

Schiller, Jonathan; Gross, Jonas

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

Jonas Gross^a, Jonathan Schiller^b

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Abstract

Central bankers express concerns that central bank digital currencies (CBDCs) might disintermediate commercial banks and facilitate bank runs. We analyze these concerns in a DSGE framework and provide a rationale for the disintermediation of the banking sector. Our focus is on the central bank's options to counteract the adverse effects of losses in bank funding depending on different CBDC designs. We find that the central bank can stabilize the financial sector by acting as a lender of last resort or by actively governing demand for CBDC.

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

JEL codes: D53, E42, E58, G21

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^aUniversity of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany, jonas.gross@uni-bayreuth.de

^bCorresponding author, University of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany, jonathan.schiller@uni-bayreuth.de

1 Introduction

Recent technological innovations in the financial sector, most prominently the distributed ledger technology (DLT), have raised concerns within central banks. DLT enables decentralized digital transactions without a trusted third party. As a result, over 7500 DLT-based private monies have emerged since Bitcoin first established this technology in 2008. While initially perceived as gimmickry, cryptocurrencies have reached sizable market capitalization and are considered as potentially viable means of payment and stores of value. Global stablecoins, such as Diem, caused central banks worldwide to rethink their current role. According to the European Central Bank (ECB), widely used global stablecoins that are not denominated in the domestic currency could weaken the transmission of monetary policy and limit financial and economic sovereignty (ECB (2020)).

At the same time, and accelerated by the Covid-19 pandemic, cash, i.e., physical central bank money, as a means of payment is in decline. Banks continuously pare down parts of the cash infrastructure, such as automated teller machines (ATMs), hampering access to the only public means of payment. This development further increases dependencies on private payment service providers. Hit by natural disasters, cyber incidents, or other extreme events, these private infrastructures might collapse and thereby threaten payment resilience.

To guarantee payment resilience in an increasingly digital environment and strengthen financial and economic sovereignty in the face of new competitors, the majority of central banks worldwide consider the issuance of digital central bank money (Boar et al. (2020)), so-called central bank digital currencies (CBDCs). In particular, central banks extensively analyze *retail* CBDCs, digital forms of central bank money, i.e., central bank liabilities, available to the general public.¹

To a certain extent, a retail CBDC can be considered a substitute for cash. Both are forms of money emitted by the central bank and legal tender. Unlike cash, however, a CBDC imposes presumably no storage cost, could be transferred comfortably, e.g., via mobile phones, and

¹In our analysis, the CBDC can be interpreted as account-based or token-based. In the case of an account-based CBDC, clients can – similar to bank deposits – deposit money directly or indirectly via banks in accounts with the central bank, while in a token-based CBDC system CBDC units are – similar to cash – issued directly in the form of tokens, e.g., stored on mobile phones. For a comparison of an account-based and a token-based CBDC, see Bank of England (2020). For simplicity, we use terminology related to an account-based CBDC.

is less likely to be stolen or lost.² With these features, a CBDC might also be considered a substitute for bank deposits as an equally user-friendly, safe, and cheap means of payment. As such, it offers a public alternative to private payment systems and increases payment resilience. A retail CBDC might also be an attractive store of value. First, it is emitted by the central bank, which, per definition, cannot go bankrupt. Therefore, unlike private forms of money, a CBDC is riskless. Second, savers might want to hold a CBDC based on its remuneration relative to other financial assets, such as bonds, and other forms of money, such as bank deposits and cash. Particularly in times of low or even negative interest rates on bonds and bank deposits, a non-interest-bearing CBDC, alongside cash, could constitute an attractive store of value.

The availability of such a riskless asset with time-invariant nominal value also imposes an effective lower bound (ELB) on interest rates. Savers have no incentive to hold a negatively remunerated asset or money when they have access to a safe store of value that does not lose nominal value over time. In the case of a CBDC, this lower bound is even more strict as currently imposed by cash as a CBDC is digital and could be stored comfortably without any storage or transaction costs. By providing a non-interest-bearing CBDC, the central bank limits its own conventional monetary policy tools.

In contrast, an interest-bearing CBDC pays a variable interest rate to the CBDC holder and allows for both positive and negative remuneration. In times of crises, the central bank can decrease the CBDC interest rate and thus, shift the lower bound downwards, increasing the range of its policy tools. This effect is particularly strong in a cashless society when savers cannot evade negative interest rates by accumulating cash. The interest rate on CBDC itself provides an additional monetary policy tool with a direct pass-through to users. This tool can be used to govern the demand for CBDC.³

Independent of the chosen design, a small interest rate spread between a CBDC and bank deposits could incentivize savers to use a CBDC as their main store of value and deposit their money directly at the central bank instead of potentially fragile commercial banks. Especially in times of financial distress, given the absence of a credible deposit insurance scheme, they might substitute substantial amounts of commercial bank money with CBDC. Following Bind-

²A structured overview of potential benefits and risks for both users and the central bank can be found in ECB (2020), Bindseil (2020), Klein et al. (2020), and Auer et al. (2020).

³Central banks could alternatively govern the supply of CBDC, e.g., via a cap on CBDC holdings.

seil (2020), we refer to this shift of funds from the aggregate banking sector to the central bank as (aggregate) disintermediation. As commercial banks rely on deposits to fund their lending business, substantial outflows of deposits might increase their funding costs and disrupt their activities. Assuming that the central bank itself does not provide loans, this disintermediation leads *ceteris paribus* to a decline in loan volume, investment, and overall economic activity.

Substantial short-term reallocations of funds from commercial banks to the central bank could result in aggregate (digital) bank runs. Bank runs are triggered when depositors doubt that they can withdraw their deposits in the future. The resulting sudden increase in demand for cash – central bank money – might cause liquidity shortages for banks. This risk potentially increases with CBDCs when depositors have the opportunity to withdraw deposits digitally with 'one-click' from the aggregate banking sector.

In light of these concerns, Bindseil (2020), Director General for Market Infrastructures and Payments at the ECB, cautions that

CBDC should be launched only if the central bank can be confident that [the issues of] undesired structural disintermediation of the banking system, and [...] facilitation of aggregate bank runs, have been solved.

In the literature, there are several design proposals that aim to prevent these issues. Bindseil (2020) argues for negative remuneration on CBDCs. While negative interest rates are controversial, the digital nature of CBDCs, in contrast to cash, makes them technically feasible. Bindseil proposes a two-tiered interest rate system where only CBDC holdings above a certain threshold are negatively remunerated. This way, a CBDC would be attractive as a means of payment, but not as a store of value, mitigating concerns for large-scale disintermediation of the financial sector. Alternatively, Panetta (2018) proposes an absolute limit on the amount of CBDC a single user can hold and Kumhof and Noone (2018) suggest restricting on-demand convertibility of bank deposits to CBDC. While these approaches aim to prevent the reallocation away from the financial sector, Brunnermeier and Niepelt (2019) argue that the central bank could act as a lender of last resort and fully compensate for losses in bank funding by providing additional central bank funding. This full allotment procedure would alter banks'

funding composition but would not affect its volume.⁴

In this paper, we contribute to the discussion by analyzing the impact of CBDCs on the financial sector based on a medium-sized New Keynesian dynamic stochastic general equilibrium (DSGE) model.⁵ Our contribution is threefold: First, we develop a DSGE model that allows for changes in bank funding structure and a sensible introduction of CBDC based on households' preferences over liquidity, risk, and remuneration. Second, we compare the effects of an interest-bearing and a non-interest-bearing CBDC in times of crises with a particular focus on the ELB. Third, we analyze the role of interest rate spreads and the allotment of central bank money to the financial sector.

Our main results are the following. First, assuming full allotment, i.e., the central bank acts as a lender of last resort, changes in bank funding structure do not substantially affect the real economy. Second, under this assumption, CBDCs do not negatively impact the stability of the financial sector, even though they crowd out deposits. This result holds for both interest- and non-interest-bearing CBDCs. If we assume that an interest-bearing CBDC can circumvent the ELB, we find substantial improvements for the whole economy. However, these improvements are not directly linked to a CBDC and changes in households' saving behavior. Instead, due to potentially negative interest rates below the ELB, the increased range for monetary policy mitigates disturbances after a crisis. Third, when 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. The disintermediation of commercial banks negatively impacts investment, the build-up of capital, and production. In this case, a CBDC destabilizes the financial sector and the whole economy. The central bank can decrease the remuneration of CBDC to mitigate this effect.

The paper is structured as follows. Section 2 outlines the current literature on CBDCs and its impact on the financial sector. Section 3 discusses our model. Section 4 explains and motivates the model calibration. Section 5 analyzes alternative versions of the model with non-interest-

⁴Apart from that, Bindseil (2020) notes that commercial banks' current extensive accumulation of excess reserves could temporarily absorb losses in deposits.

⁵Our model focuses on the link between households' portfolio decisions, the availability of CBDCs, and bank funding. It is not designed to conduct a welfare analysis regarding the introduction of a CBDC. Instead, we assume an implementation and observe a cashless economy's response to a financial crisis with and without CBDC.

bearing CBDC (5.1), with interest-bearing CBDC (5.2), with and without full allotment (5.3), and with different interest rates on CBDC (5.4). Section 6 concludes.

2 Related Literature

Due to the lack of empirical data, most CBDC analyses are based on theoretical models. These analyses are conducted in either a DSGE or a non-DSGE setting.

