag{2.28}$$

where γ_t is the lagrange multiplier associated to the ICC (2.18).

The complementary slackness conditions are

$$\begin{aligned} 0 =& \gamma_t \left\{ J_{i,t} - \mathcal{A}_{i,t} \right\}, \\ \gamma_t \geq & 0. \end{aligned} \tag{2.29}$$

In our frictionless benchmark regime, the above equations for the banking sector are replaced with

$$E_t \Lambda_{t+1|t} \left(R_{K,t+1} - \frac{R_{D,t}}{\pi_{t+1}} \right) = 0. \tag{2.30}$$

Differences to the frictionless benchmark are referenced by the term 'gap'.

We follow Gertler and Karadi (2011) in the way we model the financial friction that leads to such gaps. In their model, banks are subject to limited commitment and the incentive compatibility constraint ensures that bankers' incentives are aligned with the depositors. We view this as a convenient way of modeling the frictions. However, what is important for us is the existence of these gaps that indicate inefficiencies in the banking sector. Such gaps could also arise due to imperfect competition in the banking sector, leverage constraints that banks might face. In the empirical applications of our model, we do not take a strong stance on the exact microfoundations (apart from following Gertler and Karadi (2011) for convenience), but we make use of these gaps as observed with interest rate data.

2.3 Government

We assume that in each period the government issues $B_{N,t}$ new quasi-perpetuities at the price $P_{B,t}$ in units of the consumption basket that have a fixed probability $(1-\delta_p)$ to expire in each period after payment of the coupon.[9] We refer to these assets as long-term bonds and assume they are traded in secondary markets such that an unexpired bond is valued at $P_{B,t}$. The gross return on bonds is thus:[10]

$$R_{B,t} = \frac{\delta_p P_{B,t} + (1-\delta_p) + \bar{r}_p}{P_{B,t-1}}. \tag{2.31}$$

The total real stock of these perpetuities outstanding at the beginning of each period is

$$\mathcal{B}_t = \sum_{s=0}^{\infty} \frac{\delta_p^s}{\prod_{j=0}^{s-1} \pi_{t-j}} B_{N,t-s} = B_{N,t} + \frac{\delta_p}{\pi_t} \mathcal{B}_{t-1}. \tag{2.32}$$

[9] This assumption can be seen as a variant of the perpetuity assumed by Woodford (2001). See also Chen et al. (2012) for an application of this modelling assumption.

[10] Note that if $\delta_p = 0$, the perpetuity becomes a one-period bond.

Long-term bonds are held by households, banks and the central bank in quantities $\mathcal{B}_H$, $\mathcal{B}_{B,t}$ and $\mathcal{B}_{CB,t}$ respectively. Household bond-holdings ($\mathcal{B}_H$) are calibrated to account for difference in the data between bond-holdings by bank and central bank and the total size of government debt. Market-clearing implies that these allocations equal the total supply set by the government

$$P_{B,t}\mathcal{B}_t = P_{B,t}\mathcal{B}_H + P_{B,t}\mathcal{B}_{CB,t} + P_{B,t}\mathcal{B}_{B,t}. \tag{2.33}$$

We assume the government does not run a surplus and that government spending, G, is fixed. Taxation, $\mathcal{T}$, is lumpsum so the government budget constraint is

$$\frac{(1-\delta_p)+r_p}{\pi_t}\mathcal{B}_{t-1} + G = P_{B,t}B_{N,t} + \mathcal{T}_t + \mathcal{T}_{CB,t} \tag{2.34}$$

where $\mathcal{T}_{CB,t}$ references the lump-sum transfer from the central bank to the government, derived in the next section.

We assume the government maintains a constant real stock of debt, $\mathcal{B}$, by only issuing new quasi-perpetuities to cover expiry and inflation:

$$B_{N,t} = \left(\mathcal{B}_t - \frac{\delta_p}{\pi_t}\mathcal{B}_{t-1}\right). \tag{2.35}$$

2.4 Central bank

The central bank carries out monetary and macroprudential policy in order to reduce specific inefficiency wedges, namely inflation, output gap relative to the frictionless benchmark and credit spreads. In particular, our main focus is on the role that CBDCs ($D_{CB,t}$) play in the conduct of monetary and macroprudential policy and its interaction with the private provision of credit.

The policy instruments consist of interest rates on CBDC ($R_{CB,t}$) and bank reserves ($R_{F,t}$), and asset purchases (public and private). The central bank offers CBDC as deposits to households ($D_{CB,t}$) and reserves to financial intermediaries ($B_{F,t}$) on which it pays interest rates $R_{CB,t}$ and $R_{F,t}$ respectively. With the proceeds it acquires private sector assets (capital) denoted $Q_tK_{CB,t}$ which returns $R_{K,t}$ and government debt ($P_{B,t}\mathcal{B}_{CB,t}$) which returns $R_{B,t}$.

The central bank has costs associated with its balance sheet positions (g_t).[11] The central bank operates with own capital $N_{CB,t}$ obtained from lump-sum transfers from the government. All central bank revenue, $\mathcal{S}_t$, is also transferred lump-sum to government. The balance sheet of the central bank is:

$$P_{B,t}\mathcal{B}_{CB,t} + Q_tK_{CB,t} = N_{CB,t} + D_{CB,t} + B_{F,t} \tag{2.36}$$

where central bank net worth $N_{CB,t}$ evolves according to:

$$N_{CB,t} = R_{K,t}Q_{t-1}K_{CB,t-1} + \frac{R_{B,t}}{\pi_t}P_{B,t-1}\mathcal{B}_{CB,t-1} - \frac{R_{CB,t-1}}{\pi_t}D_{CB,t-1} - \frac{R_{F,t-1}}{\pi_t}B_{F,t-1} - \mathcal{T}_{CB,t}. \tag{2.37}$$

where $\mathcal{T}_{CB,t}$ references transfers from central bank to government. Note that if the financial friction binds

[11] In our simulations, we use a quadratic formulation.

and $\kappa_{F,t} > 0$, CBDC represent a cheaper means of funding than reserves (i.e. $R_{F,t} > R_{CB,t}$).

By replacing $N_{CB,t}$ in equation (2.36) using equation (2.37), we write the central bank budget constraint as:

$$\begin{aligned}&P_{B,t}\mathcal{B}_{CB,t} + Q_t K_{CB,t} - D_{CB,t} - B_{F,t}\\&= R_{K,t}Q_{t-1}K_{CB,t-1} + \frac{R_{B,t}}{\pi_t}P_{B,t-1}\mathcal{B}_{CB,t-1} - \frac{R_{CB,t-1}}{\pi_t}D_{CB,t-1} - \frac{R_{F,t-1}}{\pi_t}B_{F,t-1} - \mathcal{T}_{CB,t}.\end{aligned} \tag{2.38}$$

Adding (2.34) to (2.38) produces the consolidated government budget constraint:

$$G + \mathcal{R}_t = \mathcal{T}_t + \mathcal{L}_t, \tag{2.39}$$

where we define the gross government interest payments as $\mathcal{R}_t$:

$$\mathcal{R}_t := \frac{R_{CB,t-1}}{\pi_t}D_{CB,t-1} + \frac{R_{F,t-1}}{\pi_t}B_{F,t-1} + \frac{R_{B,t}}{\pi_t}P_{B,t-1}(\mathcal{B}_H + \mathcal{B}_{B,t-1}) - R_{K,t}Q_{t-1}K_{CB,t-1}, \tag{2.40}$$

and net liabilities as $\mathcal{L}_t$:

$$\mathcal{L}_t := D_{CB,t} + B_{F,t} + P_{B,t}(\mathcal{B}_H + \mathcal{B}_{B,t}) - Q_t K_{CB,t} \tag{2.41}$$

We impose a stability rule that taxation revenue must be increasing in government net liabilities and net interest payments:

$$\hat{\mathcal{T}}_t = \gamma_{CB}\hat{\mathcal{L}}_t, \tag{2.42}$$

with $\gamma_{CB} > 0$.

2.5 Firms

Firms produce using a Cobb-Douglas production technology:

$$Y_t = A_t K_{t-1}^{\alpha} H_t^{1-\alpha} \tag{2.43}$$

where total capital, K_t, is made up of bank lending, CB lending and a constant component held by households:

$$K_t = K_{F,t} + K_{CB,t} + K_H. \tag{2.44}$$

Note that K_H is set to account for the discrepancy in the data between total productive capital and bank lending to firms. In the model, for simplicity, we assume that households do not choose this optimally and hence, it does not enter the household problem.

Marginal cost is given by

$$MC_t = \frac{\sigma_P - 1}{\sigma_P}\left\{1 - \xi\left[(\pi_t - \pi)\pi_t - E_t\Lambda_{t+1|t}(\pi_{t+1} - \pi)\pi_{t+1}\frac{Y_{t+1}}{Y_t}\right]\right\}, \tag{2.45}$$

where π is the central bank's inflation target and $\xi \equiv \dfrac{\varsigma}{(1-\varsigma)(1-\beta\varsigma)}$ is the Rotemberg coefficient calculated from the Calvo probability, ς.

The labor market clearing condition is

$$W_t = MC_t(1-\alpha)\frac{Y_t}{H_t}, \tag{2.46}$$

and gross return on capital is given by

$$R_{K,t}Q_{t-1} = \alpha MC_t \frac{Y_t}{K_{t-1}} + (1-\delta)Q_t. \tag{2.47}$$

The accumulation law for capital is

$$K_t = I_t + K_{t-1}(1-\delta), \tag{2.48}$$

and the investment Euler equation defines Tobin's Q:

$$Q_t = 1 + \frac{\eta}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 + \eta\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}} - \eta\Lambda_{t+1|t}\left(\frac{I_{t+1}}{I_t}\right)^2\left(\frac{I_{t+1}}{I_t} - 1\right). \tag{2.49}$$

Finally, the goods market clearing condition is

$$Y_t\left(1 - \frac{\xi}{2}(\pi_t - \pi)^2\right) = C_t + I_t + \frac{\eta}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 + \eta\left(\frac{I_t}{I_{t-1}} - 1\right) + G. \tag{2.50}$$

2.6 Shocks

We consider a negative shock to productivity

$$A_t = \rho_A A_{t-1} - \epsilon_{A,t}, \tag{2.51}$$

and a negative financial shock by raising the multiplier associated to the bank's ICC:

$$\gamma_t = \rho_F \gamma_{t-1} + \epsilon_{F,t}. \tag{2.52}$$

This is equivalent to raising each of the marginal risk-weights on bank assets, which depend on $\{\kappa_{K_f}, \kappa_{\mathcal{B}_B}, \kappa_{B_F}\}$ proportionally.

