A Model for Central Bank Digital Currencies: Implications for Bank Funding and Monetary Policy*

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Abstract

We develop a dynamic stochastic general equilibrium (DSGE) model to study the impact of central bank digital currencies (CBDCs) on the financial sector. We focus on the effects of interest- and non-interest-bearing CBDCs during financial crises and their interactions with the effective lower bound. In addition, we analyze the role of central bank funding and a rule-based variable interest rate on CBDCs. We find that CBDCs crowd out bank deposits. However, this crowding out effect can be mitigated if the central bank chooses to provide additional central bank funds or disincentivize large-scale CBDC accumulation through low CBDC interest rates.

Keywords: CBDC, financial sector, monetary policy, disintermediation, DSGE

JEL codes: D53, E42, E58, G21

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1 Introduction

The advent of Bitcoin and other private monies, including global stablecoins, have raised concerns among central banks worldwide. If such cryptocurrencies gain additional market shares, monetary policy transmission and monetary sovereignty could be impaired (ECB (2020)). In addition, and accelerated by the COVID-19 pandemic, the use of cash as a means of payment — the only form of central bank money available for citizens — is currently declining. Consequently, dependence on private sector payment infrastructures is increasing. In particular in advanced economies, central banks consider issuing a retail central bank digital currency (CBDC) — that is digital central bank money for citizens — to guarantee payment resilience in an increasingly digital environment, avoid private sector natural monopolies in the payment market, and strengthen monetary sovereignty in the face of new competitors (ECB (2020); Brainard (2021)). To a certain extent, a retail CBDC can be considered a substitute for cash. However, unlike cash, CBDC presumably imposes no storage cost, can be transferred comfortably (e.g., via mobile phones) and is less likely to be stolen or lost.

Despite the apparent potential of CBDC, central bankers remain cautious. They fear that a CBDC could threaten financial stability by facilitating (digital) bank runs and disintermediating the financial sector. In this context, disintermediation is defined as a client-induced substantial conversion of bank deposits into CBDC. As commercial banks rely on deposits to fund their lending business, deposit outflows increase their funding costs and lead, *ceteris paribus*, to a decline in loan volume, investment, and overall economic activity. While the academic literature on CBDCs is growing remarkably, more research on their impact on bank funding is needed, particularly on the effects of different CBDC remuneration and on the role of central bank refinancing. Further, the monetary policy implications of CBDCs remain underresearched. From a central bank perspective, CBDCs can provide an additional monetary policy tool that can increase monetary policy efficiency by featuring negative rates and, in the absence of cash, circumvent the effective lower bound (ELB). Currently, there are no simulations of different CBDC remuneration designs or analyses of their impact on the ELB on nominal interest rates.

In this paper, we address these two gaps by developing a New Keynesian dynamic stochastic general equilibrium (DSGE) model with a specific focus on CBDC and the financial sector. In contrast to existing models, our model accounts for the inherent risk of bank deposits during times of financial crises and includes (different degrees of) central bank refinancing for banks. We use this model to assess CBDC-specific dynamics and transmission effects during a financial crisis to study the potential disintermediation of the financial sector. In particular, we consider two different forms of CBDCs — an interest-bearing CBDC and a non-interest-bearing CBDC — with different implication for the ELB.

We build on the model proposed by Gertler and Karadi (2011), a framework that consists of a financial sector, a public sector, different types of producers, and homogeneous households. In their cashless model, bank funding solely consists of households' deposits and is constrained by a moral hazard problem. This rigidity increases the persistence of financial shocks, that is, it introduces a financial accelerator effect that mimicks the shock persistence of the global financial crisis.

We expand their model such that our framework exhibits necessary features for analyzing CBDC. First, to allow for active portfolio decisions, households no longer automatically provide their deposits to banks based on the moral hazard constraint, but instead based on their utility maximization. We introduce heterogeneity in the forms of savings in terms of liquidity, remuneration, and risk and assume that households choose their savings portfolio based on these differences. We explicitly account for the risk of bank deposits by introducing a discount factor on the expected return on bank deposits, which decreases with the level of debt in the financial sector and the profits of banks. The intuition behind this modeling approach is that households perceive bank deposits as risky, when financial sector debt is high and profits are low. They fear that banks could become bankrupt and, thus, in the absence of a deposit insurance scheme, their deposits could become inaccessible. Second, to capture the central bank's role in bank funding and account for additional central bank policies, we introduce the option of central bank loans for commercial banks. These loans are similarly constrained by the bank's moral hazard problem, thus, keeping the financial accelerator effect intact. Third, we introduce a potentially remunerated CBDC as an additional choice for households' portfolio decisions assuming that, in terms of liquidity, it is a perfect substitute for bank deposits but, as central bank money, it exhibits no counterparty risk.

We calibrate the models with and without CBDC such that their steady states are identical and focus our analysis on the resulting dynamics — that is we deliberately abstract from potential steady state effects of a CBDC introduction. Our calibration of conventional parameters closely follows Gertler and Karadi (2011) with two differences in government expenditures and the interest rate on bonds that are calibrated based on Euro area data. The additional parameters introduced specifically in our model are mainly calibrated to match data on bank funding.

We obtain the following main results. We show that, given the assumption that during a financial crisis bank deposits are perceived as risky, the presence of a CBDC substantially reduces bank funding and, thus, increases the disintermediation of the financial sector. To secure bank funding, the central bank can compensate losses in deposits by providing additional central bank funds. Assuming full allotment, a CBDC does not impair bank funding, but only affects its composition. Consequently, for both interest- and non-interest-bearing CBDCs, the central bank can stabilize the financial sector and mitigate CBDC-specific disturbances in the real economy. If an interest-bearing CBDC can circumvent the ELB, we find substantial macroeconomic improvements for the entire economy. However, these improvements are not directly linked to a CBDC and changes in households' saving behavior. Instead, due to potentially negative interest rates, the increased room for monetary policy mitigates disturbances after a crisis. Relaxing the assumption of full allotment, the resulting imperfect substitution of deposits with funds from the central bank opens up a channel for CBDC to the real economy. Then, the disintermediation of commercial banks, negatively impacts investment, the build-up of capital, and production. In this case, a CBDC indeed destabilizes the financial sector and negatively affects the entire economy. Using the remuneration on CBDC as a policy tool, the central bank can mitigate adverse effects by disincentivizing substantial CBDC accumulation.

Our paper contributes to the growing literature on CBDCs and their impact on the financial sector. For studying these effects, Bindseil (2020) provides a starting point. In his paper, he uses a balance sheet exercise to define CBDC-specific channels that could affect the financial sector. First model-based analyses study such potential adverse effects in detail and analyze the interlinkages of a CBDC with the financial sector. Keister and Sanches (2019) use a new monetarist model with centralized and decentralized markets to conclude that a CBDC might increase banks' funding costs and crowd out deposits. Fernández-Villaverde et al. (2020b) analyze CBDCs in a Diamond and Dybvig (1983)-type model and find that the central bank faces a CBDC trilemma where a socially efficient solution, price stability, and financial stability cannot be achieved simultaneously. Brunnermeier and Niepelt (2019) provide a generic model with money and liquidity and show that — given certain assumptions — a CBDC introduction only alters the composition of bank funding and not its total size. Also using a Diamond and Dybvig (1983)-type model, Fernández-Villaverde et al. (2020a) find that a CBDC does not alter the equilibrium allocation of bank funding. However, in times of crises, the central bank becomes a deposit monopolist potentially endangering maturity transformation. Chiu et al. (2019) also study a model with centralized and decentralized markets and find that a CBDC improves efficiencies in the financial sector as banks lose market power. In an extreme scenario, a CBDC can even lead to an increase in banks' lending activities. Andolfatto (2021) uses an overlapping generations model with monopolistic banks and finds that a CBDC might reduce banks' monopoly profits, but does not necessarily lead to disintermediation of the financial sector. CBDCs might even increase financial stability, as deposits could expand due to higher deposit interest rates. Barrdear and Kumhof (2021) build a monetary-financial DSGE model and study the steady state effects of an interest-bearing CBDC. Even if the transition would lead to a crowding out of bank deposits, they find that production could increase by 3% in the long run.

We contribute to this literature on financial sector implications of CBDCs in the following manner. First, we provide a micro-founded model to study the potential adverse effects on bank funding in times of financial crises when deposits are perceived as risky. Second, we analyze implications for the financial sector based on different CBDC remuneration designs.

Our paper also relates to the literature on the implications of CBDC for monetary policy. Dyson and Hodgson (2016) and Bindseil (2020), amongst others, argue that a CBDC can provide substantial monetary stimulus during a severe recession as, in the absence of cash, CBDC interest rates can overcome the ELB and feature negative rates. Mancini-Griffoli et al. (2018) discuss how CBDCs impact the transmission mechanisms of monetary policy measures and obtain different conclusions. To study transmission channels in detail, and in the absence of empirical data, first model-based approaches have been used. Meaning et al. (2021) use a stylized model and conclude that monetary policy transmission would not change substantially, but, for a given change in policy instruments, the efficiency of the transmission might increase. Analyzing the transmission with their DSGE model, Barrdear and Kumhof (2021) find that a CBDC would improve the central bank's ability to stabilize the business cycle. Ferrari et al. (2020) examine monetary transmission in an open economy DSGE model. They conclude that a CBDC increases the size of international spillover shocks and that a national CBDC can decrease monetary policy autonomy in foreign economies.

We contribute to extant literature by studying and comparing the effects of interest-bearing and non-interest-bearing CBDC designs, with a particular focus on their implication for the ELB on nominal interest rates. Further, we highlight the role of interest rate spreads and the allotment of central bank money as monetary policy tools to mitigate CBDC-specific destabilizing effects.

Our results are important for at least three reasons. First, our model simulation provides valuable insights for the ongoing discussions on how to design a CBDC to prevent destabilizing effects for the financial sector. If the central bank is willing to provide a substantial amount of additional central bank loans to commercial banks, CBDC-induced losses in bank funding can be offset. This policy eliminates the need for restrictive designs, such as upper limits on CBDC holdings as proposed by Panetta (2018). Further, we show that designing a CBDC with a variable and potentially negative interest rate provides central banks with an effective tool to govern the demand for CBDC. This tool can be used specifically to prevent CBDC-specific disintermediation of the financial sector during times of financial distress. Second, in the absence of empirical data, our model-based analysis sheds light on the general economic impact of a CBDC. We highlight the transmission of financial shocks with CBDCs. Our model provides a microfounded framework to study the potential disintermediation of the financial sector. By accounting for the perceived risk of bank deposits in times of crises, we observe a liquidity effect — that is households substitute bank deposits with CBDC for liquidity purposes. Third, the results of our CBDC simulation are relevant for central bankers, who perceive CBDCs as an additional instrument for their monetary policy toolkit. In particular, the European Central Bank (ECB) considers a CBDC introduction also for monetary policy reasons (ECB (2020)). Our simulations of interest- and non-interest-bearing CBDCs and, in particular, our focus on the ELB provide a starting point to adequately compare the monetary policy implications of

CBDC remuneration.

The remainder of the paper is structured in the following manner. Section 2 discusses our model. Section 3 explains and motivates the model calibration. Section 4 analyzes alternative versions of the model with non-interest-bearing CBDC (4.1), with interest-bearing CBDC (4.2), with and without full allotment (4.3), and with different interest rates on CBDC (4.4). Section 5 concludes.

2 Model

Our model builds on the closed economy New Keynesian framework by Gertler and Karadi (2011). We substantially rework the utility maximization of households, financial intermediaries' funding, and the role of the central bank. In this section, we focus on a detailed discussion of our adaptions.[1]

The basic structure of our model is depicted in Figure 1. Banks obtain funds from households and the central bank and act exclusively as intermediaries, thereby providing funds for intermediate goods producers. Following Gertler and Karadi (2011), we assume that banks can default and divert obtained funds. The consequent moral hazard that arises places an endogenous limit on banks' balance sheets and restricts their ability to collect funds. While Gertler and Karadi (2011) determine the amount of deposits solely based on banks' economic performance, we determine the amount of bank deposits by households' optimal portfolio choice. We assume that households perceive commercial bank money as risky, particularly in times of financial distress. Households have an incentive to substitute bank deposits with less risky alternatives. They acquire government bonds and CBDC that, moreover, differ in terms of liquidity and remuneration. Further, note that we assume a cashless society.

Intermediate goods producers use intermediated funds to buy capital goods from capital goods producers who face investment adjustment costs. Production requires labor and capital. Competitive monopolistic final goods producers buy intermediate goods, repackage them, and sell them on the goods market to either households or the government.

[1]For an in-depth presentation of the other model parts, we refer to Gertler and Karadi (2011) and for a detailed comparison of the models to Appendix B.

