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Abstract

Since the great financial crisis, monetary policy has experienced fundamental changes and challenges. The collapse of Lehman Brothers in 2008 constituted a shock to the financial system that forced central banks to conduct policies unprecedented in scope and substance. The European Central Bank (ECB) lowered key interest rates consecutively to zero and even into negative territory for its deposit facility, provided substantial reserves to banks via targeted long-term refinancing operations, and massively increased its balance sheet via large asset purchases. Besides these economic developments, technological innovation and the appearance of cryptocurrencies led central banks worldwide to study and prepare the issuance of central bank digital currencies (CBDCs).

In this dissertation, I specifically address and study three of the novel features in the euro area within model-theoretical frameworks: the rise of so-called TARGET2 imbalances due to sudden stops in capital flows during the sovereign debt crisis, CBDCs and their effect on the financial system, and the vast accumulation of excess reserves as a result of the ECB's asset purchases.

Chapter 1 studies the effects of a reversal in capital flows during the onset of the financial crisis. The analysis focuses on euro area periphery countries' access to the

TARGET2 mechanism that allows for the substitution of private capital outflows with public inflows through commercial bank refinancing at the ECB. It applies an estimated two-region DSGE model to examine the influence of TARGET2 on credit and capital channels of core and peripheral euro area countries and to capture potential interregional feedback effects. The analysis examines how the liquidity provision to peripheral banks by the Eurosystem affects cross-border capital flows, giving rise to divergent developments across the two regions: In the periphery, TARGET2 liabilities mitigate the effects of a sudden stop and private deleveraging for consumers. Beneficial terms of trade shift household consumption to the periphery region while their output and labor decline. Core countries increase their exports and thus labor input and production while import demand decreases due to higher savings. Additionally, the distributional effects of the TARGET2 payment system lead to persistent external imbalances and real exchange rate misalignments between the regions.

Chapter 2 focuses on CBDCs and studies their effects on the financial sector and monetary policy. While CBDCs might offer several benefits for users, they could potentially disintermediate commercial banks and facilitate bank runs since CBDCs, in contrast to commercial bank money, constitute digital forms of central bank money with marginal risk. Unlike cash, CBDCs presumably do not impose increasing storage costs and could therefore be used as a large-scale store of value when interest rates are low and financial distress increases the perceived risk for bank deposits. Thus, in times of financial crises, private agents could decide to convert substantial amounts of commercial bank money into CBDC, thereby posing a risk to banks' liquidity. The chapter presents a New Keynesian dynamic stochastic general equilibrium model to analyze these concerns in the absence of any CBDC-specific empirical data and simulates the effects of a financial crisis in a world with and without CBDC. In particular, it compares the effects of interest-bearing and non-interest-bearing CBDCs. The analysis shows that CBDCs indeed crowd out bank deposits and negatively affect bank funding. However, the central bank can mitigate this crowding-out effect if it chooses to either provide additional reserves or to disincentivize large-scale CBDC accumulation via low or potentially even negative interest rates on CBDC. Thus, the results suggest that a CBDC does not necessarily impair the financial sector if the central bank chooses adequate design and policy measures.

Chapter 3 focuses on the ECB's large-scale asset purchases, which led to the substantial accumulation of excess reserves in the banking sector. This chapter presents a dynamic stochastic general equilibrium (DSGE) model based on Gertler and Karadi (2011) that captures the connection between a central bank's asset purchases and involuntary excess reserves in the banking system. With a substantially reworked financial sector that resembles the two-tier banking system in the euro area, the model explicitly accounts for the accumulation of involuntary excess reserves as a result of quantitative easing (QE). With additional reserves in the banking sector, banks could increase their loan supply, thus affecting the quantity of money in circulation and creating upwards pressure on prices. However, banks are restricted in their loan issuance by capital requirements regulation and low loan demand when the economy is sluggish.
Assuming that the central bank uses a Taylor-rule type interest rate for its deposit facility, excess reserves do not impair monetary policy pass-through and do not pose a threat to price stability even when economic conditions improve and loan demand rises. The level of reserves does not affect optimal bank behavior. Instead, banks' loan supply is primarily determined by the interest rate margin, which the central bank can effectively steer with its deposit facility rate. Additionally, the presence of excess reserves does not necessarily impinge on bank profitability unless in times of negative interest rates with a binding lower bound on deposit interest rates.

Zusammenfassung

Die globale Finanzkrise hat die Geldpolitik vor grundlegende Veränderungen und Herausforderungen gestellt. Der Zusammenbruch von Lehman Brothers im Jahr 2008 hat das weltweite Finanzsystem derart erschüttert, dass Zentralbanken gezwungen waren, Maßnahmen zu ergreifen, die in Umfang und Art bisher beispiellos waren. Die EZB senkte die Leitzinsen sukzessive auf null und für ihre Einlagenfazilität sogar in den negativen Bereich, stellte den Banken über gezielte langfristige Refinanzierungsgeschäfte zusätzliche Reserven zur Verfügung und weitete ihre eigene Bilanz durch umfangreiche Anleiheankäufe massiv aus. Neben diesen wirtschaftlichen Entwicklungen haben zeitgleich technologische Innovationen und das Aufkommen von Kryptowährungen Notenbanken auf der ganzen Welt dazu veranlasst, die Ausgabe von digitalem Zentralbankgeld zu analysieren und vorzubereiten.

In dieser Dissertation untersuche ich in einem modelltheoretischen Rahmen speziell drei neuartige geldpolitische Entwicklungen im Euroraum: den Anstieg der sogenannten TARGET2-Salden aufgrund der Umkehrung von Kapitalströmen während der Staatsschuldenkrise, digitale Zentralbankwährungen und deren Auswirkungen auf das Finanzsystem sowie die enorme Anhäufung von Überschussreserven als Folge der Anleihekaufprogramme der EZB.

Kapitel 1 untersucht die Auswirkungen der Umkehrung von Kapitalströmen zu Beginn der Finanz- und Staatsschuldenkrise. Mithilfe eines geschätzten Zwei-Regionen-DSGE-Modells wird der Einfluss von TARGET2 auf die Kredit- und Kapitalkanäle der Kern- und Peripherieländer des Euroraums untersucht, um mögliche interregionale Rückkopplungseffekte zu erfassen. Die Analyse konzentriert sich dabei auf den TARGET2-Mechanismus, der eine Substitution privater Kapitalabflüsse aus Peripherieländern durch öffentliche Zuflüsse über die Refinanzierung von Geschäftsbanken bei der EZB ermöglicht. Die Liquiditätsversorgung der Banken in der Peripherie durch das Eurosystem hat grenzüberschreitende Kapitalströme erleichtert, was zu unterschiedlichen Entwicklungen in den beiden Regionen geführt hat. In der Peripherie mildern die in den TARGET2-Salden erfassten Refinanzierungsgeschäfte die Auswirkungen eines unerwarteten Kapitalabflusses und des damit einhergehenden privaten und öffentlichen Entschuldungsdruckes ab. Günstige Handelsbedingungen verlagern den Konsum der privaten Haushalte in die Peripherieregion, während dort die Produktion und das Arbeitsangebot zurückgehen. Die Kernländer hingegen steigern ihre Exporte durch höheres Arbeitsangebot und Produktion, während die Importnachfrage aufgrund höherer Ersparnisse sinkt. Darüber hinaus führen die Verteilungseffekte des TARGET2-Zahlungssystems zu anhaltenden außenwirtschaftlichen Ungleichgewichten und realen Wechselkursverschiebungen zwischen den Regionen.

Kapitel 2 behandelt digitales Zentralbankgeld und untersucht mögliche Implikationen für den Finanzsektor und die Geldpolitik. Während digitales Zentralbankgeld diverse Vorteile für Nutzer bieten könnte, könnte es potenziell zu Disintermediation von Geschäftsbanken führen und Bank-Runs erleichtern, da digitales Zentralbankgeld im Gegensatz zu Geschäftsbankengeld von der Zentralbank ausgegeben und damit annähernd risikolos ist. Anders als Bargeld ist digitales Zentralbankgeld für digitale Zahlungen nutzbar und kann potentiell ohne Risiko und Aufbewahrungskosten in großem Umfang als Wertaufbewahrungsmittel genutzt werden. Digitales Zentralbankgeld könnte daher insbesondere in einem Niedrigzinsumfeld und bei sinkendem Vertrauen in die Liquidität von Banken als sicheres und liquides Anlageinstrument genutzt werden. In Zeiten von Finanzkrisen könnten private Akteure daher beschließen, erhebliche Mengen ihrer Bankeinlagen in digitales Zentralbankgeld umzuwandeln, was ein zusätzliches Risiko für die Liquidität der Banken darstellen würde. Um diese Bedenken in Ermangelung von empirischen Daten zu analysieren, werden in diesem Kapitel mit Hilfe eines DSGE-Modells Auswirkungen einer Finanzkrise in einem Szenario mit und ohne digitales Zentralbankgeld simuliert. Dabei werden insbesondere Auswirkungen von zinstragendem und nicht zinstragendem digitalen Zentralbankgeld unterschieden. Die Analyse zeigt, dass digitales Zentralbankgeld tatsächlich Bankeinlagen verdrängen und sich negativ auf die Finanzierung von Bankgeschäften auswirken kann. Dieser Verdrängungseffekt kann jedoch abgeschwächt werden, wenn die Zentralbank entweder zusätzliche Reserven bereitstellt oder die Akkumulation von digitalem Zentralbankgeld in großem Umfang durch niedrige oder möglicherweise sogar negative Zinssätze für digitales Zentralbankgeld unterbindet. Die Ergebnisse deuten darauf hin, dass digitales Zentralbankgeld den Finanzsektor nicht zwangsläufig beeinträchtigt, wenn die Zentralbank dieses entsprechend gestaltet und adäquate geldpolitische Maßnahmen ergreift.

Kapitel 3 konzentriert sich auf die umfangreichen Anleihekäufe der EZB, die zu einer erheblichen Anhäufung von Überschussreserven im Bankensektor geführt haben. In diesem Kapitel wird ein DSGE-Modell entwickelt, das den Zusammenhang zwischen Anleihekäufen und unfreiwilligen Überschussreserven im Bankensystem abbildet. Mit einem wesentlich überarbeiteten Finanzsektor, der dem zweistufigen Bankensystem im Euroraum ähnelt, berücksichtigt das Modell explizit die Anhäufung von unfreiwilligen Überschussreserven. Durch die Anleihekäufe stellt die Zentralbank zusätzliche Reserven zur Verfügung, die Banken für eine Ausweitung der Kreditvergabe nutzen könnten. So könnte die umlaufende Geldmenge erhöht und ein Aufwärtsdruck auf Preise erzeugt werden. Banken sind jedoch in ihrer Kreditvergabe durch Eigenkapitalanforderungen und die Kreditnachfrage beschränkt.

Unter der Annahme, dass die Zentralbank für ihre Einlagenfazilität einen Taylor-Regel-basierten Zinssatz verwendet, beeinträchtigen Überschussreserven weder die Effektivität der Geldpolitik noch stellen sie eine Gefahr für die Preisstabilität dar, wenn sich die wirtschaftliche Lage verbessert und die Kreditnachfrage steigt. Die Höhe der Überschussreserven hat zudem keinen Einfluss auf das optimale Verhalten der Banken. Stattdessen wird die Kreditvergabe der Banken primär durch die Zinsmarge bestimmt, die die Zentralbank mit ihrem Einlagenzins effektiv steuern kann. Darüber hinaus wirken sich Überschussreserven nicht zwingend negativ auf die Rentabilität von Banken aus. Falls die Einlagefazilität jedoch negativ verzinst ist und der Zinssatz auf Depositen von Haushalten an der Zinsuntergrenze liegt, können Überschussreserven eine zusätzliche Belastung für das Bankengeschäft darstellen.

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List of Acronyms

APP	Asset purchase program
CBDC	Central bank digital currency
CES	Constant elasticity of substitution
CRR	Capital requirements regulation
CSPP	Corporate sector purchase program
DSGE	Dynamic stochastic general equilibrium
ECB	European Central Bank
EONIA	Euro OverNight Index Average
ELB	Effective lower bound
GDP	Gross domestic product
IRF	Impulse response function
IRFs	Impulse response functions
LTRO	Long term refinancing operation
MLF	Marginal lending facility
MRO	Main refinancing operations
PEPP	Pandemic emergency purchase program
PSPP	Public sector purchase program
QE	Quantitative easing

Chapter 1

Capital Flows, Deleveraging, & Central Bank Liquidity Provision

Abstract

Core countries like Belgium, France, Germany, Luxembourg and the Netherlands act as safe asset providers to the global economy, and specifically to the euro area periphery. Investors would invest in those markets seeking investment with low risk of default and litigation. While in the run-up of the financial crisis investors from the core would invest in risky assets in peripherial euro area countries, the demand for safe assets in core countries rises in the event of crisis and lead to a reversal of private capital flows from periphery to core, intensified by private deleveraging of peripheral households in the course of the sovereign debt crisis. We analyze the effects of an increase in non-performing loans and a simultaneous deleveraging of private households in the euro area periphery in the context of core euro area countries as safe asset providers in an estimated model for the euro area 2001-2017. The negative effects of capital flows to safe core havens are intensified when the economy hits the Zero Lower Bound, causing a prolonged dampening of output, consumption and investment in the periphery and lower present and future real interest rates in the euro area as a total.

Keywords: safe assets, deleveraging, Euro periphery, capital flows.

JEL classification: D53, E58, F32, F41, F45, G12.

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1.1 Introduction

Before the financial crisis, investors from 'core' euro area countries like France and Germany invested in 'peripheral' countries like Greece, Italy, Ireland, Portugal, and Spain (GIIPS).[1] Thereby, core countries built up significant net foreign asset (NFA) positions against the periphery (Hale and Obstfeld, 2016). When peripheral countries experienced a sudden increase in risk after the financial crisis and during the European sovereign debt crisis, core countries became attractive for investors in their search for safe assets (Gourinchas and Rey, 2016). Private capital inflows into peripheral countries not only stopped but reversed (Schmidt and Zwick, 2015). Merler and Pisani-Ferry (2012) determine three periods of sudden stops between January 2007 and December 2011 in the euro area, i.e. the GIIPS.

Figures 1.1a - 1.1b show net capital flows from the financial account in GIIPS and core euro area countries, respectively. GIIPS experienced a net capital inflow before the crisis in 2008, mostly portfolio investments. In the years 2011-2012, the capital inflows from portfolio investments reversed and even became net outflows, a sudden stop.

Typically, sudden stops of private capital exert deleveraging pressure. The drop in portfolio investments requires compensating asset sales by banks as well as cuts in private spending and higher savings by households[2]. The process of global deleveraging after the financial crisis is discussed extensively in Mc Kinsey Global Institute (2012).

However, in the euro area additional public components ('other investments') in form of TARGET2 liabilities against the Eurosystem substitute private capital outflows in the periphery. Liquidity provision via the Eurosystem's TARGET2 (= **T**rans-European **A**utomated **R**eal-time **G**ross Settlement **E**xpress **T**ransfer) mechanism is essential for monetary policy within the European Monetary Union (EMU) and played a crucial role in mitigating sudden stops of private capital.

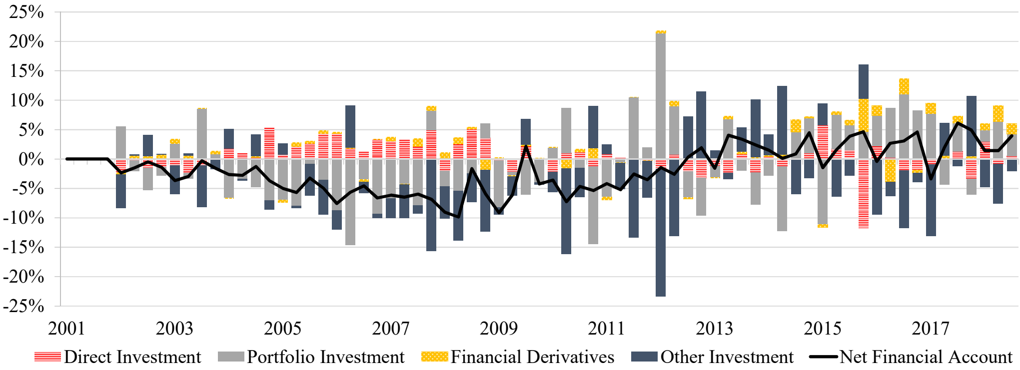
Shambaugh (2012) and Lane (2012) provide in-depth analyses of the euro area,

[1]In this chapter, we use data for Germany and France as core countries and data for GIIPS as peripheral countries; see Basse (2014) for a detailed discussion on the identification of core member countries in the European Monetary Union considering risk premia for sovereign credit risk.

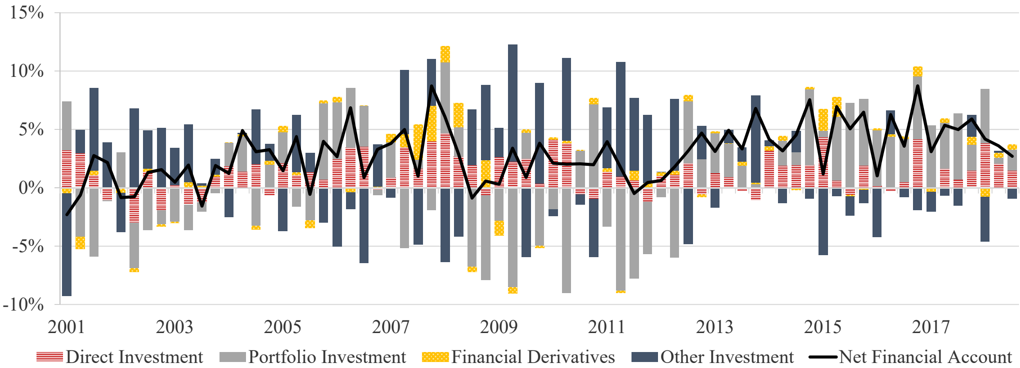
[2]In GIIPS, high government debt-to-GDP ratios play an important role for the deleveraging process; however, this chapter foregoes the government sector and focuses on private deleveraging, leaving aside public deleveraging.

Figure 1.1: Net financial accounts

(a) Net Financial Account Positions - GIIPS (in % of GDP)



(b) Net Financial Account Positions - Core (in % of GDP)



where public capital flows countered sudden stops in peripheral countries during times of financial distress (see also Merler and Pisani-Ferry, 2012; ECB, 2013). The public capital flows relaxed banks' liquidity constraints and mitigated the effects of deleveraging on the real economy (Buttiglione et al., 2016; Cour-Thimann, 2013). Buttiglione et al. (2016) illustrate that the reversal in private capital flows was much larger than the increase in overall NFA, since private outflows were partly substituted by public inflows.

Within the euro area, deficit countries are debited with TARGET2 liabilities and surplus countries credited with corresponding TARGET2 claims against the Eurosystem (Deutsche Bundesbank, 2011). By the workings of TARGET2, the Eurosystem provides direct liquidity via the euro payment system.

The fact that TARGET2 acts as a liquidity provider after a sudden stop and thus relieves pressure on crisis-hit countries to deleverage is widely accepted in literature (e.g Bindseil and König, 2012; Fahrholz and Ftag, 2012; Hristov et al., 2019). However, the implications of TARGET2 imbalances are interpreted differently: While some authors see TARGET2 as a vehicle of direct current account financing (Auer, 2014; Sinn and Wollmershäuser, 2012; Sinn, 2014), the second strand of literature interprets TARGET2 balances only as a mirror image of a balance of payment crisis. They argue that TARGET2 balances reflect a reversal of capital flows and cannot be linked to current account imbalances within the euro area (Buiter et al., 2011; Bindseil and König, 2012).

Given the controversial discussion regarding possible distributional consequences of TARGET2 across the EMU, we investigate cross-country capital flows after a sudden stop. Additional public capital flows between TARGET2 participants affect the deleveraging of distressed countries as well as consumption and savings of creditor countries in the EMU via feedback effects.

Leaving aside intra-euro area cross-border capital flows and the feedback effects on creditor countries, both Fagan and McNelis (2014) and Kraus et al. (2019) find that access to TARGET2 can help crisis-hit countries to mitigate the effects of a sudden stop on output and consumption, however with divergent results for households' welfare. Relating TARGET2 to a direct binding credit constraint shock in a small open economy business cycle model, Fagan and McNelis (2014) suggest modest welfare gains. Kraus et al. (2019) find a long run versus short run trade-off. Supply and demand shocks lead to current account deficits and thus an indirect binding credit constraint that imply welfare losses of TARGET2 flows due to higher risk premia on precautionary savings and indebtedness.