Modeling CBDC, no DSGE. Brunnermeier and Niepelt (2019) provide a generic model with money and liquidity. They show – given certain assumptions – that an introduction of a CBDC does not alter the equilibrium allocation and specifically does not undermine financial stability as it only alters the composition of bank funding, not its total size. Niepelt (2020) generalizes this result. Fernández-Villaverde et al. (2020b) analyze CBDCs in a Diamond and Dybvig (1983) model and conclude that the central bank faces a ‘CBDC trilemma’ where a socially efficient solution, price stability, and financial stability cannot be achieved simultaneously. Keister and Sanches (2019) use a new monetarist model with centralized and decentralized markets to analyze implications of CBDCs. They conclude that CBDCs might crowd out deposits and should be designed as interest-bearing. Chiu et al. (2019) also study a model with centralized and decentralized markets. While examining equilibrium effects of a CBDC introduction, they find that a CBDC improves efficiencies in the financial sector as banks lose market power. In an extreme scenario, a CBDC can even increase banks’ lending activities. Andolfatto (2018) 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. In fact, a CBDC might even increase financial stability as deposits could expand due to higher deposit interest rates. Fernández-Villaverde et al. (2020a) build a model that features a central bank that competes with commercial banks for deposits and provides funds to investment banks that use this funding to grant loans. In line with Brunnermeier and Niepelt (2019), they find that this alternative financial structure does not alter the allocation in equilibrium. However, in times of crises, central bank money is less risky and depositors shift savings accordingly such that the central bank becomes a deposit

monopolist.

Modeling CBDC, DSGE. Barrdear and Kumhof (2016) build a large-sized closed economy DSGE model. In particular, they study steady state effects of an interest-bearing CBDC for a US-calibrated economy. George et al. (2020) extend this model to analyze cross-border implications. Ferrari et al. (2020) develop a DSGE model to assess cross-border effects of a CBDC in a small open economy. They analyze the international transmission of monetary policy and technology shocks and discuss effects for optimal monetary policy and welfare.

What is missing in the literature so far is a DSGE approach that focuses explicitly on CBDCs' impact on bank funding and a comparison between interest-bearing and non-interest-bearing CBDCs. None of the papers above addresses the ELB or discusses the role of allotment of central bank refinancing and interest rates on CBDCs in a DSGE model. Our paper fills these gaps.

3 Model

The basic structure of our model is depicted in Figure 1. It builds on the closed economy New Keynesian framework by Gertler and Karadi (2011). Banks obtain funds from households and the central bank and act exclusively as intermediaries. Following Gertler and Karadi (2011), we assume that banks can default and divert obtained funds. The arising moral hazard puts an endogenous limit on banks' balance sheets and implies a financial accelerator effect. In contrast to Gertler and Karadi (2011) who determine deposits solely based on banks' performance, we assume that the amount of bank deposits is determined by households' utility maximization. Households assign a risk factor to commercial bank money that is increasing in the amount of deposits and the stress in the financial sector. Hence, households have an incentive to substitute bank deposits with less risky alternatives, i.e., either government bonds or CBDC. These three alternatives differ in risk, liquidity, and remuneration. Note that we assume a cashless society. Intermediate goods producers use intermediated funds to buy capital goods from capital goods producers that face investment adjustment costs. Production requires labor and capital. Competitive monopolistic final goods producers buy intermediate goods, repackage them, and sell

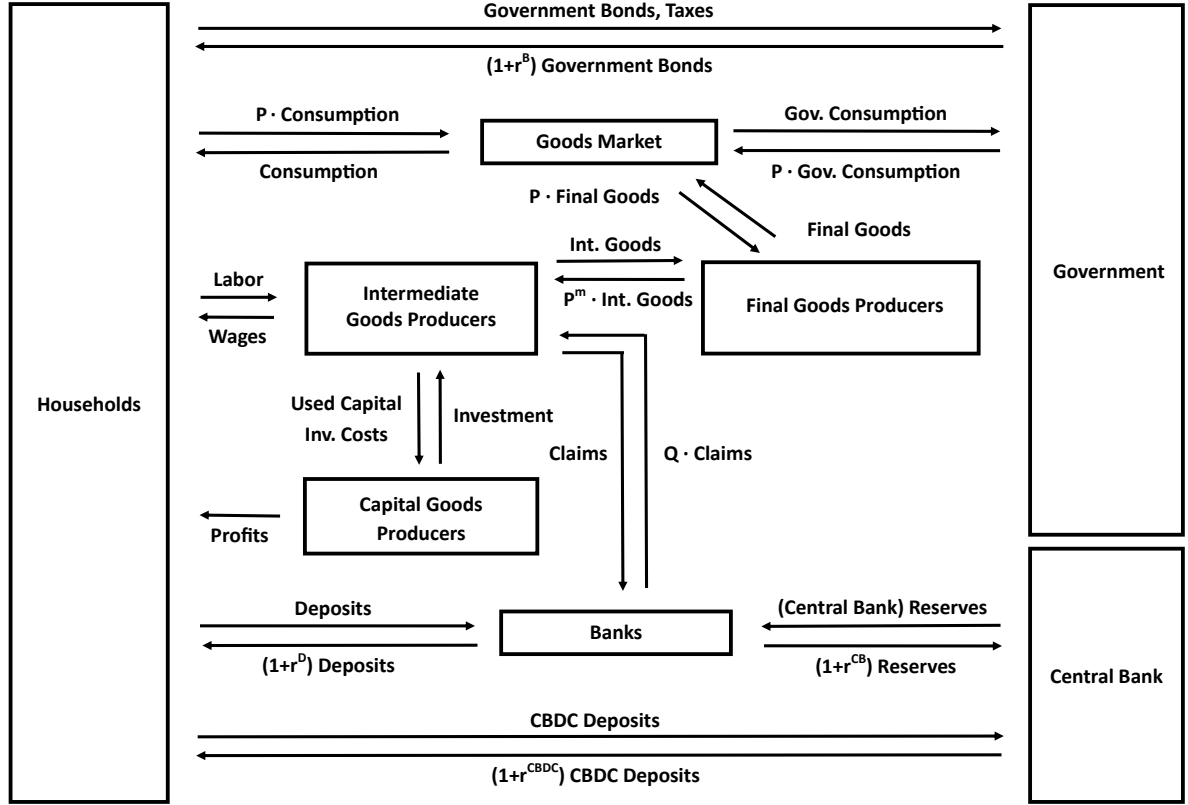


Figure 1: Model structure

them on the goods market to either households or the government.

3.1 Households

There is a continuum of identical and infinitely-lived households that supply labor (L), consume goods (C), and save for next period's consumption. Households do not invest in the production sector due to a lack of expertise. They save either via CBDC ($CBDC$), deposits (D), or government bonds (B). The three forms of saving differ in three dimensions: remuneration, liquidity, and risk (see Table 1).

First, regarding remuneration, deposits pay the real interest rate r^D , CBDC pays r^{CBDC} , and bonds pay r^B with $r^B \geq r^D \geq r^{CBDC}$. Second, regarding liquidity, CBDC and bank deposits are perfect substitutes. As both are means of payment, they generate utility by providing liquidity

	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

services. We assume that government bonds do not provide liquidity services as liquidation is costly and takes time and government bonds are no means of payment. Third, regarding risk, CBDC and government bonds are perceived as riskless, bank deposits as risky.

We can write households' maximization problem as:

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

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) or Rotemberg (1982)).⁶

Households' budget constraint can be written as:

$$C_t + D_t + CBDC_t + B_t = w_t L_t + \Pi_t + (1 + r_{t-1}^D) \psi_{t-1} D_{t-1} + (1 + r_{t-1}^{CBDC}) CBDC_{t-1} + (1 + r_{t-1}^B) B_{t-1} \quad (2)$$

where w is the real wage and Π income from the ownership of both non-financial and financial firms net of lump-sum taxes T . Real interest rates for the different forms of saving are denoted as r . The resulting first order conditions are derived in Appendix A.

While CBDC and government bonds are riskless, households assign a certain risk to bank deposits captured in the discount factor ψ .⁷ ψ is increasing in the amount of deposits and

⁶Alternatives 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 are formally equivalent (Feenstra (1986)). For a different modeling approach, see Kiyotaki and Moore (2019).

⁷Note that we abstract from deposit insurance schemes.

additionally depends on the level of stress in the financial sector:

$$\psi_t = 1 - \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}} \Omega_N \quad (3)$$

F^* denotes the maximum amount of external refinancing implied by the moral hazard in the financial sector (see Section 3.2). The elasticity Ω_D of the discount factor ψ to changes in bank deposits D is used to calibrate the steady state ratio of deposits to central bank money in bank funding. The weight Ω_N defines the impact of changes in banks' equity N on ψ .

We assume that a reduction of equity below its steady state \bar{N} signals financial stress to households, lowers households' trust in commercial banks, and, therefore, impacts the discount factor. A lower discount factor implies that households assume that their deposits with commercial banks might not be paid back in total. As a result, households reduce their bank deposits. The drop in D reduces the share of deposits in maximum external refinancing D/F^* and increases banks' dependence on central bank refinancing. Households perceive this more prominent role of the central bank as a stabilizing factor that lowers the risk in the financial sector captured in by ψ . Put differently, a drop in ψ can be interpreted as a reduction in the remuneration of bank deposits (see Equation (2)) and, hence, households decrease their bank deposits. They do so, until ψ rises again to the point, where households are indifferent between commercial bank money and its alternatives, taking into account three dimensions: remuneration, liquidity, and risk.

3.2 Banks

Banks lend their equity, households' deposits, and funds from the central bank to the production sector. Each period, banks pay back households' deposits and central bank funds with the ex ante known real interest rates r^D and r^{CB} both set by the central bank. Intermediate goods producers transfer any profits or losses ex post to banks, captured in the interest rate r^K .