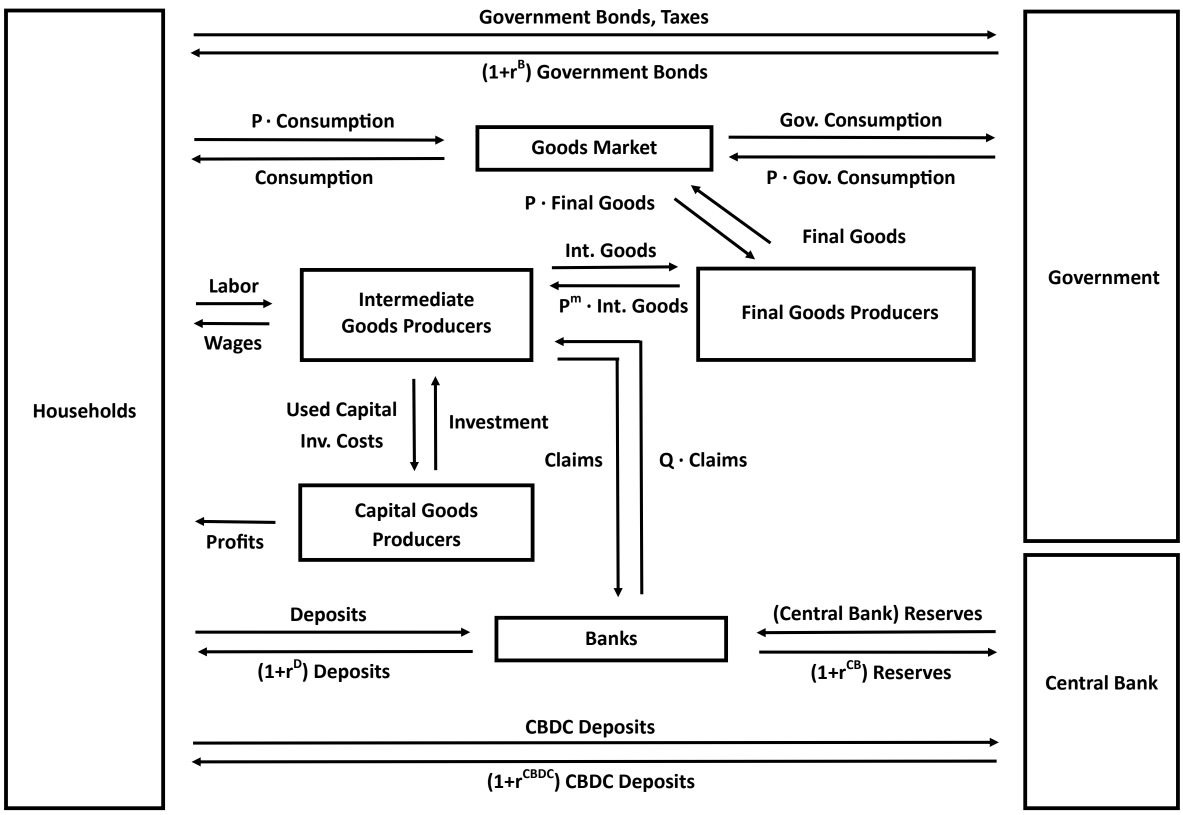


Figure 1: Model structure

2.1 Households

There is a continuum of identical and infinitely lived households that supply labor (L), consume goods (C), and save for consumption in the next period. They save either via CBDC ($CBDC$), deposits (D), or government bonds (B). They do not invest in the production sector due to their lack of expertise. We assume that households choose their portfolio in each period without any adjustment costs and not based on the love of variety. Instead, the three forms of saving differ in terms of the three dimensions: remuneration, liquidity, and risk (see Table 1).

	Remuneration	**Liquidity**	**Risk**
Bank deposits	Intermediate	Means of payment	Risky
CBDC	Low	Means of payment	Riskless
Government bonds	High	No means of payment	Riskless

Table 1: Comparison of bank deposits, CBDC, and government bonds

First, with regard to remuneration, deposits pay the real interest rate r^D, CBDC pays r^{CBDC}, and bonds pay r^B with $r^B \geq r^D \geq r^{CBDC}$.[2] Second, with regard to liquidity, CBDC and bank deposits are perfect substitutes. As both can be used as a means of payment, they generate utility by providing liquidity services. We assume that government bonds do not provide liquidity services, as liquidation is costly and takes time and government bonds are not a means of payment. Third, with regard to risk, CBDC and government bonds are perceived as riskless and bank deposits as risky.

The households' (aggregate) maximization problem can be written in the following manner:

$$\max\ E_t \sum_{i=0}^{\infty} \beta^i \left\{ ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma}\ (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\}, \quad (1)$$

where Υ and χ denote the relative utility weights of real money balances ($CBDC$ and D) and labor, respectively; Γ is the elasticity of money balances, ϕ the Frisch elasticity of labor supply, h the habit parameter for consumption, and β the intertemporal discount factor. Note that we use a money-in-the-utility-function specification (Sidrauski (1967); Rotemberg (1982)).[3]

Households believe that banks could go bankrupt and, then, their deposits would be lost. Note that we abstract away from deposit insurance schemes in our analysis.[4] The probability for this event is $1 - \psi$, such that their expected return from bank deposits can be expressed as

$$(1 - \psi_t)0 + \psi_t(1 + r_t^D)D_t = \psi_t(1 + r_t^D)D_t. \quad (2)$$

[2]In our model, we use this interest rate relation to match data before the outbreak of the global financial crisis and the initiation of substantial asset purchase programs that pushed government bond yields close to, and partially even below, zero.

[3]Alternatives to our specification would be a cash-in-advance or a shopping-time specification. Apart from slight differences caused by the cross product of consumption and liquidity, these alternatives can be formally equivalent (Feenstra (1986)). We choose this approach to account for the observed large-scale accumulation of money that cannot be justified by precautionary liquidity holdings for future consumption.

[4]Today, deposit insurance schemes are set up to address the risk of commercial bank money and to avoid that, in the case of bankruptcy of a commercial bank, depositors face substantial losses. However, deposit insurance schemes are not available in all countries, and commercial bank money is only secured until a specific threshold. Future research could analyze the interaction of deposit insurance schemes with CBDCs.

Hence, the risk can also be captured as a discount factor on bank deposits. Thus, households' (aggregate) budget constraint can, be written in the following manner:

$$C_t + D_t + CBDC_t + B_t = w_t L_t + \Pi_t + (1 + r^D_{t-1})\psi_{t-1} D_{t-1} + (1 + r^{CBDC}_{t-1}) CBDC_{t-1} + (1 + r^B_{t-1}) B_{t-1}, \tag{3}$$

where w is the real wage rate and Π income from the ownership of both non-financial (capital goods producers) and financial firms (banks) net of lump-sum taxes T. The resulting first-order conditions are derived in Appendix A.

The discount factor ψ is increasing in the amount of bank deposits (D) and additionally depends on the level of stress in the financial sector, as indicated by substantial losses in banks' equity (N):

$$\psi_t = 1 - \left(\frac{D_t}{F^*_t}\right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}} \Omega_N \tag{4}$$

Banks receive external refinancing both from households and the central bank. F^* denotes the maximum volume of external refinancing implied by the moral hazard in the financial sector (see Section 2.2). D/F^* is the share of deposits in external refinancing. Ω_D denotes the elasticity of ψ to changes in bank deposits, while Ω_N defines the impact of changes in banks' equity N.

As depicted in Figure 2, there is a negative relationship between bank deposits (D) and the discount factor ψ. When D approaches the maximum amount of external refinancing (F^*), where households fear a diversion of their deposits (see Section 2.2), they perceive deposits as more risky and the discount factor drops. When ψ decreases, such that the expected utility from holding deposits is lower than from an alternative asset, households seek less risky alternatives. In other words, a reduction in ψ can be interpreted as a reduction in the remuneration of bank deposits; subsequently, households decrease their bank deposits. The reduction in D induces banks to demand additional central bank funds in order to secure their lending activities.[5]

Households perceive this more prominent role of the central bank as a stabilizing factor that lowers the risk in the financial sector. ψ rises again up to the point at which households are indifferent between commercial bank money and its alternatives, taking into account the

[5]Note that we assume that banks always receive the maximum funding (F^*). Therefore, if bank deposits decline, a commercial bank demands and receives additional funds from the central bank. We relax this assumption in Section 4.3.

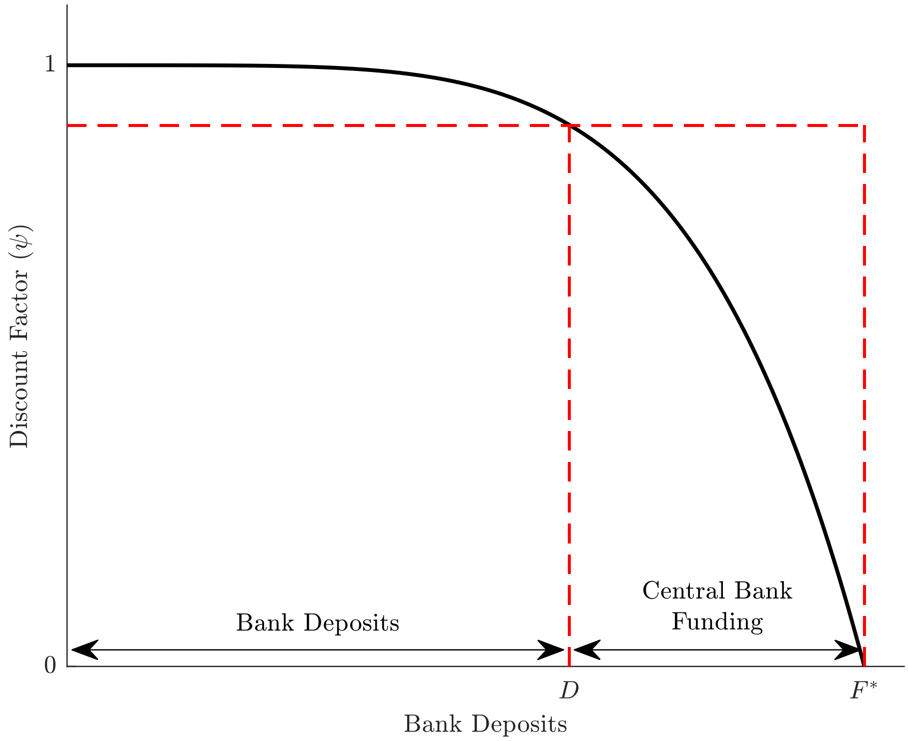


Figure 2: Relationship between bank deposits and the discount factor

three dimensions of remuneration, liquidity, and risk. The elasticity Ω_D impacts the illustrated curve by shifting it to or away from the upper right corner. Higher values for Ω_D allow for a higher share D/F^* that households tolerate before they perceive bank deposits as risky. Thus, the calibration of Ω_D, impacts the composition of banks' external refinancing. We use this parameter to calibrate steady-state deposits and central bank funding according to empirical data (for details, see Section 3).

In addition, ψ depends on the term $\Omega_N \cdot (\bar{N} - N)/\bar{N}$. We assume that a reduction of banks' equity below its steady state $\bar{N}$ signals financial stress to households and lowers households' trust in commercial banks and, therefore, the discount factor. We use this term to scale the initial impact of the simulated financial crisis on deposits.

2.2 Banks

Banks use their equity, households' deposits, and funds received from the central bank to acquire claims on intermediate goods producers. The expected return on their investment r^K depends on the performance of intermediate goods producers and is realized by a transfer of any revenues or losses in the next period. Banks pay back households' deposits and central bank funds with the *ex-ante* known real interest rates r^D and r^{CB}.

Banker j accumulates wealth N_j. Wealth can be interpreted as the banker's equity, while deposits and central bank funds R_j^{CB} represent external refinancing F_j. Therefore, banker j's balance sheet relation can be written in the following manner:

$$Q_t S_{jt} = N_{jt} + D_{jt} + R_{jt}^{CB} = N_{jt} + F_{jt}, \tag{5}$$

where S_j captures j's financial claims, priced Q, against the production sector. The evolution of banker j's equity depends on interest expenses and interest income:

$$N_{jt+1} = (1 + r_{t+1}^K)N_{jt} + (r_{t+1}^K - r_t^D)D_{jt} + (r_{t+1}^K - r_t^{CB})R_{jt}^{CB}. \tag{6}$$

Note that a banker's equity is mainly driven by the interest rate spreads — the premia $r_{t+1}^K - r_t^D$ and $r_{t+1}^K - r_t^{CB}$. Banker j intermediates funds as long as the premia are non-negative, which results in the two following participation constraints:

$$E_t \beta \Lambda_{t,t+1}(r_{t+1}^K - r_t^D) \geq 0, \tag{7}$$

$$E_t \beta \Lambda_{t,t+1}(r_{t+1}^K - r_t^{CB}) \geq 0, \tag{8}$$

where $\beta\Lambda_{t,t+1}$ is the discount factor derived from the first-order conditions of households (see Appendix A) as we assume that bankers are part of households, following Gertler and Karadi (2011). In this framework, households consist of a constant fraction of bankers and workers. Each banker might change profession with a worker in each period with a certain probability, thereby transferring all earnings to the household. Households send out new bankers and equip them with start-up funds. This exit-and-entry-mechanism ensures that, in the absence of shocks, the aggregate equity of all bankers does not increase. Therefore, bankers cannot solely satisfy the demand for funds by intermediate goods producers' with their equity and render external refinancing redundant. Banker j maximizes the expected terminal wealth, V_j, given by

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+i+1}(N_{jt+i+1}), \tag{9}$$

where θ is the probability that banker j remains a banker in the next period. Inserting the evolution of bankers' equity (6) into (9) yields:

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+i+1}\big[(1+r^K_{t+1})N_{jt} + (r^K_{t+1} - r^D_t)D_{jt} + (r^K_{t+1} - r^{CB}_t)R^{CB}_{jt}\big]. \tag{10}$$

With positive premia, bankers have an incentive to blow up their balance sheets infinitely. Following Gertler and Karadi (2011), we introduce a moral hazard to counteract this behavior. Each period, banker j can choose to 'run away', thereby diverting fraction λ of the total intermediated funds $Q_t S_{jt}$. In case of such a run, this fraction is lost for households and the central bank.[6] The banker decides to run if income from diverting funds exceeds the expected terminal wealth V_j from being a banker. Hence, j's incentive constraint can be expressed in the following manner:

$$V_{jt} \geq \lambda Q_t S_{jt}. \tag{11}$$

Note that banker j's terminal wealth can be expressed recursively as

$$V_{jt} = mu^N_t N_{jt} + mu^D_t D_{jt} + mu^R_t R^{CB}_{jt}. \tag{12}$$

The mu variables can be interpreted as the marginal utilities of changes in the different sources of funds:

$$mu^N_t = E_t[(1-\theta)\beta\Lambda_{t,t+1}(1+r^K_{t+1}) + \beta\Lambda_{t,t+1}\theta\Delta^N_{t,t+1} mu^N_{t+1}]; \tag{13}$$

$$mu^D_t = E_t[(1-\theta)\beta\Lambda_{t,t+1}(r^K_{t+1} - r^D_t) + \beta\Lambda_{t,t+1}\theta\Delta^D_{t,t+1} mu^D_{t+1}]; \tag{14}$$

$$mu^R_t = E_t[(1-\theta)\beta\Lambda_{t,t+1}(r^K_{t+1} - r^{CB}_t) + \beta\Lambda_{t,t+1}\theta\Delta^R_{t,t+1} mu^R_{t+1}]; \tag{15}$$

[6] In reality, banks cannot divert central bank money as this money is backed by collateral. Our modeling approach does not imply that bankers will actually ever divert central bank money. Instead, it creates an upper bound for central bank refinancing based on bankers' equity and households' deposits. Thus, we capture banks' natural limits in the acquisition of central bank money in a substantially simplified manner.

where $\Delta^N_{t,t+1}$, $\Delta^D_{t,t+1}$, and $\Delta^R_{t,t+1}$ are the growth rates of equity, deposits, and central bank funds, respectively. Note that we eliminate the j subscripts by assuming that deposits and central bank funds are allocated to banks in accordance with their equity shares — that is $D_{jt} = D_t N_{jt}/N_t$ and $R^{CB}_{jt} = R^{CB}_t N_{jt}/N_t$.