This chapter provides a model-based analysis of the macroeconomic effects of TARGET2 across euro area Member States, thereby attenuating private deleveraging after a sudden stop. Our analytical framework is an estimated version of the two-region model of the euro area by Quint and Rabanal (2014). We account for the policy restrictions implied by the currency union and relate sudden stops to a risk shock in perphery that increases the default rate of borrowers. The shock leads to a sudden outflow of private capital from periphery to core, improving periphery's NFA position and current account. The deleveraging process is simulated by a binding borrowing constraint that restricts credit growth between borrowers and savers, i.e. active deleveraging (Cuerpo et al., 2015). In a second step, we allow for public capital in form of TARGET2 to mitigate the effects of deleveraging via international credit markets (NFA). Through the implementation of TARGET2, public and private capital constitute before only private NFA positions.

Building on simple balance of payment mechanisms, we quantify the effects of replacing private capital by TARGET2 liabilities on the economic adjustment within EMU and contribute to the existing literature in three main dimensions: We investigate how the automatic access to public external finance via the TARGET2 payment mechanism (i) affects cross-border capital flows between regions in the euro area, and (ii) counters private deleveraging in crisis-hit countries, thereby altering macroeconomic adjustment across euro area Member States. In addition, we examine (iii) the behavior of key variables in a Zero Lower Bound (ZLB) environment.

We find that risk shocks to the durable sector that are comparable to an increase in non-performing loans are among the main drivers of sudden stops in peripheral euro area countries. Our simulations indicate that the impact on cross-border capital flows via TARGET2 enables countries in periphery to stabilize and even increase their consumption after a sudden stop and subsequent deleveraging processes, however at the cost of a severe and durable drop in output. Core countries on the other hand profit from an increase in output mainly through exports while consumption stays low (due to higher savings). In sum, the TARGET2 payment system leads to persistent external imbalances (destabilizing effects) due to interregional feedback effects, and real exchange rate misalignments between the regions. Additionally, when both regions are restricted by a ZLB, the nominal interest rate does not fall sufficiently to offset the effects of deleveraging such as the decrease in prices. This leads to prolonged deflationary processes that negatively affect output and consumption, particularly in the core region.

The paper is organized as follows: Section 1.2 describes the analytical framework of the two-region model of a monetary union and introduces deleveraging and the TARGET2 mechanism. We evaluate the estimation results that are used to simulate the union-wide effects of TARGET2 in Section 1.4. Section 1.5 provides several sensitivity analyses, including the stabilization potential of TARGET2 and the effects of a ZLB. Section 1.6 concludes.

1.2 Model

The model is based on Quint and Rabanal (2014) with a durable goods market. We account for a core and a peripheral economy, where the relative size of the core area is denoted as n and the size of periphery as $(1-n)$ with $n \in [0,1]$. Both economies consume two types of goods, durables and non-durables (e.g. housing), which are produced under monopolistic competition and nominal rigidities. While non-durable goods can be traded across the two regions, durable goods are non-tradable. In each area, there are two types of agents, savers S, and borrowers B.

The model (Quint and Rabanal, 2014) takes into account the financial accelerator mechanism of Bernanke et al. (1999) introducing credit frictions. Domestic intermediaries take deposits and provide loans. International intermediaries trade bonds between regions.

We include a risk shock that mimics an increase in non-performing loans. The shock leads to a sudden stop of private capital inflows in the periphery, and consequently to a decrease of private credits to borrowers. Private deleveraging in the form of a constraint to the credit supply limits interbank market efficiency and further decreases credits to borrowers. We address TARGET2 flows that disturb processes of private deleveraging, as the sharp decrease in cross-border capital flows after the sudden stop is substituted by TARGET2 liabilities against the respective region.

1.2.1 Households

The expected utility function of borrowers $j \in [0, \lambda]$ and savers $j \in [\lambda, 1]$ is presented in Equation (1.1). Expected utility today depends on current and future consumption of non-durables C_t^j and durables D_t^j, and the disutility of labor L_t^j.

The model includes external habit persistence by Smets and Wouters (2003) and uses ε^j to measure the influence of aggregated previous consumption. High values of habit persistence reduce the influence of the real interest rate on consumption.

Additionally, non-durable consumption is split up into goods from core $C_{H,t}^t$ and periphery $C_{F,t}^t$. The parameter γ represents the share of non-durable goods in the utility function and $\beta^{j,t}$ denotes the discount factor. φ is defined as the inverse elasticity of labor supply. The parameters ξ_t^C and ξ_t^D are preference shocks of consumers towards non-durable goods and durable goods, respectively.

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^{j,t} \left[\gamma \xi_t^C log(C_t^j - \varepsilon^j C_{t-1}^j) + (1-\gamma) \xi_t^D log(D_t^j) - \frac{(L_t^j)^{1+\varphi}}{1+\varphi} \right] \right\} \tag{1.1}$$

The superscript $i = \{B, S\}$ denotes borrower and saver specific parameters and variables. Borrowers are more impatient than savers, and their habit formation parameter differs ($\varepsilon^B \neq \varepsilon^S$). They are willing to take loans and offer their housing stock D_t^B as a collateral.

Savers maximize their utility function subject to the nominal budget constraint:

$$P_t^C C_t^S + P_t^D I_t^S + S_t^S \leq R_{t-1} S_{t-1}^S + W_t^C L_t^{C,S} + W_t^D L_t^{D,S} + \Pi_t^S \tag{1.2}$$

Savers either consume $P_t^C C_t^S$, invest $P_t^D I_t^S$ or save S_t^S their income. The variables P_t^C and P_t^D are defined as the price indices of non-durable and durable goods. Labor supply is imperfectly substitutable among sectors (Iacoviello and Neri, 2010), and wages are flexible and set sector-specific in the durable W_t^D and non-durable W_t^C sector. Additionally, savers are paid interest R_t and receive profits Π_t^S. Profits are accumulated from intermediate good producers in both sectors in each area, from domestic and international financial intermediaries and from debt collecting agencies. When agents buy durable goods or do residential investment, these purchases are used to increase the stock, but come with a lag:

$$D_t^j = (1-\delta) D_{t-1}^j + F\left(I_{t-1}^j, I_{t-2}^j\right) \tag{1.3}$$

With insights from Christiano et al. (2005), Quint and Rabanal (2014) model investment adjustment costs $F(\cdot)$ given by a convex function that meets the steady state criteria: $\bar{F} = 0$, $\bar{F}' = 0$ and $\bar{F}'' > 0$.

Since borrowers are loan takers, they do not earn any profits from intermediate goods companies, debt collecting firms, or financial intermediaries. Each borrower extends their liquidity by borrowing loans S_t^B from domestic financial intermediaries at the lending rate R_t^L and is subject to a distinctive quality shock ω_t^j, which influences the value of the investment (housing) stock D_t^B owned by borrowers:

$$(1.4)\quad S_t^B + W_t^C L_t^{C,B} + W_t^D L_t^{D,B} \geq P_t^C C_t^B + P_t^D I_t^B + P_t^D \int_0^{\bar{\omega}_{t-1}} \omega dF(\omega, \sigma_{\omega,t-1}) D_t^B \\ + [1 - F(\bar{\omega}_{t-1}, \sigma_{\omega,t-1})] R_{t-1}^L S_{t-1}^B$$

Each quality shock ω_t^j follows a log normal distribution with the cumulative distribution function $F(\omega)$. The standard deviation $\sigma_{\omega,t}$ associated with the quality shock follows an AR(1) process. The quality shock can lead borrowers to default on their loans. At the end of the period borrowers know whether they will default on their loans. This happens if borrowers draw a lower value of ω_{t-1} than the ex-post threshold $\bar{\omega}_{t-1}$, presented in Equation (1.5) (Quint and Rabanal, 2014).

$$(1.5)\qquad \bar{\omega}_{t-1}^{(post)} = \frac{R_{t-1}^L S_{t-1}^B}{P_t^D D_t^B}$$

On the contrary, a high value of ω_{t-1} allows borrowers to fully repay their loans, i.e. $R_{t-1}^L S_{t-1}^B$. Banks expect an ex-ante threshold of borrowers default $E_t(\bar{\omega}_t)$ that is given by the loan and the lending rate borrowers need to pay divided by the expected future investment prices and investment stock:

$$\bar{\omega}_t^{(ante)} = \frac{R_t^L S_t^B}{E_t[P_{t+1}^D D_{t+1}^B]}$$

The ex-ante and ex-post thresholds may be different. At the time of the loan contract, $\bar{\omega}_t^{(ante)} = E_t(\bar{\omega}_t^{(post)})$ holds.
The term $\frac{S_t^B}{P_{t+1}^D D_{t+1}^B}$ represents the loan to value (LTV) ratio. If the ratio is greater than one, loans exceed the underlying value of the collateral. Hence, a higher LTV ratio implies a higher ex ante threshold and, therefore, financial intermediaries expect more borrowers to default on their loans. If an agent defaults on his loan, a debt collecting agency collects the remaining nominal value of the investment stock after the shock occurred. The debt collecting agency that is owned by savers charges domestic financial intermediaries a fraction h of the remaining value. Financial intermediaries are risk neutral, so that the expected return of granting a loan must equal the rate at which the bank funds itself, i.e. the deposit rate (Quint and Rabanal,

2014):

$$R_t = E_t \left\{ \underbrace{(1-h)\int_0^{\bar{\omega}_t} \omega dF(\omega, \sigma_{\omega,t}) \frac{P^D_{t+1} D^B_{t+1}}{S^B_t}}_{\text{if loan defaults}} + \underbrace{[1 - F(\bar{\omega}_t, \sigma_{\omega,t})] R^L_t}_{\text{if loan is repaid}} \right\} \tag{1.6}$$

1.2.2 Deleveraging

The shadow price $\xi_t^{S^B,*}$ affects the credit channel between financial intermediaries and borrowers, such that financial intermediaries only lend a fraction of their loanable funds. The costs of the decrease in lending is transferred to households. The aggregate balance sheet of financial intermediaries in periphery ($*$) includes savers deposits ($S^{S,*}$) and borrowers demand for loans ($S^{B,*}$) as well as an excess B_t^* of domestic funds that is transferred to core:

$$(1-n)\lambda \frac{1}{\xi_t^{S^B,*}} (S_t^{S,*} + B_t^*) = (1-n)(1-\lambda) S_t^{B,*} \tag{1.7}$$

The shadow price $\xi_t^{S^B,*}$ is assumed to be constant and equal to one in the baseline scenario. When we analyze TARGET2 and its effects on private deleveraging, we allow $\xi_t^{S^B,*}$ to increase. Households' private deleveraging relates to credit growth in periphery:

$$\left[\frac{S_t^{B,*}}{S_{t-1}^{B,*}} \right]^{\gamma_\xi} \leq \xi_t^{S^B,*} \tag{1.8}$$

A positive risk shock to the durable sector per se decreases the credit-to-GDP ratio, however solely due to an increase in the lending-deposit spread. Additionally, Equation (1.8) states that credit growth of peripheral agents is restricted with the shadow price $\xi_t^{S^B,*}$ as the cost of borrowing and the parameter γ_ξ, in order to model the active reduction in credit supply/demand (Cuerpo et al., 2015; Cuerpo et al., 2013). The drop in credit availability decrases households' debt-to-GDP and the LTV ratio.

1.2.3 Firms

Periphery and core produce homogeneous durable and non-durable goods according to their size $1-n$ and n, respectively. The model uses staggered price setting of Calvo, 1983 and monopolistic competition for intermediate firms (Quint and Rabanal, 2014). Final goods proucers sell non-durables across borders. However, durable goods are not tradable between periphery and core.
The production function for final goods is:

$$Y_t^k \equiv \left[\left(\frac{1}{n} \right)^{\frac{1}{\sigma_k}} \int_0^n Y_t^k{}^{\frac{\sigma_k - 1}{\sigma_k}} \right]^{\frac{\sigma_k}{\sigma_k - 1}} \tag{1.9}$$

for the two types of final goods product $k = \{C, D\}$, where σ_k describes the price elasticity of intermediate goods. This leads to the following demand for intermediate goods:

$$Y_t^C = \left(\frac{P_t^H}{P_t^H} \right)^{-\sigma_C} Y_t^C \quad \text{and} \quad Y_t^D = \left(\frac{P_t^D}{P_t^D} \right)^{-\sigma_D} Y_t^D \tag{1.10}$$

and the price levels for domestically non-durable (P_t^H) and durable final goods (P_t^D):

$$P_t^H \equiv \left\{ \frac{1}{n} \int_0^n [P_t^H]^{1-\sigma_C} dh \right\}^{\frac{1}{1-\sigma_C}} \quad \text{and} \quad P_t^D \equiv \left\{ \frac{1}{n} \int_0^n [P_t^D]^{1-\sigma_D} dh \right\}^{\frac{1}{1-\sigma_D}} \tag{1.11}$$

The price level for non-durable goods produced in the core area consists of the price of non-durables produced in core (P_t^H) and the price of imported non-durables (P_t^F).

$$P_t^C = \left[\tau (P_t^H)^{1-\iota_C} + (1-\tau)(P_t^F)^{1-\iota_C} \right]^{\frac{1}{1-\iota_C}} \tag{1.12}$$

At the end of each period the fraction $(1-\theta_C)$ of non-durable and $(1-\theta_D)$ of durable intermediate goods producers are able to re-optimize their prices. The prices of the remaining firms (θ_C and θ_D) are linked to sector-specific inflation with the parameters ϕ_C and ϕ_D. Intermediate goods are produced with labor ($L_t^C(h)$ and

$L_t^D(h)$) as the only input factor:

$$Y_t^C(h) = A_t Z_t^C L_t^C(h), \quad Y_t^D(h) = A_t Z_t^D L_t^D(h) \quad \forall \quad h \in [0, n] \tag{1.13}$$

with A_t as a union wide technology shock as well as Z_t^C and Z_t^D as sector specific shocks in each country.

1.2.4 International Credit Markets

Demand and supply of loans (S^B and S^S) do not necessarily add up. International financial intermediaries can trade the excess funds of core B_t to periphery and vice versa (see Equation 1.7). International intermediaries can lend to peripheral financial intermediaries which can use the funds to satisfy the excess demand for loans in periphery. The international deposit rate spread is given as in Schmitt-Grohe and Uribe (2003):

$$R_t^* = R_t + \left\{ \vartheta_t \kappa_B \left(\frac{B_t}{P_t^C Y^C} \right) \right\} \tag{1.14}$$

The fraction $\frac{B_t}{P_t^C Y^C}$ denotes the private NFAs in terms of private capital flows divided by non-durable GDP in core. The parameter κ_B is the elasticity of core interest rate to the level of peripheral assets (international risk premium). The parameter ϑ_t denotes the international premium shock. Savers own the international intermediaries in core and periphery and profits are split equally to profit gaining intermediaries. Since supply does not necessarily equal demand of loans in a respective credit market area, the following condition must hold for the international bond markets. Hence, international intermediaries must completely hedge their exposure:

$$n\lambda B_t + (1-n)\lambda^* B_t^* = 0 \tag{1.15}$$

The private NFA equation is given by Equation (1.16a):

$$
\begin{aligned}
(1.16a)\qquad n\lambda B_t &= n\lambda R_{t-1}B_{t-1} + \Big\{(1-n)P_{H,t}\left[\lambda^* C^*_{H,t} + (1-\lambda^*)C^{B^*}_{H,t}\right] \\
&\quad -nP_{F,t}\left[C_{F,t} + (1-\lambda)C^{B}_{F,t}\right]\Big\} \\
(1.16b)\qquad n\lambda B_t &= n\lambda R_{t-1}B_{t-1} + \Big\{(1-n)P_{H,t}\left[\lambda^* C^*_{H,t} + (1-\lambda^*)C^{B^*}_{H,t}\right] \\
&\quad -nP_{F,t}\left[C_{F,t} + (1-\lambda)C^{B}_{F,t}\right]\Big\} + TARGET2
\end{aligned}
$$

Equation (1.16a) makes use of the balance of payment mechanisms and describes the development of private bonds over time (law of motion). Therefore, a change in NFA positions has feedback effects on output and consumption, and thus current account.

We introduce TARGET2 to Equation (1.16a) that reacts to sudden stops in periphery and the related increase in the NFA position relative to its steady state level (Equation 1.17). The reversal of private capital inflows is (partly) compensated by TARGET2 (1.16b).

$$
(1.17)\qquad TARGET2 = \zeta_{T2}\left(NFA_{H,Steady} - NFA_{H,t}\right)
$$

Thereby, the central bank provides additional liquidity to the periphery. Following the model dynamics in Equation (1.16b), TARGET2 liabilities in periphery as well as related TARGET2 credits in core affect NFA positions in bank balance sheets, and thus consumption and output in both regions[3].

In the baseline scenario, NFA positions comprise only private capital flows. Via the TARGET2 mechanism, private capital outflows are subsituted by public capital inflows, leading to negative current account positions in the region originally hit by a sudden stop.

Current account in period t is related to the change in NFA position:

$$
\begin{aligned}
(1.18)\qquad CA_t &= n\lambda R_{t-1}B_{t-1} + (1-n)P_{H,t}\left\{Y_t - \left[\lambda C_{H,t} + (1-\lambda)C^{B}_{H,t}\right] - Y_t{}^{D}\frac{P^D_t}{P^C_t}\right\} \\
&\quad - nP_{F,t}\left\{\lambda C_{F,t} + (1-\lambda)C^{B}_{F,t}\right\} - n\lambda B_t
\end{aligned}
$$

[3]As the model structure implies NFA positions that are demand driven (households domestic ($C^*_{H,t}$) and foreign ($C^*_{F,t}$) consumption), the effects of the TARGET2 mechanism in Section 1.4 are driven by changes in consumption and the terms of trade.

Relations (1.16) - (1.18) do not imply financing current account deficits by TARGET2 (e.g. Auer, 2014), but generate an indirect transmission channel from TARGET2 liabilities and NFA positions to current account imbalances. TARGET2 liabilites lead to an increase in periphery's NFA positions as well as a decrease in current account, and consequently an adjustment in the terms of trade and the consumption behavior. The interest rate is determined by the following rule:

$$R_t = \gamma_R R_{t-1} + (1-\gamma_R)\gamma_\pi(\pi_t)^n(\pi_t^*)^{(1-n)} + (1-\gamma_R)\gamma_y \hat{y}_t^{EMU} + \varepsilon_t^m \tag{1.19}$$

The monetary policy shock is defined as ε_t^m and is *i.i.d.*. The parameters γ_π, γ_y and γ_R are the reaction parameters to inflation, real growth and the interest rate smoothing.

1.3 Calibration and Parameter Estimates

Following Schorfheide (2000) and Schorfheide and Lubik (2003), we apply a two-step estimation procedure involving calibration and Bayesian techniques to represent a two-region model with financial frictions, i.e. peripheral and core euro area countries (Quint and Rabanal, 2014). The estimation results and the historical shock decomposition determine the drivers behind sudden stops in GIIPS.

The core region is obtained by aggregating data for France and Germany, whereas the GIIPS countries represent the periphery region. We use quarterly data on nominal and real GDP, nominal private consumption, nominal gross fixed capital formation, credit to households and non-profit institutions serving households, current account, the harmonized index of consumer prices, real house price index, and the three month Euro Interbank Offered Rate from 2000Q1 to 2017Q1. The data is aggregated to core and periphery using weighted GDP averages.[4]

We add several shocks to the model for both core and periphery, namely technology shocks to the durable and non-durable sector, preference shocks to the durable and non-durable sector, risk shocks to the durable sector, international risk premium shocks, and monetary policy shocks[5]. The shock processes are specified in Appendix 1.7.2.

[4]See Appendix 1.7.1 for a detailed description of the data.

[5]Other shocks like shocks to consumption, prices, investment, and output are summarized, as they have negligible influence on the main variables like output, investment, and current account.

Table 1.1: Calibrated parameters

n	Size of the Core Country	0.6000
β	Discount Factor Savers	0.9900
β^B	Discount Factor Borrowers	0.9850
δ	Depreciation Rate	0.0125
h	Monitoring Costs	0.2000
$\bar{\omega}$	Loan to Value Ratio	0.7000
ι_L	Labour Disutility Cost Parameter	0.7174
φ	Labour Disutility	0.3702
ε	Habit Formation Parameter: Savers	0.7187
ε^B	Habit Formation Parameter: Borrowers	0.4550
α	Size of Non-durable Sector in GDP Core	0.9400
α^*	Size of Non-durable Sector in GDP Periphery	0.9400
$\bar{\sigma}_\omega$	Steady State Risk	0.1742
$\bar{F}$	Default on Loans	0.0250
τ	Share of Home-produced Non-durable Consumption in Core	0.9400
τ^*	Share of Periphery-produced Non-durable Goods Available in Periphery	$1-\frac{n(1-\tau)}{1-n}$

1.3.1 Calibrated Parameters

We calibrate parameters following Quint and Rabanal (2014), except the elasticity of substitution between intermediate goods σ as well as the weight of non-durables in the utility function in core (γ) and periphery (γ^*) that are estimated.