3 Empirical application to the United States

The financial friction in the banking sector is at the heart of our model. This friction manifests itself in terms of spreads on the interest rates between assets that banks hold and interest rates they pay on deposits. While our model thus far has remained fairly general, optimal long-run central bank policy hinges critically on the empirical values of risk weights entering into the incentive compatibility constraints of banks, denoted by κ functions.

In designing the optimal central bank policy, both the signs and the ordering of these risk weights are crucial. We analyze the data on the banking system in the United States in order to guide our selection of the empirical values for the risk weights. We take two different approaches. First, we start with constructing the empirical counterparts of the spreads that appear in the first order conditions in the bank problem. The sign and the ranking of these spreads map one to one to the sign and the ranking of the risk weights. Next, we study how reserves, long-term bonds and investment in capital (ie. loans) affect bank risk and bank profitability at the cross-section. Both approaches suggest a selection of positive values for $\{\kappa_{K_f}, \kappa_{\mathcal{B}_B}, \kappa_{B_F}\}$.

3.1 Interest rate spreads

One way to gauge the sign and the economic magnitude of the risk weights arising in the first order conditions is to compare the spreads of lending rates, the rate that banks earn for reserves and the rate on long-term bonds over the deposit rates, using our first order conditions, (2.22), (2.23), and (2.24).

In our model, banks hold reserves, make investments, and also hold long-term bonds. Due to the simplicity of the model, in particular due to the absence of a housing sector, we make several assumptions to map the model to the data. We proxy banks' investment in productive capital by bank lending excluding real estate loans. We map long-term bonds to a sum of held-to-maturity securities plus real estate loans.

In order to compare the interest rates, we obtain time series on lending rates, rates on long-term bonds, the rate banks earn on reserves and deposit rates. We estimate the lending rate, the rate on long-term bonds and various deposit rates using data on US banks' call reports, between March 1987 and March 2020 (Drechsler et al., 2017, 2021). We estimate these rates by dividing total interest income or expense by the amounts outstanding on bank balance sheets. We use the effective federal funds rate until 2009 and the interest rate on excess reserves starting from 2009 and refer to it as the rate on reserves. All interest rates are annualized.

We plot the time series of these interest rates in Figure 2. In Panel 2a, we plot the average lending rate, the average rate on long-term bonds and the rate on reserves as well as a weighted average deposit rate, weighted by the average share of different deposit rates (i.e. transactional and savings) on bank balance sheets.[12] In Panel 2b, we plot the spreads of the lending rate, the rate on long-term bonds and the rate on reserves over the weighted average deposit rate.

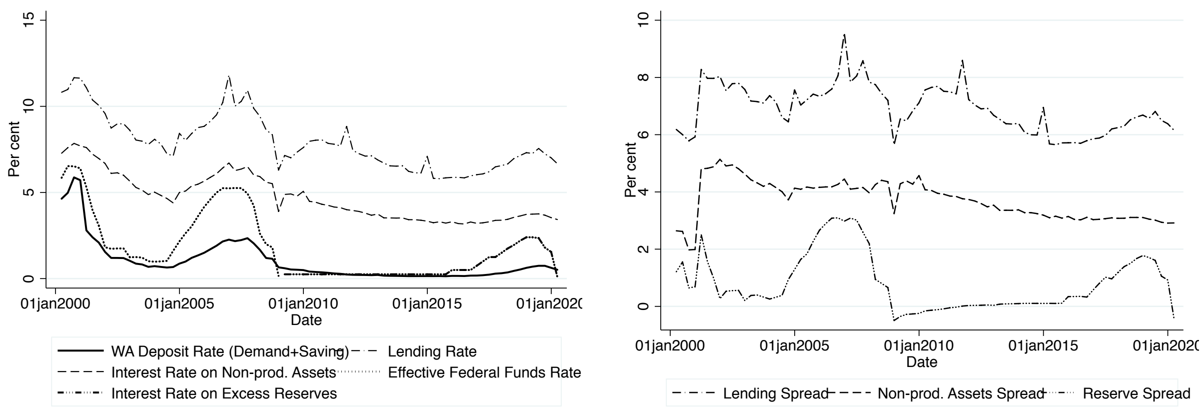
Overall, Figure 2 shows that spreads of all interest rates over deposit rates are almost always positive. In the pre-GFC period (between 2000 and 2009), the mean of the lending spread is 7.37% (with the 95% CI between 7.09% and 7.64%), the mean of the long-term bond spread is 4.10% (with the 95% CI between 3.84% and 4.35%) and the spread of reserves is 1.35% (with the 95% CI between 0.99% and 1.71%). In the post-GFC period, the mean of the lending spread is 6.56% (with the 95% CI between 6.36% and 6.77%), the mean of the long-term bond spread is 3.42% (with the 95% CI between 3.28% and 3.56%) and the spread of reserves is 0.38% (with the 95% CI between 0.20% and 0.57%). Statistically, hypotheses that test the equality between two spreads or between a spread and zero are rejected, against the alternative hypotheses. This result suggests an ordering of risk-weights on loans, long-term bonds and reserves, from highest to the lowest, with all risk-weights being positive both in the pre-GFC and in

[12] We omit time deposits. The results are qualitatively similar, but spreads are smaller when we include time deposits. There are two reasons for this omission. First, we assume a CBDC design, which would be similar to transactional and savings deposits. Moreover, in an extension, we study the presence of monetary frictions where deposits alleviate transaction costs. Time deposits are often not easily converted to payment instruments.

Figure 2: Interest rates and spreads
Panel 2a plots interest rates over time, including the average lending rate calculated from the Call Reports, the average rate banks obtain on their security holdings (including Treasuries, MBS etc.) and real estate loans also calculated from the Call Reports, the effective funds rate until 2009 replaced by the interest rate on excess rates after 2009 obtained from FRED, and the weighted average deposit rates (including transactional and savings deposits) obtained from the Call Reports. Panel 2b plots the spread of lending, long-term bonds, and reserves on the weighted average deposit rates.

(a) All rates

(b) Spread over deposit rates



the post-GFC period.

3.2 A panel data analysis of bank risk

In this section, we study how bank asset composition is associated with bank risk using a panel dataset of bank balance sheets and measures of default risk. We obtain 5-year CDS rates for banks and regress them on several relevant balance sheet variables (all as a share of total assets): $Shr\_Reserves_{bt}$ is the share of reserves (at the Federal Reserve), $Shr\_HTM\_Securities_{bt}$ is the share of the hold-to-maturity securities (Treasury, MBS etc.), $Shr\_Mortgages_{bt}$ is the share of loans backed by real estate, $Shr\_Loans\_exMortgages_{bt}$ is total loans held for investment, minus loans backed by real estate and loan loss allowances, Shr_Equity_{bt} is the share of equity. We also control for bank and date fixed effects. The sample contains 29 bank holding companies (BHCs), which is limited due to the lack of broader availability of CDS data. However, the sample of 30 BHCs with available CDS data covers around 50% of total bank balance sheets throughout the sample period (2005Q1-2020Q1).

In effect, we are interested in the marginal effect of each asset on bank's default risk controlling for bank and time characteristics, as well as bank leverage. We interpret a positive sign a a positive risk weight and vice versa.

We present the results in Table 1. In column (1), the report the results for the whole sample. Overall, the share of reserves, the share of hold-to-maturity securities and the share of loans excluding those backed by real estate are positively associated with bank CDS spreads. For example, one percentage point higher reserve share is associated with 8 basis points higher bank CDS. The share of equity to total assets and the share of loans backed with real estate have a negative, but insignificant coefficient. In column (2), when we divide the sample between pre- and post-GFC periods and interact a time dummy these variables, we find that the share of reserves and loans excluding real estate loans are positively associated with greater market perceptions of bank riskiness in the post-GFC period, whereas the share of equity is negatively associated with bank risk. In column (3), we focus on the post-GFC period and test whether the share of reserves are associated with bank CDS in a non-linear manner. While the coefficient on the quadratic term suggests that it is a convex relationship, it is statistically insignificant. In columns (4), (5) and (6), we repeat the regressions with the standardized values of the independent variables.

All in all, the results seem to point towards the calibration of risk weights on reserves, long-term bond holdings and loans to be positive as does the evidence presented in the previous section. The coefficient estimates on standardized values also point towards a similar ranking of risk weights as the interest rate spreads from the previous section.

3.3 A panel data analysis of bank profitability

We next explore potential economic mechanisms behind the results presented in Table 1. In particular, we focus on reserves which is a counter-intuitive result since reserves are essentially risk-free assets. One potential mechanism through which reserves could be related to bank risk could be due to reserves leading to lower profitability of banks and thereby increasing market perceptions of risks. It might be driven by either a loss of income due to reserves being remunerated lower than loans or due to a potential increase in funding costs for banks if higher reserve holdings could increase banks' funding costs to the extent they increase bank leverage. We explore these possibilities below. But, contrary to previous regression where we only focused on banks with available CDS data, we now run our regressions on the entire sample of bank holding companies as we are not constrained by data availability for these regressions. For this section, we use a sample period between 2000Q1-2019Q4 and do the analysis using both bank holding company data and data from call reports.

We present the results in Table 2. We report how different asset compositions are associated with interest income. Our results indicate that reserve holdings indeed impact bank profitability negatively, in particular in the post-GFC period and for banks with large amounts of reserve holdings. In columns (1) and (3), we compare the pre-GFC and the post-GFC periods in the BHC and call report data, respectively. Results indicate that, especially in the post-GFC period, higher reserve holdings as a share of total assets are significantly associated with lower profitability. Focusing on the post-GFC period, in columns (2) and (4), we show that there is a non-linear relationship, that is higher reserve holdings (as measured by the share of reserves squared) are associated with lower interest incomes after some point.