Hence, we can derive the growth rates in the following manner:

$$\Delta^N_{t,t+1} = \frac{N_{jt+1}}{N_{jt}} = (1 + r^K_{t+1}) + (r^k_{t+1} - r^D_t)\frac{D_t}{N_t} + (r^k_{t+1} - r^{CB}_t)\frac{R^{CB}_t}{N_t}; \tag{16}$$

$$\Delta^D_{t,t+1} = \frac{D_{jt+1}}{D_{jt}} = \frac{D_{t+1}}{D_t}\Delta^N_{t,t+1}\frac{N_t}{N_{t+1}}; \tag{17}$$

$$\Delta^R_{t,t+1} = \frac{R^{CB}_{jt+1}}{R^{CB}_{jt}} = \frac{R^{CB}_{t+1}}{R^{CB}_t}\Delta^N_{t,t+1}\frac{N_t}{N_{t+1}}; \tag{18}$$

Inserting (12) in (11) yields the following incentive constraint:

$$mu^N_t N_{jt} + mu^D_t D_{jt} + mu^R_t R^{CB}_{jt} \geq \lambda Q_t S_{jt}. \tag{19}$$

Assuming that the incentive constraint (19) is binding and summing accross all bankers, we calculate the maximum amount of external refinancing F^* in the following manner:

$$F^*_t = \frac{\lambda - mu^N_t}{mu^R_t - \lambda}N_t + \frac{mu^R_t - mu^D_t}{mu^R_t - \lambda}D_t. \tag{20}$$

Accordingly, we express bankers' individual balance sheets (5) in aggregate terms in the following manner:

$$Q_t S_t = N_t + D_t + R^{CB}_t. \tag{21}$$

Note that N comprises the equity of existing bankers (N_e) and equity of new bankers (N_n).

$$N_t = N_{et} + N_{nt}. \tag{22}$$

N_e can be expressed in the following manner:

$$N_{et} = \theta\Delta^N_{t-1,t}N_{t-1}. \tag{23}$$

New bankers receive a fraction $\omega/(1-\theta)$ of the current value of last period's total intermediated funds $Q_t S_{t-1}$. The equity of new bankers can be expressed in the following manner:

$$N_{nt} = \frac{\omega}{1-\theta}(1-\theta) Q_t S_{t-1} = \omega Q_t S_{t-1}. \tag{24}$$

2.3 Intermediate Goods Producers

Intermediate goods producers receive funds exclusively from banks, buy capital goods, and use these capital goods, combined with labor, to produce intermediate goods. Intermediate goods are sold to final goods producers that repackage the intermediate goods and offer them on the goods market. In detail, intermediate goods producers sell S claims to banks at a price Q to obtain funds in return. At the end of period t, intermediate goods producers use all the acquired funds to finance investments — that is they buy capital goods K at a price Q per unit. In period $t+1$, these capital goods are used for production. Consequently, total intermediated funds pose a restriction on the accumulation of capital goods for production.

Following Gertler and Karadi (2011), the price of capital is equal to the price of claims. Therefore, we can express the following equation:

$$Q_t K_{t+1} = Q_t S_t. \tag{25}$$

Intermediate goods production is given by the following Cobb-Douglas function:

$$Y_t^M = A_t (U_t \xi_t K_t)^\alpha L_t^{1-\alpha}, \tag{26}$$

where A is technology, U the utilization rate of capital, and ξ the quality of capital. Maximizing the profits of intermediate goods producers yields the following first-order conditions for the utilization rate (27) and labor demand (28):

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta'(U_t) \xi_t K_t, \tag{27}$$

$$P_t^M (1-\alpha) \frac{Y_t^M}{L_t} = W_t, \tag{28}$$

where P^M is the price of intermediate goods and $\delta(U)$ the depreciation rate of capital, with $\delta(U) = \delta_c + U_t^{1+\zeta} b/(1+\zeta)$; δ_c, b, and ζ are adjustment parameters. As all profits from intermediate goods producers are transferred to banks, R_t^K can be written as:

$$R_t^K = \frac{[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta(U_t)]\xi_t}{Q_{t-1}}. \tag{29}$$

Note that the quality of capital (ξ) directly affects banks' return on capital. Hence, a negative shock to ξ can induce substantial loan defaults and critical deterioration of banks' balance sheets, which are characteristics of e.g. the global financial crisis.

2.4 Capital Goods Producers

Capital goods producers create new capital goods and refurbish depreciated capital goods. The refurbishment cost is fixed at 1, while new capital goods are priced Q. The creation of new capital goods is subject to (flow) adjustment costs. Capital producers' profits are transferred in each period to their owners. Gross capital goods created are defined as I and net investment I^N as the difference between I and refurbished capital goods $I^N = I - \delta(U)\xi K$. $\bar{I}$ denotes the steady state level of investment. Capital goods producers maximize the sum of their discounted profits:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left[(Q_{t+i} - 1) I_{t+i}^N - f\Big(\frac{I_{t+i}^N + \bar{I}}{I_{t-1+i}^N + \bar{I}} \Big) (I_{t+i}^N + \bar{I}) \right], \tag{30}$$

where $f(\cdot)$ is defined as $\frac{\eta_i}{2} \left[\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} - 1 \right]^2$ with η_i as a scaling parameter. Maximizing profits yields the following equation:

$$Q_t = 1 + f(\cdot) + \Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} \Big) f'(\cdot) - E_t \beta \Lambda_{t,t+1} \Big(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}} \Big)^2 f'(\cdot). \tag{31}$$

Hence, in the steady state $\bar{Q} = 1$, while changes in the level of investment increase production costs and, consequently, the price of capital. Note that capital evolves according to the following equation:

$$K_{t+1} = \xi_t K_t + I_t^N. \tag{32}$$

2.5 Final Goods Producers

Final goods producers buy intermediate goods, repackage them, and sell them on the goods market — that is one unit of intermediate goods is converted into one unit of final goods. Final goods producers act as profit-maximizing competitive monopolists. With ε being the elasticity of substitution, the total output Y is defined as a constant elasticity of substitution (CES) composite of differentiated final goods:

$$Y_t = \Big[\int_0^1 {Y_{ft}}^{\frac{\varepsilon-1}{\varepsilon}} df \Big]^{\frac{\varepsilon}{\varepsilon-1}}. \tag{33}$$

Consumers' cost minimization yields the following definitions for firm f's production Y_f and for prices P:

$$Y_{ft} = \Big(\frac{P_{ft}}{P_t}\Big)^{-\varepsilon} Y_t, \tag{34}$$

$$P_t = \Big[\int_0^1 {P_{ft}}^{1-\varepsilon} df \Big]^{\frac{1}{1-\varepsilon}}. \tag{35}$$

Following Calvo (1983), only the fraction $1-\gamma$ of final goods producers can adjust retail prices in period t to the new optimal level P^*. The fraction γ of final goods producers is not able to adjust prices to the new optimal level but applies last period's inflation rate $\pi_{t-1,t} = P_t/P_{t-1}$ weighted by an indexation parameter γ_π. Final goods producers do not know, *ex ante*, whether they are able to adjust their prices in the next period. They set prices optimally taking this uncertainty into account. As the only cost factor for final goods producers is the price of intermediate goods P^M, their maximization problem can be expressed in the following manner:

$$\max E_t \sum_{i=0}^{\infty} \gamma^i \beta^i \Lambda_{t,t+i} \Big[\frac{P_t^*}{P_{t+i}} \prod_{k=1}^{i} (\pi_{t+k-1,t+k})^{\gamma_\pi} - P_{t+1}^M \Big] Y_{ft+i}. \tag{36}$$

Applying the law of large numbers yields the following definition of retail prices:

$$P_t = [(1-\gamma)(P_t^*)^{1-\varepsilon} + \gamma(\pi_{t-1,t}^{\gamma_\pi} P_{t-1})^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}}. \tag{37}$$

Thus, the retail price level is a weighted average of adjusted and non-adjusted prices.

2.6 Central Bank

The central bank sets the nominal interest rate on central bank funding i^{CB} according to a standard Taylor rule without interest rate smoothing (Gertler and Karadi (2011)). Interest rates on different forms of saving — bonds, CBDC, and bank deposits — depend on i^{CB} to ensure that $i^B \geq i^D \geq i^{CBDC}$ (see Table 1). In this manner, the central bank 'leads' all interest rates with its rule-based interest rate on central bank funding:

$$i_t^{CB} = (1 + \bar{r}^{CB}) + \kappa_\pi \pi_t + \kappa_{y_{gap}} y_{gap,t}, \tag{38}$$

where κ_π the inflation weight, $\kappa_{y_{gap}}$ the weight of the output gap, and $\bar{r}^{CB}$ the neutral (steady state) real interest rate. Following Gertler and Karadi (2011), we use minus the price markup as a proxy for the output gap.

The nominal interest rate on deposits follows the interest rate on central bank funding with the fixed spread Δ^D:[7]

$$i_t^D = i_t^{CB} - \Delta^D. \tag{39}$$

We introduce this spread to match data indicating that, in normal times, central bank refinancing is more expensive than refinancing via deposits.

In Section 4, we analyze scenarios, in which the ELB is binding. If the interest rate on deposits is constrained by the ELB, it is defined in the following manner:

$$i_t^D = \begin{cases} i_t^{CB} - \Delta^D & \text{for } i_t^{CB} - \Delta^D \geq 0, \\ 0 & \text{for } i_t^{CB} - \Delta^D < 0. \end{cases} \tag{40}$$

The central bank also sets the interest rate on CBDC. We explicitly differentiate between an interest-bearing CBDC and a non-interest-bearing CBDC. In the case of a non-interest-bearing CBDC, we set i^{CBDC} to zero:

$$i_t^{CBDC} = 0. \tag{41}$$

[7]Note that in reality, banks determine the interest rate on deposits themselves. However, maximizing their profits, banks use the central bank-set interest rates as the benchmark rate, as indicated by a high correlation between these interest rates.

For an interest-bearing CBDC, the interest rate on CBDC strictly follows the interest rate on central bank funding with the fixed spread Δ^{CBDC}, such that $i^{CBDC} < i^{CB}$, as proposed in Bindseil (2020):

$$i_t^{CBDC} = i_t^{CB} - \Delta^{CBDC}. \tag{42}$$

In Section 4.4, we decouple these interest rates and allow for an individual rule-based determination, in which the CBDC rate is used as a policy tool. Note that the interest rate on CBDC can be negative.

The interest rate on government bonds follows the interest rate on central bank funding with the fixed spread Δ^B. We assume a positive spread based on bond yield data for the period before the global financial crisis and the rationale that the lack of liquidity services has to be compensated for by a higher remuneration.[8]

$$i_t^B = i_t^{CB} + \Delta^B. \tag{43}$$

The connection between nominal and real interest rates is given by the following Fisher relations:

$$1 + i_t^D = (1 + r_t^D)(1 + E_t\pi_{t,t+1}); \tag{44}$$

$$1 + i_t^{CBDC} = (1 + r_t^{CBDC})(1 + E_t\pi_{t,t+1}); \tag{45}$$

$$1 + i_t^B = (1 + r_t^B)(1 + E_t\pi_{t,t+1}). \tag{46}$$

Apart from setting interest rates, the central bank also provides funding to commercial banks via central bank loans. As refinancing via the central bank is more expensive than refinancing via deposits ($r^{CB} > r^D$), banks will only demand central bank funding to fill the gap between the supply of deposits (D) and the maximum amount of total external refinancing (F^*):

$$R_t^{CB} = F_t^* - D_t. \tag{47}$$

Note that this expression implicitly assumes a full allotment procedure: As long as the banks' incentive constraint holds — that is as long as they can provide sufficient collateral —, the

[8]Note that the fixed spread is a simplifying assumption. In reality, bond prices and yields exhibit more complex dynamics.

central bank fully meets their money demand. We relax this assumption of full allotment in Section 4.3.