We assume that the discount factors are the same in both countries ($\beta = \beta^*$ and $\beta^B = \beta^{B*}$). The cut-off point for loan defaults is set to $\bar{\omega} = 0.7$ for both regions (Gerali et al., 2010). Pre-crisis data from the IMF for the EMU reveal an average default value ($\bar{\mathrm{F}}$) of about 2.5% (Time period: 2000-2007) as in Quint and Rabanal (2014). Using GDP data, the average size of the core region is set to 60%. Using the weighted average of total imports to private consumption, we set the share parameter for home produced non-durable consumption in core to 0.94. Furthermore, following the findings by Iacoviello and Neri (2010), we set labour disutility $\varphi = 0.37$. Table 1.1 summarizes the calibrated values.

1.3.2 Prior and Posterior Distributions

Table 1.2 depicts the prior and posterior distribution for the estimates in the benchmark model. Further, estimation results for the shock processes are in Tables 1.4 - 1.5 in Appendix 1.7.2.

The choice of the prior distribution is in line with Ratto and Iskrev (2011) and Ratto et al. (2001), in order to increase the model fit[6]. We run 200,000 draws with four distinct chains, using the Metropolis-Hastings algorithm. We drop the first 50 % to account for any dependence of the chains from its starting values (Röhe, 2012).

Results from posterior and Metropolis-Hastings estimation are shown in the last three columns of Table 1.2, including the Highest Posterior Density Interval (HPDI)[7].

The prior estimates for the mean of the shock processes are set to 0.75 with a standard deviation of 0.1 and thus lie within the range of 0.5 and 0.8, as suggested by Marcellino and Rychalovska (2012) and Justiniano and Preston (2010). In order to estimate the standard deviation of shocks and the measurement errors, inverse gamma distributions are specified. The posterior mean for shock persistences (Table 1.4) are consistently higher for GIIPS, except for preference shocks in the non-durable sector.

A comparison of the posterior estimates indicates a somewhat higher markup for each firm of 3.4455 than the prior mean of 2.500 with a large standard deviation of 0.5, in order to fit the data. However, the posterior estimates are lower than those calibrated by Quint and Rabanal (2014). The parameter κ_B describes the international risk premium elasticity, which is the elasticity of domestic interest rates to the level of foreign assets. Posterior estimates show that a one percent increase in the external debt-to-GDP ratio leads to a 4.55 basis points move of the risk premium elasticity between countries. Additionally, we find a large elasticity of substitution between home and foreign goods ι_C with a value of 2.66.

The estimates for the Taylor rule indicate a strong response to inflation in the euro

[6]The identification analysis deals with the challenge to identify best estimates of parameters within a statistical computation.

[7]In contrast to confidence intervals, the HPDI has two important properties: (1) the density for each point lying within the interval is greater than for those points lying outside. (2) The interval is of the shortest length for a default probability content (e.g. Chen and Shao, 1999).

Table 1.2: Prior and posterior distribution of estimated parameters

Parameter		Prior			Metropolis Hastings		
		Type	Mean	sd.	Mean	90% HPD Interval	
σ	EOS bw. intermediate goods	Gamma	2.5000	0.5000	3.4455	2.7665	4.1432
κ_B	International risk premium	Gamma	0.0300	0.0100	0.0455	0.0275	0.0653
ι_C	EOS bw. goods	Gamma	2.5000	0.5000	2.6619	1.7800	3.5189
ψ	Investment adjustment costs	Gamma	2.5000	0.5000	3.0040	2.3240	3.6354
λ	share of savers	Beta	0.5000	0.1000	0.4087	0.3770	0.4431
γ_π	Taylor rule reaction to inflation	Gauss.	2.0000	0.2000	2.3739	1.9785	2.5526
γ_r	Interest rate smoothing	Beta	0.7000	0.1000	0.8296	0.7891	0.8700
γ_y	Taylor rule reaction to real growth	Gamma	0.4000	0.1000	0.4778	0.2932	0.6693
γ	Weight of non-durables in the utility function	Beta	0.6000	0.1000	0.4473	0.3881	0.5051
γ^*	Weight of non-durables in the utility function	Beta	0.6000	0.1000	0.7707	0.7120	0.8291
θ_C	Calvo lottery, non-durables	Beta	0.7000	0.1500	0.7970	0.7210	0.8711
θ_D	Calvo lottery, durables	Beta	0.7000	0.1500	0.9508	0.9246	0.9756
θ^*_C	Calvo lottery, non-durables	Beta	0.7000	0.1500	0.6289	0.5304	0.7418
θ^*_D	Calvo lottery, durables	Beta	0.7000	0.1500	0.8967	0.8720	0.9221
ϕ_C	Indexation, non-durables	Beta	0.3300	0.1500	0.2174	0.0405	0.3787
ϕ_D	Indexation, durables	Beta	0.3300	0.1500	0.3082	0.0689	0.5452
ϕ^*_C	Indexation, non-durables	Beta	0.3300	0.1500	0.1730	0.0280	0.3153
ϕ^*_D	Indexation, durables	Beta	0.3300	0.1500	0.4001	0.1638	0.6149

Note: Table 1.2 depicts the prior and posterior distribution of the estimated EMU parameters. Asterisks(*) indicate parameters of GIIPS; The term 'Elasticity of Substitution' is abbreviated by EOS.

area (2.37) and a high degree of interest smoothing (0.90), while the reaction to real GDP growth (0.48) is moderate compared to the prior mean, however, higher than suggested by Quint and Rabanal (2014) (0.20).

Our posteriors for the duration of price contracts suggest an average contract length of approximately 10 (periphery) to 20 (core) quarters for the price stickiness of durable goods. Posteriors of non-durable goods indicate that prices are reset approximately every 3 (periphery) to 5 (core) quarters.

1.3.3 Historical Shock Decomposition

We estimate the individual contribution of each shock to the movements of specific endogenous variables.

Figure 1.2: Historical shock decomposition for GIIPS

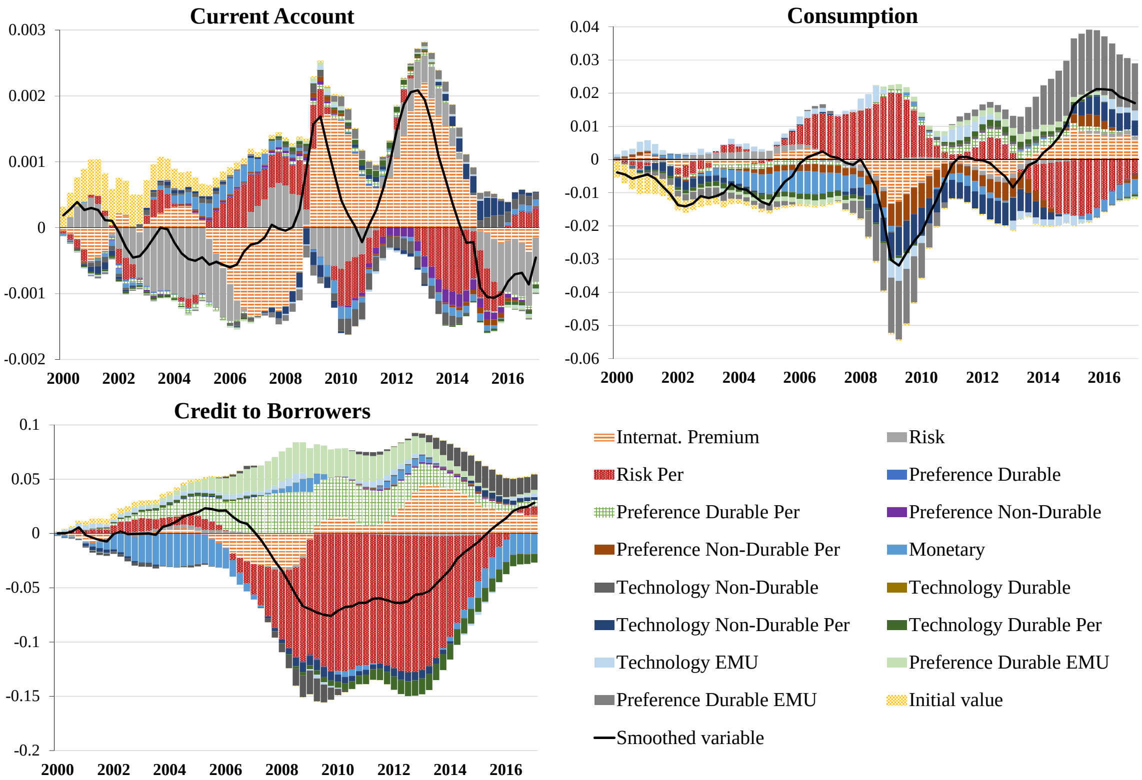


Figure 1.2 plots the historical shock decomposition for credit to borrowers, consumption, and current account relative to GDP in periphery. The solid line depicts the smoothed value of the deviation of a variable's historical value from its steady state, whereas the vertical bars show the contribution of the different smoothed shocks

and initial values to the development of the variable.
The shock decomposition indicates that the regions are strongly driven by the risk shock to the durable sector, which is associated with a sudden stop of private capital, next to the international premium shock and the preference shock in the durable sector for the estimated period 2000Q1-2017Q1.
We find that the risk shock to the durable sector drives down credits during the crisis and afterward, until the end of the estimation period (Figure 1.2). This can be attributed to the massive increase in non-performing loans in the periphery during the financial crisis and the subsequent debt crisis.
Using the findings from the shock decomposition, the subsequent analysis focuses on the simulation of risk shocks to the durable sector in periphery.

1.4 Simulation

Figures 1.3 - 1.4 present the development of key variables. In the baseline scenario (solid line), we illustrate the effects of a risk shock in periphery, the main driver of sudden stops of private capital inflows. Then, we implement a restriction of loans to borrowers in periphery, in order to replicate active deleveraging of most peripheral countries in the course of the financial as well as the subsequent sovereign debt crisis (dotted line). Finally, we introduce TARGET2 as a payment by the central bank that is based on the private NFA position (dashed line), i.e. we replenish to a certain extent capital in periphery that moved to core and evaluate the influence on the deleveraging process in periphery as well as feedback effects on the core (creditor) region.

1.4.1 Baseline scenario

The risk shock to the durable sector of about 11.7% (see Table 1.5) increases the amount of non-performing loans of borrowers in periphery, which forces them to reduce their consumption. As a result, total consumption in periphery drops and prices fall, leading to deflationary processes with a decline in wages and labor supply, and thus output. This recession is caused by a loss in value of borrower's collateral, which impedes their credit-financed consumption, while consumption in core slightly increases. To sum up, the risk shock induces private capital outflows, i.e. a sudden stop in periphery. In the baseline scenario, this capital outflows increase periphery's current account.

1.4.2 Deleveraging

The binding constraint in Equation (1.8) directly relates deleveraging in periphery with respect to credit growth with the shadow price $\xi_t^{S^B}$ as the cost of borrowing. Higher shadow prices $\xi_t^{S^B}$ decrease credits (dotted line) due to higher exposure on peripheral balance sheets. The binding constraint shuts down the credit channel between financial intermediaries and borrowers and thus intensifies the deleveraging process.

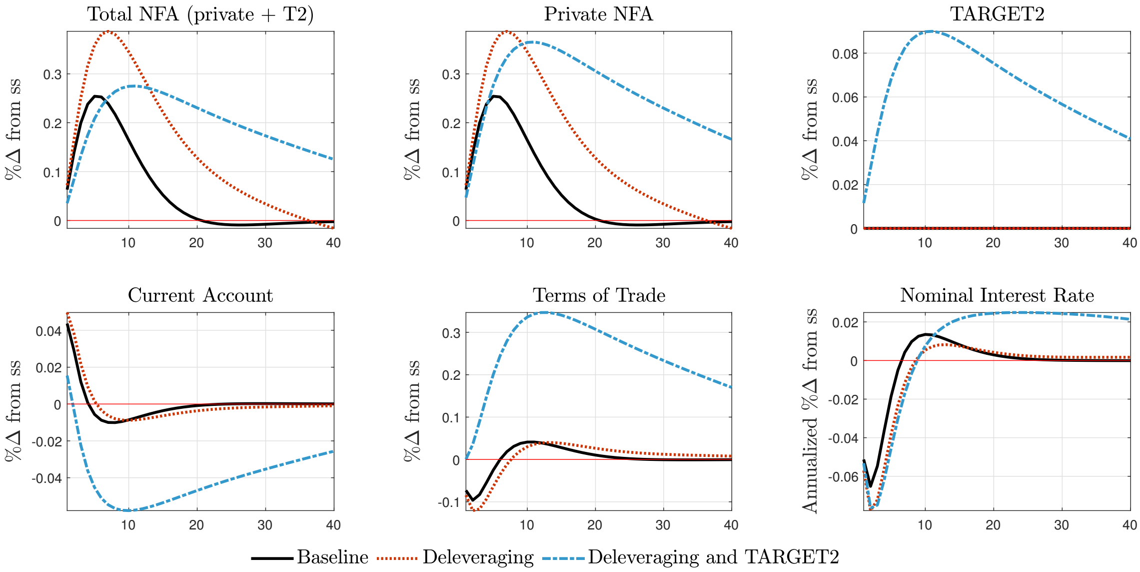
Active deleveraging magnifies the initial effects of the baseline scenario: The substantial drop in credits to borrowers leads to significantly higher capital flows from periphery to core and private NFA positions increase. The parameter γ_ξ is chosen such that private deleveraging in periphery corresponds to a total decline in private capital inflows (NFA) of about 25% of steady state GDP, which is in the range for the GIIPS countries (e.g. Merler and Pisani-Ferry, 2012; Higgins and Klitgaard, 2014). The effects on other parts of the economy are rather small. This is in line with Justiniano et al. (2015), who show that, given two household types, borrowers' deleveraging and lower consumption are counteracted by savers' increasing activity. However, in total, deleveraging slightly accelerates the recovery of consumption and output in GIIPS after an initial higher drop in the respective variables.

1.4.3 TARGET2

Allowing additional TARGET2 flows (partly) compensates for a reversal of private capital inflows by an increase in public capital inflows. TARGET2 is introduced by increasing the parameter ζ_{T2} from zero to 0.9. The increase in TARGET2 liabilities allows for a decrease in peripheral NFA positions that now consist of private flows plus (negative) TARGET2 (dashed line). The parameter choice follows the estimation by Kraus et al. (2019) and implies that the initial drop in NFA through deleveraging is nearly substituted by TARGET2 financing as in Figure 1.3.[8] We

[8] Higgins and Klitgaard (2014) calculate a nearly 1:1 substitution of private capital through TARGET2 financing for peripheral euro area countries; see Section 1.5 for a sensitivity analysis with lower intervention parameter $\zeta_{T2} = 0.1$.

Figure 1.3: Cross-border capital flows after a risk shock in periphery



Note: Total NFA, private NFA, TARGET2 liabilities, and current account are represented from periphery's perspective, while the terms of trade are defined as the price level of core's imported non-durables from periphery relative to non-durables produced in core. The nominal interest rate is the interest rate set by the ECB.

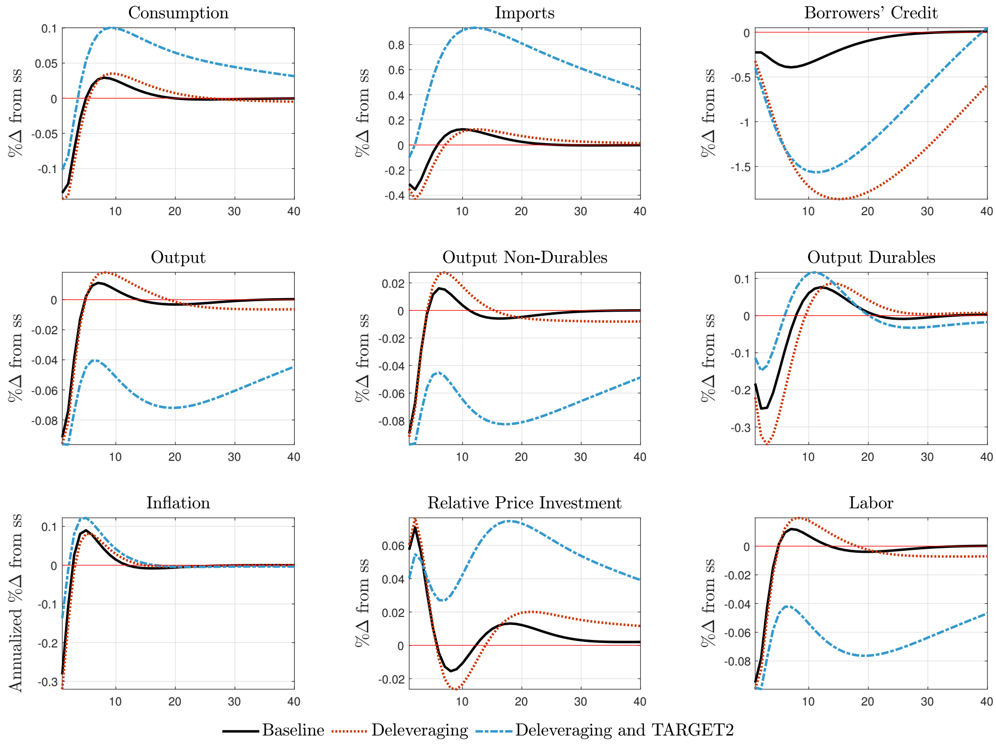
compare the results to the private NFA position under pure deleveraging (dotted line) in order to determine the shortfall of external finance.

Private capital outflows trigger the automated central bank response via the TARGET2 system, thereby mitigating the sudden stop, i.e. capital outflows are substituted by central bank liquidities, which closely represents the influence of TARGET2 during the crisis. The unevenly distribution of central bank liquidity leads to the well known TARGET2 imbalances. Total NFA positions of private and public capital increase considerably, leading to distortionary effects of TARGET2 via the credit channel:

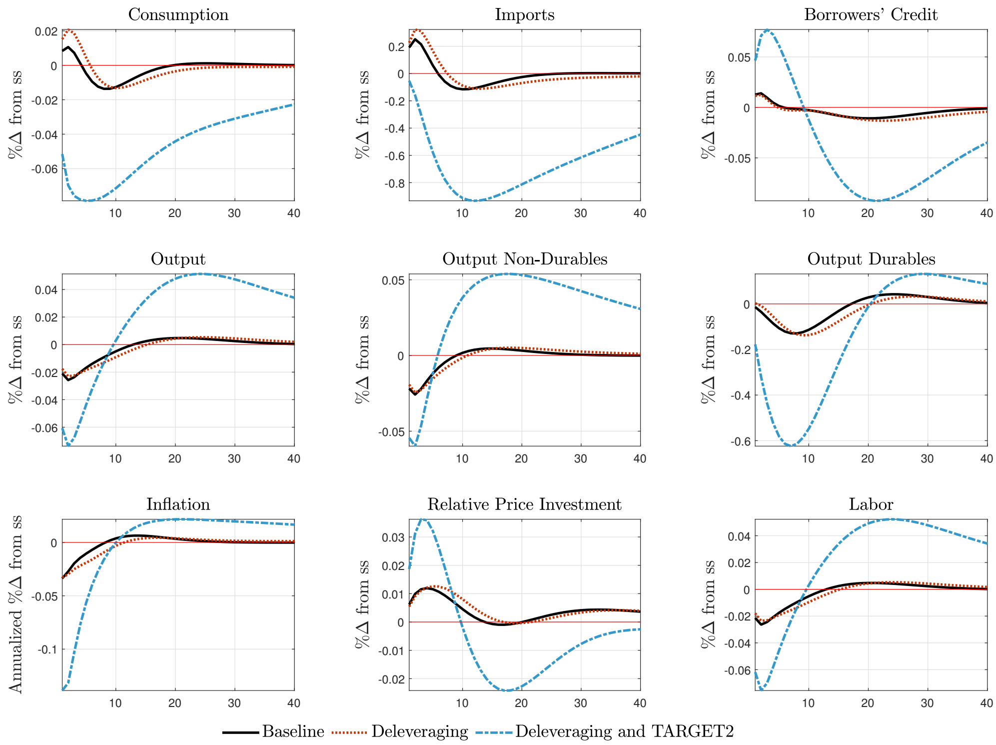
In periphery, public capital inflows induce higher inflation rates, and beneficial terms of trade allow for higher consumption. However, due to their ability to consume goods from abroad at lower prices, households can increase consumption through imports from core while labor declines. Thus, while consumption levels highly benefit from TARGET2 'subsidies', production of non-durable goods stays far beneath its steady state level in periphery. Additionally, higher consumption prices in periphery extrude households' consumption from core (exports) and lead to a further

Figure 1.4: Cross-regional economic effects after a risk shock in periphery

(a) Economic effects in GIIPS



(b) Economic effects in Core



decrease in labor and drop in output.