Banker j accumulates wealth N_j . Wealth can be interpreted as the banker's equity, while deposits and central bank funds (R^{CB}) represent liabilities. Therefore, banker j 's balance sheet can be written as:

$$Q_t S_{jt} = N_{jt} + D_{jt} + R_{jt}^{CB} \quad (4)$$

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:

$$N_{jt+1} = (1 + r_{t+1}^K)N_{jt} + (r_{t+1}^K - r_t^D)D_{jt} + (r_{t+1}^K - r_t^{CB})R_{jt}^{CB} \quad (5)$$

Note that a banker's equity is mainly driven by the interest rate spreads, and 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 following two participation constraints:

$$E_t \beta \Lambda_{t,t+1} (r_{t+1}^K - r_t^D) \geq 0 \quad (6)$$

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

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

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1 - \theta) \theta^i \beta^{i+1} \Lambda_{t,t+i+1} (N_{jt+i+1}) \quad (8)$$

where θ is the probability that banker j stays a banker in the next period. Inserting the evolution of bankers' equity (5) into (8) yields:

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1 - \theta) \theta^i \beta^{i+1} \Lambda_{t,t+i+1} [(1 + r_{t+1}^K)N_{jt} + (r_{t+1}^K - r_t^D)D_{jt} + (r_{t+1}^K - r_t^{CB})R_{jt}^{CB}] \quad (9)$$

With positive premia, bankers have an incentive to increase 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 exit the market, thereby diverting the fraction λ of total intermediated funds $Q_t S_{jt}$. This fraction is lost for households and the central bank.⁸ The banker decides to 'run' if income from diverting funds exceeds the expected terminal wealth V_j from staying a banker. Hence, j 's incentive constraint can be expressed as follows:

$$V_{jt} \geq \lambda Q_t S_{jt} \quad (10)$$

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

$$V_{jt} = mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB} \quad (11)$$

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

$$mu_t^N = E_t[(1 - \theta)\beta\Lambda_{t,t+1}(1 + r_{t+1}^K) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^N mu_{t+1}^N] \quad (12)$$

$$mu_t^D = E_t[(1 - \theta)\beta\Lambda_{t,t+1}(r_{t+1}^K - r_t^D) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^D mu_{t+1}^D] \quad (13)$$

$$mu_t^R = E_t[(1 - \theta)\beta\Lambda_{t,t+1}(r_{t+1}^K - r_t^{CB}) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^R mu_{t+1}^R] \quad (14)$$

where $\Delta_{t,t+1}^N$, $\Delta_{t,t+1}^D$, and $\Delta_{t,t+1}^R$ are the growth rates of equity, deposits, and central bank funds. Note that we eliminate the j subscripts by assuming that deposits and central bank funds are allocated to banks according to their equity shares, i.e., $D_{jt} = D_t N_{jt}/N_t$ and $R_{jt}^{CB} = R_t^{CB} N_{jt}/N_t$.

⁸In 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. This way, we – substantially simplified – capture banks' natural limits in the acquisition of central bank money.

Hence, we can derive the growth rates as follows:

$$\Delta_{t,t+1}^N = \frac{N_{jt+1}}{N_{jt}} = (1 + r_{t+1}^K) + (r_{t+1}^k - r_t^D) \frac{D_t}{N_t} + (r_{t+1}^k - r_t^{CB}) \frac{R_t^{CB}}{N_t} \quad (15)$$

$$\Delta_{t,t+1}^D = \frac{D_{jt+1}}{D_{jt}} = \frac{D_{t+1}}{D_t} \Delta_{t,t+1}^N \frac{N_t}{N_{t+1}} \quad (16)$$

$$\Delta_{t,t+1}^R = \frac{R_{jt+1}^{CB}}{R_{jt}^{CB}} = \frac{R_{t+1}^{CB}}{R_t^{CB}} \Delta_{t,t+1}^N \frac{N_t}{N_{t+1}} \quad (17)$$

Inserting (11) in (10) yields the following incentive constraint:

$$mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB} \geq \lambda Q_t S_{jt} \quad (18)$$

By assuming that the incentive constraint (18) is binding and summing over all bankers, we can calculate the maximum amount of external refinancing F^* :

$$F_t^* = \frac{\lambda - mu_t^N}{mu_t^R - \lambda} N_t + \frac{mu_t^R - mu_t^D}{mu_t^R - \lambda} D_t \quad (19)$$

Accordingly, we can express bankers' individual balance sheets (4) in aggregate terms as follows:

$$Q_t S_t = N_t + D_t + R_t^{CB} \quad (20)$$

Note that N consists of equity of existing bankers N_e and equity of new bankers N_n that replace those returning to their households:

$$N_t = N_{et} + N_{nt} \quad (21)$$

N_e can be expressed as follows:

$$N_{et} = \theta \Delta_{t-1,t}^N N_{t-1} \quad (22)$$

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

$$N_{nt} = \frac{\omega}{1-\theta} (1-\theta) Q_t S_{t-1} = \omega Q_t S_{t-1} \quad (23)$$

3.3 Intermediate Goods Producers

Intermediate goods producers acquire 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, i.e., 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 for production.

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

$$Q_t K_{t+1} = Q_t S_t \quad (24)$$

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

$$Y_t^M = A_t (U_t \xi_t K_t)^\alpha L_t^{1-\alpha} \quad (25)$$

where A is technology, U the utilization rate of capital, and ξ the quality of capital. Maximizing intermediate goods producers' profits yields the following first order conditions for the utilization rate (26) and labor demand (27):

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta'(U_t) \xi_t K_t \quad (26)$$

$$P_t^M (1 - \alpha) \frac{Y_t^M}{L_t} = W_t \quad (27)$$

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:

$$R_t^K = \frac{[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta(U_t)] \xi_t}{Q_{t-1}} \quad (28)$$

Note that the quality of capital ξ directly affects banks' returns. Hence, a negative shock to ξ can induce substantial loan defaults and critical deterioration of banks' balance sheets, characteristics of e.g. the great financial crisis.

3.4 Capital Goods Producers

Capital goods producers create new 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 each period to their shareholders (households). 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} is the steady state level of investment. Capital goods producers maximize the sum of their discounted profits:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left[(Q_{t+i} - 1)I_{t+i}^N - f\left(\frac{I_{t+i}^N + \bar{I}}{I_{t-1+i}^N + \bar{I}}\right)(I_{t+i}^N + \bar{I}) \right] \quad (29)$$

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:

$$Q_t = 1 + f(\cdot) + \left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} \right) f'(\cdot) - E_t \beta \Lambda_{t,t+1} \left(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}} \right)^2 f'(\cdot) \quad (30)$$

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

$$K_{t+1} = \xi_t K_t + I_t^N \quad (31)$$

3.5 Final Goods Producers

Final goods producers buy intermediate goods, repackaging them, and sell them on the goods market, i.e., 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, total output Y is defined as a constant elasticity of substitution (CES) composite

of differentiated final goods:

$$Y_t = \left[\int_0^1 Y_{ft}^{\frac{\varepsilon-1}{\varepsilon}} df \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad (32)$$

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

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\varepsilon} Y_t \quad (33)$$

$$P_t = \left[\int_0^1 P_{ft}^{1-\varepsilon} df \right]^{\frac{1}{1-\varepsilon}} \quad (34)$$

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 as follows:

$$\max E_t \sum_{i=0}^{\infty} \gamma^i \beta^i \Lambda_{t,t+i} \left[\frac{P_t^*}{P_{t+i}} \prod_{k=1}^i (\pi_{t+k-1,t+k})^{\gamma_\pi} - P_{t+1}^M \right] Y_{ft+i} \quad (35)$$

Maximizing (35) and applying the law of large numbers yields the following definition of retail prices:

$$P_t = [(1 - \gamma)(P_t^*)^{1-\varepsilon} + \gamma(\pi_{t-1,t}^{\gamma_\pi} P_{t-1})^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} \quad (36)$$

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

3.6 Central Bank

The central bank sets the nominal interest rate on central bank funding i^{CB} according to a standard Taylor rule. We define the interest rates on different forms of saving – bonds, CBDC, and bank deposits – depending on i^{CB} to ensure that $i^B \geq i^D \geq i^{CBDC}$ (see Table 1). This way, the central bank 'leads' all interest rates with its rule-based interest rate on central bank

funding:

$$i_t^{CB} = (1 - \rho)[(1 + \bar{r}^{CB}) + \kappa_\pi \pi_t + \kappa_{y_{gap}} y_{gap,t}] + \rho i_{t-1}^{CB} \quad (37)$$

where ρ is the interest rate smoothing parameter, 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.

The nominal interest rate on deposits follows the interest rate on central bank funding with a fixed spread Δ^D :⁹

$$i_t^D = i_t^{CB} - \Delta_t^D \quad (38)$$

We introduce the spread to capture two factors. First, in normal times, central bank refinancing is more expensive than refinancing via deposits. Second, central bank refinancing requires collateral, implying additional monetary and non-monetary transaction costs.

In Section 5, we analyze scenarios, in which the ELB is binding. If the interest rate on deposits is constrained by the ELB, it is defined as:

$$i_t^D = \begin{cases} i_t^{CB} - \Delta_t^D & \text{for } i_t^{CB} - \Delta_t^D \geq 0 \\ 0 & \text{for } i_t^{CB} - \Delta_t^D < 0 \end{cases} \quad (39)$$

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:

$$i_t^{CBDC} = 0 \quad (40)$$

For an interest-bearing CBDC, the interest rate on CBDC strictly follows the interest rate on central bank funding with a fixed spread Δ^{CBDC} , as proposed in Bindseil (2020), and is, therefore, not used as a policy tool. In Section 5.4, we decouple the interest rates and allow for an individual rule-based determination.

Similar to the deposit facility rate today, we assume for both cases that CBDC, i.e., deposits

⁹Note 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 very high correlation between these interest rates.

at the central bank, face a remuneration below the central bank refinancing rates:

$$i_t^{CBDC} = i_t^{CB} - \Delta_t^{CBDC} \quad (41)$$

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 a fixed spread Δ^B : We assume a positive spread based on bond yield data and the rationale that the lack of liquidity services has to be compensated for by a higher remuneration.¹⁰

$$i_t^B = i_t^{CBDC} + \Delta_t^B \quad (42)$$

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

$$1 + i_t^D = (1 + r_t^D)(1 + E_t\pi_{t,t+1}) \quad (43)$$

$$1 + i_t^{CBDC} = (1 + r_t^{CBDC})(1 + E_t\pi_{t,t+1}) \quad (44)$$

$$1 + i_t^B = (1 + r_t^B)(1 + E_t\pi_{t,t+1}) \quad (45)$$

The central bank provides funding to commercial banks. 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^* :

$$R_t^{CB} = F_t^* - D_t \quad (46)$$

Note that this expression implicitly assumes a full allotment procedure. As long as the banks' incentive constraint holds, i.e., as long as they can provide sufficient collateral, the central bank fully meets their money demand. We relax this assumption in Section 5.3.