2.7 Government and Aggregation

The government receives income from lump-sum taxes T and issues government bonds B_t. It finances government spending (G) and repays last period's bond holdings B_{t-1} including interest payments i^B_{t-1}. Note that we define G as a constant share of steady state output.

$$\bar{G} + (1 + i^B_{t-1})B_{t-1} = T + B_t. \tag{48}$$

Output is divided into consumption, investment, investment adjustment costs, and government expenditures. Hence, the economy-wide budget constraint can be expressed in the following manner:

$$Y_t = C_t + I_t + f\Big(\frac{I^N_t + \bar{I}}{I^N_{t-1} + \bar{I}}\Big)(I^N_t + \bar{I}) + \bar{G}. \tag{49}$$

3 Calibration

Table 2 summarizes the calibration of our model. We use a total of 24 parameters, 17 of which are conventional and also used in Gertler and Karadi (2011). We introduce additional parameters related to the inclusion of money in the utility function (Υ, Γ), the discount factor ψ (Ω_D, Ω_N), and the interest rate spreads (Δ^B, Δ^D, Δ^{CBDC}). Since no CBDC has been introduced in an industrialized economy thus far, there is a lack of micro data for the key parameters related to CBDC. Therefore, we calibrate these parameters such that the model dynamics match available macro data in the absence of CBDC.

The calibration of the conventional parameters closely follows that of Gertler and Karadi (2011). Our calibration differs in terms of the following two aspects: First, we derive the discount factor β from the data for the average bond interest rate from 2003 to 2008 (Bindseil (2020)). Second, we adjust the steady state government expenditure share to match Euro Area data (Eurostat (2020)).

We calibrate the additional parameters in the following manner. We use Ω_D to target a steady state share of central bank funding of 17% in external refinancing. This value might be reasonable in the absence of capital market refinancing, which we neglect in our analysis. Note that, due to the functional form of ψ, higher values for Ω_D do not only decrease the aforementioned share but also the elasticity of households' deposits to changes in interest rates. Ω_N is used to alter the impact of financial stress on deposits. As there is no reliable Euro Area data on how households adjust their bank deposits in times of financial crisis and in the absence of deposit insurance schemes, we calibrate Ω_N such that — with CBDC — deposits initially drop approximately by 20% after the shock. Υ and Γ determine the absolute and the marginal utility of liquidity, respectively. We calibrate both parameters such that households do not hold any non-interest-bearing CBDC in the steady state — that is households' bank deposits fully meet their liquidity needs.

The model features four different interest rates. In the baseline setting, we assume that r^D, r^B, and r^{CBDC} follow r^{CB} with time-invariant spreads. Δ^B and Δ^D are set to 1%, such that $\bar{r}^B = 4\%$ and $\bar{r}^D = 2\%$ approximately match the observed data. Following Bindseil (2020), we assume that in the steady state, the CBDC rate lies 2% below the interest rate on central bank loans. As the model output presents quarterly data, interest rate spreads are adjusted accordingly.

Households		
β	Intertemporal Discount Factor	0.990
h	Habit Parameter for Consumption	0.815
χ	Relative Utility Weight of Labor	3.409
ϕ	Inverse Frisch Elasticity of Labor Supply	0.276
Υ	Utility Weight of Liquidity	0.125
Ω_D	Elasticity of ψ to Bank Deposits	51.000
Ω_N	Impact of Financial Stress on ψ	0.050
Γ	Elasticity of Liquidity	-0.950
Banks		
θ	Survival Probability of Bankers	0.975
λ	Divertible Fraction of Intermediated Funds	0.381
ω	Proportional Transfer to Entering Bankers	0.002
Intermediate Goods Producers		
α	Capital Share	0.330
ζ	Elasticity of Marginal Depreciation	7.200
δ_i	Steady State Depreciation Rate	0.025
Capital Goods Producers		
η_i	Elasticity of Investment Adjustment Costs	1.728
Final Goods Producers		
ε	Elasticity of Substitution between Goods	4.167
γ	Calvo Parameter	0.779
γ_π	Price Indexation of Inflation	0.241
Central Bank and Government		
κ_π	Taylor Rule Response Coefficient to Inflation	1.500
$\kappa_{y_{gap}}$	Taylor Rule Response Coefficient to Output Gap	$0.5/4$
Δ^B	Spread between Central Bank Reserves and Bonds	$0.01/4$
Δ^D	Spread between Central Bank Reserves and Deposits	$0.01/4$
Δ^{CBDC}	Spread between Central Bank Reserves and CBDC	$0.02/4$
$\bar{G}/\bar{Y}$	Steady State Share of Government Expenditures	0.470

Table 2: Parameter calibration

4 Introducing CBDC

In this chapter, we discuss the implications of two different forms of CBDCs, an interest-bearing and non-interest-bearing CBDC. For an interest-bearing CBDC, the central bank sets a variable interest rate that can be either positive or negative. In contrast, a non-interest-bearing CBDC is not remunerated and is, in this respect, the digital equivalent of cash. In a cashless economy, these two CBDC alternatives differ fundamentally: a non-interest-bearing CBDC anchors interest rates and imposes, just like cash, an ELB on deposit interest rates. The interest-bearing alternative imposes a similar lower bound. However, this lower bound is variable and co-moves with the CBDC interest rate.[9] Therefore, the central bank can react to a crisis by setting interest rates to go below the ELB — that is in our case below zero — and stimulate the economy more effectively.

Our CBDC analysis involves four steps: First, in Section 4.1, we compare the baseline model without CBDC with a non-interest-bearing CBDC model under the impact of a quality of capital shock. We assume that both models are constrained by an ELB. Second, in Section 4.2, we use the same shock to compare the baseline model (constrained and unconstrained) to an unconstrained interest-bearing CBDC model. Third, in Section 4.3, we relax the assumption of full allotment of central bank money. Finally, in Section 4.4, we conclude with an analysis of a variable rule-based interest rate on CBDC, such that the CBDC interest rate is used as an additional monetary policy tool.

We choose this order, as it allows us to address CBDC implications step-by-step. The first two sections highlight the reallocation of households' savings and the resulting change in the structure of bank funding. These sections also establish the general result that full allotment can replace losses in bank funding and offset negative consequences beyond the financial sector. Relaxing the assumption of full allotment, we focus on the impact of a CBDC on the real economy and, finally, on the central bank's option to use the interest rate on CBDC as an additional monetary policy tool to mitigate destabilizing effects.

For all simulations, we use a negative quality of capital shock of 5% with persistence 0.66 to simulate a financial crisis that features substantial loan defaults, such that the simulation leads

[9] Note that this variability of the lower bound only holds in a cashless society, which we assume for our analysis.

to dynamics comparable to the global financial crisis (Gertler and Karadi (2011)). The general model mechanics and a comparison to Gertler & Karadi's model is presented in Appendix B.[10]

4.1 Non-interest-bearing CBDC

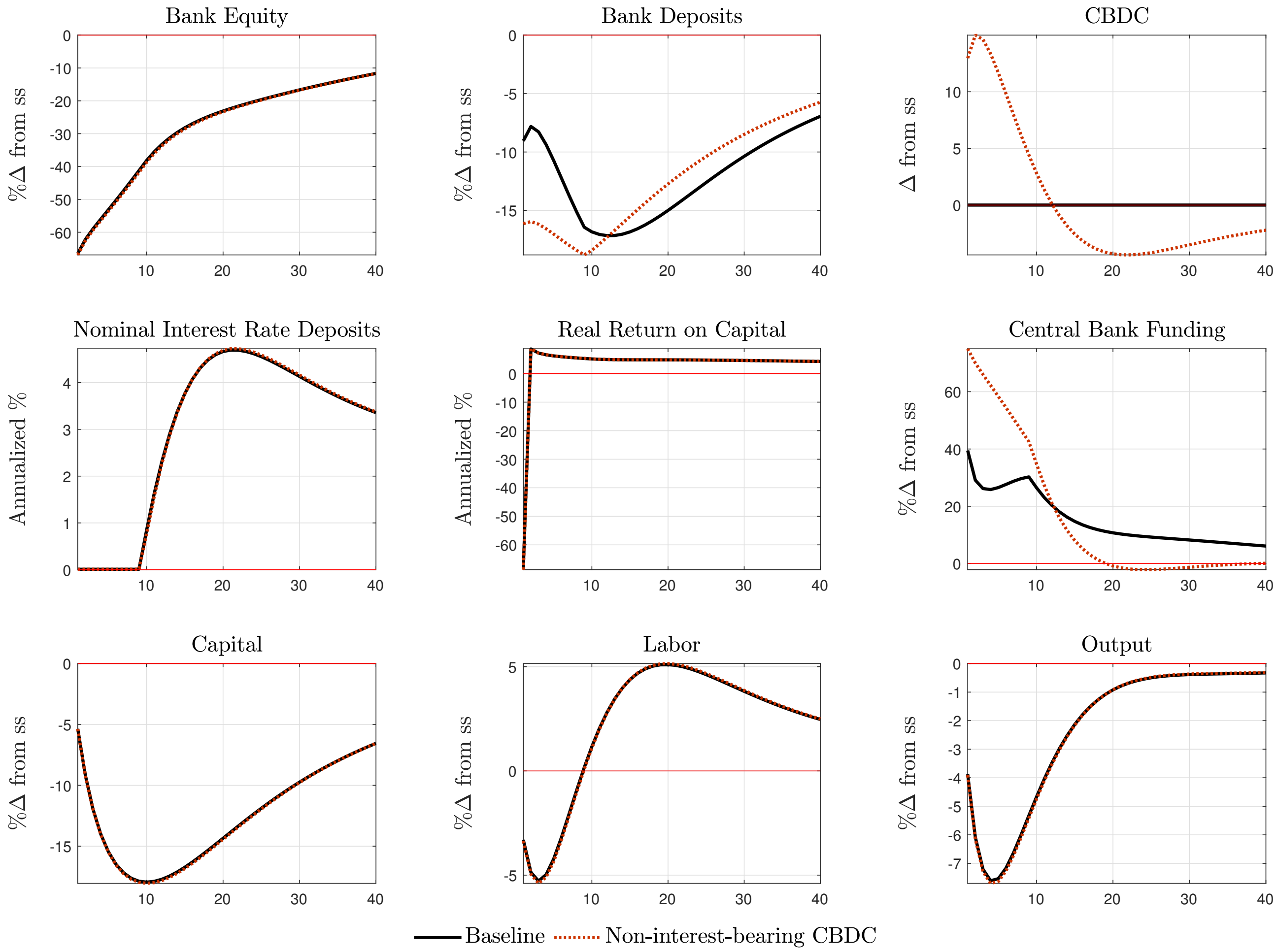


Figure 3: Baseline with ELB vs. non-interest-bearing CBDC with ELB

Figure 3 compares the dynamics of the baseline model without a CBDC with a model with a non-interest-bearing CBDC. The negative quality of capital shock implies a major reduction in the output of intermediate goods. This reduction leads to loan defaults[11] and a deterioration

[10]We conduct our simulations using Dynare (Adjemian et al. (2011)) and implement occasionally binding constraints via OccBin (Guerrieri and Iacoviello (2015)). We provide additional impulse response functions (IRFs) for additional variables in Appendix C.

[11]Note that there are no actual loan defaults in the model. The fall in capital efficiency leads to a fall in firm value and, hence, in bank equity because banks are the residual owners of firms. Following Gertler and Karadi (2011), this mechanism can be broadly interpreted as a loan default.

of banks' balance sheets. A 5% quality of capital shock amounts to a default of approximately 70% of loans, thereby resulting in an equally high percentage loss of bank equity. The starting recession and deflationary developments call the central bank into action. The central bank lowers the nominal interest rate on central bank funding to stimulate lending and investment. Accordingly, also the interest rate on deposits drops. As the non-interest-bearing CBDC imposes an ELB, the deposit interest rate remains slightly above the CBDC interest rate.

The lower spread between bank deposits and CBDC incentivizes households to substitute bank deposits with CBDC. Based on our calibration, with CBDC, bank deposits decrease by an additional 7%–16%. This reduction in deposits leads to an increase in central bank funding by 70%, as banks substitute lost funds from households with central bank funds. The share of central bank funds in the external refinancing of banks increases from initially 17% to 29%.

The central bank's balance sheet is additionally extended in the case with a CBDC, as households deposit their savings with the central bank – that is in CBDC. Note that the substantial increase in CBDC is not primarily driven by a decline in deposits. Instead, as the interest rate on bonds declines, households, additionally, substitute bonds with CBDC. This effect is in line with the observed increased use of central bank money (cash) in times of financial distress. As a CBDC offers the same attractive features as cash — a constant, non-negative, and guaranteed nominal interest rate of zero — but imposes no marginal costs, a non-interest-bearing CBDC might be used intensively as a store of value in times of low interest rates.[12] As the economy recovers and prices rise above the steady state level, the central bank reacts by increasing the interest rate on central bank funding. Accordingly, the deposit interest rate follows, and the spread between CBDC and alternative forms of savings increases. As the effect overshoots steady state levels, households decrease their CBDC holdings below zero.[13] Part of the liquidity created by CBDC debt is deposited with banks, where households profit from the increased spread, such that bank deposits in the CBDC model exceed their counterpart in the baseline

[12] In this simulation, CBDC deposits increase substantially and exceed central bank funds provided to banks by a factor of 6.5, thereby leading to a considerable expansion of the central bank's balance sheet. Considering that, according to Eurostat and ECB data, the total net financial assets of households in the Euro Area amount to approximately 34,000 billion Euro and central bank reserves that currently account for 3% of banks' external refinancing amount to approximately 624 billion Euro, this value seems high but not implausible.