In core, labor increases and output by far exceeds its steady state level, while higher import prices channel households' activity from consumption of imports to savings. The recovery process is significantly prolonged, reflected in periphery's current account against the core, which is still negative after 40 periods, as well as private and public capital that point to an extended phase of cross-border flows relative to the baseline scenario.

Thus, additional public capital flows create inflation differentials between the two regions and consequently real exchange rate misalignments within the euro area: TARGET2 enables countries in periphery to stabilize and even increase their (import) consumption. However, this comes at the cost of a severe and persistent drop in output and current account. Core countries, on the other hand, heavily increase their exports, which leads to an increase in output, while consumption of non-durable goods stays low.

1.5 Sensitivity Analysis

The sensitivity analyses for a peripheral risk shock for the three cases of (1) the baseline scenario, (2) deleveraging, and (3) deleveraging & TARGET2 assess differences in macroeconomic adjustments in core versus periphery and illustrate the stabilization effects of TARGET2. The section closes with the introduction of a ZLB, that amplifies the negative effects on output and consumption and leads to stronger deflationary processes.

Table 1.3 supports the simulation results, that additional TARGET2 flows stabilize credit to borrowers in periphery relative to pure deleveraging, but increase the volatility of credits to borrowers in core. Volatility in consumption increases in both regions, albeit for different reasons: Households in periphery consume more imported goods with public capital inflows, yet extrude core households' consumption due to beneficial terms of trade. Low inflation volatility in periphery due to a moderated fall in prices contrasts with destabilizing effects of TARGET2 in core, leading to higher deflation. This contrast is also reflected in the interest rate volatility. While additional TARGET2 flows stabilize interest rates in periphery, deflation rates cause higher volatility in core.

Table 1.3: Theoretical moments - Comparison of standard deviations (in %)

	Baseline	Deleveraging	Deleveraging & TARGET2
Variable	sd.	sd.	sd.
NFA	0.68	1.29	1.34 (1.41)
Current Account	0.04	0.05	0.42 (0.07)
Credit Borrowers			
Core	0.05	0.06	0.45 (0.1)
Periphery	1.26	9.45	7.43 (8.98)
Consumption			
Core	0.04	0.05	0.36 (0.07)
Periphery	0.21	0.25	0.46 (0.25)
Inflation			
Core	0.01	0.02	0.07 (0.02)
Periphery	0.09	0.10	0.07 (0.09)
Interest Rate			
Core	0.03	0.04	0.05 (0.04)
Periphery	0.05	0.08	0.06 (0.08)

Note: Table 1.3 reports the comparison of standard deviations (in %) between the three cases 1. baseline scenario 2. deleveraging in periphery and 3. Deleveraging in periphery plus TARGET2 assistance for the risk premium shock in periphery (sudden stop); numbers in parentheses indicate sensitivity results for lower $\zeta_{T2} = 0.1$.

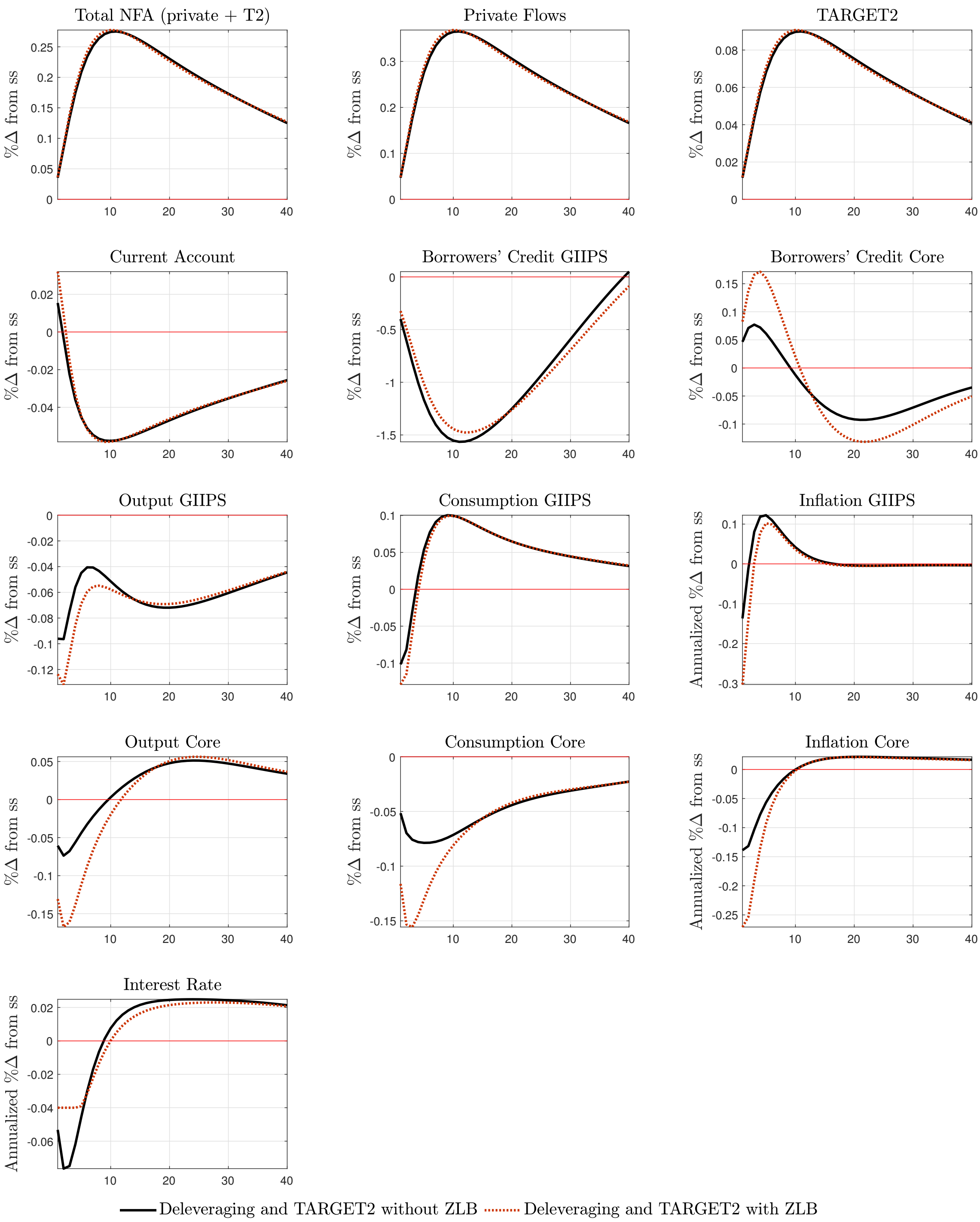
In summary, the substitution of private through public capital reveals a rather destabilizing effect, particularly in the core region. This relates to the disturbing effects of beneficial terms of trade in the NFA position, caused by additional public financing in a system of international capital flows.

Sensitivity analyses for alternative values of the parameter ζ_{T2} in parentheses show that lowering the parameter ζ_{T2} to 0.1 brings volatility values close to a case of pure deleveraging. However, NFA positions indicate an increase in volatility for parameter values $\zeta_{T2} = [0; 0.7]$, as (low) TARGET2 flows are out-weighed by the prolonged stabilization of NFA positions due to a disturbance of cross-border flows.

Zero Lower Bound (ZLB)

The simulation of TARGET2 at the ZLB ties in with the wide-ranging debate on the economic consequences when the short-term nominal interest rates are at or near

Figure 1.5: Risk shock in periphery: Private capital flows and economic effects at the ZLB



zero, limiting central banks to fight deflation.
Figure 1.5 resembles the results from Figure 1.4 for key variables in a ZLB environment. To implement a ZLB, we make use of the perturbation approach as in (Iacoviello and Neri, 2010). Note that in our model, interest rates are jointly determined by a mutual central bank and deviate slightly due to region-specific premia. Hence, TARGET2 increases risk premia on interest rates in GIIPS due to higher foreign indebtedness (see Section 1.4) and mitigate the economic effects of a ZLB in periphery.
The lower bound on nominal interest rates leads to intensified and prolonged deflationary processes that amplify the recession (e.g. Justiniano et al., 2015; Arce et al., 2016): in both regions relatively higher interest rates make savings more attractive relative to consumption. Financial intermediaries lend money at increased interest rates to borrowers. The tightening balance sheet of borrowers delays the deleveraging process (Benigno et al., 2020). An overall drop in consumption affects the profits of firms and forces down wages and, consequently, labor. Output decreases while prices deteriorate and lead into a deflationary spiral with limited option for central banks to intervene. However, interest rate and inflation differentials between regions due to TARGET2 lead to stronger effects of a ZLB on core variables.

1.6 Conclusion

This chapter uses a two-sector two-region model with financial frictions to analyze the role of the euro area's payment system TARGET2 in the adjustment to a sudden stop of private capital and subsequent deleveraging processes. We contribute to the existing literature on TARGET2 by examining (i) cross-border capital flows and the macroeconomic adjustment of euro area Member States, (ii) the mitigation of private deleveraging and (iii) the behavior of key macroeconomic variables when a Zero Lower Bound intensifies the deleveraging process.
In this chapter, we make several findings. First, the historical shock decomposition confirms the existence of post-crisis sudden stops for the GIIPS. Second, TARGET2 impedes recovery processes and leads to higher economic divergence within monetary union due to adverse terms of trade developments: The substitution of private by public capital leads to inflation differentials between core and peripheral

euro area countries. Beneficial terms of trade for consumers in periphery maintain negative current account levels. On the contrary, core's consumption drops with additional TARGET2 flows, as households tend to increase their savings and reduce their import demand from periphery. As a consequence, output in periphery drops considerably, while output in core increases. A sensitivity analysis confirms that access to TARGET2 has a slightly destabilizing effect within the euro area. Output, consumption and current account volatilities increase relative to a case of pure deleveraging.

The results are robust to changes in the liquidity provision by the central bank. The lower TARGET2 liabilities in GIIPS, the closer we get to the case of pure deleveraging concerning volatility of key macroeconomic variables such as consumption and output.

The alternative scenario with constrained monetary policy at the ZLB shows that the euro area is driven into prolonged deflationary processes, aggravating the effects of deleveraging on consumption and output in both regions. However, inflation differentials between core and periphery caused by TARGET2 lead to more pronounced effects of a lower bound on interest rates in the core region.

Our analysis contributes to the controversial debate on the macroeconomic effects of TARGET2 balances with distributional aspects of disturbed cross-border capital flows within the euro area. The TARGET2 payment system is of crucial importance for smooth cross-border transfers within the Monetary Union. Nonetheless, the need for reforms to improve the workings of the euro area's payment system calls for further research. Considering our results, one key aspect would be targeting real exchange rate misalignments between core and peripheral euro area countries.

1.7 Appendix

1.7.1 Data and Sources

The estimation of the two-region DSGE model includes 14 observables for the EMU. Thereby, six observables are designated to the core economy (y_t^{data}, $c_t^{tot,data}$, $inv_t^{tot,data}$, $s_t^{B,data}$, ca_t^{data}, dpd_t^{data}), another six observables are linked to GIIPS ($y_t^{*,data}$, $c_t^{*,tot,data}$, $inv_t^{*,tot,data}$, $s_t^{B*,data}$, $ca_t^{*,data}$, $dpd_t^{*,data}$) and two observables are used for the entire euro area ($dpemu_t^{data}$, r_t^{data}). The data except the EURIBOR is seasonally adjusted. The X-12-ARIMA adjustment process, in most of the cases a one-sided HP filter, was applied to detrend the data.

GDP: Seasonally adjusted data for the *gross domestic product at market value* denoted by y_t^{data} for the core and $y_t^{*,data}$ for the periphery. Source: Eurostat (*namq*_10_*gdp*).

Consumption: *household and NPISH final consumption expenditure.* Modified data is provided by $c_t^{tot,data}$ for core and $c_t^{*,tot,data}$ for periphery. Source: Eurostat (*namq*_10_*gdp*).

Investment: *gross fixed capital formation* denoted by $inv_t^{tot,data}$ for the core and $inv_t^{*,tot,data}$ for the periphery. Source: Eurostat (*namq*_10_*gdp*).

Credit to Borrowers: Data for Ireland is available from 2002Q1 onwards, only. Data used is *credit to households and NPISH* denoted by $s_t^{B,data}$ for the core and $s_t^{B*,data}$ for the periphery. Source: BIS.

Current Account: Data for Greece and Ireland is available from 2002Q1 onwards, only. The data used is the *current account.* Modified data is provided by ca_t^{data} for core and by $ca_t^{*,data}$ for periphery. Current account is the only variable divided by GDP instead of taking the logarithm. Source: Eurostat (*bop*_*c*6_*q*).

Consumption Prices: The CPI is given by the Harmonized Index of Consumer Prices *HICP* to describe union wide inflation in non-durable prices with quarter on quarter logarithmic differences, denoted by $dpemu_t^{data}$. Source: ECB ECB Statistical Data Warehouse.

Investment Prices: This input variable represents the change in the prices of durable goods. The data used is the seasonally adjusted *real house prices* index with quarterly logarithmic differences to describe the differences in durable prices per period. Modified data for the core area is given in dpd_t^{data} for the core and in $dpd_t^{*,data}$ for the periphery. Source: OECD.

Nominal Interest Rate: The *three month EURIBOR* data enters the model using r_t^{data}. Interest rates are not seasonally adjusted. Source: ECB Statistical Data Warehouse.

1.7.2 Shock Processes

The shocks evolve according to the following AR(1) processes:

$$\begin{aligned}
\vartheta_t &= \rho_\vartheta \vartheta_{t-1} + \epsilon_\vartheta \\
log(\sigma_{\omega,t}) &= (1-\rho_{\sigma_\omega}) log(\bar{\sigma}_\omega) + \rho_{\sigma_\omega} log(\sigma_{\omega,t-1}) + u_{\omega,t} \\
log(\sigma^*_{\omega,t}) &= (1-\rho_{\sigma_\omega}) log(\bar{\sigma}^*_\omega) + \rho_{\sigma_\omega} log(\sigma^*_{\omega,t-1}) + u^*_{\omega,t} \\
\xi_t^D &= \rho_{\xi^D} \xi_{t-1}^D + \epsilon_{\xi^D} + \epsilon_{\xi^D,COM} \\
\xi_t^{D*} &= \rho_{\xi^{D*}} \xi_{t-1}^{D*} + \epsilon_{\xi^{D*}} + \epsilon_{\xi^{D*},COM} \\
\xi_t^C &= \rho_{\xi^C} \xi_{t-1}^C + \epsilon_{\xi^C} \\
\xi_t^{C*} &= \rho_{\xi^{C*}} \xi_{t-1}^{C*} + \epsilon_{\xi^{C*}} \\
Z_t^C &= \rho_{Z^C} Z_{t-1}^C + \epsilon_{Z^C,t} + \epsilon_{Z^C,COM} \\
Z_t^{C,*} &= \rho_{Z^{C,*}} Z_{t-1}^{C,*} + \epsilon_{Z^{C,*},t} \epsilon_{Z^{C,*},COM} \\
Z_t^D &= \rho_{Z^D} Z_{t-1}^D + \epsilon_{Z^D,t} \\
Z_t^{D,*} &= \rho_{Z^{D,*}} Z_{t-1}^{D,*} + \epsilon_{Z^{D,*},t}
\end{aligned}$$

However, the non-stationary innovation to the union-wide technology shock ε_t^A and the monetary policy shock ε_t^m are *i.i.d.*

1.7.3 Estimation Results

Posterior estimates

Table 1.4: Prior and posterior distribution of shock persistence parameters

Parameter		Prior			Metropolis Hastings		
		Type	Mean	SD	Mean	90% HPD Interval	
ρ_{ϑ}	Risk premium, int.	Beta	0.7500	0.1000	0.8163	0.7454	0.8827
ρ_{ω}	Risk shock, durables	Beta	0.7500	0.1000	0.7974	0.7610	0.8348
ρ_{ω}^{*}	Risk shock, durables*	Beta	0.7500	0.1000	0.9163	0.8744	0.9566
$\rho_{\xi,D}$	Preference shock, durables	Beta	0.7500	0.1000	0.8813	0.7832	0.9654
$\rho_{\xi,D}^{*}$	Preference shock, durables*	Beta	0.7500	0.1000	0.9539	0.9391	0.9918
$\rho_{\xi,C}$	Preference, non-durables	Beta	0.7500	0.1000	0.9220	0.8753	0.9680
$\rho_{\xi,C}^{*}$	Preference, non-durables*	Beta	0.7500	0.1000	0.8005	0.6374	0.9640
$\rho_{Z,C}$	Technology., non-durables	Beta	0.7500	0.1000	0.8598	0.7898	0.9250
$\rho_{Z,C}^{*}$	Technology, non-durables*	Beta	0.7500	0.1000	0.8823	0.8232	0.9484
$\rho_{Z,D}$	Technology, durables	Beta	0.7500	0.1000	0.7615	0.6174	0.9154
$\rho_{Z,D}^{*}$	Technology, durables*	Beta	0.7500	0.1000	0.9494	0.9138	0.9881

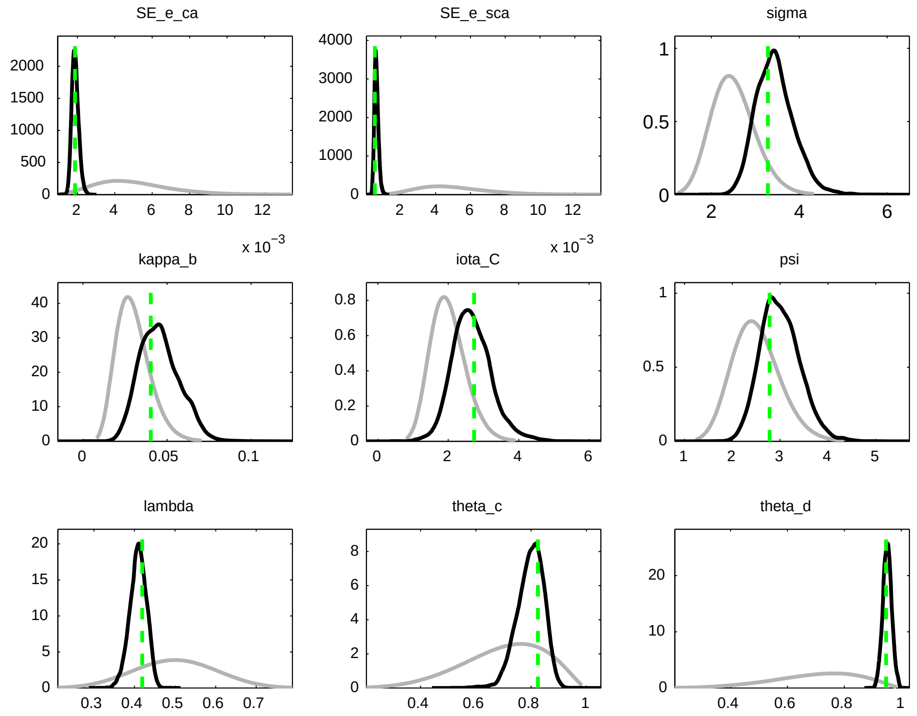
Table 1.5: Prior and posterior distribution of shock standard deviations