¹⁰Note that the fixed spread is a simplifying assumption. In reality, bond prices and yields exhibit more complex dynamics.

3.7 Government and Aggregation

The government receives income from lump-sum taxes T and issues bonds B_t . It finances government spending G and repays last period's bonds B_{t-1} including interest payments i_{t-1}^B . We define \bar{G} as a constant share of steady state output.

$$\bar{G} + (1 + i_{t-1}^B)B_{t-1} = T + B_t \quad (47)$$

Output is divided between consumption, investment, investment adjustment costs, and government expenditures. Hence, the economy-wide budget constraint can be expressed as:

$$Y_t = C_t + I_t + f\left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}}\right)(I_t^N + \bar{I}) + \bar{G} \quad (48)$$

4 Calibration

Table 2 summarizes the calibration of our model. In total, we use 28 parameters, 21 of them are also used in Gertler and Karadi (2011). We introduce additional parameters related to the inclusion of money in the utility function (Υ, Γ), the subjective discount factor ψ (Ω_D, Ω_N), and the interest rate spreads ($\Delta^B, \Delta^D, \Delta^{CBDC}$). As currently there is no CBDC in use, we lack micro data for the key parameters related to CBDC. Therefore, we calibrate these parameters such that the model dynamics match available macro data.

The calibration of the conventional parameters closely follows Gertler and Karadi (2011). Our calibration differs in the following two aspects: First, we derive the discount factor β from 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 Ω_D targeting a steady state share of central bank reserves in external refinancing of 17%. This value might be reasonable in the absence of capital market refinancing. Note that, due to the functional form of ψ , higher values of Ω_D do not only decrease the before-mentioned 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 deposits initially drop roughly 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, i.e., 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 $\bar{r}^D = 2\%$ roughly 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 reserves. 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
ρ_k	Persistence Quality of Capital Shock	0.660
Capital Good 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
ρ_i	Taylor Rule Smoothing Parameter	0
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

5 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 both positive or negative. In contrast, a non-interest-bearing CBDC is not remunerated and is, in this respect, a digital equivalent to 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 to 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.¹¹ Therefore, the central bank can react to a crisis by setting interest rates below the ELB, i.e., in our case below zero, and stimulate the economy more effectively.

We analyze both forms of CBDC in four steps: First, in Section 5.1, we compare the ELB-constrained baseline model to an ELB-constrained non-interest-bearing CBDC model by using a quality of capital shock. Second, in Section 5.2, we use the same shock to compare the baseline model (constrained and unconstrained) to an unconstrained interest-bearing CBDC model. Third, in Section 5.3, we relax the assumption of full allotment of central bank money and assume that the central bank does not act as a lender of last resort. Finally, in Section 5.4, we conclude with an analysis of a rule-based interest rate on CBDC.

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 outside 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.

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 and deterioration of banks' balance sheets. We scale the shock such that it leads to dynamics comparable to the global

¹¹Note that this variability of the lower bound only holds in a cashless society, which we assume for our analysis.

financial crisis (Gertler and Karadi (2011)). The general model mechanics and a comparison to the Gertler and Karadi (2011) model can be found in Appendix B.

5.1 Non-Interest-Bearing CBDC

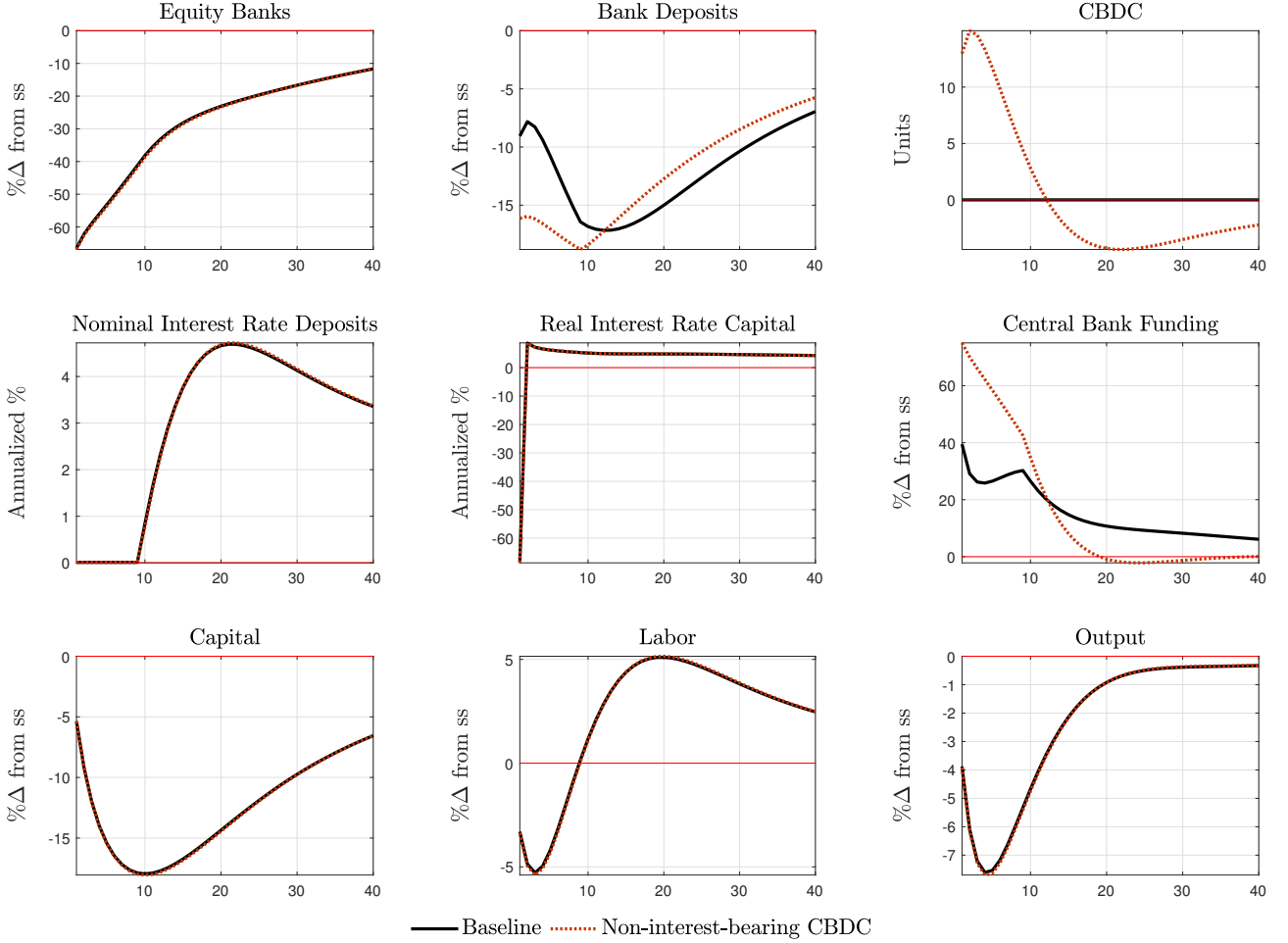


Figure 2: Baseline with ELB vs. non-interest-bearing CBDC with ELB

Figure 2 compares the dynamics of the baseline model without CBDC with a model introducing a non-interest-bearing CBDC.¹² The negative quality of capital shock implies a major reduction in intermediate goods production. This reduction leads to loan defaults and an overall lower return on capital. A 5% quality of capital shock amounts to a default of roughly 70% of loans resulting in an equally high percentage loss of banks' equity. The starting recession and

¹²We 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 all other variables in Appendix C.

deflationary developments call the central bank to action. Central bankers lower the nominal interest rate on central bank reserves to stimulate lending and investment. Accordingly, the interest rate on deposits drops. As the non-interest-bearing CBDC imposes an ELB, the deposit interest rate remains positive, slightly above the CBDC interest rate.

The lower spread between bank deposits and CBDC incentivizes households to substitute bank deposits with CBDC. Thus, deposits initially drop by an additional 7%. This drop 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 as households deposit their savings with the central bank, i.e., 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 cash in times of low interest rates and 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. Here, CBDC deposits increase such that they exceed central bank funds by the factor 6.5.¹³

As the economy recovers and prices rise above the steady state level, the central bank reacts with an increase in 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.¹⁴ 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 model after period twelve. With the increase in bank deposits, central bank

¹³Considering that, according to Eurostat and ECB data, total net financial assets of households in the Euro Area amount to roughly 34,000 billion Euro and central bank reserves that currently account for 3% of banks' external refinancing amount to roughly 624 billion Euro, this value seems high but not implausible.

¹⁴Here, we assume that households can accumulate debt in CBDC. This assumption is necessary due to the OccBin toolbox's limitations when in the steady state of a variable, here CBDC, the constraint is binding. However, in the subsequent analyses, we impose an occasionally binding constraint and prevent negative values of CBDC.

funds slowly return to their steady state level.

Note that there are some 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 ten 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, leading to a small drop 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 an immediate one-to-one increase in central bank funds. Thus, losses in deposits do not affect total intermediated funds. Hence, capital does not deviate from its baseline path, 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 and the central bank’s voluntarily chosen role as a lender of last resort. This result is in line with Brunnermeier and Niepelt (2019) and Niepelt (2020).

5.2 Interest-Bearing CBDC

Figure 3 shows the simulation results for the baseline model with and without an ELB and a model with an interest-bearing CBDC.¹⁵ 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 elimination 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.

The major advantage of an unconstrained deposit interest rate is that monetary policy directly affects households’ savings decisions. As the nominal deposit interest rate follows the central bank-set interest rate on its reserves, it is in line with the Taylor rule. Hence, the central bank’s reaction to economic changes, i.e., the inflation rate and the output gap, transmits directly to

¹⁵We 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.