[13] Note that the negative values of CBDC can occur due to technical limitations of the OccBin toolbox. However, in the subsequent analyses, we impose an occasionally binding constraint and prevent negative values of CBDC.

model after period twelve. With the increase in bank deposits, central bank funds slowly return to the steady state level.

There are only minor effects on refinancing and production. First, banks rely more on central bank funding. Therefore, they initially face lower refinancing costs as the interest rate on central bank funding is not constrained by an ELB. As interest rates quickly recover in the first 10 periods and central bank funds are reduced, this effect is relatively small. Second, as households substitute CBDC for bank deposits, they experience a change in their budget constraint, thereby leading to a small reduction in labor supply — and thus output — of further 0.05%.

To summarize, the major effects of a non-interest-bearing CBDC are limited to the financial sector and do not substantially affect production. Any losses in deposits are counterbalanced by a one-to-one increase in central bank funds. Thus, losses in deposits do not affect total intermediated funds, as the size of bank's balance sheets does not change. Hence, capital does not deviate from its baseline path, thereby creating no further disturbances in labor, output, and real return on intermediated funds. Note that this neutrality is driven by the assumption of full allotment. This result is in line with Brunnermeier and Niepelt (2019) and Niepelt (2020).

4.2 Interest-bearing CBDC

Figure 4 depicts the simulation results for the baseline model with and without an ELB and a model with an interest-bearing CBDC.[14] We present the baseline model both with and without an ELB to highlight that the major real effects do not occur due to disturbances created by the CBDC. Instead, the real effects can be explained by the circumvention of the ELB. We assume that, in the CBDC model, households do not have access to cash or any other non-interest-bearing asset. Hence, there is no way to avoid negative interest rates, and the ELB is no longer imposed, thereby allowing deposit interest rates to below zero.

The major advantage of an unconstrained deposit interest rate is that monetary policy measures directly affect households' savings decisions, also for negative interest rates. In this case, the nominal deposit interest rate follows the central bank-set interest rate on central bank funds based on the Taylor rule. Hence, the central bank's reaction to economic changes — that

[14]We acknowledge that negative interest rates on CBDC are controversial. In this paper, we do not address associated concerns, but solely focus on monetary policy aspects.

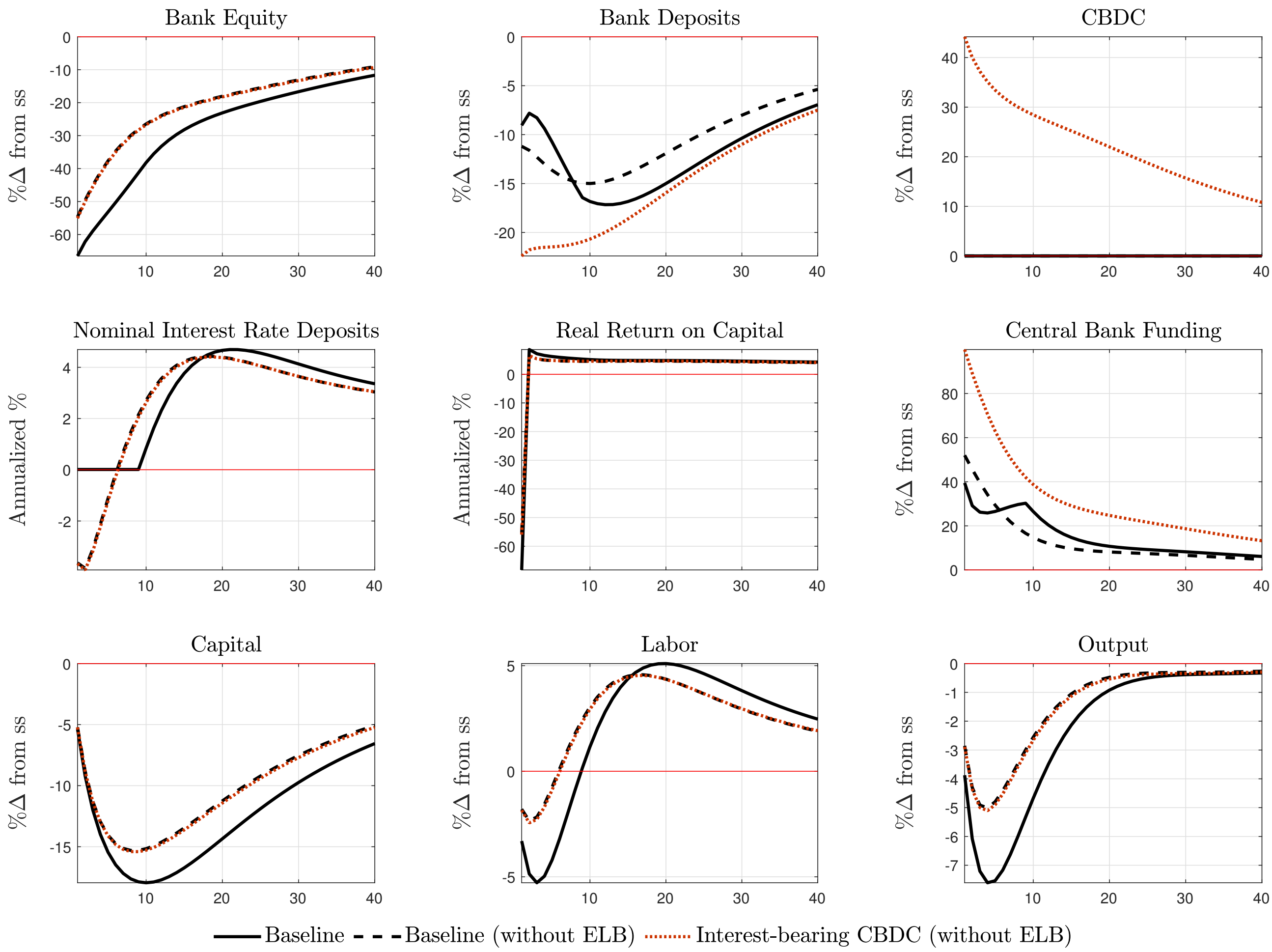


Figure 4: Baseline with ELB vs. interest-bearing CBDC

is the inflation rate and the output gap — translates directly to households. Lower deposit interest rates incentivize households to initially increase labor by approximately 1.5% and lead to a 1% higher output compared to the ELB-constrained baseline model. In addition, lower deposit interest rates imply a higher premium for banks and accelerate the build-up of new equity. Therefore, in the unconstrained case, monetary policy is better equipped to mitigate adverse effects. The increased reduction in the nominal interest rate on bank deposits leads to a further decline in deposits by 2%. This decline becomes larger and moves to 11% when households have the opportunity to shift savings to an equally liquid CBDC. Note that this effect is not driven by changes in the interest rate spread. Instead, as financial stress reduces households' demand for deposits, a CBDC offers a viable alternative to satisfy their demand for liquidity. By holding CBDC, households increase their overall liquidity, while the marginal utility of liquidity decreases. This *liquidity effect* renders deposits less attractive and leads to a further reduction.[15] In the steady state, households hold approximately 27% of their liquidity in CBDC.[16] Initially, after the shock, this share increases to 41%. Simultaneously, the loss in deposits is offset by an increase in central bank funds. The share of central bank funding in total external refinancing doubles from 18% to 36%. In contrast to the non-interest-bearing CBDC model, CBDC only slightly exceeds central bank funds in the central bank's balance sheet ($CBDC/R^{CB} = 1.25$).

Again, for the same reasons discussed in the previous section, the major effects of the interest-bearing CBDC are limited to the financial sector and do not substantially affect production. However, taking into account that an interest-bearing CBDC might eliminate the ELB, it improves monetary policy transmission and enables the central bank to counteract a financial crisis more efficiently. Nevertheless, this effect on the real economy, including production, is not directly linked to CBDC or changes in the households' saving options, but the elimination of the ELB. Note that, again, these results are driven by the assumption of full allotment. This assumption is relaxed in the next section.

4.3 Alternative Allotment of Central Bank Funds

Thus far, we assumed that the central bank fully compensates for losses in deposits by providing additional central bank funds. This assumption is in line with the current monetary policy of the ECB that, as a reaction to the global financial crisis, adapted its tender procedure for open market operations to full allotment in October 2008. Hence, the ECB began to fully allocate demanded funds to banks to stabilize the interbank market. While full allotment currently appears to be the 'new normal', it is not axiomatic.

This observation begs the question of whether our results still hold under alternative allotment procedures. In fact, as we show in this section, the assumption of full allotment is necessary to obtain the result that CBDC does not affect the economy beyond the financial sector.

[15] Note that this drop is additionally amplified by a comparably high elasticity of demand for deposits on changes in banks' equity.

[16] This value results from two assumptions. First, in the steady state, the remuneration for CBDC is 1%. Second, for consistency, we apply the same parametrization (particularly Υ) as in the non-interest-bearing CBDC model.

To analyze restricted allotment, we adapt Equation (47) in the following manner:

$$R_t^{CB} = \bar{R}^{CB} + X[(F_t^* - \bar{F}^*) - (D_t - \bar{D})], \tag{50}$$

where X is the share of lost deposits outside the steady state that the central bank substitutes. Thus, losses of deposits after a shock are only partially compensated. Note that this functional form does not affect the steady state allocation of central bank funds, such that $\bar{R}^{CB}$ is equal in all models. Thus, the results from different model specifications are comparable.

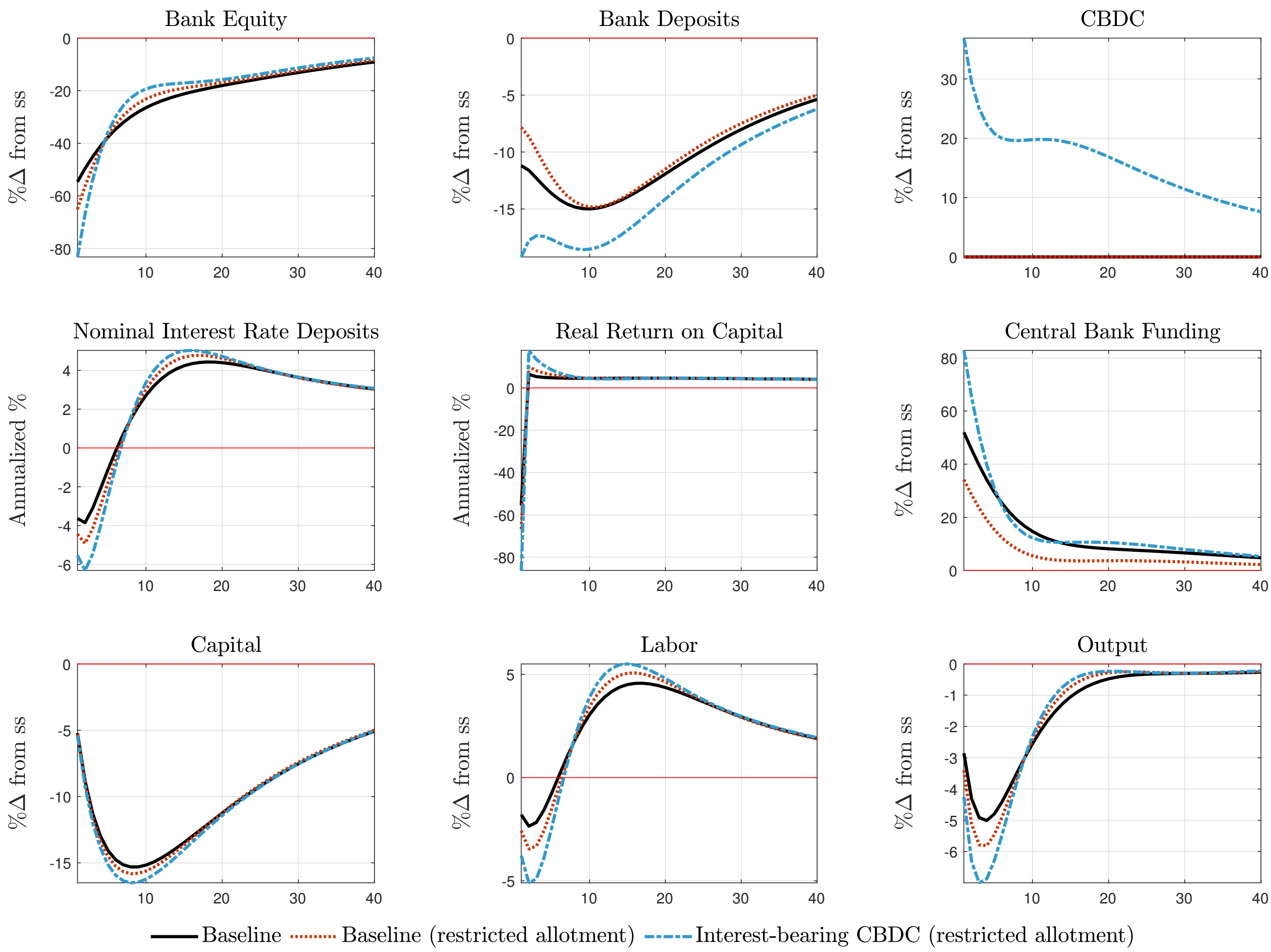


Figure 5: Interest-bearing CBDC with different allotment of central bank funds

Figure 4 compares the baseline model for full allotment and restricted allotment ($X = 0.5$) with the interest-bearing CBDC model ($X = 0.5$). Note that the central bank decides on the fraction of compensated funds. The more funds the central bank provides, the lower the real effects. In our simulation, we use $X = 0.5$ as an example. As the central bank does not fully compensate for lost deposits in both models, total intermediated funds, and, thus, the size of banks' balance sheets, decrease. This decrease negatively affects the next periods' levels of capital, thereby resulting in lower output. In addition, lower levels of capital increase the marginal productivity of capital and decrease the marginal productivity of labor. Hence, the real return on capital increases in periods after the initial shock, while wages drop. Households react with a reduction in labor, which is, due to consumption smoothing, already present in the first period. With $X = 0.5$, this 0.5% (2%) stronger drop in labor results in a 0.3% (1.2%) lower output for the baseline (interest-bearing CBDC) model. The real return on capital and, thus, banks' equity drop an additional 10% (25%). Then, the central bank reacts with a reduction in interest rates. This reduction, in combination with the higher expected return on capital, increases the premium and profits for banks. As these higher expected profits ease the moral hazard problem, households are willing to deposit more funds with banks. Even though this easing increases the central bank's willingness to provide funds, central bank funding decreases due to the lower allotment rate. Driven by the high premia, banks promptly restore large parts of their equity and trigger an accelerated recovery process for the entire economy.