3.4 An instrumental variables analysis of the causal effect of reserve holdings on bank profitability

In this section, we present causal evidence using an instrumental variables approach to identify the negative effect of reserves on bank profitability. A good instrument for reserves should be highly correlated with it, while having no direct effect on bank profitability. We argue that the Treasury General Account

Table 1: Bank balance sheet composition and bank risk measured by credit default swaps

Regressions are at the bank (b) - date (t) level. The dependent variable is the CDS spread of a BHC measured in percentage points. The sample contains 30 BHCs. The full sample covers the quarters between 2005Q4 and 2020Q1. The Post-GFC sample covers between 2009Q1-2020Q1. $Shr\_Reserves_{bt}$ is the share of reserves (at the Federal Reserve), $Shr\_HTM\_Securities_{bt}$ is the share of the hold-to-maturity securities (Treasury, MBS etc.), $Shr\_Mortgages_{bt}$ is the share of loans backed by real estate, $Shr\_Loans\_exMortages_{bt}$ is total loans held for investment, minus loans backed by real estate and loan loss allowances, Shr_Equity_{bt} is the share of equity, all shares with respect to total assets. All these independent variables are measured in percentage points (i.e. go between 0 and 100). $\mathbb{1}(t > 2008Q4)$ is a dummy variable that indicates whether the observation is from 2009 or later. Variables with the prefix "*Sta_*" are standardized. Standard errors double clustered at the bank and quarter level are in parentheses. ***, **, * denote significance at the 1, 5 and 10% level respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Sample:	Full	Full	Post-GFC	Full	Full	Post-GFC
	CDS_{bt}	CDS_{bt}	CDS_{bt}	CDS_{bt}	CDS_{bt}	CDS_{bt}
$Shr\_Reserves_{bt}$	0.08**	-0.05	0.05			
	(0.04)	(0.05)	(0.12)			
$\mathbb{1}(t > 2008Q4) * Shr\_Reserves_{bt}$		0.16**				
		(0.08)				
$Shr\_Reserves^2_{bt}$			0.003			
			(0.01)			
$Shr\_HTM\_Securities_{bt}$	0.08*	0.04	0.07**			
	(0.04)	(0.04)	(0.03)			
$\mathbb{1}(t > 2008Q4) * Shr\_HTM\_Securities_{bt}$		0.03				
		(0.04)				
$Shr\_Mortgages_{bt}$	-0.05	-0.02	-0.05			
	(0.04)	(0.04)	(0.05)			
$\mathbb{1}(t > 2008Q4) * Shr\_Mortgages_{bt}$		-0.01				
		(0.02)				
$Shr\_Loans\_exMortgages_{bt}$	0.18*	0.11*	0.24**			
	(0.10)	(0.06)	(0.11)			
$\mathbb{1}(t > 2008Q4) * Shr\_Loans\_exMortgages_{bt}$		0.12*				
		(0.06)				
Shr_Equity_{bt}	-0.16	0.43***	-0.17			
	(0.23)	(0.12)	(0.25)			
$\mathbb{1}(t > 2008Q4) * Shr\_Equity_{bt}$		-0.61**				
		(0.29)				
$Std\_Shr\_Reserves_{bt}$				0.39**	-0.24	0.34
				(0.19)	(0.23)	(0.35)
$\mathbb{1}(t > 2008Q4) * Std\_Shr\_Reserves_{bt}$					0.77**	
					(0.37)	
$Std\_Shr\_Reserves^2_{bt}$						0.07
						(0.14)
$Std\_Shr\_HTM\_Securities_{bt}$				0.54*	0.28	0.48*
				(0.30)	(0.24)	(0.23)
$\mathbb{1}(t > 2008Q4) * Std\_Shr\_HTM\_Securities_{bt}$					0.23	
					(0.26)	
$Std\_Shr\_Mortgages_{bt}$				-0.73	-0.37	-0.76
				(0.60)	(0.58)	(0.81)
$\mathbb{1}(t > 2008Q4) * Std\_Shr\_Mortgages_{bt}$					-0.09	
					(0.26)	
$Std\_Shr\_Loans\_exMortgages_{bt}$				3.42*	2.05*	4.65**
				(1.92)	(1.13)	(2.15)
$\mathbb{1}(t > 2008Q4) * Std\_Shr\_Loans\_exMortgages_{bt}$					2.34*	
					(1.20)	
$Std\_Shr\_Equity_{bt}$				-0.55	1.50***	-0.60
				(0.79)	(0.44)	(0.87)
$\mathbb{1}(t > 2008Q4) * Std\_Shr\_Equity_{bt}$					-2.14**	
					(1.00)	
Observations	920	920	700	920	920	700
R-squared	0.42	0.45	0.45	0.42	0.45	0.45
Bank FE	✓	✓	✓	✓	✓	✓
Date FE	✓	✓	✓	✓	✓	✓

Table 2: Bank balance sheet variables and income: Panel data analysis

Regressions are at the bank (b) - date (t) level. In columns (1) and (2) bank refers to bank holding companies (BHC), with data obtained from FRY9-C filings. In columns (3) and (4) bank refers to depository institutions, with data obtained from Call Reports. The dependent variable is $Log(Int.Income)_{bt}$. In columns (1) and (3), the sample covers the quarters between 2000Q1 and 2019Q4. In (2) and (4), the sample covers the post-GFC period: 2009Q1-2019Q4. $Shr\_Reserves_{bt}$ is the share of reserves (at the Federal Reserve), $Shr\_Reserves^2_{bt}$ is the share of reserves squared. $Shr\_HTM\_Securities_{bt}$ is the share of the securities (Treasury, MBS etc.), $Shr\_Mortgages_{bt}$ is the share of loans backed by real estate, $Shr\_Loans\_exMortagesbt$ is total loans, minus loans backed by real estate and loan loss allowances, Shr_Equity_{bt} is the share of equity, to total assets. $Log(Assets)_{bt}$ is the log of total assets. $Log(LoanLossProv.)_{bt}$ is the log of loan and lease loss allowances. $\mathbb{1}(t > 2008Q4)$ is a dummy variable that indicates whether the observation is from 2009 or later. All share variables are measured in percentage points (i.e. go between 0 and 100). Standard errors are double clustered at the bank and quarter level and are shown in parentheses. ***, **, * denote significance at the 1, 5 and 10% level respectively.

	(1)	(2)	(3)	(4)
Data:	Bank Holding Company		Call Reports	
Sample:	Full	Post-GFC	Full	Post-GFC
	OLS	OLS	OLS	OLS
Dep. Var:	$Log(Int.Income)_{bt}$		$Log(Int.Income)_{bt}$	
$Shr\_Reserves_{bt}$	-0.0004	-0.0001	-0.0065***	-0.0047***
	(0.0011)	(0.0009)	(0.0004)	(0.0006)
$Shr\_Reserves_{bt} * \mathbb{1}(t > 2008Q4)$	-0.0044***		-0.0010**	
	(0.0013)		(0.0004)	
$Shr\_Reserves^2_{bt}$		-0.0001***		-0.0001***
		(0.0000)		(0.0000)
$Shr\_HTM\_Securities_{bt}$	0.0013***	0.0028***	-0.0038***	-0.0048***
	(0.0004)	(0.0008)	(0.0003)	(0.0002)
$Shr\_Mortgages_{bt}$	0.0050***	0.0061***	0.0004	0.0002*
	(0.0004)	(0.0007)	(0.0003)	(0.0001)
$Shr\_Loans\_exMortgages_{bt}$	0.0041***	0.0058***	0.0030***	0.0031***
	(0.0006)	(0.0008)	(0.0003)	(0.0003)
Shr_Equity_{bt}	0.0029*	0.0012	-0.0051***	-0.0022
	(0.0017)	(0.0031)	(0.0008)	(0.0018)
$Log(Assets)_{bt}$	0.9674***	0.9464***	1.0410***	1.0186***
	(0.0182)	(0.0148)	(0.0043)	(0.0079)
$Log(LoanLossProv.)_{bt}$	0.0185***	0.0176***	0.0007	0.0027***
	(0.0029)	(0.0028)	(0.0010)	(0.0008)
Observations	78,713	31,663	382,713	191,670
R-squared	0.9962	0.9967	0.9946	0.9964
Bank FE	✓	✓	✓	✓
Date FE	✓	✓	✓	✓

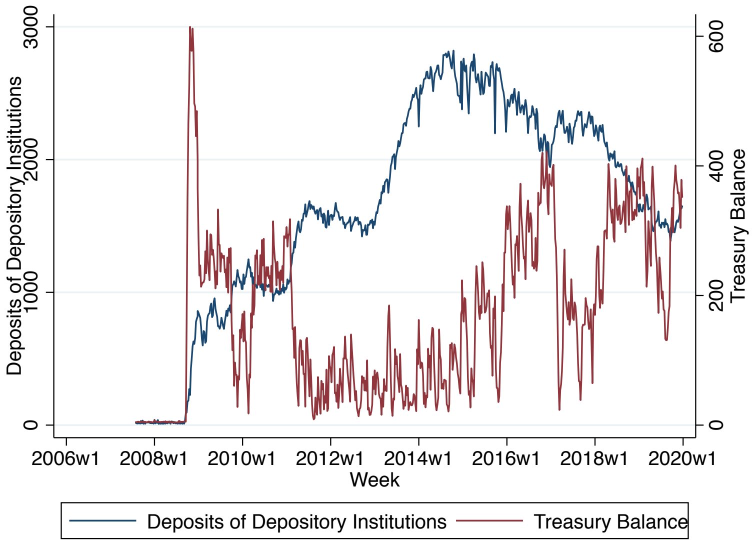
(TGA) at the Federal Reserve is an ideal instrument for bank reserves.

The TGA is the checking account of the US Treasury at the Federal Reserve. Prior to the GFC, most of the cash of the Treasury was held at commercial banks in the form of bank deposits. Following the GFC, the Treasury shifted these balances to the TGA at the Federal Reserve. In May 2015, the TGA balances increased further with precautionary motives to protect the Treasury from an interruption in market access (see Correa et al. (2020) and the references therein). Holding the balance sheet of the Federal Reserve constant, whenever private agents make a payment to the Treasury, the Federal Reserve credits the TGA and debits the reserves of the bank whose clients made the payment, hence reducing the overall amount of bank reserves in its balance sheets, and vice versa. Importantly, the Federal Reserve considers the TGA as an autonomous factor and does not react to fluctuations by adding or reducing reserves to keep them stable. Therefore, all else equal, there should be a negative relationship between the TGA balance and the overall level of bank reserves.