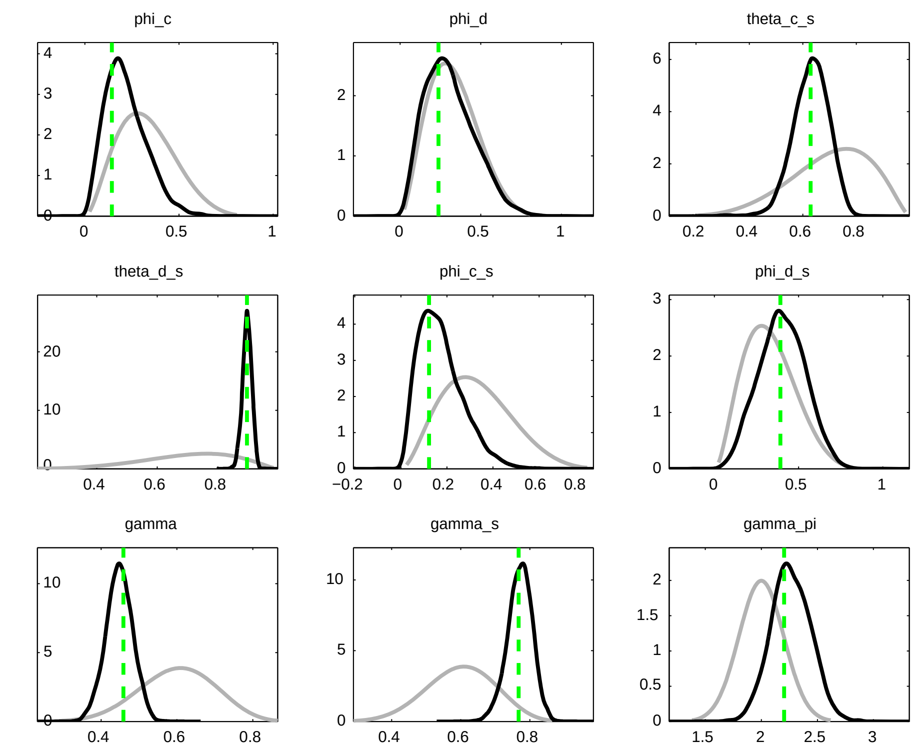
Parameter		Prior			Metropolis Hastings		
		Type	Mean	SD	Mean	90% HPD Interval	
σ_{m}	Monetary	Gamma	0.0050	0.0020	0.0014	0.0010	0.0017
$\sigma_{u_{\omega},t}$	Risk shock, durables	Gamma	0.2500	0.1250	0.1620	0.1264	0.1998
$\sigma_{u_{\omega},t}^{*}$	Risk shock, durables*	Gamma	0.2500	0.1250	0.1166	0.0751	0.1555
σ_{ϑ}	Risk premium	Gamma	0.0050	0.0020	0.0027	0.0018	0.0035
σ_{ξ}^{D}	Pref., durables	Gamma	0.0100	0.0050	0.0150	0.0031	0.0256
σ_{ξ}^{D*}	Pref., durables*	Gamma	0.0100	0.0050	0.0140	0.0045	0.0224
$\sigma_{\xi}^{D,COM}$	Pref., durables, EMU	Gamma	0.0100	0.0050	0.0138	0.0054	0.0222
σ_{ξ}^{C}	Pref., non-durables	Gamma	0.0100	0.0050	0.0076	0.0053	0.0098
σ_{ξ}^{C*}	Pref., non -durables*	Gamma	0.0100	0.0050	0.0046	0.0020	0.0072
σ_{Z}^{D}	Tech., durables	Gamma	0.0070	0.0020	0.0072	0.0038	0.0103
σ_{Z}^{D*}	Tech., durables*	Gamma	0.0070	0.0020	0.0113	0.0077	0.0151
σ_{Z}^{C}	Tech., non-durables	Gamma	0.0070	0.0020	0.0072	0.0045	0.0098
σ_{Z}^{C*}	Tech., non-durables*	Gamma	0.0070	0.0020	0.0046	0.0028	0.0063
$\sigma_{Z}^{C,COM}$	Tech., non-durables, EMU	Gamma	0.0070	0.0020	0.0058	0.0041	0.0074
σ_{EMU}	Technology, EMU	Gamma	0.0070	0.0020	0.0030	0.0019	0.0041

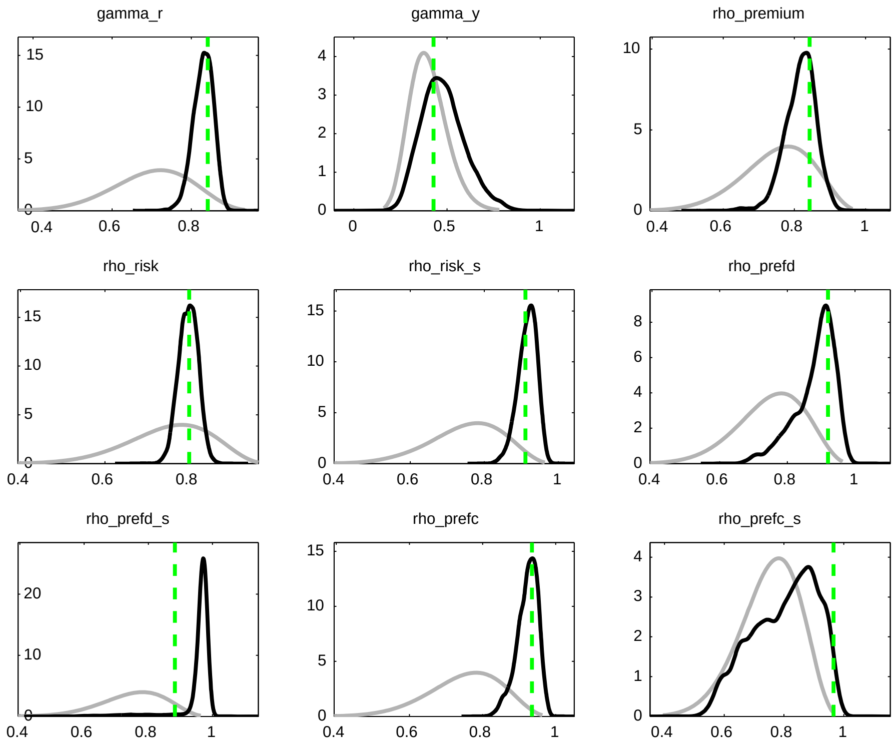
Note: Tech.=Technology; Pref.=Preferences; EMU indicates shocks affecting both areas simultaneously; Asterisks(*) indicate shocks on the peripheral area.

Prior and Posterior Distribution

The estimation generated the following prior-posterior mode plots:



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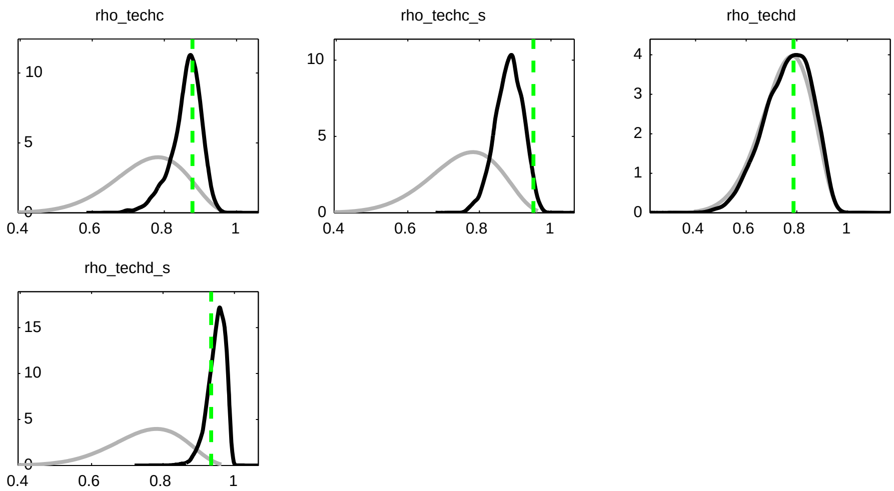
gamma_y
rho_premium
rho_risk
rho_risk_s
rho_prefd
rho_prefd_s
rho_prefc
rho_prefc_s


rho_techc
rho_techc_s
rho_techd
rho_techd_s

Chapter 2

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

Abstract

We develop a dynamic stochastic general equilibrium 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, also on the effective lower bound. In addition, we analyze the role of central bank funding and a rule-based flexible interest rate on CBDC. We find that, in times of crises, CBDCs can crowd out bank deposits and negatively affect bank funding. However, this crowding-out effect can be mitigated if the central bank chooses to provide additional central bank funds or to disincentivize large-scale CBDC accumulation through low CBDC interest rates.

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

JEL classification: D53, E42, E58, G21.

Chapter 2 is a discussion paper. An earlier version of this work has been published as Schiller and Gross (2021). We are very grateful for the helpful comments by Katrin Assenmacher, Alexander Bechtel, Lea Bitter, Carl-Andreas Claussen, Sonja Davidovic, Peter Dittus, Bernhard Herz, Stefan Hohberger, Dirk Niepelt, Werner Röger, David Tercero-Lucas, Mauricio Ulate, Taojun Xie, Johannes Zahner, Corinne Zellweger-Gutknecht, the participants of the MSY seminar at the ECB, the participants of the CBDC Research Forum at the University of Bern, the participants of the Annual Meeting 2021 of the Verein für Socialpolitik, and the participants of the 1st Annual Central Bank Conference on Development Economics in the Middle East and North Africa.

2.1 Introduction

The advent of Bitcoin and other private monies, such as global stablecoins, have raised concerns among central banks worldwide. If such cryptocurrencies gain significant market shares, monetary policy transmission and monetary sovereignty could be impaired (European Central Bank, 2020). In addition, 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 retail central bank digital currencies (CBDCs) — that is digital central bank money for private agents — 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, such as global stablecoins and foreign CBDCs (European Central Bank, 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 customer-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, in general, the academic literature on the effects of CBDCs on the financial sector is growing remarkably, more research on their impact on bank funding is needed, particularly (i) on the effects of different CBDC remuneration and (ii) on the role of central bank refinancing. Further, (iii) 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 allowing for 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 of 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. This paper (i) studies the options for the central bank to combat potential disintermediation of the financial sector and (ii) analyzes the effects of using a CBDC as a policy instrument. In particular, we consider two different forms of CBDCs — an interest-bearing CBDC and a non-interest-bearing CBDC — with different implications 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 accounts for a moral hazard problem. This rigidity increases the persistence of financial shocks, that is, it introduces a financial accelerator effect that mimics 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 be lost. Second, to capture the central bank's prominent 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 CBDC, which can be remunerated, as an additional option for households' portfolio decisions. We assume 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 exceptions, namely related to government expenditures and the interest rate on bonds, which are both calibrated based on euro area data. The additional parameters introduced specifically in our model are mainly calibrated to match data on bank funding.

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 replacement 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 for the financial sector and the real economy by disincentivizing substantial CBDC accumulation. A negative remuneration on CBDC, for example, could render

CBDC less attractive compared to its alternatives, thereby reducing the demand for CBDC.

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 greater 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 then 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 significantly.

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 channels 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 flexible and potentially negative interest rate provides central banks with an effective tool to govern the demand for CBDC. This tool can be used, amongst others, 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 (European Central Bank, 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 different CBDC remuneration designs.

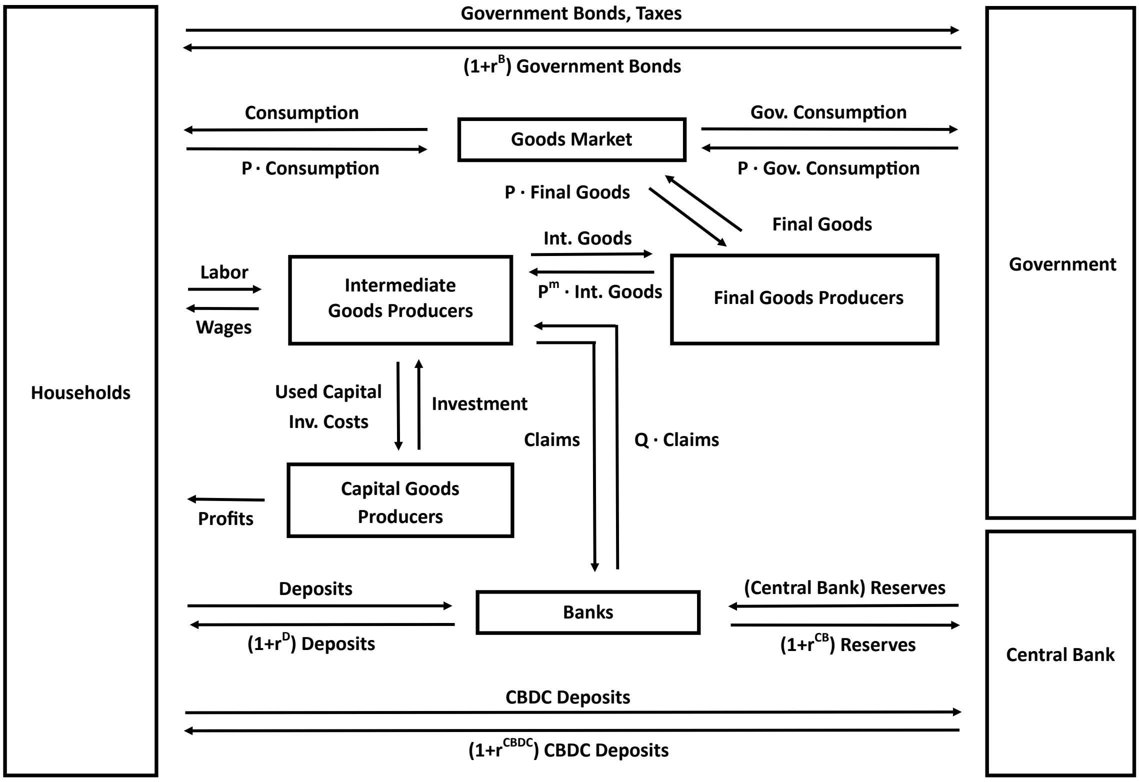
The remainder of the paper is structured as follows. Chapter 2.2 discusses our model. Chapter 2.3 explains and motivates the model calibration. Chapter 2.4 analyzes alternative versions of the model with non-interest-bearing CBDC (2.4.1), with interest-bearing CBDC (2.4.2), with and without full allotment (2.4.3), and with different interest rate rules on CBDC (2.4.4). Chapter 2.5 concludes.

2.2 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 chapter, we focus on a detailed discussion of our adaptions.[9] The basic structure of our model is depicted in Figure 2.1.

[9]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 Chapter 2.6.2.

Figure 2.1: Model structure



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, additionally, 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.

2.2.1 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 love of variety. Instead, the three forms of saving differ in terms of the three dimensions remuneration, liquidity, and risk (see Table 2.1).

Table 2.1: Comparison of bank deposits, CBDC, and government bonds

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

First, with regard to remuneration, deposits pay the real interest rate r^D, CBDC pays r^{CBDC}, and bonds pay r^B with $r^B \geq r^D \geq r^{CBDC}$.[10] 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:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Big(ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma} \; (D_{t+i} + CBDC_{t+i})^{1+\Gamma} \\ - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \Big), \tag{2.1}$$

where Υ and χ denote the relative utility weights of real money balances ($CBDC$

[10]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.

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).[11]

Households believe that banks could go bankrupt and, then, their deposits would be lost. The probability for this event is $1 - \psi$. Note that we abstract from deposit insurance schemes in our analysis.[12] The expected payout of bank deposits can be expressed as

$$(1 - \psi_t)0 + \psi_t(1 + r_t^D)D_t = \psi_t(1 + r_t^D)D_t. \tag{2.2}$$

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

$$\begin{aligned} C_t + D_t + CBDC_t + B_t = w_t L_t + \Pi_t &+ (1 + r_{t-1}^D)\psi_{t-1}D_{t-1} \\ &+ (1 + r_{t-1}^{CBDC})CBDC_{t-1} + (1 + r_{t-1}^B)B_{t-1}, \end{aligned} \tag{2.3}$$

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 Chapter 2.6.1.

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 losses in banks' equity (N):

$$\psi_t = 1 - \left(\frac{D_t}{F_t^*}\right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}}\Omega_N. \tag{2.4}$$

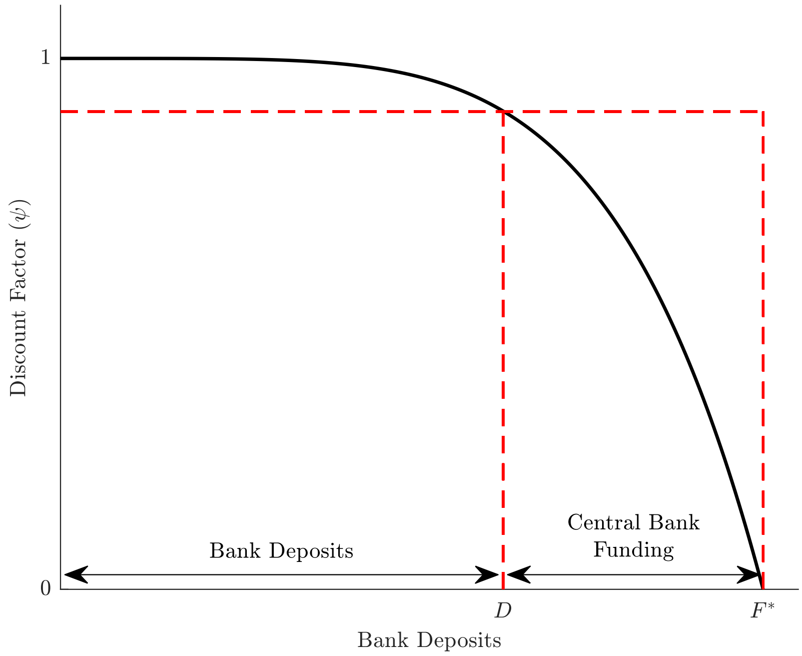
Banks receive external refinancing both from households and the central bank. F^*

[11] 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.

[12] 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.

denotes the maximum volume of external refinancing implied by the moral hazard in the financial sector (see Chapter 2.2.2). 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 is a scaling parameter and defines the impact of changes in banks' equity N.

Figure 2.2: Relationship between bank deposits and the discount factor



As depicted in Figure 2.2, 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 Chapter 2.2.2), they perceive deposits as more risky and the discount factor drops. When ψ decreases, such that the expected utility from holding deposits is lower relative to alternative assets, 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.[13]

[13]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. This assumption also implies that banks always own sufficient collateral to provide in exchange for additional central bank funds. We relax this assumption in Chapter 2.4.3.

Households perceive this more prominent role of the central bank as a stabilizing factor that lowers the risk in the financial sector. ψ rises up to the point at which households are indifferent between commercial bank money and its alternatives, taking into account the three dimensions 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 Chapter 2.3).

In addition, ψ depends on the term $\Omega_N \cdot (\bar{N} - N)/\bar{N}$. Thus, 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.

2.2.2 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 nominal interest rates i^D and i^{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 is given by:

$$Q_t S_{jt} = N_{jt} + D_{jt} + R_{jt}^{CB} = N_{jt} + F_{jt}, \tag{2.5}$$

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

$$N_{jt+1} = (1 + r_{t+1}^K) N_{jt} + (r_{t+1}^K - r_t^D) D_{jt} + (r_{t+1}^K - r_t^{CB}) R_{jt}^{CB}. \tag{2.6}$$

Note that a banker's equity is 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:

$$E_t \beta \Lambda_{t,t+1}(r_{t+1}^K - r_t^D) \geq 0, \tag{2.7}$$

$$E_t \beta \Lambda_{t,t+1}(r_{t+1}^K - r_t^{CB}) \geq 0, \tag{2.8}$$

where $\beta \Lambda_{t,t+1}$ is the discount factor derived from the first-order conditions of households (see Chapter 2.6.1), as we assume that bankers are part of the household sector, 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. These assumptions ensure that bankers cannot solely satisfy the demand for funds by intermediate goods producers with their equity and render external refinancing redundant (Gertler and Karadi, 2011). Banker j maximizes the expected terminal wealth, V_j, given by

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+i+1}(N_{jt+i+1}), \tag{2.9}$$

where θ is the probability that banker j remains a banker in the next period. Inserting the evolution of bankers' equity (2.6) into (2.9) yields:

$$\begin{aligned} V_{jt} = & E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+i+1} \\ & \Big[(1 + r_{t+1}^K) N_{jt} + (r_{t+1}^K - r_t^D) D_{jt} + (r_{t+1}^K - r_t^{CB}) R_{jt}^{CB}\Big]. \end{aligned} \tag{2.10}$$

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.[14] 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:

$$V_{jt} \geq \lambda Q_t S_{jt}. \tag{2.11}$$

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

$$V_{jt} = mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB}. \tag{2.12}$$

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

$$mu_t^N = E_t[(1-\theta)\beta\Lambda_{t,t+1}(1+r_{t+1}^K) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^N mu_{t+1}^N]; \tag{2.13}$$

$$mu_t^D = E_t[(1-\theta)\beta\Lambda_{t,t+1}(r_{t+1}^K - r_t^D) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^D mu_{t+1}^D]; \tag{2.14}$$

$$mu_t^R = E_t[(1-\theta)\beta\Lambda_{t,t+1}(r_{t+1}^K - r_t^{CB}) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^R mu_{t+1}^R], \tag{2.15}$$

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, 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 $R_{jt}^{CB} = R_t^{CB} N_{jt}/N_t$. Hence, we can derive the growth rates in the following manner:

$$\Delta_{t,t+1}^N = \frac{N_{jt+1}}{N_{jt}} = (1+r_{t+1}^K) + (r_{t+1}^k - r_t^D)\frac{D_t}{N_t} + (r_{t+1}^k - r_t^{CB})\frac{R_t^{CB}}{N_t}; \tag{2.16}$$

$$\Delta_{t,t+1}^D = \frac{D_{jt+1}}{D_{jt}} = \frac{D_{t+1}}{D_t}\Delta_{t,t+1}^N \frac{N_t}{N_{t+1}}; \tag{2.17}$$

$$\Delta_{t,t+1}^R = \frac{R_{jt+1}^{CB}}{R_{jt}^{CB}} = \frac{R_{t+1}^{CB}}{R_t^{CB}}\Delta_{t,t+1}^N \frac{N_t}{N_{t+1}}. \tag{2.18}$$

[14] In reality, banks cannot divert central bank money, as this money is backed by collateral. Thus, for banks, it is not possible to receive additional central bank funds without owning sufficient 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, e.g., resulting from insufficient collateral, in a substantially simplified manner.