With CBDC, households have an incentive to exchange parts of their deposits for CBDC. Thus, deposits and total intermediated funds as well as capital decrease. As described above, this decrease further eases the moral hazard problem, and the central bank provides more funds. Nevertheless, this increase in central bank funding cannot fully compensate for the increased loss in deposits, thereby leading to a deeper recession.

In summary, relaxing the assumption of full allotment leads to remarkably different results. The resulting imperfect substitution of deposits with central bank funds opens up a channel for CBDC to the real economy. The disintermediation of commercial banks negatively impacts investment, the build-up of capital, and production. In this case, CBDC indeed has the potential to destabilize the financial sector and the entire economy.

4.4 CBDC Interest Rate Rule

While the previous analysis suggests that full allotment is necessary to prevent destabilizing effects, the central bank can also use another tool. Bindseil (2020) proposes that central banks can actively use the interest rate on CBDC to disincentivize its accumulation in a crisis and, thus, to counteract disintermediation. Using this new policy instrument, the central bank can govern the demand for CBDC. As the CBDC interest rate in our model is close to zero in the steady state, this approach implies highly negative interest rates.

For the following analysis, we adapt Equation (42) in the following manner:

$$i_t^{CBDC} = i_t^{CB} - \left(\Delta^{CBDC} + \frac{\bar{N} - N_t}{\bar{N}} \kappa_N \right). \tag{51}$$

The term in parentheses defines the spread between the interest rates on central bank funding and CBDC. We keep its steady state level unchanged and allow the central bank to increase the spread based on financial stress after the shock. We use the measure from Section 2.1, such that financial stress is expressed as the percentage deviation of banks' equity from steady state. κ_N specifies the intensity of the reaction.[17]

The blue and the green lines in Figure 5 indicate the results for models with restricted allotment ($X = 0.5$). As expected, decreasing the nominal interest rate on CBDC reduces CBDC holdings, in our case to zero. The effect on deposits is relatively small, as households do not substitute CBDC primarily with deposits but with bonds. The liquidity effect drives the smaller drop in deposits: As households decrease their CBDC holdings, total liquidity declines, and its marginal utility rises. This effect increases the marginal utility of deposits, and thus, deposits themselves, but is rapidly outweighed by the rising risk.[18] With restricted allotment, higher deposits increase total intermediated funds and result in higher labor, capital, and output. However, all these improvements fall short of the full allotment scenario. In other words, while targeting CBDC can positively impact an economy with restricted allotment in a crisis, full allotment is the more effective policy. Nevertheless, lowering interest rates effectively limits the accumulation of CBDC and is a valid tool to prevent disintermediation and destabilization specifically caused by a CBDC.

[17] κ_N is calibrated such that households in this exercise initially reduce their CBDC holdings to zero. Note that we restrict these holdings to be non-negative.

[18] Note that CBDC is increasingly attractive when deposits fall, such that households almost fully substitute lost liquidity. Vice versa, this is not the case. The attractiveness of deposits only partially depends on the presence or absence of CBDC (liquidity effect). The determining factor is households' perceived risk of commercial bank money. Households are willing to forgo liquidity when remuneration on CBDC is too low to avoid this risk.

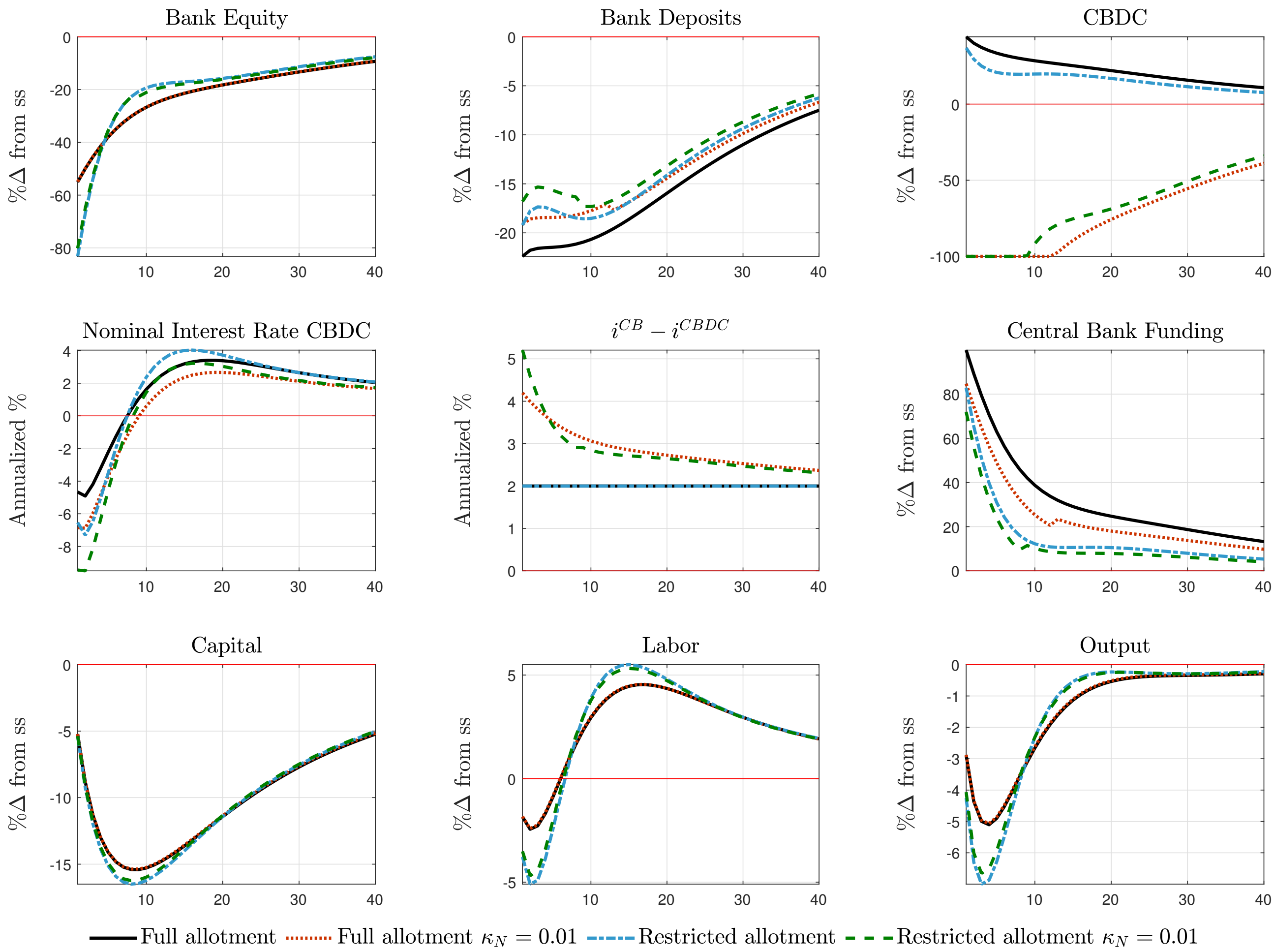


Figure 6: Variable interest rate spread on CBDC

With full allotment, the CBDC interest rate proves to be an effective instrument to impact both CBDC holdings and central bank funds. When the interest rate is reduced, households decide to hold less CBDC and more deposits, such that the share of central bank funding in total external refinancing decreases. Thus, there is a twofold contraction in the central bank's balance sheet, while economic activity is unaffected.

5 Conclusion

While CBDCs offer several benefits, their implications for the financial sector in general and commercial banks' funding in particular remain subject to debate. To contribute to this debate, we developed a medium-sized DSGE model that provides a basis for analyzing the effects of CBDCs. The model features endogenously limited bank funding via households and the central bank, households that actively choose the amount of deposits as part of their utility maximization, and a CBDC as a liquidity providing substitute for deposits. In addition, our model includes specific interest rates on bonds, deposits, central bank funds, and CBDC.

The design of the model implies that households reduce their deposits with commercial banks in times of crises due to a liquidity effect. When households can satisfy their demand for liquidity with CBDC, they lose their main incentive to store their savings in the form of risky deposits. The resulting disintermediation implies a contraction in the balance sheets of commercial banks and, thus, reduced loan volume, investment, and economic activity.

In our model, the central bank has two options to react to this disruption in commercial bank funding and combat destabilizing effects. First, it can adjust its allotment policy. When faced with a decreasing supply of deposits, commercial banks increase their demand for central bank funds. In case the central bank chooses to fully meet this demand, a reduction in deposits only implies a shift in the composition of bank funding, but no contraction of banks' balance sheets. The central bank commits itself to act as a lender of last resort, thereby substantially expanding its own balance sheet and using it as a monetary policy tool (Curdia and Woodford (2011)). While we abstract from the aspect of collateral in our model, the question remains whether banks can provide sufficient eligible assets. If collateral is scarce, the central bank might be pressurized to reduce collateral requirements — that is it might accept collateral with higher risk, potentially threatening financial stability. Further research is needed to address these issues.

Second, the central bank can decrease the remuneration of CBDC to disincentivize its accumulation. This approach effectively lowers CBDC holdings but does not necessarily incentivize households to hold substantially more deposits. Therefore, on its own, it is not a sufficient tool to counteract the adverse effects resulting from losses in bank funding in a crisis. Nevertheless, lowering interest rates effectively limits the accumulation of CBDC and is a useful tool to prevent disintermediation and destabilization caused specifically by a CBDC. In combination with full allotment, it helps control the demand of CBDC and central bank funds without causing CBDC-specific disturbances beyond the financial sector.

Note that this second option is only available for an interest-bearing CBDC. For a non-interest-bearing CBDC, the central bank cannot directly govern the demand and prevent substantial accumulation. Apart from a strong commitment to full allotment, at least two alternative policies mitigate CBDC-induced disintermediation. First, the central bank can limit the supply of CBDC, for example, by imposing a cap on individual CBDC holdings, as proposed by Panetta (2018). However, a cap could weaken a CBDC's competitiveness relative to private digital means of payment, such as global stablecoins, undermining one of the key motives for introducing a CBDC. Second, policy-makers could target the perceived risk in the financial sector by providing deposit insurance schemes, such as those implemented in Germany. While these schemes helped to maintain trust in the financial sector during the global financial crisis, there is evidence that deposit insurances themselves can threaten financial stability (Demirgüç-Kunt and Detragiache (2002)). Further research is needed to analyze CBDC in a model that includes deposit insurance schemes.

Apart from the limitations of our analysis mentioned above, two additional aspects are worth pointing out: First, we model government bonds in a rather simplistic manner. We neglect that the supply of bonds could be limited and that prices and yields are determined by supply and demand in capital markets. Increasing collateral needs from commercial banks would affect demand for bonds and might open up new channels for a CBDC to impact the economy even with full allotment. Second, we analyze the impact of a CBDC in a cashless economy. Since, currently, households continue to hold substantial amounts of their savings in cash, a model including cash could provide further relevant insights.

References

Adjemian, S., Bastani, H., Juillard, M., Karamé, F., Maih, J., Mihoubi, F., Perendia, G., Pfeifer, J., Ratto, M., and Villemot, S. (2011). Dynare Reference Manual Version 4. *Dynare Working Paper*, 1.

Andolfatto, D. (2021). Assessing the impact of central bank digital currency on private banks. *The Economic Journal*, 131(634):525–540.

Barrdear, J. and Kumhof, M. (2021). The macroeconomics of central bank digital currencies. *Journal of Economic Dynamics and Control*, 104148.

Bindseil, U. (2020). Tiered CBDC and the financial system. *ECB Working Paper*, 2351.

Brainard, L. (2021). Private money and central bank money as payments go digital: an update on CBDCs. Website. https://www.federalreserve.gov/newsevents/speech/brainard20210524a.htm (access: June 18th, 2021).

Brunnermeier, M. K. and Niepelt, D. (2019). On the equivalence of private and public money. *Journal of Monetary Economics*, 106:27–41.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics*, 12(3):383–398.

Chiu, J., Davoodalhosseini, S. M., Hua Jiang, J., and Zhu, Y. (2019). Central bank digital currency and banking. *Bank of Canada Staff Working Paper*, (2019-20).

Curdia, V. and Woodford, M. (2011). The central-bank balance sheet as an instrument of monetary policy. *Journal of Monetary Economics*, 58(1):54–79.