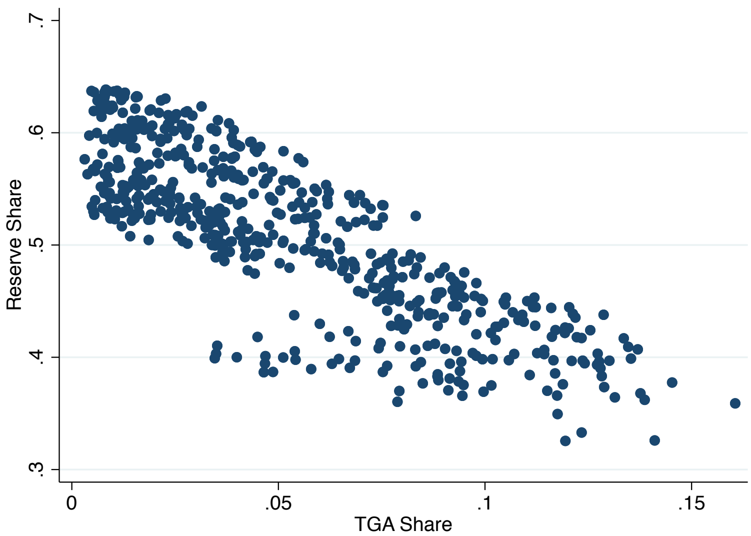
A closer look at the liabilities of the Federal Reserve makes a strong case for the use of the TGA as an instrument.[13] In Panel 3a, we show the weekly time series of bank reserves and the TGA. The TGA is volatile, especially after 2015. Moreover, the negative relationship between the share of the TGA and bank reserves in the liabilities of the Fed hold in the data, with a statistically significant regression coefficient of -0.33. Moreover, since the balances at the TGA move almost randomly, we do not expect it to have any meaningful direct impact on bank profitability, satisfying the exclusion restriction.

Figure 3: TGA and bank reserves

(a) Time series of TGA and bank reserves ($ billions)



(b) Scatterplot of TGA and bank reserves



We report the results of the second stage regressions instrumenting the variable $Shr\_Reserves_{bt}$ with $log(TGA)_t$ with quarterly data taking the value of TGA at the quarter-end. Note that this gives us

[13]We are not the first ones to use this as a shock to bank reserves. Hamilton (1997) uses the forecasting error in Treasury cash holdings as liquidity shocks in the pre-GFC period. Correa et al. (2020) use the TGA as a shock to dollar funding conditions in the post-GFC period.

variation at the time series level, so our identification argument relies on differences at various quarter-end for an average bank. As we did previously, we repeat this exercise for both bank holding companies and depository institutions (with data obtained from call reports). We control for a dummy variable which indicates whether the quarter is after 2014Q4 to account for the changes in the levels of the TGA. We also control for bank fixed effects and a number of variables at the bank-date level, such as the share of securities, mortgages and loans, leverage, log assets, log loan loss provisions; and date level (since our instrument is at the date level, we cannot use date fixed effects), such as the federal funds rate, VIX, total size of the Fed balance sheet and 10-year yields on US Treasuries. We double cluster standard errors both at the bank level and the quarter level to account for both cross-sectional and time-series correlation in the error terms. In line with our earlier results, we find that a greater share of reserves leads to lower incomes for banks, which intensifies after 2015 (as indicated by the interaction term $Shr\_Reserves_{bt} * \mathbb{1}(t > 2014Q4)$).[14].

Table 3: Second stage regression: Bank reserve holdings and income

Regressions are at the bank (b) - date (t) level. Table reports the second stage regressions of the 2SLS estimation. In columns (1) and (2) bank refers to bank holding companies (BHC) with data obtained from FRY9-C filings. In columns (3) and (4) bank refers to depository institutions, with data obtained from Call Reports. The dependent variable is $Log(Int.Income)_{bt}$. The sample covers the quarters between 2000Q1 and 2019Q4. $Shr\_Reserves_{bt}$ is the share of reserves (at the Federal Reserve) and it is instrumented by $log(TGA)_t.\mathbb{1}(t > 2014Q4)$ is a dummy variable indicating whether the quarter is after 2014Q4. $Shr\_Reserves_{bt} * \mathbb{1}(t > 2014Q4)$ is instrumented by $log(TGA)_t * \mathbb{1}(t > 2014Q4)$. Bank-Date controls include the following variables: $Shr\_HTM\_Securities_{bt}$ is the share of the hold-to-maturity securities (Treasury, MBS etc.), $Shr\_Mortgages_{bt}$ is the share of loans backed by real estate, $Shr\_Loans\_exMortgagesbt$ is total loans, minus loans backed by real estate and loan loss allowances, Shr_Equity_{bt} is the share of equity, to total assets, and also $Log(Assets)_{bt}$, which is the log of total assets, and $Log(LoanLossProv)_{bt}$, which is the log of loan loss provisions. Date controls are the federal funds rates, VIX, the log of total Federal Reserve balance sheet size, and the 10-year Treasury yield. All these variables are measured in percentage points (i.e. go between 0 and 100). Standard errors double clustered at the bank and quarter level are in parentheses. ***, **, * denote significance at the 1, 5 and 10% level respectively.

	(1)	(2)	(3)	(4)
Data:	Bank Holding Company		Call Reports	
Sample:	Post-GFC	Post-GFC	Post-GFC	Post-GFC
	2SLS	2SLS	2SLS	2SLS
Dep. Var:	$Log(Int.Income)_{bt}$		$Log(Int.Income)_{bt}$	
$Shr\_Reserves_{bt}$	-0.5532*	-0.3986*	-0.0378**	-0.0339**
	(0.3166)	(0.2364)	(0.0170)	(0.0141)
$Shr\_Reserves_{bt} * \mathbb{1}(t > 2014Q4)$		-1.2553**		-0.0311
		(0.6107)		(0.0896)
$\mathbb{1}(t > 2014Q4)$	-0.1864	4.9872*	-0.0497*	0.2054
	(0.1762)	(2.5437)	(0.0254)	(0.7178)
Observations	31,663	31,663	191,670	191,670
Bank-Date Controls	✓	✓	✓	✓
Date Controls	✓	✓	✓	✓
Bank FE	✓	✓	✓	✓

We report the results of the first stage in Table 4. The coefficient on $log(TGA)_t$ is significantly negative. Moreover, the F-statistics are large, suggesting that the instrument is not weak.

[14]In columns (2) and (4), we use $log(TGA)_t$ and $log(TGA)_t * \mathbb{1}(t > 2014Q4)$ as instruments for $Shr\_Reserves_{bt}$ and $Shr\_Reserves_{bt} * \mathbb{1}(t > 2014Q4)$

Table 4: First stage regression: Bank reserve holdings and the TGA
Regressions are at the bank (b) - date (t) level. Table reports the first stage regressions of the 2SLS estimation. In column (1), bank refers to bank holding companies (BHC) with data obtained from FRY9-C filings. In column (2) bank refers to depository institutions, with data obtained from Call Reports. The dependent variable is $Shr\_Reserves_{bt}$. The sample covers the quarters between 2000Q1 and 2019Q4. $Shr\_Reserves_{bt}$ is the share of reserves (at the Federal Reserve) and it is instrumented by $log(TGA)_t$. Bank-Date controls include the following variables: $Shr\_HTM\_Securities_{bt}$ is the share of the hold-to-maturity securities (Treasury, MBS etc.), $Shr\_Mortgages_{bt}$ is the share of loans backed by real estate, $Shr\_Loans\_exMortgagesbt$ is total loans, minus loans backed by real estate and loan loss allowances, Shr_Equity_{bt} is the share of equity, to total assets, and also $Log(Assets)_{bt}$, which is the log of total assets, and $Log(LoanLossProv)_{bt}$, which is the log of loan loss provisions. Date controls are $\mathbb{1}(t > 2014Q4)$, which is a dummy variable indicating whether a quarter is after 2014Q4, the federal funds rates, VIX, the log of total Federal Reserve balance sheet size, and the 10-year Treasury yield. All these variables are measured in percentage points (i.e. go between 0 and 100). Standard errors double clustered at the bank and quarter level are in parentheses. ***, **, * denote significance at the 1, 5 and 10% level respectively.

	(1)	(2)
Data:	BHC	Call Reports
Sample:	Post-GFC	Post-GFC
	First Stage	First Stage
Dep. Var:	$Shr\_Reserves_{bt}$	
$log(TGA)_t$	-0.3529**	-0.3939**
	(0.1322)	(0.1834)
Observations	31,663	191,786
R-squared	0.7248	0.7218
F-stat	34.21	66.62
Bank-Date Controls	✓	✓
Date Controls	✓	✓
Bank FE	✓	✓

3.5 Modeling banks and reserves in light of the evidence

Our empirical results on reserves so far suggest that the interest rate spread between reserves and deposits is positive, higher reserves are associated with greater default risk and lower profitability. All in all, these results all suggest that the steady state value of κ_{B_F} is greater than zero. However, it is important to also consider that holding some level of reserves might be beneficial for banks in order to facilitate payments, comply with the liquidity coverage ratio etc.

To reconcile the benefits of reserves and the costs, we consider a version of our model with a linear-quadratic form for $\mathcal{A}$:

$$\mathcal{A} := \left(\kappa_{K_f} K_F + \kappa_{\mathcal{B}_B} P_b \mathcal{B}_B + \kappa_{F1} B_F + \frac{\kappa_{F2}}{2} B_F^2\right) \tag{3.1}$$

which implies that

$$\kappa'_{K_f} = \kappa_{K_f} \tag{3.2}$$

$$\kappa'_{\mathcal{B}_B} = \kappa_{\mathcal{B}_B} \tag{3.3}$$

$$\kappa'_{B_F} = -\kappa_{F1} + \kappa_{F2} B_F, \tag{3.4}$$

This specification suggests that while a certain level of reserves can be beneficial for banks, higher reserve holdings exacerbate the financial friction, which is in line with our empirical findings.

4 Calibration to the United States

In order to proceed with our numerical analysis we need to assign values to the parameters of our model. To this aim we separate the parameters in four groups. The first group consists of parameters that are not at the core of our frictions, relating to households and firms (e.g. labor supply elasticity, price stickiness etc.). For this set we take standard parameter values from the literature. The second group pertains to key parameters of our financial frictions, specifically to banks and government (e.g. fraction of defaultable assets of each type). For this set we assess the sensitivity of our model for a range of values around those emerging from the literature or suggested by the empirical evidence. The third group consists of policy parameters of the central bank – note that we abstract from simple rules by imposing full price and spread stabilization. Finally, we report the size and persistence of the shocks considered. We report the parameters in Table 5.