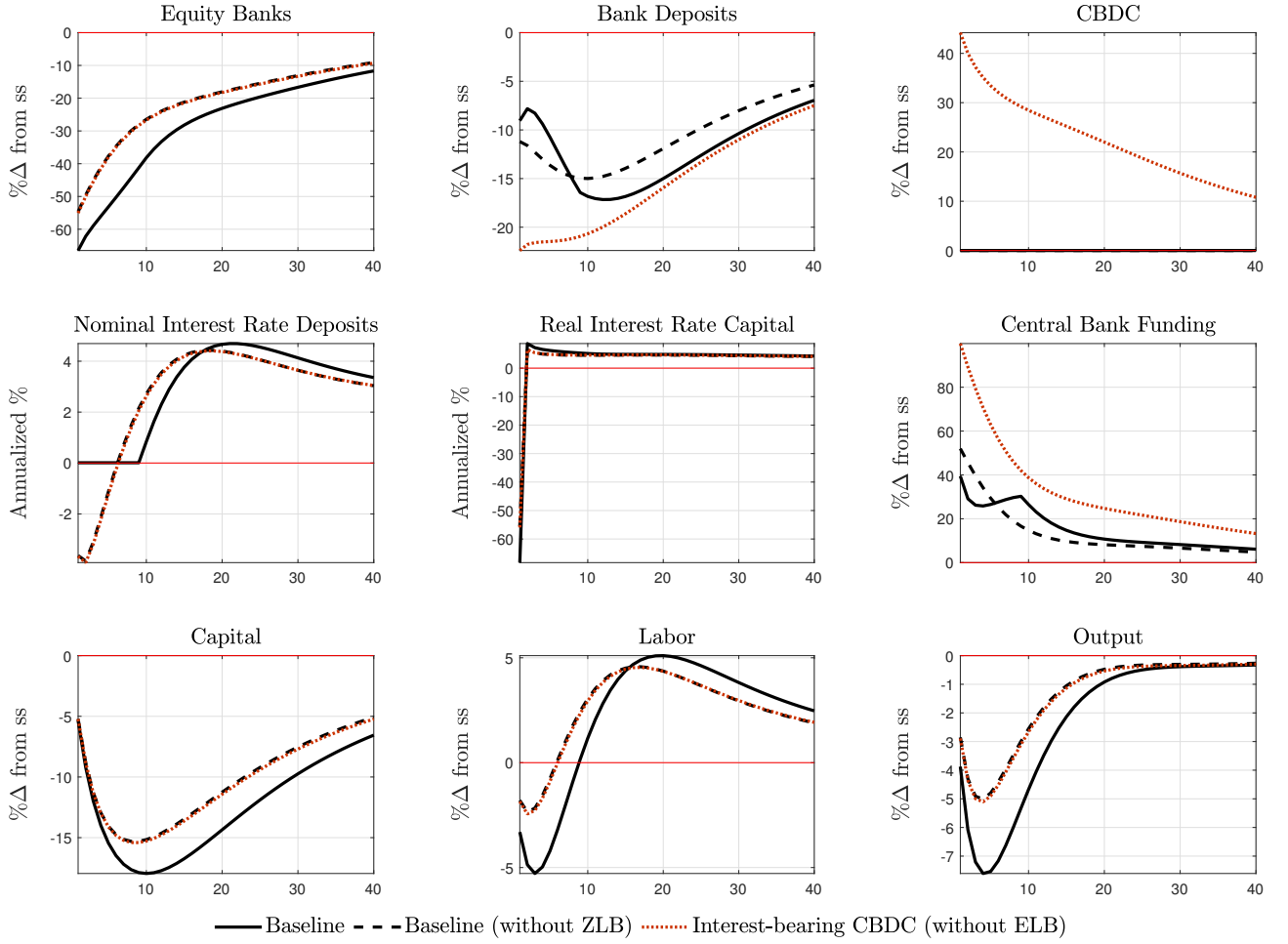


Figure 3: Baseline with ELB vs. interest-bearing CBDC

households. Lower deposit interest rates incentivize households to initially increase labor by roughly 1.5% and lead to a 1% higher output compared to the ELB-constrained baseline model. Additionally, 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 the crisis's adverse effects. The increased drop in the nominal interest rate on bank deposits leads to a further decline in deposits by 2.2%. This decline is increased to 11.2% when households have the opportunity to shift savings to 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 liquidity's marginal utility

decreases. This *liquidity effect* renders deposits less attractive and leads to a further drop.¹⁶ In the steady state, households hold roughly 27.2% of their liquidity in CBDC.¹⁷ Initially, after the shock, this share increases to 41%. At the same time, 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 17.7% to 35.7%. In contrast to the non-interest-bearing CBDC model, CBDC just 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 allows the central bank to counteract the crisis more efficiently. Still, 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.

5.3 Alternative Allotment of Central Bank Funds

So far, we assumed that the central bank fully compensates for losses in deposits by providing more 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 started to fully allocate demanded funds to banks to stabilize the interbank market. In the preceding years, from 2003 to 2008, the allotment was, on average, 60.33%. Note that banks could have received more reserves, albeit at higher costs. 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 derive the result that CBDC does not affect the economy outside the financial sector.

¹⁶Note that this drop is additionally amplified by slight changes in the steady state and by a comparably high elasticity of demand for deposits on changes in banks' equity.

¹⁷This value results from two assumptions. First, in the steady state, the remuneration for CBDC is 1%. Second, for consistency, we apply the same parametrization (especially Υ) as in the non-interest-bearing CBDC model.

To analyze restricted allotment, we adapt Equation (46) as follows:

$$R_t^{CB} = \bar{R}^{CB} + X * [(F_t^* - \bar{F}^*) - (D_t - \bar{D})] \quad (49)$$

where X is the share of lost deposits outside the steady state that the central bank substitutes. Thus, the steady state share of central bank funding in total external refinancing remains unaltered to allow for comparable results. Losses of deposits after a shock are only partly compensated.

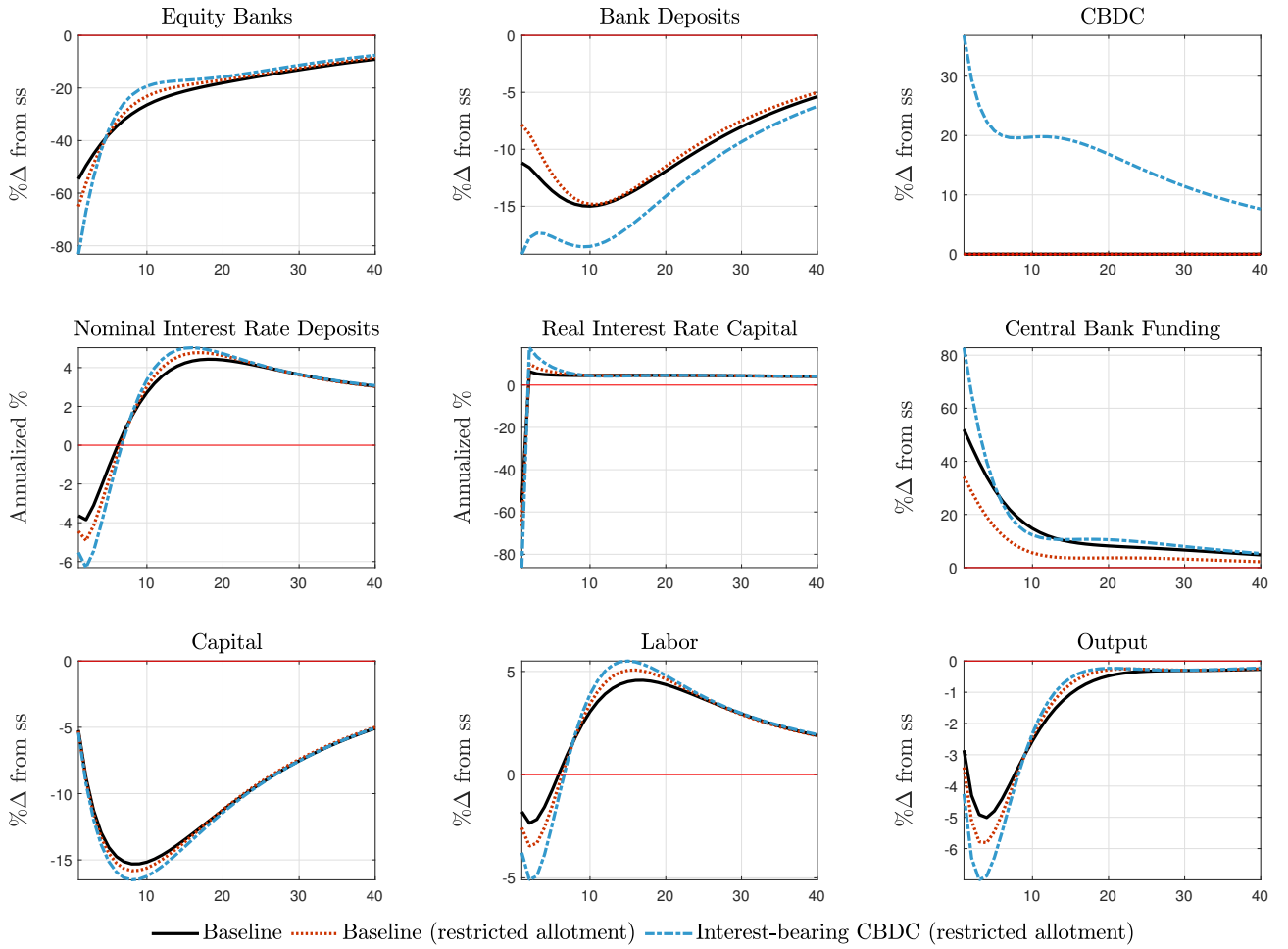


Figure 4: Interest-bearing CBDC with different allotment of central bank funds

Figure 4 compares the baseline model for full allotment and an restricted allotment with $X = 0.5$ with the interest-bearing CBDC model with $X = 0.5$. As the central bank does not fully

compensate for lost deposits in both models, total intermediated funds decrease. This decrease negatively affects the next periods' levels of capital, resulting in lower output. Additionally, lower levels of capital increase the marginal productivity of capital and decrease the marginal productivity of labor. Hence, the real interest rate on capital increases in periods after the initial shock, while wages drop. Households react with a reduction in labor that 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 interest rate on capital and, thus, banks' equity drop by an additional 10% (25%). 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 equally increases the central bank's willingness to provide funds, lower allotment outweighs. Driven by the high premia, banks quickly restore large parts of their equity and trigger an accelerated recovery process for the whole economy.