Demirgüç-Kunt, A. and Detragiache, E. (2002). Does deposit insurance increase banking system stability? an empirical investigation. *Journal of Monetary Economics*, 49(7):1373–1406.

Diamond, D. W. and Dybvig, P. H. (1983). Bank runs, deposit insurance, and liquidity. *Journal of Political Economy*, 91(3):401–419.

Dyson, B. and Hodgson, G. (2016). Digital cash: why central banks should start issuing electronic money. *Positive money*.

ECB (2020). Report on a digital euro.

Eurostat (2020). Government finance statistics. Website. https://ec.europa.eu/eurostat/statistics-explained (access: October 26th, 2020).

Feenstra, R. C. (1986). Functional equivalence between liquidity costs and the utility of money. *Journal of Monetary Economics*, 17(2):271–291.

Fernández-Villaverde, J., Sanches, D., Schilling, L., and Uhlig, H. (2020a). Central bank digital currency: Central banking for all? *Review of Economic Dynamics*, 41:225–242.

Fernández-Villaverde, J., Sanches, D., Schilling, L., and Uhlig, H. (2020b). Central bank digital currency: When price and bank stability collide. *Available at SSRN.*

Ferrari, M., Mehl, A., and Stracca, L. (2020). Central bank digital currency in an open economy. *CEPR Discussion Paper*, 15335.

Gertler, M. and Karadi, P. (2011). A model of unconventional monetary policy. *Journal of Monetary Economics*, 58(1):17–34.

Guerrieri, L. and Iacoviello, M. (2015). Occbin: A toolkit for solving dynamic models with occasionally binding constraints easily. *Journal of Monetary Economics*, 70:22–38.

Keister, T. and Sanches, D. (2019). Should central banks issue digital currency? *FRB Philadelphia Working Paper*, 19-26.

Mancini-Griffoli, T., Peria, M. S. M., Agur, I., Ari, A., Kiff, J., Popescu, A., and Rochon, C. (2018). Casting light on central bank digital currency. *IMF Staff Discussion Note*, 8.

Meaning, J., Dyson, B., Barker, J., and Clayton, E. (2021). Broadening narrow money: monetary policy with a central bank digital currency. *International Journal of Central Banking*, 68.

Niepelt, D. (2020). Monetary policy with reserves and cbdc: Optimality, equivalence, and politics. *EPR Discussion Paper*, 15457.

Panetta, F. (2018). 21st century cash: central banking, technological innovation and digital currency. In Gnan, E. and Masciandaro, D., editors, *Do We Need Central Bank Digital Currency?*, pages 23–33.

Rotemberg, J. J. (1982). Sticky prices in the united states. *Journal of Political Economy*, 90(6):1187–1211.

Sidrauski, M. (1967). Rational choice and patterns of growth in a monetary economy. *The American Economic Review*, 57(2):534–544.

A Households' Maximization Problem

Households maximize their utility based on the following five variables: consumption C, labor L, bank deposits D, central bank digital currency $CBDC$, and government bonds B. Households' utility function comprises a standard log-utility from consumption with habit formation, disutility from labor, and utility from liquidity:

$$\max\ E_t \sum_{i=0}^{\infty} \beta^i \left\{ ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma}\ (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi}. \right\} \tag{52}$$

Households' budget constraint can be written in the following manner:

$$C_t + D_t + CBDC_t + B_t = w_t L_t + \Pi_t + (1 + r_{t-1}^D)\psi_{t-1} D_{t-1} + (1 + r_{t-1}^{CBDC})CBDC_{t-1} + (1 + r_{t-1}^B) B_{t-1} \tag{53}$$

with

$$\psi_t = 1 - \left(\frac{D_t}{F_t^*}\right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}} \Omega_N. \tag{54}$$

To derive households' savings decision, we set up the Lagrangian in the following manner:

$$\begin{aligned}
\mathcal{L} =& E_t \sum_{i=0}^{\infty} \beta^i \left\{ ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma}\ (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right. \\
&-\lambda_{t+i} \left[C_{t+i} + D_{t+i} + CBDC_{t+i} + B_{t+i} - w_{t+i} L_{t+i} - \Pi_{t+i} \right. \\
&-(1 + r_{t+i-1}^D)(1 - \left(\frac{D_{t+i-1}}{F_{t+i+1}^*}\right)^{\Omega_D} - \frac{\bar{N} - N_{t+i-1}}{\bar{N}} \Omega_N) D_{t+i-1} \\
&\left. \left. -\ (1 + r_{t+i-1}^{CBDC}) CBDC_{t+i-1} - (1 + r_{t+i-1}^B) B_{t+i-1} \right] \ \right\}.
\end{aligned} \tag{55}$$

Now, we derive the Lagrangian with respect to C_t, L_t, D_t, $CBDC_t$, and B_t:

$$\frac{\partial \mathcal{L}}{\partial C_t} = (C_t - hC_{t-1})^{-1} - \beta h (C_{t+1} - hC_t)^{-1} - \lambda_t; \tag{56}$$

$$\frac{\partial \mathcal{L}}{\partial L_t} = -\chi L_t^{\phi} + \lambda_t w_t; \tag{57}$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial D_t} &= \Upsilon (D_t + CBDC_t)^{\Gamma} - \lambda_t \\ &+ \beta \lambda_{t+1} (1 + r_t^D) \left\{ \psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right\};\end{aligned} \tag{58}$$

$$\frac{\partial \mathcal{L}}{\partial CBDC_t} = \Upsilon (D_t + CBDC_t)^{\Gamma} - \lambda_t + \beta \lambda_{t+1} (1 + r_t^{CBDC}); \tag{59}$$

$$\frac{\partial \mathcal{L}}{\partial B_t} = -\lambda_t + \beta \lambda_{t+1} (1 + r_t^B). \tag{60}$$

As households maximize their utility, all of the above equations must equal 0. Combining (57) and (56) yields:

$$\varrho_t w_t = \chi L_t^{\phi}, \tag{61}$$

where ϱ is the marginal utility of consumption and is equal to λ_t in (56):

$$\varrho_t = \frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t}. \tag{62}$$

Inserting (56) in (60) yields:

$$1 = \beta \Lambda_{t,t+1} (1 + r_t^B), \tag{63}$$

where $\Lambda_{t,t+1}$ is the expected relative change in the marginal utility of consumption:

$$\Lambda_{t,t+1} = \frac{\varrho_{t+1}}{\varrho_t}. \tag{64}$$

Similar to eq. (63), we derive the following equation for (58):

$$1 = \beta \Lambda_{t,t+1} (1 + r_t^D) \left(\psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right) + \frac{\Upsilon}{\varrho_t} (D_t + CBDC_t)^{\Gamma} \tag{65}$$

and the following equation for (59):

$$1 = \beta\Lambda_{t,t+1}(1 + r_t^{CBDC}) + \frac{\Upsilon}{\varrho_t}(D_t + CBDC_t)^{\Gamma}. \tag{66}$$

To analyze the impact of the interest rate spread between r^B and r^{CBDC}, we equate (59) and (60):

$$\beta\varrho_{t+1}(r_t^B - r_t^{CBDC}) = \Upsilon(D_t + CBDC_t)^{\Gamma}. \tag{67}$$

In equilibrium, the discounted real interest rate spread multiplied with the next period's expected marginal utility of consumption equals the marginal utility gained from holding liquidity. Since Γ is negative, a decreasing interest rate spread will be offset by higher CBDC holdings – assuming that bank deposits are constant. Intuitively, a lower spread implies that households will keep their savings primarily in the form of a liquid means of payment. Households do not consider the slightly higher interest income from bonds and the resulting additional consumption in period $t+1$ as worth giving up liquidity.

Equating the first-order conditions for CBDC (59) and deposits (58) yields:

$$\left[\frac{(1 - \frac{1+r_t^{CBDC}}{1+r_t^D} - \frac{\bar{N}-N_t}{\bar{N}}\Omega_N)}{1+\Omega_D}\right]^{\frac{1}{\Omega_D}} = \frac{D_t}{F_t^*}. \tag{68}$$

Note that the effect of liquidity is cancelled out, as deposits and CBDC provide the same liquidity services. The share of deposits to the total maximum external refinancing of banks D/F^* depends on the interest rate spread between CBDC and deposits, the financial stress in the market, and the elasticity of the discount factor to changes in bank deposits Ω_D. Note that, in the steady state, equality of interest rates implies that deposits are reduced to zero unless Ω_D reaches infinity. Intuitively, Ω_D determines households' subjective discount factor on bank deposits. Higher values of Ω_D 'push' D closer to F^* and, at the same time, reduce the interest rate elasticity of deposits.

The model cannot be solved as soon as we allow for the economically unreasonable case $r^{CBDC} \geq r^D$. First, there is no incentive for households to hold any deposits, thereby leading to negative values that imply a central bank refinancing over the maximum F^*. Second, a first-order approximation is not capable of capturing this non-linearity and produces misleading results. Therefore, we assume that r^{CBDC} imposes a lower bound on r^D.

Finally, to compare bank deposits and government bonds, we equate (60) and (58):

$$\beta\varrho_{t+1}(1+r_t^B) = \beta\varrho_{t+1}(1+r_t^D)\left(\psi_t - \Omega_D\left(\frac{D_t}{F_t^*}\right)^{\Omega_D}\right) + \Upsilon(D_t + CBDC_t)^{\Gamma}. \tag{69}$$

In equilibrium, the discounted marginal utility gain from future consumption financed by interest income on bonds equals the same marginal utility from interest income on deposits, thereby accounting for subjective risk and the marginal utility from liquidity services.

To sum up, households' decision to allocate their savings depends on three dimensions: remuneration, liquidity, and risk.

B Model Comparison with Gertler & Karadi (2011)

Our baseline model is based on Gertler and Karadi (2011). We adapt their model (hereafter referred to as GK) to make the introduction of a CBDC possible. The aim is to create a framework (1) that allows for changes in the level of deposits based on financial conditions and households' preferences and (2) that — before the introduction of a CBDC — preserves the main implications of Gertler and Karadi (2011) — that is we retain the financial accelerator mechanism. This section outlines the implications of our implemented changes in households' maximization problem for the model output.

We make the following four assumptions. First, households actively choose between different forms of saving, accounting for different remuneration, liquidity, and risk. Second, banks do not merely intermediate funds from households to the production sector. Instead, they can additionally refinance themselves through the central bank. Third, the central bank fully allocates demanded funds to banks (full allotment) as long as their participation constraint holds. Fourth, refinancing via central bank money is more expensive than refinancing via deposits (Bindseil (2020)).

These assumptions imply that an increase in central bank funds will offset a decline in households' deposits in the case of full allotment. Therefore, changes in deposits have only a minimal impact on total intermediated funds, capital, and production.

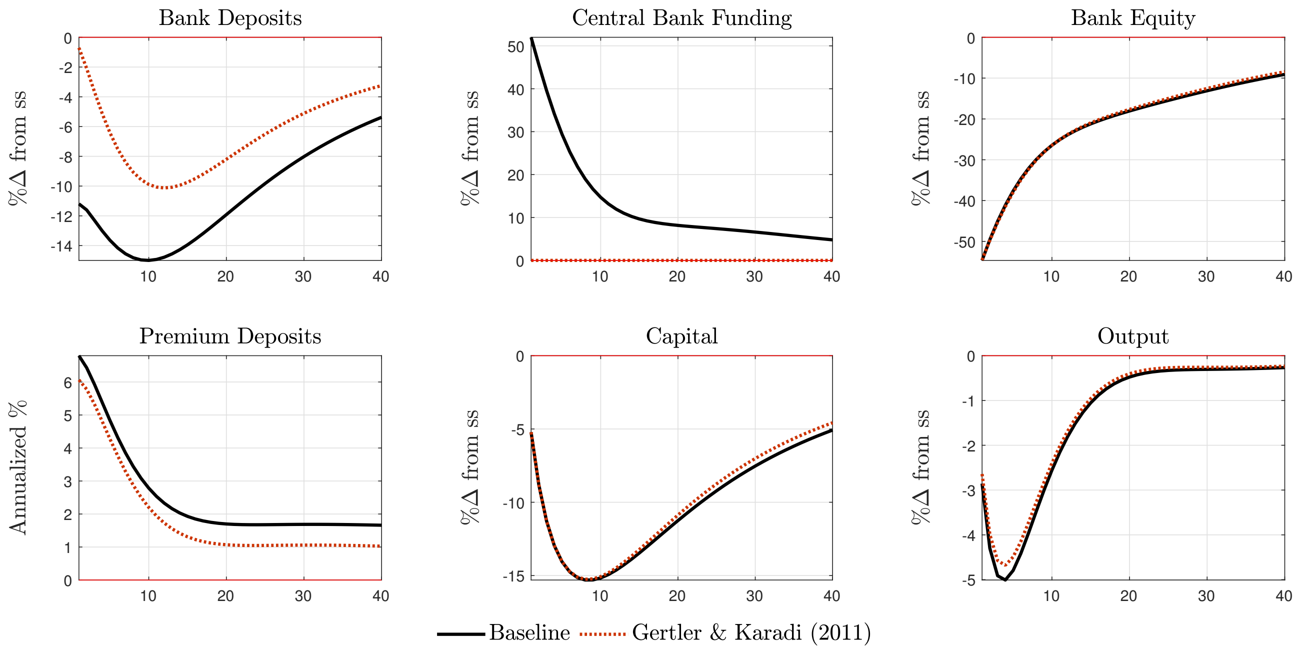


Figure 7: Baseline vs. Gertler & Karadi (2011)

Figure 7 compares our model with GK. For both models, we induce a quality of capital shock of 5% with persistence 0.66 to simulate a crisis similar to the great financial crisis starting in 2007 (Gertler and Karadi (2011)). The fall in the quality of capital reduces effective capital and production. This reduction in production causes losses for intermediate goods producers and loan defaults. Hence, the losses are captured in a major decline in banks' equity — in our case, approximately 55%. Consequently, banks' participation constraint tightens, and households reduce their deposits. This reduction is amplified in our model, as households assign a risk to their deposits and distrust banks. As a result, banks substitute deposits with central bank funds. While the structure of bank funding is different for the two models, banks receive the same amount of total external refinancing, i.e., the roughly 10% difference in bank deposits between the models is offset by a 50% increase in central bank funding in our model. Nonetheless, driven by the loss in equity, total external refinancing and total intermediated funds decline over the following periods in both models and lead to a further reduction in capital and output — the financial accelerator effect. Less capital implies higher marginal productivity and grants banks higher returns. In combination with a decrease in the deposit interest rate, these returns yield higher premia on deposits. Consequently, banks quickly rebuild parts of their lost equity.