We assume a linear form for private bank costs:

$$\mathcal{A} := \left(\kappa_{K_f} Q_t K_{F,t} + \kappa_{\mathcal{B}_B} P_{B,t} \mathcal{B}_{B,t} + \kappa_{F1} B_{F,t}\right) \tag{4.1}$$

and quadratic form for central bank costs

$$g = \frac{1}{2}\left(g_{K_{CB}}(Q_t K_{CB,t})^2 + g_{\mathcal{B}_{CB}}(P_{B,t}\mathcal{B}_{CB,t})^2 + g_{B_F} B_{F,t}^2 + g_{D_{CB}} D_{CB,t}^2\right) \tag{4.2}$$

Most parameter values are standard. The discount factor is particularly high at 0.999 to produce a small deposit rate in lieu of including a liquidity premium. We include long-run inflation at an annual rate of 1.6 percent. Long-term bonds are set to have a maturity of 5 years, or 20 quarters and a fixed return of three percent. The risk-weights on bank lending, bond-holdings and reserves are all positive and are set to match the spreads found in Section 3. Similarly, for stability reasons, we include a positive coefficient of 0.1 on the rule governing CB revenue.

In Table 6, we report the unconditional means for a version of our model without CBDC and where the central bank operates a Taylor rule, and compare it to the data obtained from the FRED (means and 95% confidence intervals for the post-GFC period).

The model is broadly consistent with the data. There are some discrepancies which are due to several simplifying assumptions we have made in the model. First, consumption is lower in the model than in the data since we model a closed economy and ignore trade deficits. Second, deposits are higher in the model than in the data, since in the data we only focus on transactional and savings deposits. Finally, returns on deposits and reserves are higher in the model since we abstract from monetary frictions and associated convenience yields in the benchmark model. Consequently, the spreads are too low in the model.

Table 5: Parameters

Description	Parameter	Value
Households		
Discount factor	β	0.999
Labor share	α	0.33
Labor utility weight	χ	1
Risk-aversion	σ	0.5
Inverse Frisch elasticity	ψ	1.3
Utility constant	$\bar{U}$	1
Firms		
Capital adjustment cost	η	1.728
Depreciation	δ	0.01
Demand elasticity	σ_p	6
Calvo probability	ς	0.75
Banks		
Survival probability	θ	0.95
Start-up transfer	δ_T	0.01
Risk-weight coefficients		
Lending	κ_{K_f}	0.51
Long-term non-productive assets	$\kappa_{\mathcal{B}_B}$	0.27
Reserves	κ_{B_F}	0.03
Government		
Perpetuity expiry probability	δ_p	0.95
Perpetuity fixed return	$\bar{r}_p$	0.01
Central Bank		
Inflation objective (quarterly)	π	1.004
Seigniorage stability coefficient	Ψ	0.1
Resource costs		
Lending	$g_{K_{CB}}$	0.00001
Long-term non-productive assets	$g_{\mathcal{B}_{CB}}$	0.00001
Reserves	g_{B_F}	0.00001
CBDC	$g_{D_{CB}}$	0.00001
Shocks		
Productivity shock persistence	ρ_A	0.9
Financial shock persistence	ρ_F	0.9
Productivity shock size	σ_A	0.001
Financial shock size	σ_F	0.01

5 Optimal central bank policy

In this section, we use our framework to evaluate central bank stabilization policies in response to shocks. The central bank can set both short- and long-term interest rates. In addition, it can manipulate the size and composition of its balance sheet. We concentrate on the case where the central bank conducts optimal monetary policy to maximize the welfare of households. We report our results for productivity shocks next, and relegate the results for financial shocks to Appendix B for brevity.

Table 6: Unconditional means: model versus data

Sample covers between 2009Q1 and 2019Q4. †indicates variables are reported as proportion of output. Inflation, interest and spreads are annualized. Spreads are in basis points. ‡: Deposits exclude time deposits. Deposit return is the weighted average rate of checking and savings rates calculated from the Call Report data. *: We include total federal debt and mortgages in $\mathcal{B}$. $\tilde{}$: K_f is calculated as total lending less reserves for losses, loans backed by real estate and total cash and deposits due from depository institutions. $\mathcal{B}_B$ is calculated as securities plus loans backed by real estate. *Reserves* are the total cash and deposits due from depository institutions in the FDIC quarterly bank balance sheet data. *Source:* FRED, FDIC, Call reports.

Variable	Symbol	Model Benchmark	Data (post-GFC mean) [95% CI]
Consumption†	C/Y	0.65	0.679 [0.6778,0.6801]
Investment†	I/Y	0.167	0.163 [0.1594,0.0.1682]
Government spending†	G/Y	0.182	0.187 [0.1832,0.1919]
Deposits†,‡	D/Y	0.815	0.543 [0.5300,0.5569]
CBDCs†	D_{CB}/Y	0	-
Long-term non-prod assets†,*	$\mathcal{B}/Y$	1.747	1.797 [1.7892,1.8047]
Velocity of deposits‡	C/D	0.798	1.258 [1.2235,1.2934]
Bank lending$^{\dagger,\tilde{}}$	K_f/Y	0.222	0.218 [0.2119,0.2250]
Bank long-term non-prod. asset holdings$^{\dagger,\tilde{}}$	$\mathcal{B}_B/Y$	0.438	0.431 [0.4249,0.4382]
CB long-term non-prod. asset holdings$^{\dagger,\tilde{}}$	$\mathcal{B}_{CB}/Y$	0.181	0.185 [0.1716,0.1984]
Reserves$^{\dagger,\tilde{}}$	B_f/Y	0.09	0.088 [0.0846,0.0924]
Net worth†	N/Y	0.115	0.098 [0.0981,0.0989]
Leverage‡	D/N	7.106	5.516 [5.3750,5.6581]
Capital return (real)	R_k	1.026	1.051 [1.0483,1.0537]
Long-term non-prod. asset return (real)	R_b/π	1.014	1.0201 [1.0181,1.0222]
Reserves return (real)	R_f/π	1.002	0.9903 [0.9884,0.9921]
Deposit return (real)‡	R_d/π	1.001	0.9864 [0.9854,1.9874]
Inflation	π	1.017	1.016 [1.0158,1.0178]
Bank spread	$R_k/(R_d/\pi)-1$	2.5%	6.54% [6.34%,6.74%]
Long-term non-prod. asset spread	R_b/R_d-1	1.33%	3.41% [3.27%,3.54%]
Reserve spread	R_f/R_d-1	0.16%	0.38% [0.20%,0.57%]
Liquidity premium	R/R_d-1	0.32%	0.35% [0.20%,0.57%]

Specifically, the central bank chooses its pricing rule, its holdings of long-term government securities ($\mathcal{B}_{CB}$) and direct-lending (K_{CB}) as well as its issuance of CBDC (D_{CB}). Its reserve issuance is given residually from the central bank balance sheet.

We compute optimal policy with the following objective function for the central bank:

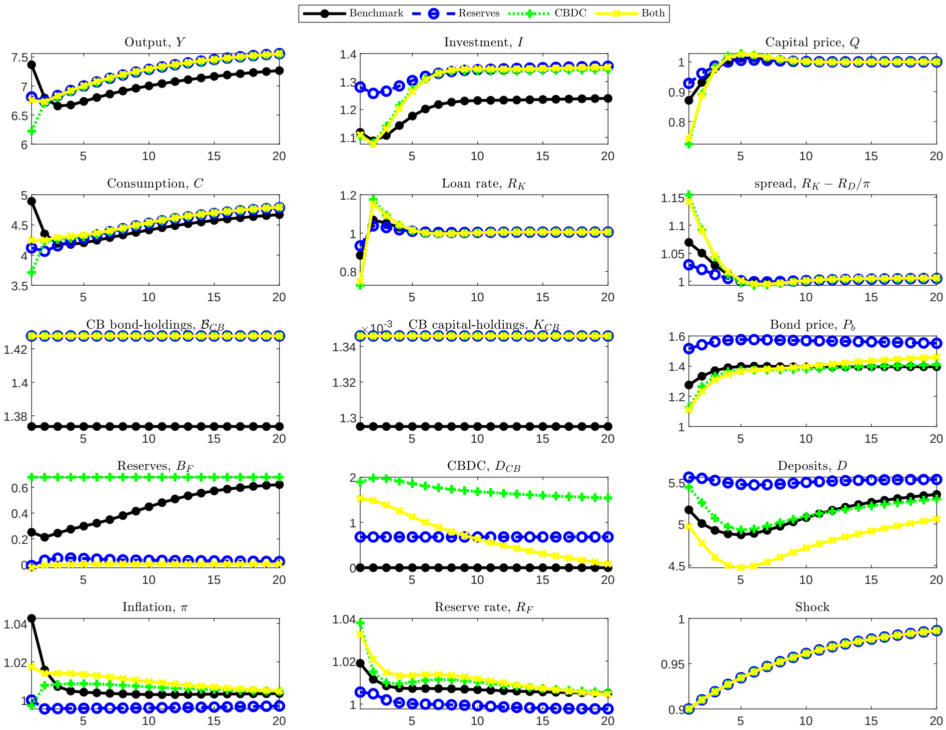
$$\mathcal{W}_t - g\left(K_{CB,t}, P_{B,t}\mathcal{B}_{CB,t}, B_{F,t}, D_{CB,t}\right) \tag{5.1}$$

where $\mathcal{W}_t$ denotes household welfare given in (2.1) and $g(\cdot)$ is the cost of central bank balance sheet manipulation. Specifically, we assume $g(\cdot)$ is quadratic.[15] We assume a high cost on direct central bank lending and a small cost on CBDC-issuance. These costs could be motivated by political economy concerns for central bank lending or costs due to KYC/AML regulations for CBDC. For simplicity, we do not put costs on bond-purchases and reserve-issuance since both are in the normal operation of central banks. The large cost on direct central bank lending is sufficient to prevent this instrument being used.

In the first experiment, we compute the optimal solution with respect to the price stability rule. We show the results in Figure 4. We report the sub-optimal regime with a Taylor rule as a benchmark (solid black line). We compare the cases where the central bank maintains stability using reserves (dashed blue line) or CBDC (dotted green line), keeping the other liability constant. We then include the case whereby the central bank can optimally set its liability composition, that is both reserves and CBDC can be used to pursue its objective (solid yellow line).

[15] $g(\cdot) = \left(\lambda_{K_{CB}}(Q_t K_{CB,t})^2 + \lambda_{\mathcal{B}_C B}(P_{B,t}\mathcal{B}_{CB,t})^2 + \lambda_{B_f} B_{f,t}^2 + \lambda_{D_{CB}} D_{CB,t}^2\right)$

Figure 4: Optimal policy responses to a TFP shock



When the central bank chooses optimally, its choices are very similar whether its assets are funded with reserves, CBDCs or optimally choosen as a mixture of both (visually, the green and yellow lines coincide).