With CBDC, households have an incentive to exchange some of their deposits for CBDC. Deposits and, thus, 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. Still, this increase in central bank funding cannot fully compensate for the increased loss in deposits, leading the economy into a deeper recession.

In summary, relaxing the assumption of full allotment leads to remarkably different results. The resulting imperfect substitution of deposits with reserves 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 has indeed the potential to destabilize the economy.

5.4 CBDC Interest Rate Rule

While the analysis above suggests that full allotment is necessary to prevent destabilizing effects, the central bank has another possibility. Bindseil (2020) proposes that central banks actively set the interest rate on CBDC to disincentivize its accumulation in a crisis and, thus,

to counteract structural disintermediation. Using this new policy instrument, the central bank can govern the demand for CBDC with a direct pass-through. As the CBDC interest rate in our model is initially close to zero, this approach implies highly negative interest rates.

We adapt Equation (41) as follows:

$$i_t^{CBDC} = i_t^{CB} - \left(\Delta_t^{CBDC} + \frac{\bar{N} - N_t}{\bar{N}} \kappa_N \right) \quad (50)$$

The term in brackets defines the spread between the interest rates on central bank funding and CBDC. We keep its steady state unchanged and allow the central bank to increase the spread based on financial stress after the shock. We use the measure from Section 3.1, such that financial stress is expressed as the percentage deviation of banks' equity from steady state. κ_N specifies the reaction's intensity.¹⁸

The blue and the green lines in Figure 5 face restricted allotment with $X = 0.5$. As expected, decreasing the nominal interest rate on CBDC lowers CBDC holdings, in our case even to zero. Note that we restrict these holdings to be non-negative. The effect on deposits is relatively small as households do not substitute CBDC primarily with deposits but with bonds. The liquidity effect causes the increase in deposits: As households decrease 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.¹⁹ 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. Put differently, while targeting CBDC can positively impact an economy with restricted allotment in a crisis, full allotment is the more effective policy. Still, lowering interest rates effectively limits the accumulation of CBDC and is a valid tool to prevent disintermediation and destabilization specifically caused by a CBDC.

With full allotment, the CBDC interest rate proves to be an effective instrument to impact

¹⁸ κ_N is calibrated such that households in this exercise initially reduce their CBDC holdings to zero.

¹⁹ Note that CBDC is increasingly attractive when deposits fall, such that households nearly fully substitute lost liquidity. Vice versa, this is not the case. The attractiveness of deposits only partly 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.

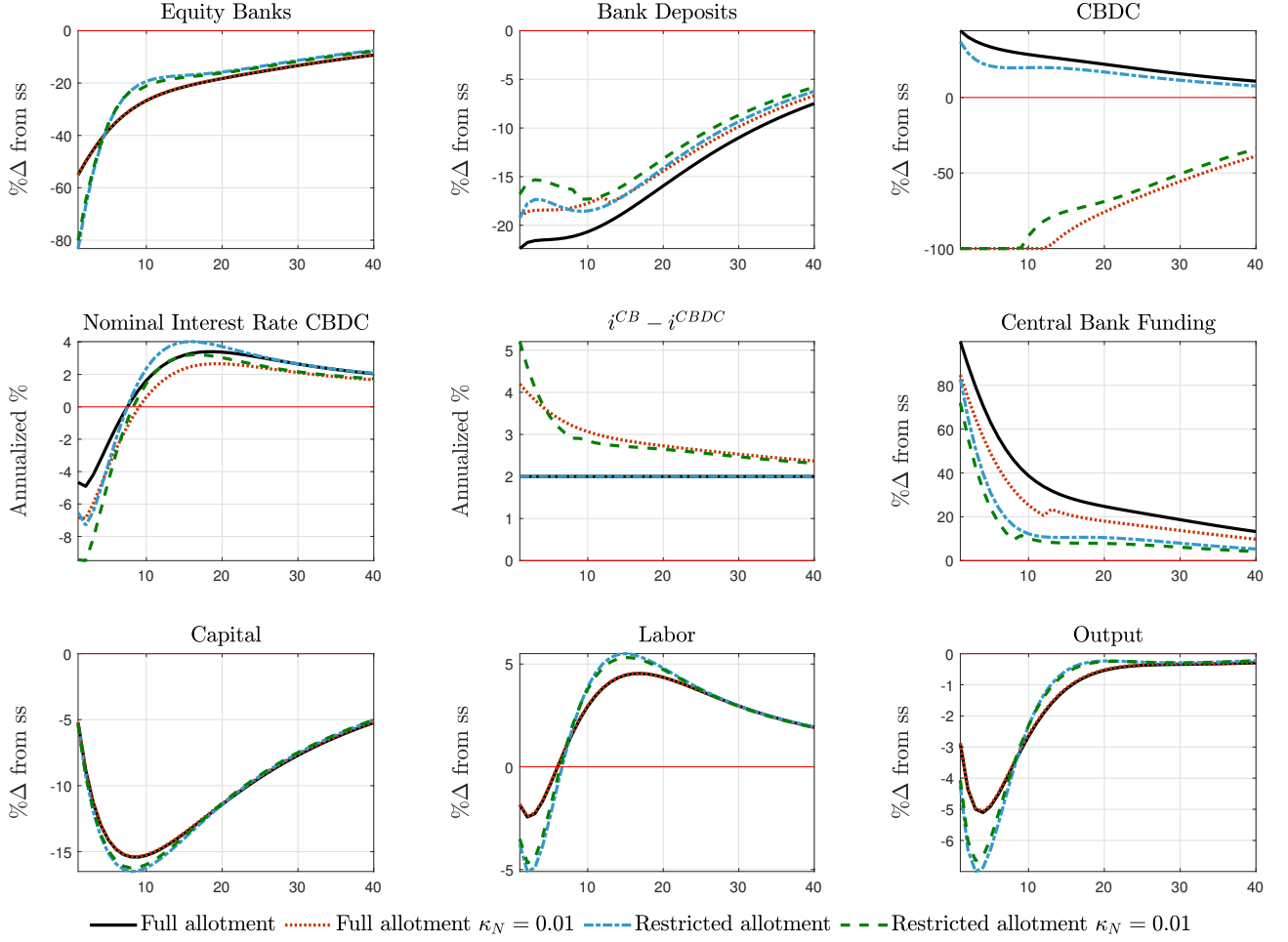


Figure 5: Variable interest rate spread on CBDC

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, the central bank's balance sheet contracts twofold, while economic activity is unaffected.

6 Conclusion

While CBDCs offer several benefits, their implications for the financial sector and commercial banks' funding are still subject to debate. We contribute to this debate by developing 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, house-

holds that actively choose the amount of deposits as part of their utility maximization, and a CBDC as a liquidity providing substitute for deposits. Additionally, our model includes specific interest rates on bonds, deposits, central bank reserves, and CBDC.

The model's design 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 commercial banks' balance sheets 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 meet this demand fully, a drop 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 increasing its own balance sheet and using it as a monetary policy tool (see 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 pressured to reduce collateral requirements, i.e., 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 the amount of CBDC but does not necessarily incentivize households to hold substantially more deposits. Therefore, on its own, it is no appropriate tool to counteract the adverse effects resulting from losses in bank funding in a crisis. Still, 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 outside 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. Besides a strong commitment to full allotment, at least two alternative poli-

cies mitigate CBDC-induced disintermediation. First, the central bank can limit the supply of CBDC, e.g., by imposing a cap on individual CBDC holdings as proposed by Panetta (2018). The introduction of such a cap would imply that users have to be identified. Thus, regarding data privacy, a CBDC would not be a close substitute for cash, a means of payment that is valued for its anonymity. A cap could also 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 (see Demirgüç-Kunt and Detragiache (2002)). Further research is needed to analyze CBDC in a model with deposit insurance schemes.

Besides the limitations of our analysis mentioned above, two additional aspects are worth pointing out: First, we model government bonds in a rather simplistic way. We neglect that the supply of bonds could be limited and that prices and yields are determined by supply and demand on 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. As, today, households still hold substantial amounts of their savings in cash, a model including cash could provide further relevant insights.