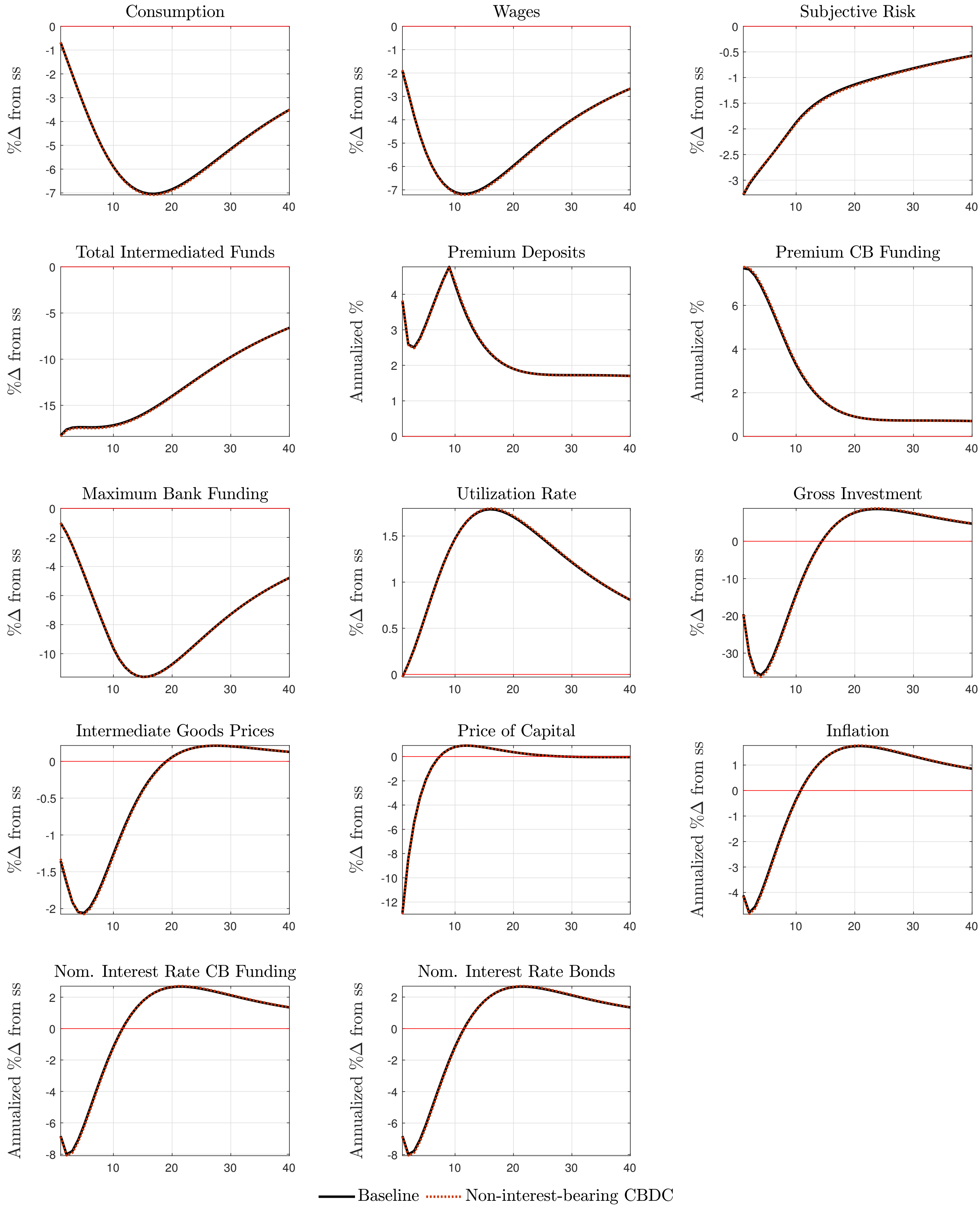
However, with a declining premium, this process slows down after 10 quarters and impedes further recovery processes. As a result, capital and output for both models remain below their steady states even after 40 quarters (10 years).

To sum up, our model — in contrast to Gertler and Karadi (2011) — allows for an active deposit decision of households, includes central bank refinancing, and features three different interest rates. Nevertheless, the model produces results similar to those obtained by Gertler and Karadi (2011) and retains their financial accelerator effect. Assuming full allotment, changes in bank funding structure do not affect the economy's overall performance.

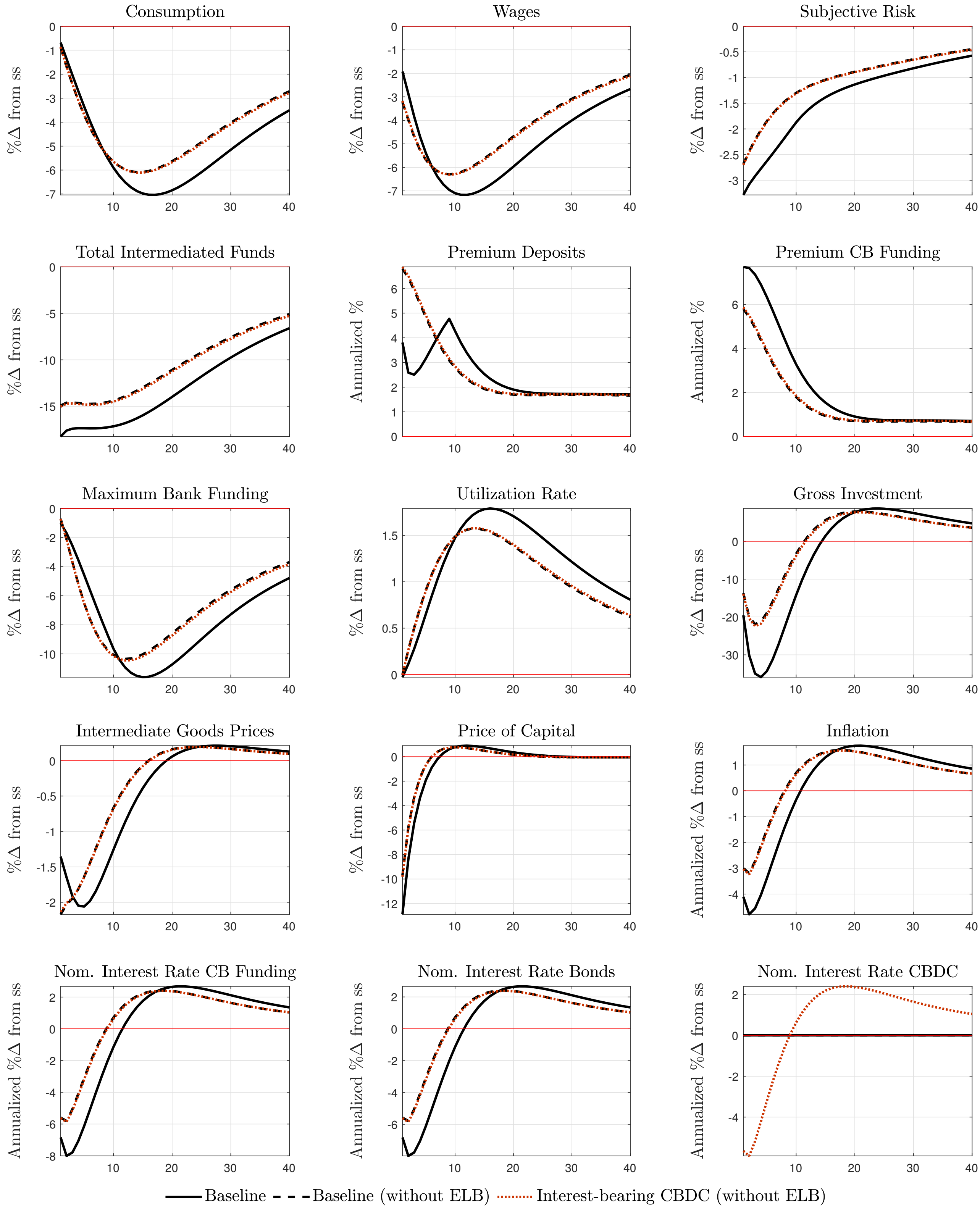
C Additional IRFs

In the following section, we present the remaining IRFs for the exercises conducted above. Note that we do not provide them for the simulations in Appendix B. In addition, we exclude a few variables that do not provide additional information or that can be directly derived from the presented figures. The authors can provide additional material upon request.

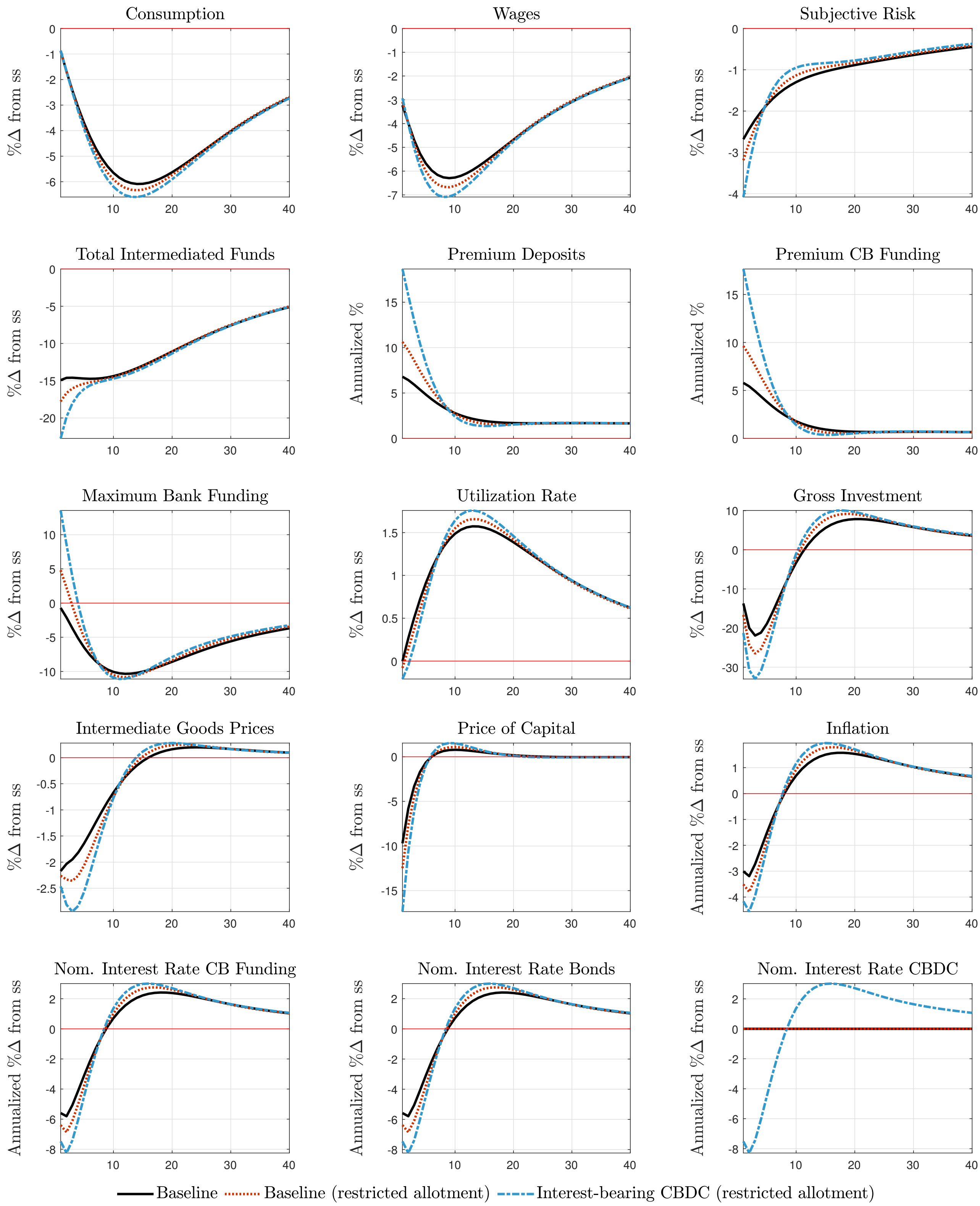
C.1 Baseline with ELB vs. non-interest-bearing CBDC with ELB



C.2 Baseline with ELB vs. interest-bearing CBDC



C.3 Interest-bearing CBDC with different allotment of central bank funds



C.4 Variable interest rate spread on CBDC with restricted allotment