We obtain *efficient disintermediation* in the long run if the central bank conducts optimal monetary policy. Table 7 reports the unconditional means of variables in the model when the central bank conducts optimal monetary policy ("Optimal") compared with the benchmark case in which the central bank operates a Taylor rule with respect to the rate on reserves keeping bonds, lending and CBDC constant ("Benchmark"). Key variables of interest are deposits (D/Y), CBDC (D_{CB}/Y), bank and central bank long-term non-productive asset holdings ($\mathcal{B}_B/Y$ and $\mathcal{B}_{CB}/Y$, respectively) and investment (I/Y).

Efficient disintermediation results in smaller bank balance sheets with higher investment regardless. A reduction of reserves and non-productive asset holdings (long-term bonds) of banks on the asset side is mirrored by a reduction in deposits. Reduction of these assets results in an easing of the financial frictions for banks and opens rooms for greater investment. Under optimal monetary policy, CBDC issuance amounts to 13.7% of GDP. Deposits fall by around 10 percentage points. Yet, investment is larger in the optimal policy with positive CBDC holdings by about one percentage point.

The intuition of this result is the following. The central bank purchases assets until its relative inefficiency matches the relative inefficiency of the banks. When the central bank should chooses between funding these assets by reserves versus CBDC, it compares how reserves affect the financial friction of banks and the resource costs of issuing CBDC versus reserves for the central bank. If the central bank funds its purchases by issuing reserves, assuming that the risk-weight of reserves are lower than other assets, it generates efficiency gains by altering the asset composition of banks' balance sheet without affecting the size. However, if the risk-weight of reserves is positive at the margin, it is optimal to fund most of these purchases by CBDC. In this case, the central bank disintermediates banks, but this disintermediation is efficient. Reducing bank balance sheets alleviates the constraints imposed by the financial frictions on banks. Reduced financial frictions increase total investment through higher bank lending, despite the disintermediation of deposits.

Table 7: Unconditional means: model versus optimal

Variable	Symbol	Benchmark	Optimal
Consumption	C/Y	0.65	0.641
Hours	H/Y	0.25	0.244
Investment	I/Y	0.167	0.176
Government spending	G/Y	0.182	0.182
Deposits	D/Y	0.777	0.675
CBDC	D_{CB}/Y	0	0.137
Velocity of deposits	C/D	0.837	0.95
Bank lending	K_f/Y	0.174	0.204
Bank long-term non-prod. asset holdings	$\mathcal{B}_B/Y$	0.438	0.389
CB lending	K_{CB}/Y	0	0
CB long-term non-prod. asset holdings	$\mathcal{B}_{CB}/Y$	0.185	0.228
Reserves	B_f/Y	0.088	0.001
Net worth	N/Y	0.096	0.104
Leverage	D/N	8.135	6.494
Tax-revenue	T/Y	0.19	0.187
Long-term non-prod assets	$\mathcal{B}/Y$	1.75	1.749
Capital return (real)	R_k	1.026	1.023
Long-term non-prod. asset return (real)	R_b/π	1.014	1.01
Reserves return (real)	R_f/π	1.002	0.997
Deposit return (real)	R_d/π	1	0.995
CBDC return (real)	R_{CB}/π	1	0.996
Inflation	π	1.016	1.007
Bank spread	$R_k/(R_d/\pi) - 1$	2.54%	2.75%
Long-term non-prod. asset spread	$R_b/R_d - 1$	1.33%	1.45%
Reserve spread	$R_f/R_d - 1$	0.16%	0.16%
Liquidity premium	$R/R_d - 1$	0.36%	0.84%

6 Other considerations

In this section, we first discuss the overnight reverse repurchase facility (ON RRP) of the Federal Reserve as a tool that can be helpful in understanding the impact of CBDC. In essence, this facility allows entities other than banks to hold interest-bearing central bank liabilities. Following the Covid-19 crisis, this facility has helped the central banks to reduce reserves banks would have needed to hold. It has also been useful during other episodes. We draw lessons from these episodes about how CBDC can be useful in promoting better market functioning and conducting monetary policy. In the next subsection, we use available data in a cross-country setting to gauge in which jurisdictions CBDC could improve efficiency through the lens of our model.

6.1 Lessons from the ON RRP for CBDC

Empirical evidence on how CBDC can work in practice has been scant since many central banks are still considering the prospects of introducing CBDC. The ON RRP of the Federal Reserve shares similar characteristics with CBDC, in that it is an innovation that has increased the set of eligible counterparties that can access to the balance sheet of the Federal Reserve and earn interest from banks to a wider variety of participants. The design of the ON RRP and its response during crises episodes and other periods of disruptions to intermediation by banks hold lessons for how CBDC could be used for monetary policy transmission.

The Federal Reserve introduced the overnight reverse repurchase agreement facility in 2014 as an additional tool to improve its implementation of monetary policy with abundant reserves. Its introduction was motivated by the fact that unlike banks, government-sponsored-enterprises (GSEs) did not have the possibility of holding reserve balances at the Federal Reserve even though they were lending their funds to banks at the federal funds market. Therefore, they had incentives to lend to banks below the interest rate on excess reserves (IOER) and banks would place those funds as reserves to earn the IOER. Due to the segmentation in the access to interest-bearing reserves at the Federal Reserve, there was no effective floor on the federal funds rate.

The introduction of the ON RRP aimed to provide an effective floor on the federal funds rate. The ON RRP is an overnight reverse repurchase agreement whereby the Federal Reserve pledges Treasuries as collateral and obtains funds from eligible counterparties. The interest rate on ON RRP is set below the IOER and market participants without access to reserves (that earn the IOER) can earn this rate. The open market trading desk determines how much to auction each day at the offered rate (historically total amount auctioned has been much higher than the demand). The eligible set of counterparties in the ON RRP facility includes US money market funds (MMFs), GSEs, primary dealers and banks. As such, the ON RRP effectively reduces market segmentation in the access to interest-bearing central bank liabilities. In reality, US MMFs account for almost all ON RRP take up.

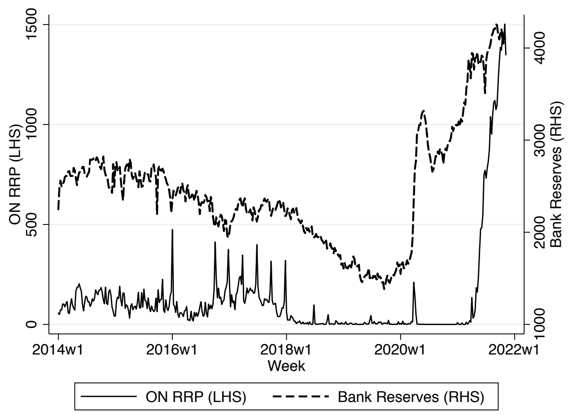
Three different episodes of spikes in the usage of ON RRP highlight how allowing access to interest-bearing central bank liabilities to entities other than banks could improve monetary policy transmission and market functioning. Periods when the ON RRP take up spiked are quarter-ends when European banks temporarily exit repo markets (Aldasoro et al., 2019), the March 2020 turmoil in money markets (Eren et al., 2020) and the period after the exemptions from the supplementary leverage ratio (SLR) ended (Covas, 2021). Next, we discuss each of these episodes and how they potentially relate to CBDC.[16]

ON RRP take up spikes during quarter-ends when banks stop intermediating markets suggest that

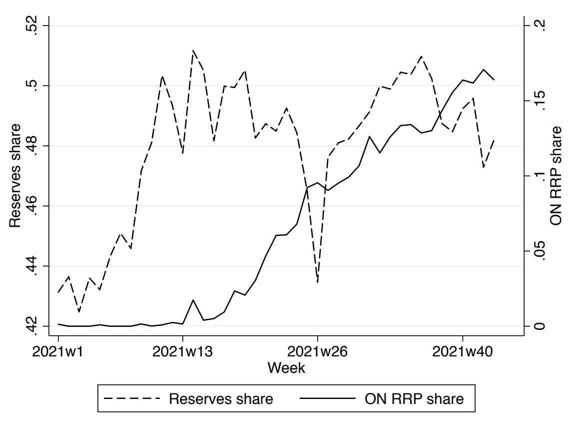
[16] It is important to note how the existence of the ON RRP affected monetary policy implementation and market functioning depend on the specific design on the ON RRP, namely the fact that it pays a lower interest rate than bank reserves and its limits are very large so they are almost never binding.

Figure 5: ON RRP and bank reserves

(a) ON RRP and bank reserves ($ billions)



(b) Shares in central bank liabilities



allowing broader access to interest-bearing central bank liabilities could help markets weather short-term market disruptions smoothly. Despite how large the total reduction in bank intermediation can be (in the order of hundreds of billions within days (Aldasoro et al., 2019)), thanks to the existence of the ON RRP, no major market disruptions occurred and the ON RRP usage declined as banks returned to intermediate after the quarter-end.

The ON RRP has also proved to be a useful tool during the "dash-for-cash" episode in March 2020. During this episode, the assets under management of government and Treasury MMFs rose significantly as market participants viewed those MMFs as safe (Eren et al., 2020). In the absence of the ON RRPs, these MMFs would have invested the inflows into T-bills and repos putting a large downward pressure on the rates on these instruments. The existence of the ON RRP that absorbed the liquidity at a fixed interest rate helped markets function smoothly.