Inserting (2.12) in (2.11) yields the following incentive constraint:

$$mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB} \geq \lambda Q_t S_{jt}. \tag{2.19}$$

Assuming that the incentive constraint (2.19) is binding and summing across all bankers, we calculate the maximum amount of external refinancing F^*:

$$F_t^* = \frac{\lambda - mu_t^N}{mu_t^R - \lambda} N_t + \frac{mu_t^R - mu_t^D}{mu_t^R - \lambda} D_t. \tag{2.20}$$

Accordingly, we express bankers' individual balance sheets (2.5) in aggregate terms in the following manner:

$$Q_t S_t = N_t + D_t + R_t^{CB}. \tag{2.21}$$

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

$$N_t = N_{et} + N_{nt}. \tag{2.22}$$

N_e can be expressed in the following manner:

$$N_{et} = \theta \Delta_{t-1,t}^N N_{t-1}. \tag{2.23}$$

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:

$$N_{nt} = \frac{\omega}{1-\theta}(1-\theta) Q_t S_{t-1} = \omega Q_t S_{t-1}. \tag{2.24}$$

2.2.3 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:

$$Q_t K_{t+1} = Q_t S_t. \tag{2.25}$$

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

$$Y_t^M = A_t (U_t \xi_t K_t)^\alpha L_t^{1-\alpha}, \tag{2.26}$$

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 (3.22) and labor demand (2.28):

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta'(U_t)\xi_t K_t, \tag{2.27}$$

$$P_t^M (1-\alpha) \frac{Y_t^M}{L_t} = W_t, \tag{2.28}$$

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:

$$R_t^K = \frac{[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta(U_t)]\xi_t}{Q_{t-1}}. \tag{2.29}$$

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.

2.2.4 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:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left[(Q_{t+i} - 1) I^N_{t+i} - f\left(\frac{I^N_{t+i} + \bar{I}}{I^N_{t-1+i} + \bar{I}} \right) (I^N_{t+i} + \bar{I}) \right], \tag{2.30}$$

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

$$Q_t = 1 + f(\cdot) + \left(\frac{I^N_t + \bar{I}}{I^N_{t-1} + \bar{I}} \right) f'(\cdot) - E_t \beta \Lambda_{t,t+1} \left(\frac{I^N_{t+1} + \bar{I}}{I^N_t + \bar{I}} \right)^2 f'(\cdot). \tag{2.31}$$

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

$$K_{t+1} = \xi_t K_t + I^N_t. \tag{2.32}$$

2.2.5 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:

$$Y_t = \left[\int_0^1 Y_{ft}^{\frac{\varepsilon-1}{\varepsilon}} df \right]^{\frac{\varepsilon}{\varepsilon-1}}. \tag{2.33}$$

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

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\varepsilon} Y_t, \tag{2.34}$$

$$P_t = \left[\int_0^1 P_{ft}^{1-\varepsilon} df \right]^{\frac{1}{1-\varepsilon}}. \tag{2.35}$$

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:

$$\max E_t \sum_{i=0}^{\infty} \gamma^i \beta^i \Lambda_{t,t+i} \Big[\frac{P_t^*}{P_{t+i}} \prod_{k=1}^{i} (\pi_{t+k-1,t+k})^{\gamma_\pi} - P_{t+1}^M \Big] Y_{ft+i}. \tag{2.36}$$

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

$$P_t = [(1-\gamma)(P_t^*)^{1-\varepsilon} + \gamma(\pi_{t-1,t}^{\gamma_\pi} P_{t-1})^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}}. \tag{2.37}$$

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

2.2.6 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 2.1). In this manner, the central bank 'leads' all interest rates with its rule-based interest rate on central bank funding:

$$i_t^{CB} = (1 + \bar{r}^{CB}) + \kappa_\pi \pi_t + \kappa_{y_{gap}} y_{gap,t}, \tag{2.38}$$

where κ_π is 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.

We assume that the nominal interest rate on deposits follows the interest rate on central bank funding with the fixed spread Δ^D:[15]

$$i_t^D = i_t^{CB} - \Delta^D. \tag{2.39}$$

We introduce this spread to match data indicating that, in normal times, central bank refinancing is more expensive than refinancing via deposits (Bindseil, 2020). While a fixed spread is a simplified assumption, it is heavily used in the literature, e.g., in Bindseil (2020).

In Chapter 2.4, we analyze scenarios, in which the ELB is binding. In these cases, if the interest rate on deposits would become negative, it is constrained by the ELB.[16] Accounting for the ELB, the interest rate on deposits is determined as follows:

$$i_t^D = \begin{cases} i_t^{CB} - \Delta^D & \text{for } i_t^{CB} - \Delta^D \geq 0, \\ 0 & \text{for } i_t^{CB} - \Delta^D < 0. \end{cases} \tag{2.40}$$

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:

$$i_t^{CBDC} = 0. \tag{2.41}$$

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):

$$i_t^{CBDC} = i_t^{CB} - \Delta^{CBDC}. \tag{2.42}$$

In Chapter 2.4.4, 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

[15]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.

[16]In the following, we assume that the ELB lies at 0% and is, thus, a zero lower bound.

lack of liquidity services has to be compensated for by a higher remuneration.[17]

$$i_t^B = i_t^{CB} + \Delta^B. \tag{2.43}$$

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

$$1 + i_t^D = (1 + r_t^D)(1 + E_t \pi_{t,t+1}); \tag{2.44}$$

$$1 + i_t^{CBDC} = (1 + r_t^{CBDC})(1 + E_t \pi_{t,t+1}); \tag{2.45}$$

$$1 + i_t^B = (1 + r_t^B)(1 + E_t \pi_{t,t+1}). \tag{2.46}$$

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 (R^{CB}) to fill the gap between the supply of deposits (D) and the maximum amount of total external refinancing (F^*):

$$R_t^{CB} = F_t^* - D_t. \tag{2.47}$$

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 central bank fully meets their money demand. We relax this assumption of full allotment in Chapter 2.4.3.

2.2.7 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_{t-1}^B. Note that we define G as a constant share of steady state output.

$$\bar{G} + (1 + i_{t-1}^B) B_{t-1} = T + B_t. \tag{2.48}$$

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

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:

$$Y_t = C_t + I_t + f\left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}}\right)(I_t^N + \bar{I}) + \bar{G}. \tag{2.49}$$

2.3 Calibration

Section 2.2.7 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 to 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.[18] 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 define 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,

[18] From 2003–2008, central bank refinancing, on average, accounted for 3% of bank funding, while capital market refinancing accounted for 30% (Bindseil, 2020). In our analysis, we neglect capital market refinancing. As a consequence, it seems reasonable to assume a higher share of central bank funding than the 3% outlined in Bindseil (2020).

Table 2.2: Parameter calibration

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

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.

2.4 Introducing CBDC

In this chapter, we discuss the implications of two different forms of CBDCs, an interest-bearing and a non-interest-bearing CBDC. For an interest-bearing CBDC, the central bank sets a flexible 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 can be flexible and co-moves with the CBDC interest rate.[19] Therefore, the central bank can react to a crisis by setting interest rates below the original ELB — that is, in our case, below zero — and stimulate the economy more effectively.

Our CBDC analysis involves four steps: First, in Chapter 2.4.1, 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 Chapter 2.4.2, we use the same shock to compare the baseline model (ELB-constrained and -unconstrained) to an unconstrained interest-bearing CBDC model. Third, in Chapter 2.4.3, we relax the assumption of full allotment of central bank money. Finally, in Chapter 2.4.4, we conclude with an analysis of a flexible rule-based interest rate on CBDC, such that the CBDC interest rate is used

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

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 first focus on the impact of a CBDC on the real economy and, then, 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 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 Chapter 2.6.2.[20]

2.4.1 Non-Interest-Bearing CBDC

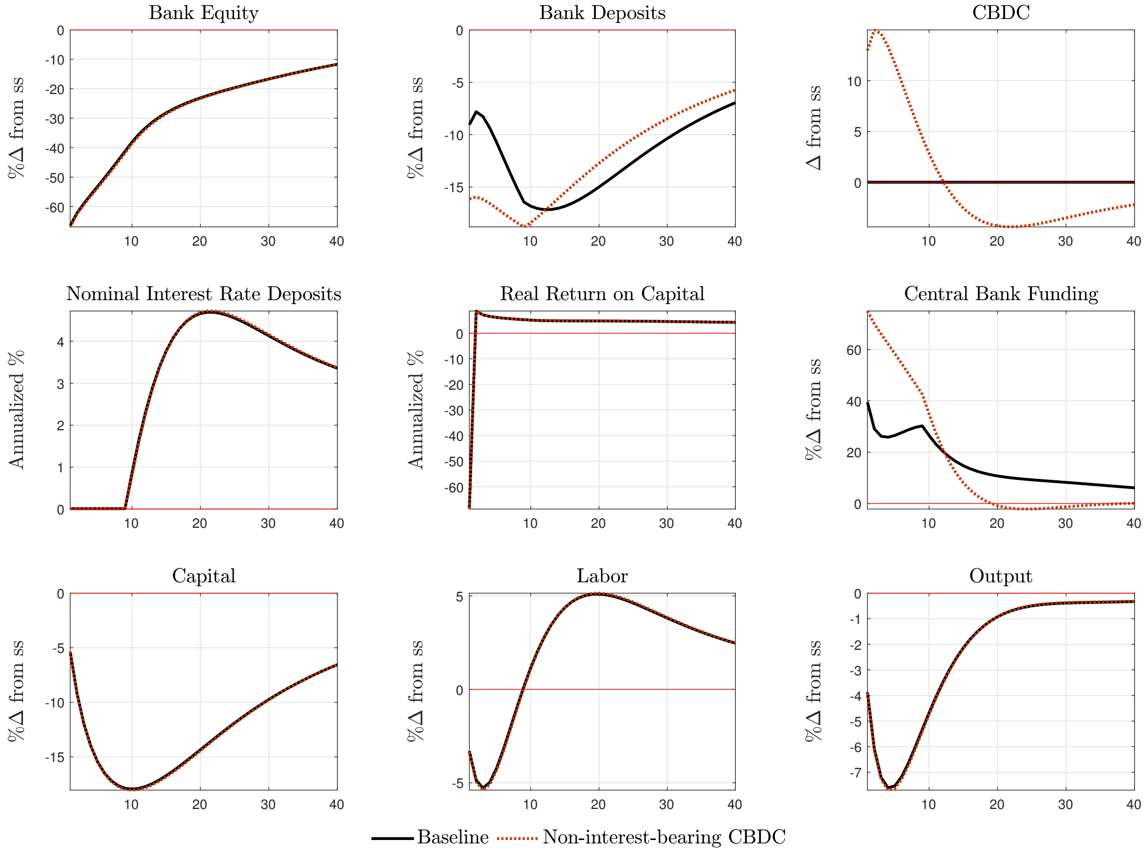
Figure 2.3 compares the dynamics of the baseline model without a CBDC with a model with a non-interest-bearing CBDC. The negative quality of capital shock implies a major reduction in the output of intermediate goods. This reduction leads to loan defaults[21] and a deterioration of banks' balance sheets.

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.

[20]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 functionss (IRFss) for additional variables in Chapter 2.6.3.

[21]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 write-off.

Figure 2.3: Baseline with ELB vs. non-interest-bearing CBDC with ELB



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%. 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%.

Note that the main reason for the substantial increase in CBDC is not the 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.[22] 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.[23] 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 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).

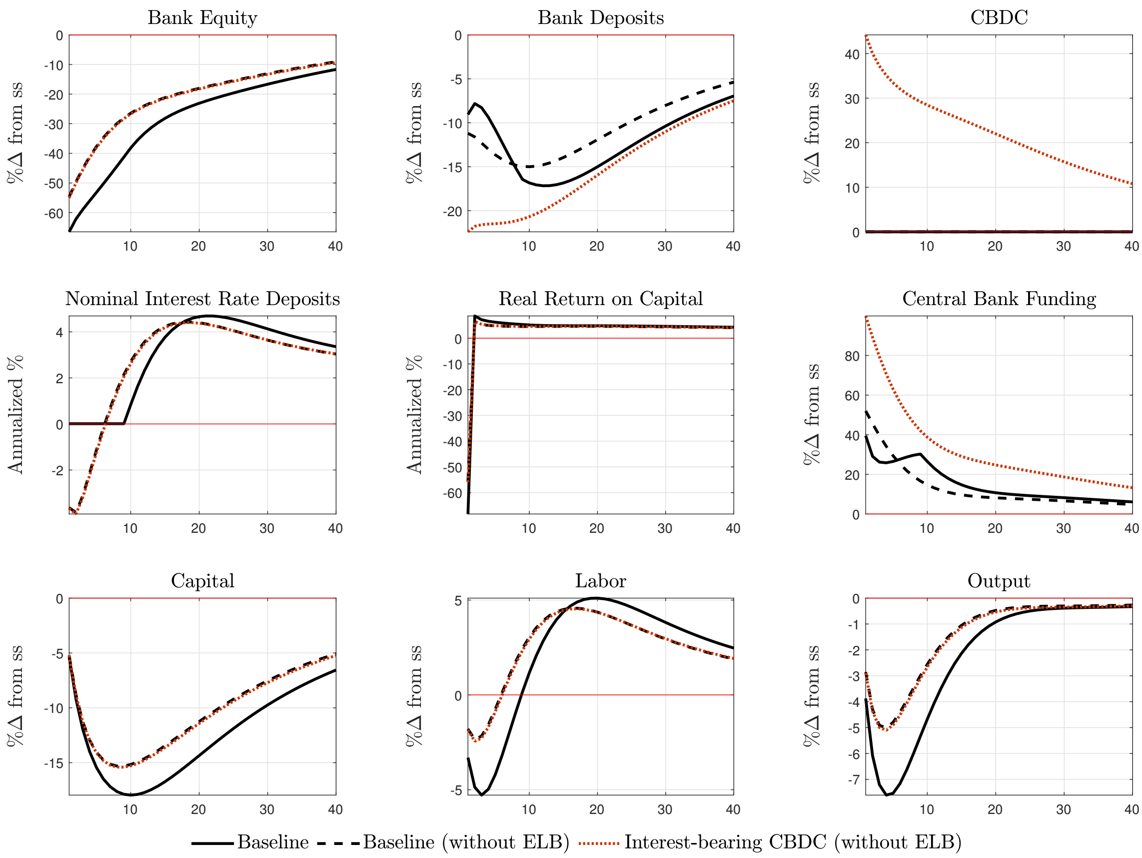
[22] In this simulation, CBDC deposits increase substantially and exceed central bank funds provided to banks by a factor of 6.5. Considering that, according to Eurostat and ECB data, the total net financial assets of households in the euro area amount to approximately 34,000 billion euro and central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

[23] 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.

2.4.2 Interest-Bearing CBDC

Figure 2.4 depicts the simulation results for the baseline model with and without an ELB and a model with an interest-bearing CBDC.[24] We present the baseline model both with and without an ELB to highlight that the major real effects do not occur due to disturbances caused 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.

Figure 2.4: Baseline with ELB vs. interest-bearing CBDC



The major advantage of an unconstrained deposit interest rate for monetary policy is that monetary policy measures directly affect households' savings decisions, for

[24] 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.

positive as well as negative interest rates. In this case, the nominal deposit interest rate follows the interest rate on central bank funds set by the central bank based on the Taylor rule. Hence, the central bank's reaction to economic changes — that 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 stronger 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 in deposits.[25] In the steady state, households hold approximately 27% of their liquidity in CBDC.[26] 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 the 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

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

[26]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.

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.

2.4.3 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. 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 should not be taken for granted.

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.

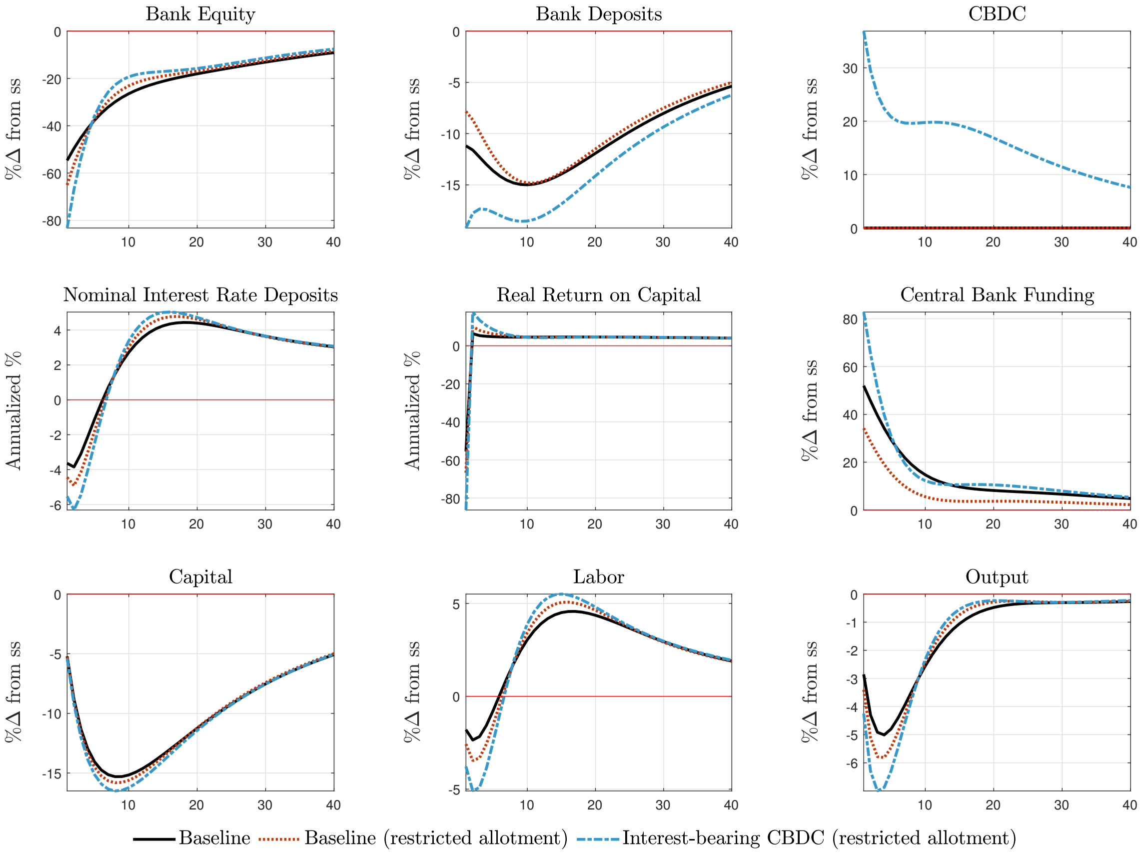
To analyze restricted allotment, we adapt 2.47 in the following manner:

$$R_t^{CB} = \bar{R}^{CB} + X[(F_t^* - \bar{F}^*) - (D_t - \bar{D})], \tag{2.50}$$

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 2.5 compares the baseline model for full allotment and restricted allotment ($X = 0.5$) with the interest-bearing CBDC model ($X = 0.5$). All models are not constrained by the ELB. 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.

Figure 2.5: Interest-bearing CBDC with different allotment of central bank funds



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% stronger drop in labor results in a 0.3% lower output in the baseline model. In the interesting-bearing CBDC model, labor drops an additionally 2%, leading to a further decline in output by 1.2%. The real return on capital and, thus, banks' equity drop an additional 10% in the baseline model and 25% in the interest-bearing CBDC model. 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, generalizing 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.