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A Households' Maximization Problem

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

$$\max E_t \sum_{i=0}^{\infty} \beta^i \left\{ \ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma} (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\} \quad (51)$$

Households' budget constraint can be written as:

$$C_t + D_t + CBDC_t + B_t = w_t L_t + \Pi_t + (1 + r_{t-1}^D) \psi_{t-1} D_{t-1} + (1 + r_{t-1}^{CBDC}) CBDC_{t-1} + (1 + r_{t-1}^B) B_{t-1} \quad (52)$$

with

$$\psi_t = 1 - \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}} \Omega_N \quad (53)$$

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

$$\begin{aligned} \mathcal{L} = & E_t \sum_{i=0}^{\infty} \beta^i \left\{ \ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma} (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right. \\ & - \lambda_{t+i} [C_{t+i} + D_{t+i} + CBDC_{t+i} + B_{t+i} - w_{t+i} L_{t+i} - \Pi_{t+i} \\ & - (1 + r_{t+i-1}^D) (1 - \left(\frac{D_{t+i-1}}{F_{t+i+1}^*} \right)^{\Omega_D} - \frac{\bar{N} - N_{t+i-1}}{\bar{N}} \Omega_N) D_{t+i-1} \\ & \left. - (1 + r_{t+i-1}^{CBDC}) CBDC_{t+i-1} - (1 + r_{t+i-1}^B) B_{t+i-1} \right\} \end{aligned} \quad (54)$$

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

$$\frac{\partial \mathcal{L}}{\partial C_t} = (C_t - hC_{t-1})^{-1} - \beta h(C_{t+1} - hC_t)^{-1} - \lambda_t \quad (55)$$

$$\frac{\partial \mathcal{L}}{\partial L_t} = -\chi L_t^\phi + \lambda_t w_t \quad (56)$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial D_t} = & \Upsilon(D_t + CBDC_t)^\Gamma - \lambda_t \\ & + \beta \lambda_{t+1}(1 + r_t^D) \left\{ \psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right\} \end{aligned} \quad (57)$$

$$\frac{\partial \mathcal{L}}{\partial CBDC_t} = \Upsilon(D_t + CBDC_t)^\Gamma - \lambda_t + \beta \lambda_{t+1}(1 + r_t^{CBDC}) \quad (58)$$

$$\frac{\partial \mathcal{L}}{\partial B_t} = -\lambda_t + \beta \lambda_{t+1}(1 + r_t^B) \quad (59)$$

As households maximize their utility, all of the above equations have to equal 0. Combining (56) and (55) yields:

$$\varrho_t w_t = \chi L_t^\phi \quad (60)$$

where ϱ is the marginal utility of consumption and is equal to λ_t in (55):

$$\varrho_t = \frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t} \quad (61)$$

Inserting (55) in (59) yields:

$$1 = \beta \Lambda_{t,t+1}(1 + r_t^B) \quad (62)$$

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

$$\Lambda_{t,t+1} = \frac{\varrho_{t+1}}{\varrho_t} \quad (63)$$

Similar to eq. (62), we can derive for (57):

$$1 = \beta \Lambda_{t,t+1}(1 + r_t^D) \left(\psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right) + \frac{\Upsilon}{\varrho_t} (D_t + CBDC_t)^\Gamma \quad (64)$$

and for (58):

$$1 = \beta \Lambda_{t,t+1}(1 + r_t^{CBDC}) + \frac{\Upsilon}{\varrho_t} (D_t + CBDC_t)^\Gamma \quad (65)$$

To analyze the impact of the interest rate spread between r^B and r^{CBDC} , equate (58) and (59):

$$\beta \varrho_{t+1}(r_t^B - r_t^{CBDC}) = \Upsilon(D_t + CBDC_t)^\Gamma \quad (66)$$

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. As 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 as 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 (58) and deposits (57) yields:

$$\left[\frac{(1 - \frac{1+r_t^{CBDC}}{1+r_t^D} - \frac{\bar{N}-N_t}{\bar{N}}\Omega_N)}{1 + \Omega_D} \right]^{\frac{1}{\Omega_D}} = \frac{D_t}{F_t^*} \quad (67)$$

Note that the effect of liquidity cancels 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 deposits' interest rate elasticity.

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, 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, equate (59) and (57):

$$\beta \varrho_{t+1}(1 + r_t^B) = \beta \varrho_{t+1}(1 + r_t^D) \left(\psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right) + \Upsilon(D_t + CBDC_t)^F \quad (68)$$

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 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 model is based on Gertler and Karadi (2011). We adapt their model (GK) to make the introduction of a CBDC possible. The aim is to create a framework that (1) allows for changes in the level of deposits based on financial conditions and households' preferences and that (2) does not imply substantial changes outside the financial sector. We intend to (3) keep the financial accelerator mechanism intact, i.e., preserve the main implications of Gertler and Karadi (2011). This section outlines the implications of our implemented changes in households' maximization problem on the model output.

We make the following four assumptions to implement these features. First, households actively choose between different forms of saving, accounting for different remuneration, liquidity, and risk. Second, banks do not just intermediate funds from households to the production sector. Instead, they can additionally refinance themselves at the central bank. Third, the central bank fully allocates demanded funds to banks (full allotment) as long as their participation constraint holds.²⁰ Forth, 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. Therefore, changes in deposits have a minimal impact on total intermediated funds, capital, and production.

²⁰We relax this assumption in Section 5.3.

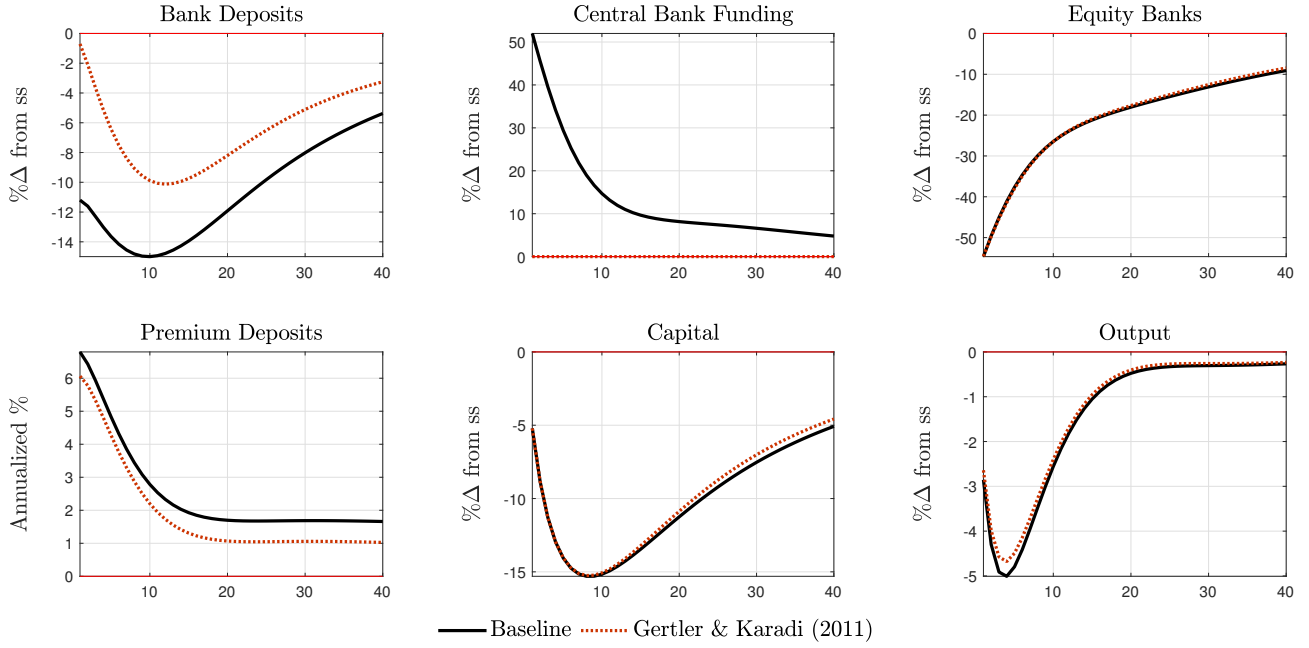


Figure 6: Baseline vs. Gertler & Karadi (2011)

Figure 6 compares our model to 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 drop in the quality of capital reduces effective capital and production. This drop in production causes losses of intermediate goods producers and loan defaults. Hence, the losses are captured in a major decline in banks' equity, in our case, roughly 55%. As a result, banks' participation constraint tightens, and households reduce their deposits. This drop 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.²¹ Nonetheless, driven by the loss of equity, total external refinancing and total intermediated funds decline over the following periods in both models leading 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

²¹Note that, in absolute terms, these effects are equal as initially central bank funding only accounts for a small fraction of total external refinancing.

premia on deposits. As a result, banks quickly rebuild parts of their lost equity.²² However, with a declining premium, this process slows down after ten 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).

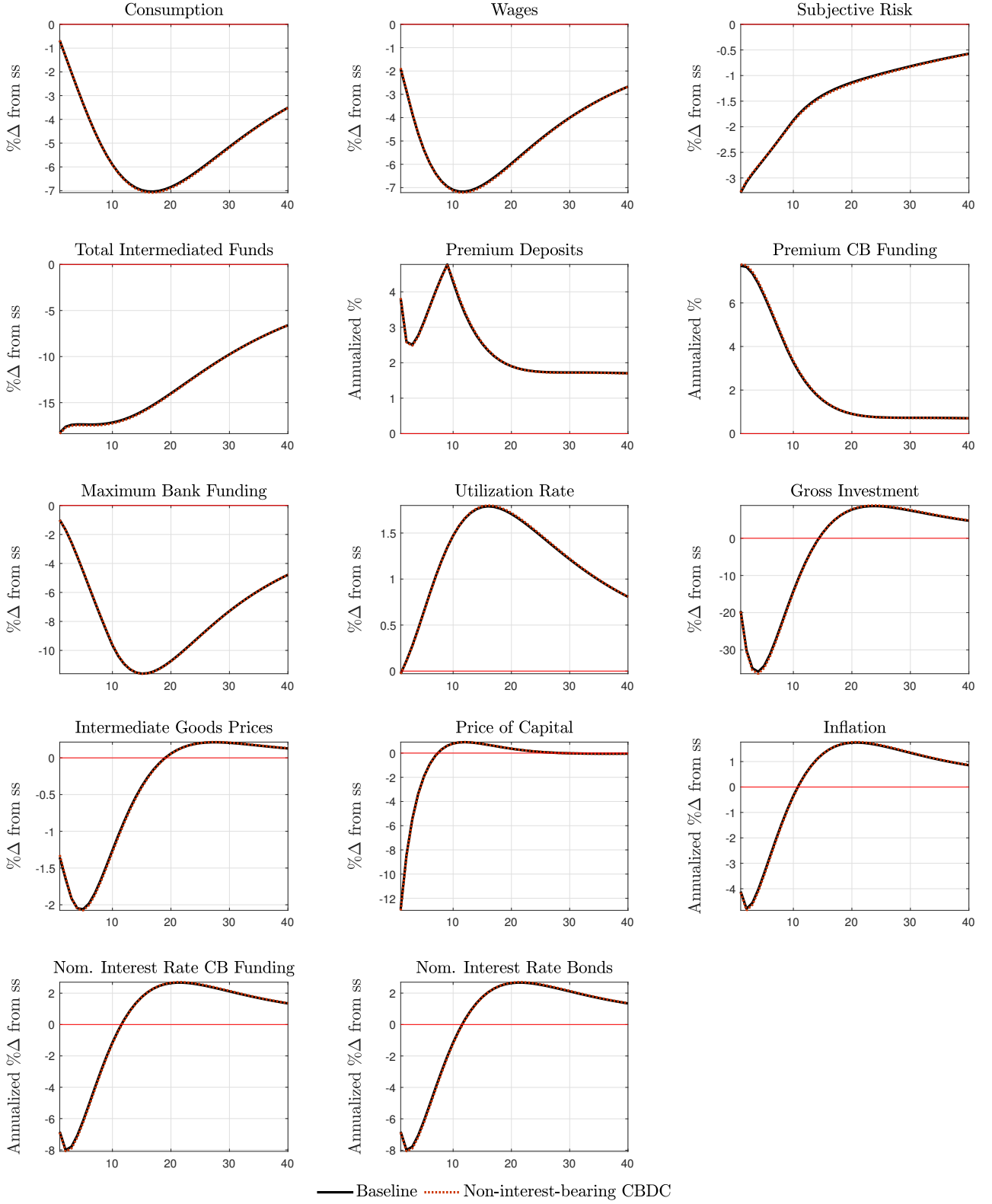
To sum up, our model, in contrast to Gertler and Karadi (2011), allows for an active deposit decision of households, includes central bank refinancing, and features three different interest rates. Still, the model produces results similar to Gertler and Karadi (2011) and keeps their financial accelerator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