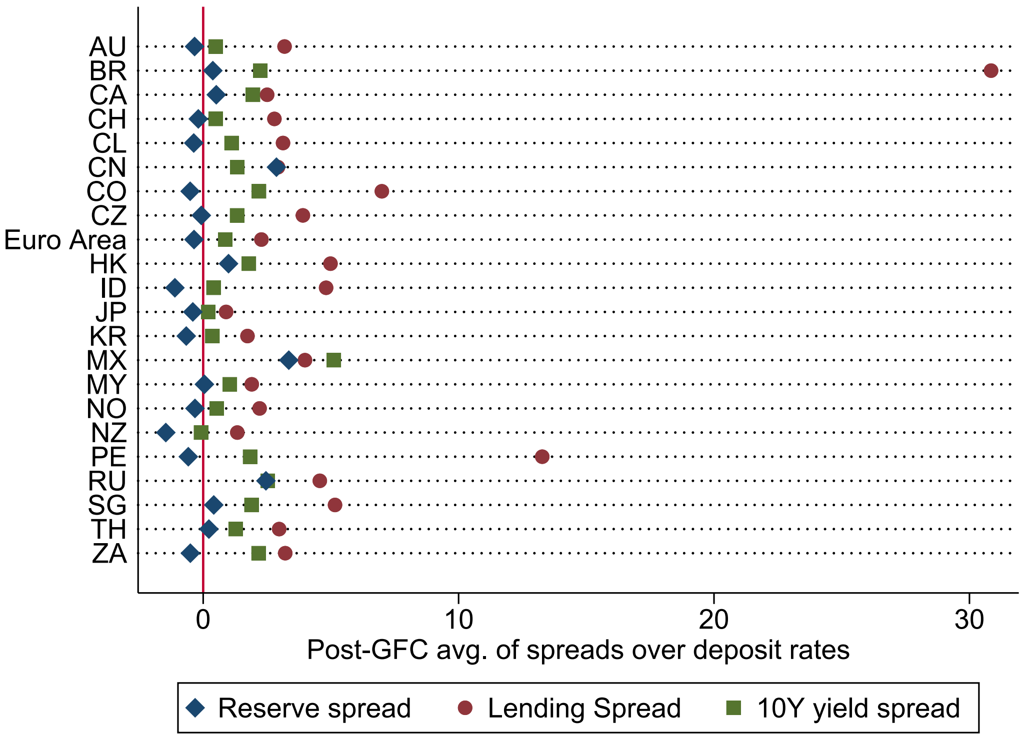
The rise in the ON RRP usage in the summer of 2021 highlights another potential use of CBDC in periods of abundant liquidity and during exit strategies from unconventional monetary policy. Following the expiration of the SLR relief given to banks, the cost of banks' intermediating deposits into reserves increased significantly (Covas, 2021), which resulted in an abrupt rise in the take up of the ON RRP. Interestingly, towards the middle of the year, bank reserves started a precipitous decline, going down from around \$3.9 trillion to \$3.5 trillion. In 2021, the take up of the ON RRP facility rose to around \$750 billion from nothing. As a result, the share of reserves in the central bank balance sheet declined by around 6 percentage points, as the share of ON RRP rose to around 10% of central bank liabilities.

This evidence directly speaks to our results: if intermediation frictions are present, then CBDC might help divert deposits from banks that would otherwise be invested in reserves harming bank profitability and alleviating spreads between interest rate on reserves and deposit rates. Furthermore, if central banks want to exit from unconventional monetary policy, CBDC can act as a tool that drains bank reserves without selling central bank assets to the markets which might have adverse consequences for market functioning.

6.2 Cross-country analysis

We have applied our model to the data from the United States due to the availability of high quality and high frequency data on bank balance sheets. However, in principle, our model can also be applied to other jurisdictions to gauge the potential benefits of issuing CBDC through the lens of our model.

Figure 6: Spreads of various interest rates over deposit rates. *Source:* World Bank, ECB, Bloomberg, authors' calculations.



In this section, we collect aggregate data on deposit rates, lending rates, yields on 10-year government bonds and do a cross-country comparison of these rates, which according to our model, pin down the sign of marginal risk weights in the banking sector.

Overall, the ordering of these rates are similar to those in the United States with the lending rate over deposit rate spreads being the largest, and the policy rate over deposit rates being the smallest as shown in Figure 6.

A key parameter of our model, which helps determine the efficiency gains from issuing CBDC, is governed by κ_{B_F}, which is related to the interest rate spreads between the rate on reserves and the deposit rates in the economy. A positive spread correspond to a positive value for κ_{B_F} in the steady state and implies efficiency gains from the issuance of CBDC.

With this in mind, through the lens of our model, there is a wide variation between the efficiency gains from issuing CBDC across countries. According to our model, countries with positive reserve spreads would obtain efficiency gains if they issue CBDC (see diamonds in Figure 6).

7 Conclusion

The introduction of CBDC can have important implications for how monetary policy is conducted and its transmission as well as for financial stability. Our paper presents a rich quantitative macroeconomic model to show that a well-designed CBDC can improve the long-run efficiency of allocations and improve bank lending despite reducing the size of bank balance sheets: i.e. *efficient disintermediation.* This is in contrast to the conventional wisdom that CBDC would cause a disintermediation of banks which is socially costly. We also show that in reaction to shocks in the short-run, the central bank can implement quantitative easing programmes equally effectively funding asset purchases by CBDC or reserves, and optimal monetary policy features a positive amount of CBDC.

Our model can be enriched in interesting ways to gain more insights about the impact of CBDC, which we leave for further research. For example, in our model, banks' incentive compatibility constraint ensures that bank runs do not happen. While this is a reasonable assumption as most bank deposits are insured, it is nevertheless important to study whether the availability of CBDC results in a flight from CBDC to deposits. Another possible avenue for research is to study the impact of bank market power on the inefficiency of allocations and how CBDC can improve upon those. Since inefficiencies are measured through spreads in our model and bank market power is a channel that likely operates through spreads, this might be a particularly promising avenue.

Finally, it is important to note that the trade-offs related to the introduction of CBDC are multi-faceted. The scope of our analysis is limited to studying the potential macroeconomic and financial stability impacts of the introduction of CBDC. We do not study the impact of CBDC on payments, the operational features or the design choices related to privacy and anonymity. All these factors need to be carefully taken into account to determine whether the introduction of CBDC ultimately generates social gains.

References

Adrian, T. and Mancini-Griffoli, T. (2019). The rise of digital money. FinTech Notes 19/001, International Monetary Fund.

Aldasoro, I., Ehlers, T., and Eren, E. (2019). Global banks, dollar funding, and regulation. *BIS Working Papers*, (708).

Andolfatto, D. (2018). Assessing the impact of central bank digital currency on private banks. *FRB St. Louis Working Paper*, (25).

Auer, R., Cornelli, G., and Frost, J. (2020). Taking stock: ongoing retail cbdc projects. *BIS Quarterly Review*.

Auer, R., Frost, J., Gambacorta, L., Monnet, C., Rice, T., and Shin, H. (2021). Central bank digital currencies: motives, economic implications and the research frontier. Technical Report 976, BIS Working Papers.

Barrdear, J. and Kumhof, M. (2016). The macroeconomics of central bank issued digital currencies. *Bank of England Staff Working Paper*, (605).

Bech, M. and Garratt, R. (2017). Central bank cryptocurrencies. *BIS Quarterly Review*.

BIS (2018). Central bank digital currencies. Technical report, Committee on Payments and Market Infrastructures, and Markets Committee.

BIS (2021). Cbdcs: an opportunity for the monetary system. Technical report, Bank for International Settlements.

Brunnermeier, M. and Niepelt, D. (2019). On the equivalence of private and public money. *Journal of Monetary Economics*, 27(41).

Chapman, J. and Wilkins, C. (2019). Crypto “money”: Perspective of a couple of Canadian central bankers. *Bank of Canada Staff Discussion Papers*, (1).

Chen, H., Cúrdia, V., and Ferrero, A. (2012). The macroeconomic effects of large-scale asset purchase programmes*. *The Economic Journal*, 122(564):F289–F315.

Chiu, J., Davoodalhosseini, M., Jiang, J., and Zhu, Y. (2019). Bank market power and central bank digital currency: theory and quantitative assessment. Technical Report 2019-20, Bank of Canada Staff Working Paper.

Correa, R., Du, W., and Liao, G. (2020). Us banks and global liquidity. *NBER working paper series*, (27491).

Covas, F. (2021). Take-up at the federal reserve's on rrp facility: much larger and more persistant than planned, getting larger, and the reasons why. Technical report, Bank Policy Institute.

Drechsler, I., Savov, A., and Schnabl, P. (2017). The deposit channel of monetary policy. *Quarterly Journal of Economics*, 132(4).

Drechsler, I., Savov, A., and Schnabl, P. (2021). Banking on deposits: Maturity transformation without interest rate risk. *Journal of Finance*, 76(3):1091–1143.

Duffie, D., Mathieson, K., and Pilav, D. (2021). Central bank digital currency: principles for technical implementation. Technical report, Digital Asset White Paper.

Eren, E., Schrimpf, A., and Sushko, V. (2020). Us dollar funding markets during the Covid-19 crisis: the money market fund turmoil. *BIS Bulletin*, (14).

Faure, S. and Gersbach, H. (2018). Money creation in different architectures. *CEPR Discussion Paper*, (13156).

Ferrari, M. M., Mehl, A., and Stracca, L. (2020). Central bank digital currency in an open economy. Technical Report 2488, European Central Bank Working Paper Series.

Garratt, R., Martin, A., McAndrews, J., and Nosal, E. (2015). Segregated balance accounts. *Federal Reserve Bank of New York Staff Reports*, (730).

Gertler, M. and Karadi, P. (2011). A Model of Unconventional Monetary Policy. *Journal of monetary Economics*, 58(1):17–34.

Gertler, M. and Kiyotaki, N. (2010). Financial Intermediation and Credit Policy in Business Cycle Analysis. In Friedman, B.M. and Woodford, M., editor, *Handbook of Monetary Economics*, volume 3, page 547. North-Holland.

Goodhart, C. A. (1993). Can we improve the structure of financial systems? *European Economic Review*, 37(2):269–291.

Greenwood, J., Hercowitz, Z., and Huffman, G. W. (1988). Investment, Capacity Utilization, and the Real Business Cycle. *American Economic Review*, 78:402–417.

Group of Central Banks (2020). Central bank digital currencies: foundational principles and core features. Technical report, Bank for International Settlements.

Gurley, J. and Shaw, E. (1960). Money in a theory of finance. *Brookings Institution.*

Hamilton, J. D. (1997). Measuring the liquidity effect. *American Economic Review*, pages 80–97.

Jackson, T. and Pennacchi, G. (2021). How should governments create liquidity? *Journal of Monetary Economics*, 118:281–295.

Keister, T. and Sanches, D. (2019). Should central banks issue digital currency? *Working Paper*.

Kumhof, M., Pinchetti, M., Rungcharoenkitkul, P., and Sokol, A. (2021). The open economy macroeconomics of central bank digital currencies. *mimeo*.

McCauley, R. (2021). Unstuffing banks with fed deposits: why and how. Technical report, VoxEU.

Piazzesi, M., Rogers, C., and Schneider, M. (2019). Money and banking in a New Keynesian model. *Working Paper*.