2.4.4 CBDC Interest Rate Rule

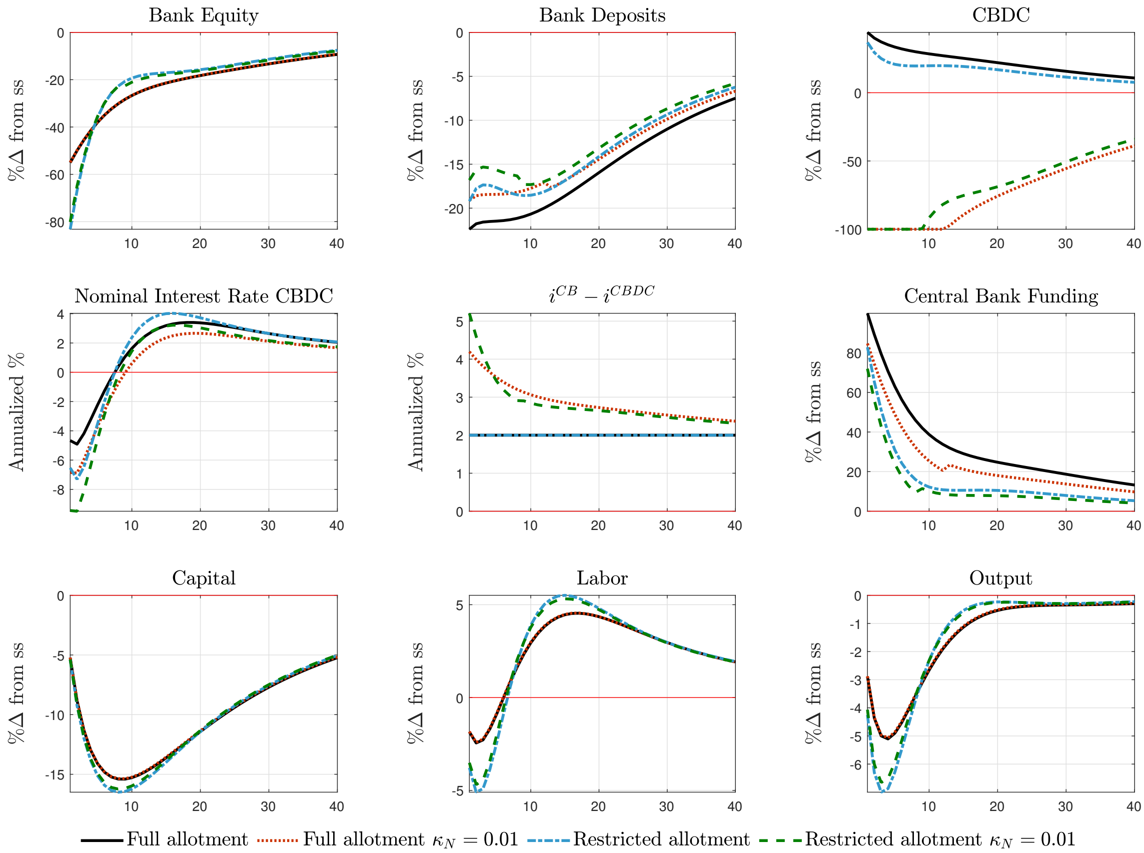
While the previous analysis suggests that full allotment is necessary to prevent destabilizing effects, the central bank can also use another tool. Bindseil (2020) proposes that central banks can actively use the interest rate on CBDC to disincentivize its accumulation in a crisis and, thus, to counteract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

For the following analysis, we adapt the CBDC interest rate rule (2.42) in the following manner:

$$i_t^{CBDC} = i_t^{CB} - \left(\Delta^{CBDC} + \frac{\bar{N} - N_t}{\bar{N}} \kappa_N \right). \tag{2.51}$$

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 Chapter 2.2.1, such that financial stress is expressed as the percentage deviation of banks' equity from steady state. κ_N specifies the intensity of the reaction.[27]

Figure 2.6: Flexible interest rate spread on CBDC



The blue and the green lines in Figure 2.6 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,

[27] 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.

and thus, deposits themselves, but is outweighed by the rising risk.[28] With restricted allotment, (relatively) 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 mitigate disintermediation and destabilization specifically caused by a 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.

2.5 Conclusion

While CBDCs can offer several benefits to individuals, 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, and can account for an ELB on nominal interest rates.

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, their main incentive to store their savings in the form of risky deposits is mitigated. The resulting disintermediation implies a contraction in the balance sheets of commercial banks and, thus, reduced loan volume, investment, and economic activity.

[28]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.

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 to substitute lost deposits with additional central bank funds, thereby substantially expanding its own balance sheet. 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 might not be 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 mitigate disintermediation and destabilization caused specifically by a CBDC. 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 steer the demand and prevent substantial accumulation. Apart from a strong commitment to full allotment, at least two alternative policies can 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, reducing 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.

2.6 Appendix

2.6.1 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:

$$\max\ E_t \sum_{i=0}^{\infty} \beta^i \Big(ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma}\ (D_{t+i} + CBDC_{t+i})^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \Big). \tag{2.52}$$

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

$$\begin{aligned} C_t + D_t + CBDC_t + B_t = {} & w_t L_t + \Pi_t + (1 + r_{t-1}^D)\psi_{t-1} D_{t-1} \\ & + (1 + r_{t-1}^{CBDC}) CBDC_{t-1} + (1 + r_{t-1}^B) B_{t-1}, \end{aligned} \tag{2.53}$$

with

$$\psi_t = 1 - \left(\frac{D_t}{F_t^*}\right)^{\Omega_D} - \frac{\bar{N} - N_t}{\bar{N}} \Omega_N. \tag{2.54}$$

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

$$\begin{aligned} \mathcal{L} = {} & E_t \sum_{i=0}^{\infty} \beta^i \Big\{ ln(C_{t+i} - hC_{t+i-1}) + \frac{\Upsilon}{1+\Gamma}\ (D_{t+i} + CBDC_{t+i})^{1+\Gamma} \\ & - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \\ & - \lambda_{t+i} \big[C_{t+i} + D_{t+i} + CBDC_{t+i} + B_{t+i} - w_{t+i} L_{t+i} - \Pi_{t+i} \\ & - (1 + r_{t+i-1}^D)(1 - \left(\frac{D_{t+i-1}}{F_{t+i+1}^*}\right)^{\Omega_D} - \frac{\bar{N} - N_{t+i-1}}{\bar{N}} \Omega_N) D_{t+i-1} \\ & - (1 + r_{t+i-1}^{CBDC}) CBDC_{t+i-1} - (1 + r_{t+i-1}^B) B_{t+i-1} \big] \Big\}. \end{aligned} \tag{2.55}$$

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

$$\frac{\partial \mathcal{L}}{\partial C_t} = (C_t - hC_{t-1})^{-1} - \beta h (C_{t+1} - hC_t)^{-1} - \lambda_t; \tag{2.56}$$

$$\frac{\partial \mathcal{L}}{\partial L_t} = -\chi L_t^{\phi} + \lambda_t w_t; \tag{2.57}$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial D_t} = {} & \Upsilon (D_t + CBDC_t)^{\Gamma} - \lambda_t \\ & + \beta \lambda_{t+1} (1 + r_t^D) \left\{ \psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right\};\end{aligned} \tag{2.58}$$

$$\frac{\partial \mathcal{L}}{\partial CBDC_t} = \Upsilon (D_t + CBDC_t)^{\Gamma} - \lambda_t + \beta \lambda_{t+1} (1 + r_t^{CBDC}); \tag{2.59}$$

$$\frac{\partial \mathcal{L}}{\partial B_t} = -\lambda_t + \beta \lambda_{t+1} (1 + r_t^B). \tag{2.60}$$

As households maximize their utility, all of the above equations must equal 0. Combining (2.57) and (2.56) yields:

$$\varrho_t w_t = \chi L_t^{\phi}, \tag{2.61}$$

where ϱ is the marginal utility of consumption and is equal to λ_t in (2.56):

$$\varrho_t = \frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t}. \tag{2.62}$$

Inserting (2.56) in (2.60) yields:

$$1 = \beta \Lambda_{t,t+1} (1 + r_t^B), \tag{2.63}$$

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

$$\Lambda_{t,t+1} = \frac{\varrho_{t+1}}{\varrho_t}. \tag{2.64}$$

Similar to (2.63), we derive the following equation for (2.58):

$$1 = \beta \Lambda_{t,t+1} (1 + r_t^D) \left(\psi_t - \Omega_D \left(\frac{D_t}{F_t^*} \right)^{\Omega_D} \right) + \frac{\Upsilon}{\varrho_t} (D_t + CBDC_t)^{\Gamma}, \tag{2.65}$$

and the following equation for (2.59):

$$1 = \beta \Lambda_{t,t+1} (1 + r_t^{CBDC}) + \frac{\Upsilon}{\varrho_t} (D_t + CBDC_t)^{\Gamma}. \tag{2.66}$$

To analyze the impact of the interest rate spread between r^B and r^{CBDC}, we equate (2.59) and (2.60):

$$\beta \varrho_{t+1}(r_t^B - r_t^{CBDC}) = \Upsilon(D_t + CBDC_t)^{\Gamma}. \tag{2.67}$$

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 more of their savings in the form of a liquid means of payment. Then, 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 (2.59) and deposits (2.58) yields:

$$\left[\frac{(1 - \frac{1+r_t^{CBDC}}{1+r_t^D} - \frac{\bar{N}-N_t}{\bar{N}}\Omega_N)}{1+\Omega_D}\right]^{\frac{1}{\Omega_D}} = \frac{D_t}{F_t^*}. \tag{2.68}$$

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.

To compare bank deposits and government bonds, we equate (2.60) and (2.58):

$$\beta \varrho_{t+1}(1+r_t^B) = \beta \varrho_{t+1}(1+r_t^D)\left(\psi_t - \Omega_D \left(\frac{D_t}{F_t^*}\right)^{\Omega_D}\right) + \Upsilon(D_t + CBDC_t)^{\Gamma}. \tag{2.69}$$

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.

2.6.2 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 differences in 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 2.7: Baseline vs. Gertler & Karadi (2011)

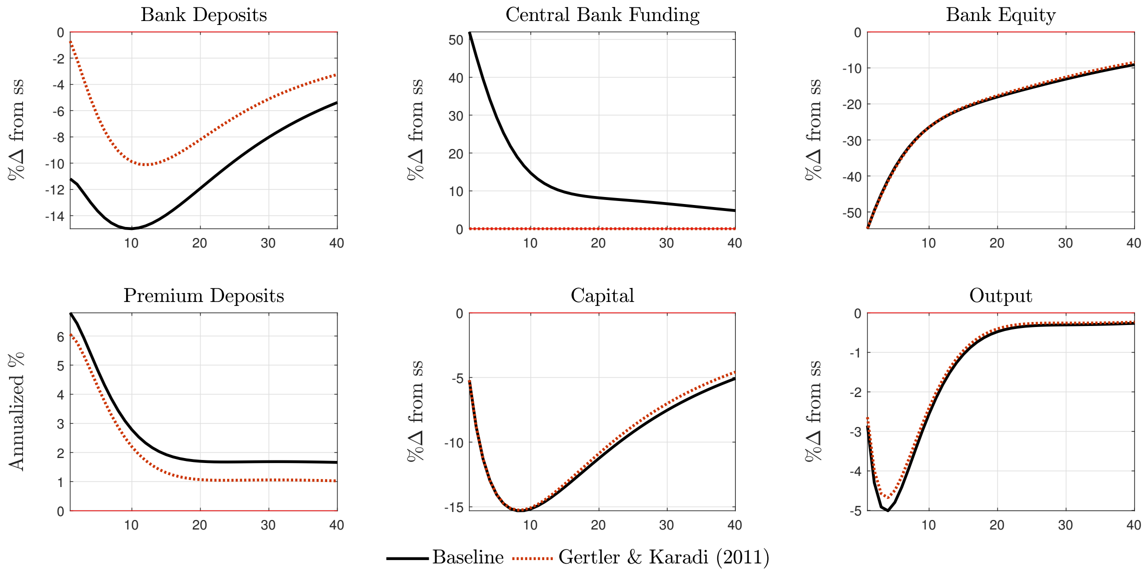


Figure 2.7 compares our model with GK. For both models, we induce a quality of capital shock of 5% with persistence 0.66 to simulate a crisis similar to the global financial crisis starting in 2007 (Gertler and Karadi, 2011). The fall in the quality of capital reduces effective capital and production. 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 have to 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.

2.6.3 Additional IRFs

In the following section, we present the remaining IRFss for the exercises conducted above. Note that we do not provide them for the simulations in Chapter 2.6.2. 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.

Figure 2.8: Additional IRFs baseline vs. non-interest-bearing CBDC (with ELB)

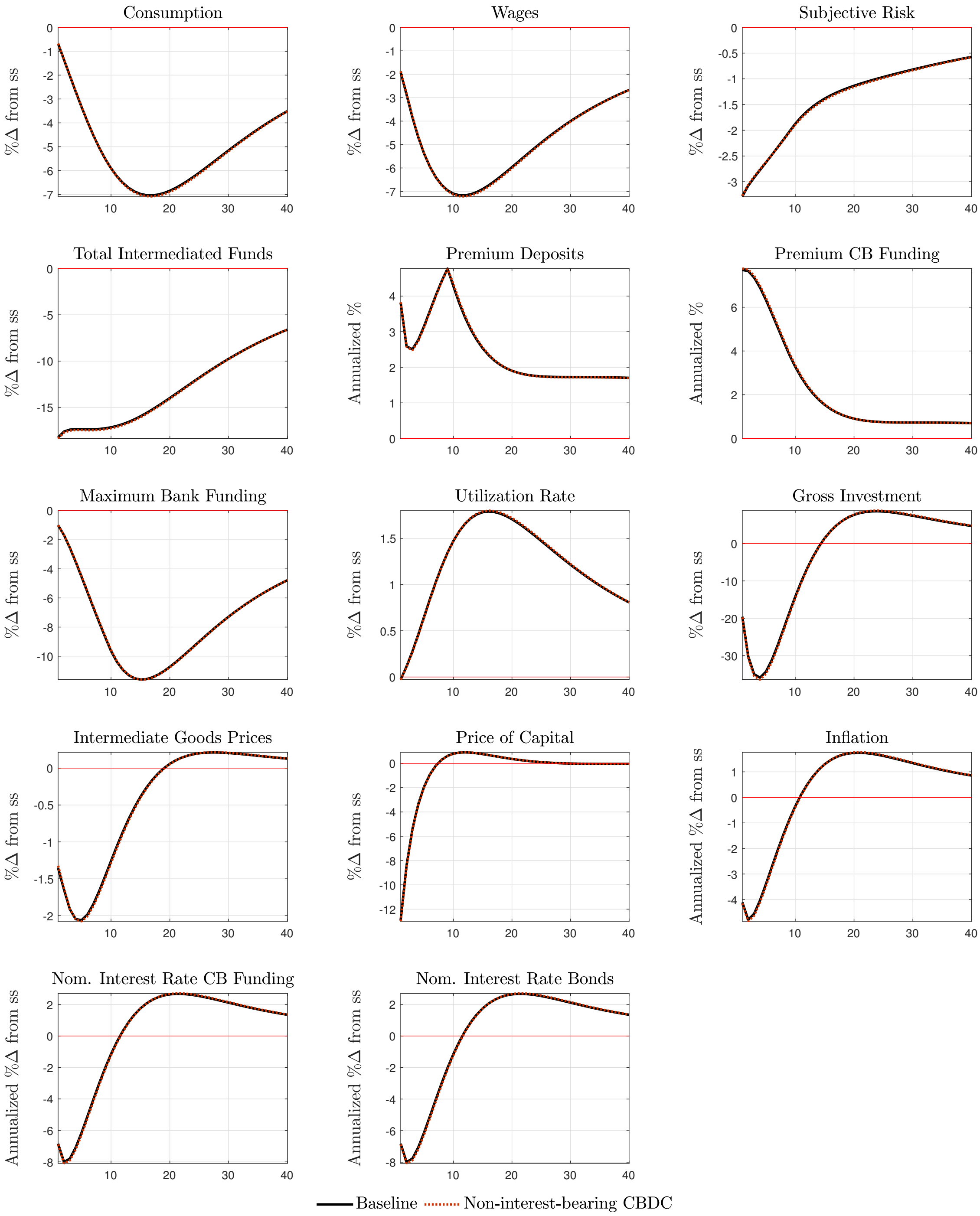


Figure 2.9: Additional IRFs baseline with ELB vs. interest-bearing CBDC

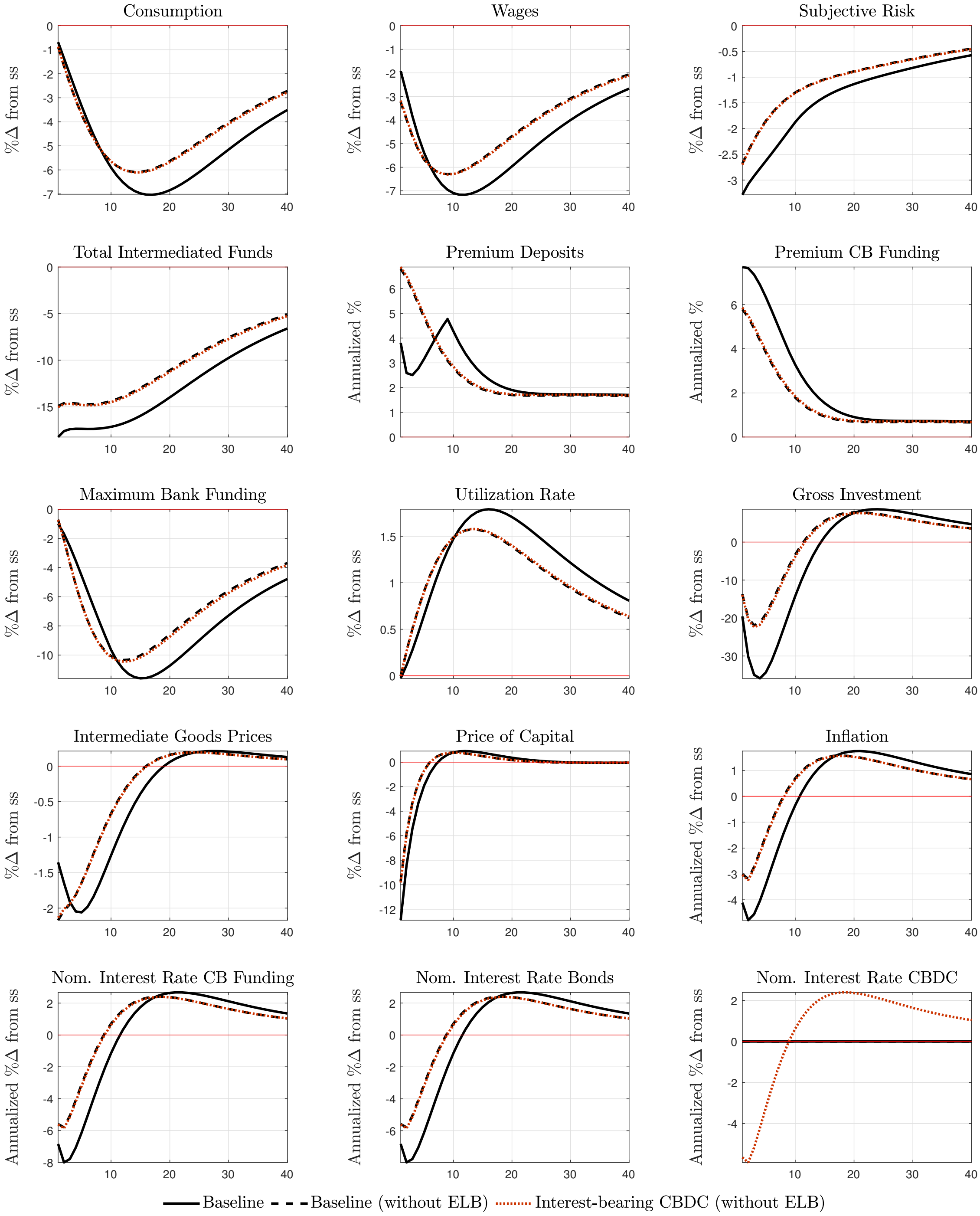


Figure 2.10: Additional IRFs interest-bearing CBDC with different allotment of central bank funds