C Additional IRFs

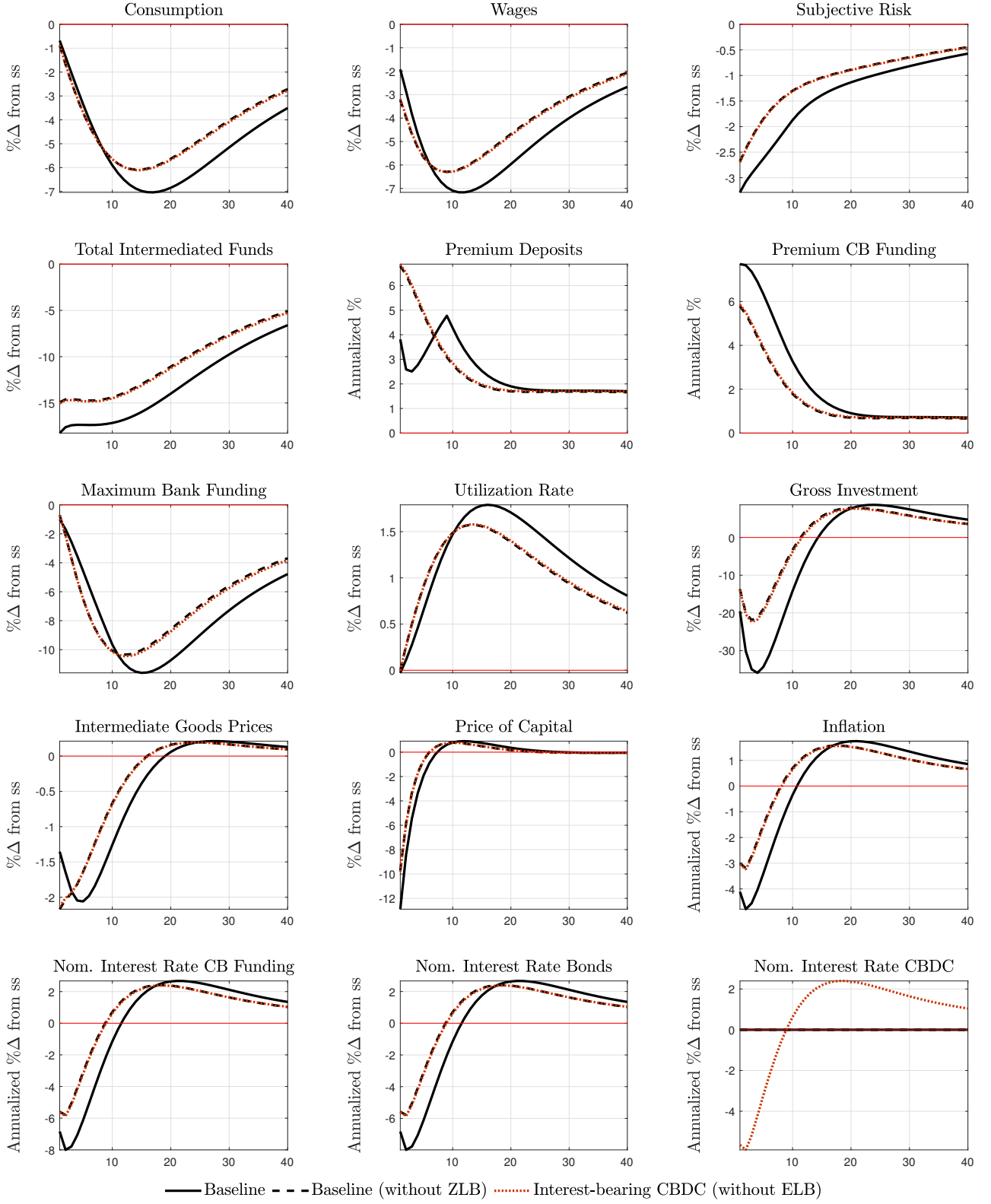
In the following, we present the remaining IRFs for the exercises conducted above. Note that we do not provide them for Appendix B. Additionally, we exclude some variables that do not provide additional information or can be directly derived from the presented figures. The authors can provide additional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

²²In our model, the premium is higher, yet equity increases equally. The higher premium is caused by differing steady state interest rates on deposits as we – unlike GK – assume different interest rates on bonds and deposits to match data. As banks additionally refinance themselves with more expensive central bank funding, the total premium on intermediation is roughly equal in both models.

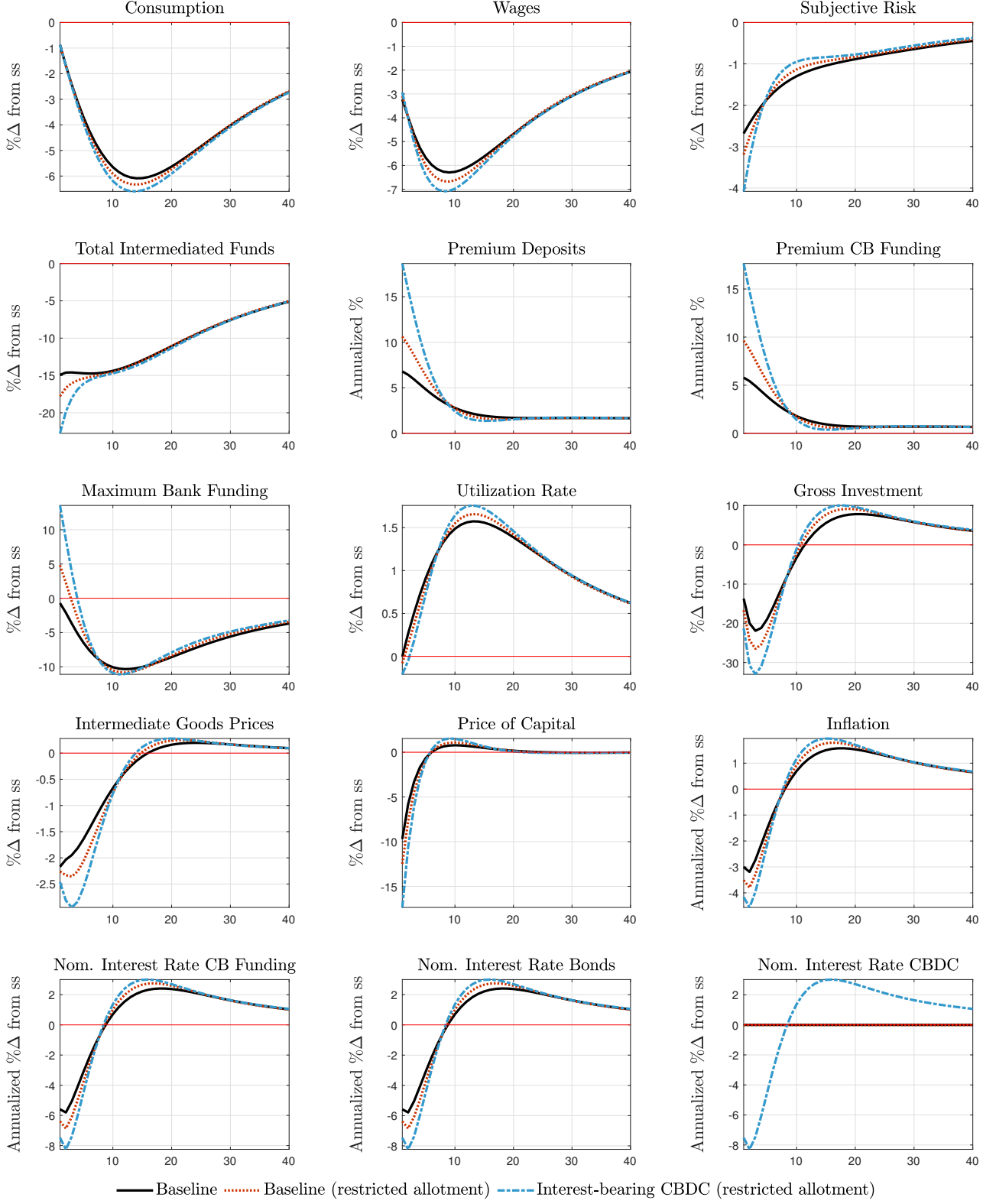
C.1 Baseline with ZLB vs. non-interest-bearing CBDC with ZLB



C.2 Baseline with ZLB 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