Piazzesi, M. and Schneider, M. (2020). Credit lines, bank deposits or CBDC? Competition and efficiency in modern payment systems. *Working Paper*.

Schilling, L., Fernandez-Villaverde, J., and Uhlig, H. (2020). Central bank digital currency: when price and bank stability collide. *NBER Working Papers*, (28237).

Schmitt-Grohé, S. and Uribe, M. (2010). The optimal rate of inflation. In *Handbook of Monetary Economics*, volume 3, pages 653–722. Elsevier.

Svensson, L. E. (1985). Money and asset prices in a cash-in-advance economy. *Journal of political Economy*, 93(5):919–944.

Tobin, J. (1985). Financial innovation and deregulation in perspective. *Bank of Japan Monetary and Economic Studies*, 3(2):19–29.

Woodford, M. (2001). Fiscal requirements for price stability. *Journal of Money, Credit and Banking*, 33(3):669–728.

A Appendices

A.1 Deterministic steady states

We pick long-run bank asset holdings of loans (K_F), long-term bonds ($\mathcal{B}_B$) and reserves (B_F) such that a bank's risk-weighted assets are:

$$\mathcal{A} := \kappa(K_F, P_b\mathcal{B}_B, B_F), \tag{A.1}$$

where we use $Q = 1$ in steady state and solve numerically for the bond-price (P_b).

One of these is determined by a residual condition, leaving us free to choose the other two.

Evaluating the bank's optimal value (2.15) in the deterministic steady state, yields the representative bank's optimal value:

$$J_i = \beta \left[(1-\theta)N_i + \theta \frac{N_i}{N} J_i \right], \tag{A.2}$$

where the final term is multiplied by $\frac{N_i}{N}$ to account for changes in surviving banks' net worth. It is convenient to express this value relative to total net worth:

$$v_i \equiv \frac{J_i}{N} = \beta \left[(1-\theta) + \theta v_i \right] \frac{N_i}{N}. \tag{A.3}$$

From aggregate net worth (2.21), we have:

$$\frac{N_i}{N} = \frac{1}{\theta}\left(1 - \frac{\Delta_T}{N}\right), \tag{A.4}$$

where $\Delta_T = \delta_T Q K_F$ is the startup transfer to new banks. Hence we can rewrite (A.3) as:

$$v_i = \beta \frac{1-\theta}{\theta} \frac{1 - \frac{\Delta_T}{N}}{1 - \beta\left(1 - \frac{\Delta_T}{N}\right)}. \tag{A.5}$$

When the ICC (2.18) binds, we can state that

$$v_i = \mathcal{A}/N, \tag{A.6}$$

and where bank risk-weighted assets ($\mathcal{A}$) are defined in (2.19) and we use that $Q = 1$ in steady state. Equating (A.5) and (A.6) yields a quadratic in v_i:

$$(v_i)^2 + \left(\frac{1-\beta}{\beta} \frac{\mathcal{C}}{\Delta_T} + \frac{1-\theta}{\theta} \right) v_i - \frac{1-\theta}{\theta} \frac{\mathcal{C}}{\Delta_T} = 0, \tag{A.7}$$

which is satisfied by:

$$v_i = -m(\mathcal{C}) \pm \sqrt{m(\mathcal{C})^2 + p(\mathcal{C})} \tag{A.8}$$

where

$$m(\mathcal{C}) = \frac{1}{2}\left(\frac{1-\beta}{\beta}\frac{\mathcal{C}}{\Delta_T} + \frac{1-\theta}{\theta}\right) > 0, \tag{A.9}$$

$$p(\mathcal{C}) = \frac{1-\theta}{\theta}\frac{\mathcal{C}}{\Delta_T} > 0, \tag{A.10}$$

where the signs are determined since $\beta,\ \theta \in (0,1)$; $\Delta_T > 0$; and positive risk-weights and non-negativity constraints ensure bank's risk-weighted assets are non-negative $\mathcal{C} \geq 0$. The negative solution can be ruled out since it would imply a negative bank value, hence we have:

$$v_i = -m(\mathcal{C}) + \sqrt{m(\mathcal{C})^2 + p(\mathcal{C})}, \tag{A.11}$$

such that v_i is determined given $\mathcal{C}$ and Δ_T.

Using the linearity of net-worth such that $J_i' = \frac{J_i}{N} \equiv v_i$, the bank discount factor evaluated in steady state is

$$\Omega = \beta\left(1 - \theta + \theta\frac{\mathcal{A}}{N}\right). \tag{A.12}$$

The envelope condition (2.28) evaluated in the steady state solves for the Lagrange multiplier (γ) associated with the bank ICC:

$$\gamma = (1-\theta)\left(1 - \frac{1}{v_i}\right). \tag{A.13}$$

When the ICC binds, we have $\gamma > 0$ which implies the ratio of bank value to net worth is greater than one: $v_i > 1$ i.e. $J_i > N$. Evaluating the bank's FOCs (2.22)-(2.24) in steady state yields:

$$K_i: \quad \Omega R_K - \frac{R_D}{\pi} = \kappa_{K_f}\gamma, \tag{A.14}$$

$$P_B\mathcal{B}_{i,B}: \quad \Omega\frac{R_B - R_D}{\pi} = \kappa_{\mathcal{B}_B}\gamma, \tag{A.15}$$

$$B_{i,F}: \quad \Omega\frac{R_F - R_D}{\pi} = \kappa_{B_F}\gamma, \tag{A.16}$$

which solve for long-run asset returns (R_K, R_B and R_F respectively). The long-run deposit rate is simply the discount factor adjusted for steady-state inflation, $R_D = \pi/\beta$. The long-term bond price is:

$$P_B = \frac{1-\delta_p+\bar{r}_p}{R_B-\delta_p}. \tag{A.17}$$

Using (2.20) evaluated in steady state, we can re-write long-run aggregate net worth (A.4) as:

$$\frac{1}{1-\theta/\beta}\left[\theta\left(\left(R_K - \frac{R_D}{\pi}\right)K_F + \frac{R_B - R_D}{\pi}P_b\mathcal{B}_B + \frac{R_F - R_D}{\pi}B_f\right) + \Delta_T\right] \tag{A.18}$$

Aggregating the bank's balance sheet (2.17) gives aggregate deposits:

$$D = K_F + P_B\mathcal{B}_B + B_F - N. \tag{A.19}$$

Having obtained the return to capital given the financial friction, R_K, we can solve the rest of the model as follows. Marginal cost is given by

$$MC = \frac{\sigma_P - 1}{\sigma_P}. \tag{A.20}$$

Using $A = 1$, the production function (2.43) in steady state can be written:

$$\frac{Y}{H} = \left(\frac{K}{H}\right)^{\alpha}. \tag{A.21}$$

Re-arranging the return for capital (2.47) yields

$$\frac{K}{Y} = \frac{\alpha MC}{R_K - (1-\delta)}, \tag{A.22}$$

hence

$$\frac{K}{H} = \frac{\alpha MC}{R_K - (1-\delta)}\left(\frac{K}{H}\right)^{\alpha} = \left(\frac{\alpha MC}{R_K - (1-\delta)}\right)^{\frac{1}{1-\alpha}}. \tag{A.23}$$

Equating household labor supply (2.7) and the labor market condition (2.46) yields long-run hours worked:

$$H = \left[MC(1-\alpha)\frac{Y}{H}\frac{1}{\chi}\right]^{\frac{1}{\psi}} = \left[\frac{MC(1-\alpha)}{\chi}\left(\frac{MC\alpha}{R_K - (1-\delta)}\right)^{\frac{\alpha}{1-\alpha}}\right]^{\frac{1}{\psi}} \tag{A.24}$$

This can be used to solve for output and capital in levels (as opposed to per hour) i.e.

$$K = \left[\frac{MC(1-\alpha)}{\chi}\left(\frac{\alpha MC}{R_K - (1-\delta)}\right)^{\frac{\psi+\alpha}{1-\alpha}}\right]^{\frac{1}{\psi}}, \tag{A.25}$$

and

$$Y = \left[\frac{MC(1-\alpha)}{\chi}\left(\frac{MC\alpha}{R_K - (1-\delta)}\right)^{\frac{\alpha}{1-\alpha}(\psi+1)}\right]^{\frac{1}{\psi}}. \tag{A.26}$$

The accumulation law for capital gives long-run investment,

$$I = \delta K, \tag{A.27}$$

and government spending is kept at a constant fraction of output

$$G = \psi_G Y. \tag{A.28}$$

The goods market clearing condition can be solved for consumption:

$$C = Y - I - G = H\left[(1-\psi_G)\left(\frac{K}{H}\right)^{\alpha} - \delta\frac{K}{H}\right]. \tag{A.29}$$

Household welfare is

$$\mathcal{W} = \frac{1}{1-\beta}\frac{1}{1-\sigma}\left(\bar{U} + C - \frac{\chi}{1+\psi}H^{1+\psi}\right)^{1-\sigma}. \tag{A.30}$$

Household bond-holdings are

$$\mathcal{B}_H = \phi_H^{-1}\left(\frac{\pi/\beta - 1}{R_B - 1}\right) \tag{A.31}$$

where $\phi_H^{-1}(\cdot)$ references the inverse of the function specifying household inefficiency in bond-trading. In the simulation, we use $\phi_H^{-1}(x) = \bar{\phi}_H \mathcal{B}_t / x$

The Central Bank chooses is free to choose its long-run allocation of bonds ($\mathcal{B}_{CB}$,) and lending to firms (K_{CB}); as well as its liabilities of reserves (B_F) and CBDCs (D_{CB}). Market clearing determines $\mathcal{B}_B$ and K_F:

$$\mathcal{B}_B = \mathcal{B} - \mathcal{B}_H - \mathcal{B}_{CB}, \tag{A.32}$$

$$K_F = K - K_H - K_{CB}, \tag{A.33}$$

where household capital holdings (K_H) is a constant used in calibrating bank-lending (K_F). We can then use the definition of bank's risk-weighted assets ($\mathcal{A}$) as a residual condition to find a fixed-point for an initial guess of $\mathcal{A}$. Finally, CB costs are

$$g_t = g_{K_{CB}} K_{CB} + g_{\mathcal{B}_{CB}} \mathcal{B}_{CB} + g_{B_F} B_F + g_{D_{CB}} D_{CB} \tag{A.34}$$

B Financial shock

In the case of a financial shock the equivalence in terms of aggregate output stability remains:

Figure 7: Optimal policy responses to a spread shock