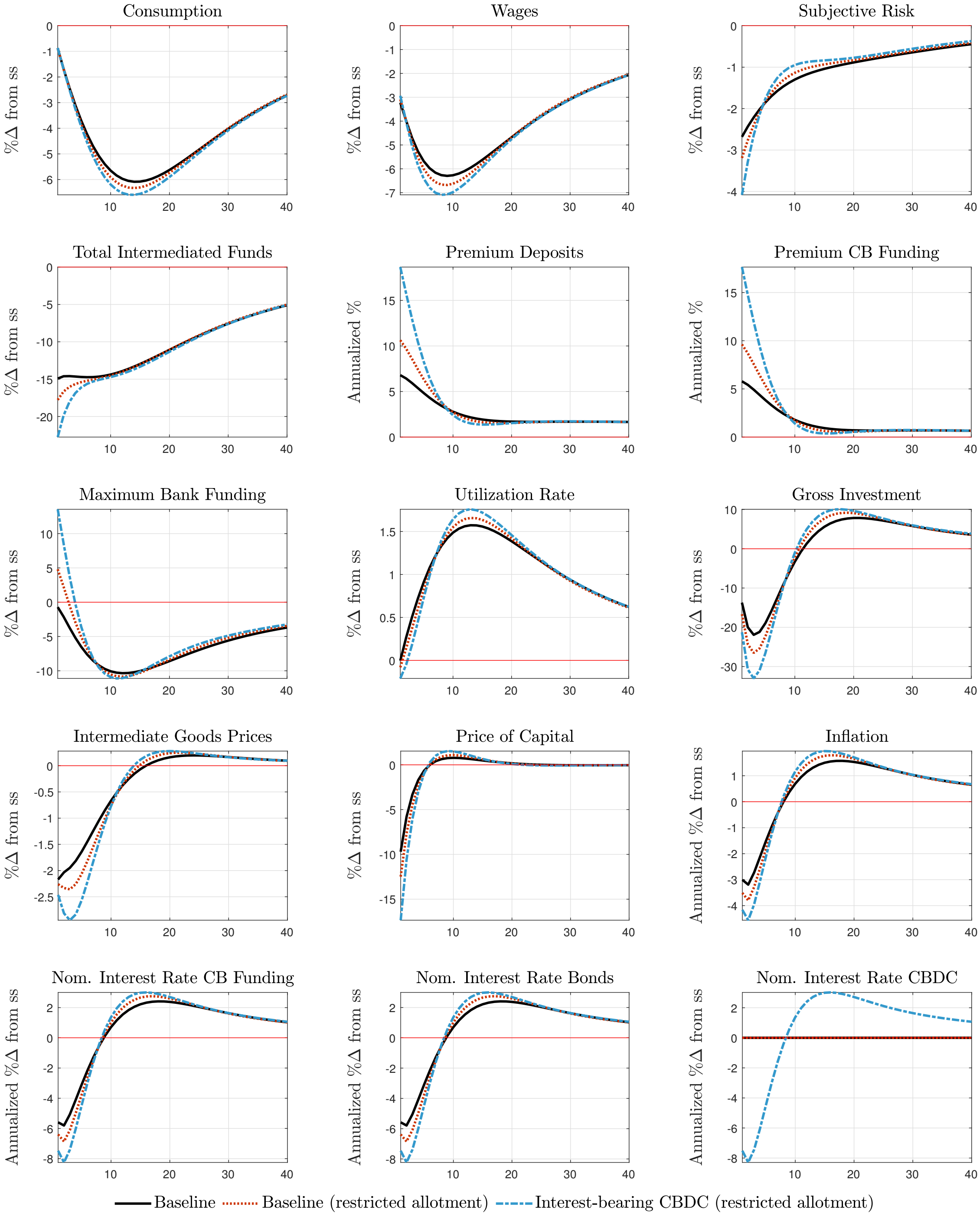
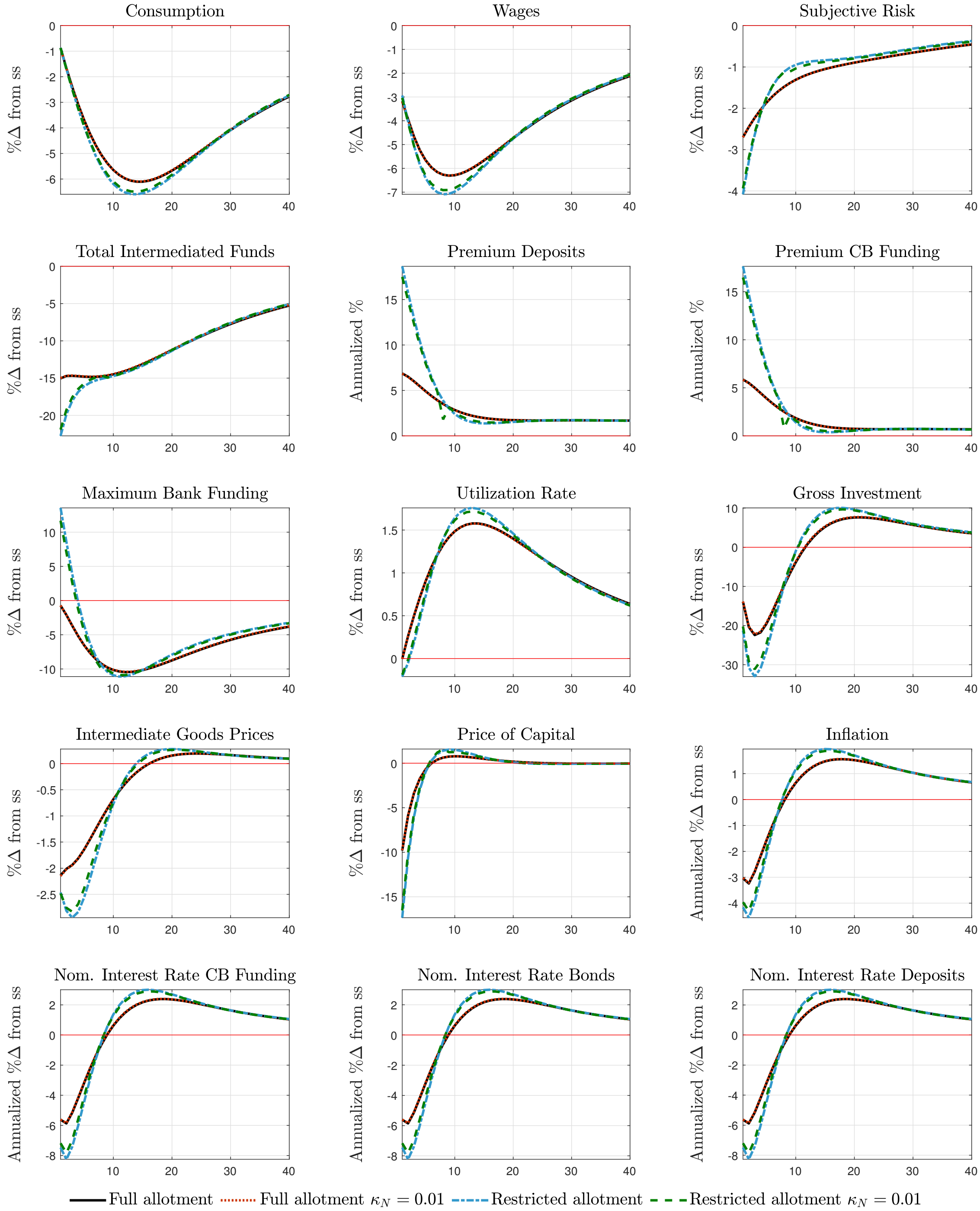


Figure 2.11: Flexible interest rate spread on CBDC with restricted allotment



Chapter 3

Quantitative Easing and Excess Reserves

Abstract

Since the great financial crisis, central banks worldwide have conducted large-scale asset purchases, which led to a substantial accumulation of excess reserves. I develop a dynamic stochastic general equilibrium (DSGE) model based on Gertler and Karadi (2011) that captures this effect. The model explicitly accounts for the accumulation of involuntary excess reserves as a result of quantitative easing (QE) and the resulting expansion of the central bank's balance sheet. While improving economic conditions and loan demand can then create additional inflationary pressures, the central bank can use a Taylor-rule type interest rate on its deposit facility to preserve price stability independent of the level of excess reserves. Furthermore, the presence of excess reserves does not necessarily impinge on bank profitability but can do so in times of negative interest rates with a binding effective lower bound (ELB), which justifies measures like the two-tier policy from the European Central Bank (ECB).

Keywords: financial sector, excess reserves, quantitative easing, DSGE.

JEL classification: D53, E42, E58, G21.

3.1 Introduction

Reserves in the euro area banking system increased dramatically throughout the great financial crisis, the sovereign debt crisis, and the COVID-19 pandemic. The banking sector accumulated vast amounts of excess reserves[29], which, close to zero before the great financial crisis in 2007, reached nearly 4.5 trillion euros by the end of 2021. This accumulation is driven primarily by the expansion of the monetary base through unconventional monetary policy like long term refinancing operations (LTROs) and large-scale asset purchases. With nominal interest rates on deposits at the central bank below zero, excess reserves have become a substantial cost factor for banks (see e.g. Demiralp et al. (2017), Macchiarelli (2018)). Additionally, among others, Bassetto and Phelan (2015), Phelan et al. (2015), and Saxegaard (2006) argued that, when economic conditions improve, excess reserves could lead to a rapid expansion of lending and to strong inflation.

Despite the obvious relation between large-scale asset purchases, excess reserves, and potential associated problems, most New Keynesian models that analyze unconventional monetary policy do not explicitly account for reserves. In general, the model-theoretical literature, e.g., Gertler and Karadi (2011) and Gertler and Karadi (2018), avoid accounting for excess reserves and model asset purchases via short-term debt issued by the government or the central bank, thereby sterilizing liquidity effects as their additional assets absorb created reserves. Other models ignore the banking sector and the topic of reserves entirely (see e.g. Hohberger et al. (2019) and Falagiarda (2014)).Two noteworthy exceptions are Jouvanceau (2019) who addresses excess reserves by including an exogenous shock to banks' balance sheets, and Curdia and Woodford (2011) who model asset purchases via the central bank balance sheet. However, Jouvanceau (2019)'s approach lacks an endogenous link between quantitative easing (QE) and reserves, and Curdia and Woodford (2011) do not explicitly analyze excess reserves.

The paper addresses this gap in the literature by providing a medium-sized dynamic

[29]Excess reserves are defined as any funds that banks hold in excess of their reserves requirements. For the euro area, this includes both funds held in the account for minimum reserves and in the deposit facility, which are remunerated equally since the introduction of a negative remuneration on the deposit facility. These funds are interchangeably called excess reserves and excess liquidity in the literature.

stochastic general equilibrium (DSGE) model based on Gertler and Karadi (2011). I expand the model along the lines of Ulate (2021), add a market for potentially risky short-term government bonds, and allow for endogenous excess reserves as a result of central bank asset purchases. The model features capital requirements regulation (CRR), endogenous remunerated excess reserves, and two different asset purchase programs: a corporate sector purchase program (CSPP), where the central bank acquires debt from producers, and a public sector purchase program (PSPP), where the central bank purchases short-term government debt. This research is an essential contribution to the literature on QE as it is, to my knowledge, the first DSGE model that explicitly addresses excess reserves that are being endogenously imposed on the banking sector as a result of central bank asset purchases. As I argue in the following, these involuntary excess reserves can create additional costs for banks and slow down the recovery process after financial distress.

The literature identifies two kinds of excess reserves: those held voluntarily and those held involuntarily. Voluntary excess reserves are held as a precautionary measure in case interbank markets fail or are unreliable. Thus, banks hold additional reserves to avoid falling short of the required minimum reserve or payment requirements. Unlike involuntary excess reserves, this phenomenon is well researched and understood for countries with developing financial sectors, where unstable institutional and legal frameworks incentivize precautionary liquidity buffers (see e.g. Saxegaard (2006), Agénor et al. (2004), Nissanke and Aryeetey (1998)). Apart from the potential threat to price stability, the authors argue that excess reserves are likely to reduce central banks' ability to control demand and stabilize the economy. With more liquidity in the banking sector than needed, additional liquidity provision for economic stimulation might prove largely ineffective.

Dressler and Kersting (2015) and Primus (2017) study voluntary excess reserves in the context of the global financial crisis for developed financial markets. Dressler and Kersting (2015) assume heterogeneous banks, where a fraction of banks face prohibitively high costs for lending, such that they prefer to hold their acquired deposits as excess reserves. In this framework, excess reserves arise independent of central bank liquidity provision and only due to interest rate spreads. Primus (2017) includes excess reserves with a specified cost function, such that banks have an incentive to hold excess reserves to avoid a potential shortfall of required reserves associated with high costs. Both models provide insights into a situation where excess reserves arise voluntarily, i.e., demand-driven, but do not address involuntary accumulation through central bank asset purchases, i.e., when excess reserves are essentially supply-driven.

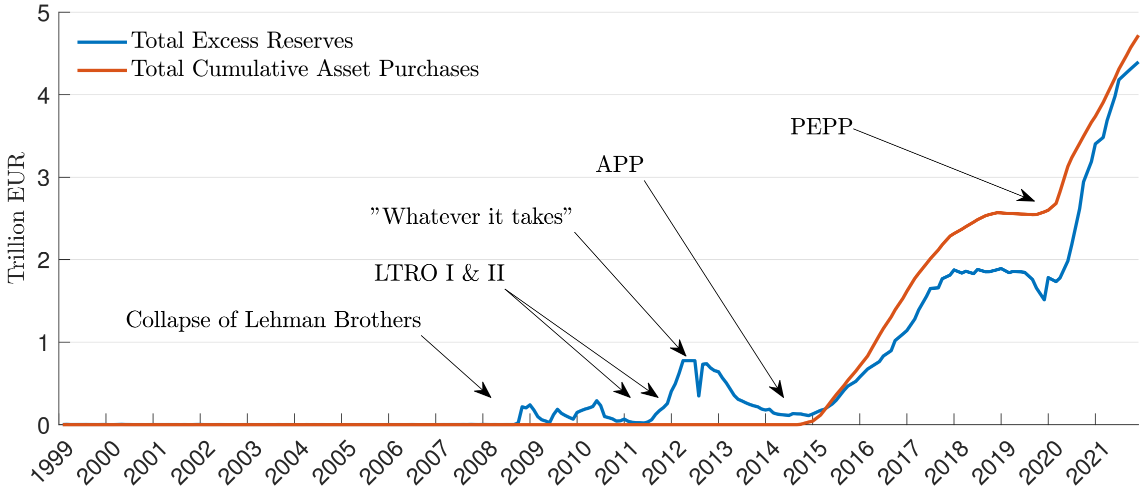
The effects of voluntary and involuntary excess reserves differ as voluntary excess reserves imply a suboptimal allocation of reserves in the banking sector, which involuntary excess reserves do not. In the former case, banks with excess reserves forgo profits on the interbank market and increase costs for those banks that lack reserves and have to refinance themselves at the central bank at the higher marginal lending rate. With the latter, the interbank market offers no substantial profits as the additional supply of liquidity pushes the Euro OverNight Index Average (EONIA) rate to the deposit facility rate. Banks that lack reserves can easily acquire those on the interbank market or by selling assets to the central bank. Thus, unlike voluntary excess reserves, involuntary excess reserves do not directly increase refinancing costs and imply opportunity costs. However, in holding involuntary excess reserves, banks can still face higher costs when deposit rates decouple from the deposit facility rate at the effective lower bound (ELB).

The current high levels of excess reserves are involuntary and the direct consequence of asset purchase programs. The logic is quite simple: any purchase the central bank conducts exchanges an asset for newly created central bank money. This central bank money ends up as physical cash or a deposit at a bank. When banks in total are reluctant to increase lending, either due to a lack of profitable investment opportunities or due to CRR, additional deposits necessarily end up as deposits at the central bank, i.e., it increases reserves and potentially leads to excess reserves.[30]

Figure 3.1 highlights this direct link between the expansion of the central bank balance sheet through asset purchases and total excess reserves from 1999 to 2021. Before the financial crisis in 2007, banks held close to no excess reserves. With a functioning interbank market, the whole sector had enough reserves to fulfill minimum requirements but did not hold any additional reserves, as these had to be

[30]See Keister and McAndrews (2009) for a thorough and visual exposition of the basic mechanism.

Figure 3.1: Asset purchases and excess reserves in the euro area



Development of ECB asset purchases and total excess reserves from 1999 to 2021 in trillion euros in the euro area. Total excess reserves are calculated as the sum of reserves above the minimum reserve requirement and the deposit facility. Asset purchases include both the APP and the PEPP. Source: ECB Statistical Data Warehouse.

acquired from the central bank at high costs. When the interbank market crashed due to the collapse of Lehman Brothers in 2008, banks could not rely on additional reserves from the interbank market and started building up precautionary reserves. The central bank reacted by announcing a full allotment procedure and bought covered bonds, which led to an increase in the monetary base and excess reserves from 2008 to 2011. During the following sovereign debt crisis, the central bank purchased government bonds from certain euro area members (SMP) and conducted two LTRO to provide cheap liquidity for banks and ease the consequences of the debt crisis. These policies led to a further increase in the monetary base and excess reserves. However, this upsurge was temporary, as the LTRO matured after three years. In 2015, the European Central Bank (ECB) announced its asset purchase program (APP) program and conducted large-scale asset purchases in the corporate and public sector, followed by the pandemic emergency purchase program (PEPP) in 2020. In December 2021, the central bank held assets worth 3.25 trillion under the APP and an additional 1.6 trillion under the PEPP, while excess reserves reached similar heights.

While LTROs were designed to specifically address liquidity shortages in the banking sector and resulting excess reserves were demand-driven, asset purchases are used to steer interest rate spreads and stimulate the economy when conventional policy measures are close or at the ELB. The provision of liquidity and the following dramatic accumulation of excess reserves in the banking sector can be considered a side-effect, not the intended outcome. As such, excess reserves are currently supply-driven.

I develop a model that tracks liquidity in the banking sector and allows for excess liquidity to capture this mechanism. Generalizing from Gertler and Karadi (2018) and Gertler and Karadi (2011), I assume that lending to the production sector is not a residual from banks' balance sheets but an active choice based on the expected return on loans and costs associated with potential CRR violations. As a result, banks actively choose between expanding lending and holding excess reserves when faced with additional liquidity from asset purchases. The CRR constraint is calibrated to be lax, i.e., banks primarily adapt their lending to expected returns, which is in line with the empirical results of Ennis and Wolman (2018) and Darvas and Pichler (2018). The model is calibrated to match an average euro area country in times of interest rates close to zero, loosely resembling the situation before the start of large-scale asset purchases. I assume homogeneous banks and well-functioning interbank markets, such that there are no excess reserves in the steady state. Excess reserves only increase when the central bank injects additional liquidity into the sector. The aggregate banking sector cannot avoid the accumulation of excess reserves, as an expansion of lending leads to an equal increase of deposits, which, assuming low minimum reserve requirements, does not substantially reduce excess reserves. Large increases in lending, which could lead to an absorption of excess reserves as minimum reserves, are further disincentivized by increasing costs for violating CRR and by declining expected returns from lending. In the model, the central bank uses the remuneration on excess reserves as a policy tool based on a Taylor rule.

I obtain the following results. First, excess reserves do not pose a direct threat to monetary policy efficiency. If the central bank uses a Taylor-rule type remuneration on excess reserves, it can effectively control interest rate spreads and avoid inflation after economic recovery. This observation follows directly from banks' profit maximization, where optimal choices are independent of the amount of reserves. This result is in line with Armenter and Lester (2017), Ennis (2018), and Bratsiotis (2021), who argue theoretically and empirically that interest on excess reserves is sufficient for monetary policy pass-through.

Second, unless interest rates are at the ELB, there is an equivalence between asset purchases conducted with new money or financed via government or central bank bonds as long as the bonds' interest rate equals the deposit facility rate, i.e., in this case, the level of excess reserves is irrelevant. Third, excess reserves negatively impact bank profitability if the remuneration of the asset the central bank bought is higher than the remuneration on excess reserves. Additionally, at the ELB for household deposits, negative deposit facility rates can create an unwanted spread that makes deposits an inferior source of funding that further depresses bank profitability. Fourth, while excess reserves can decrease bank profitability, the positive impact from asset purchases is stronger when credit supply is impaired. As asset purchases increase asset prices, this enhances bank equity, reduces capital costs, boosts investment, and improves the economic situation.

Involuntary excess reserves, thus, have an ambiguous effect on bank profitability and do not impair monetary policy pass-through. With interest on excess reserves, central banks have the necessary tool to avoid excessive growth in lending and soaring inflation.

The remainder of the paper is structured in the following manner. Section 3.2 presents the model. Section 3.3 explains and motivates the model calibration. In Section 3.4 the impulse response functionss (IRFss) for different simulations are presented and discussed. In particular, Section 3.4.1 compares corporate and public sector purchases to a simple liquidity injection. Section 3.4.2 analyzes asset purchases as a reaction to a financial crisis, and Section 3.4.3 highlights the role of the ELB for excess reserves and bank profitability. Section 3.5 concludes.

3.2 Model

The model builds on the closed economy New Keynesian framework by Gertler and Karadi (2011). As in Schiller and Gross (2021), the level of deposits is not determined solely in the financial sector but depends on households' utility maximization. As Gertler and Karadi (2011) model the financial sector without outside money, I substantially rework the financial sector by using and adapting elements from Ulate (2021) and include a market for government bonds. The resulting model explicitly accounts for reserves in the banking sector and endogenously explains the accumu-

lation of excess reserves. It is fully closed, i.e., it accounts for every transaction, keeping inside and outside money tractable. The central bank can intervene both in the bonds market (PSPP) and in the loan market (CSPP) by acquiring bonds or loans from banks, thereby increasing liquidity in the banking sector. In this section, I focus on the implemented changes in the household and financial sectors. For an in-depth presentation of the other sectors, see Gertler and Karadi (2011).
Banks intermediate funds between saving households and investing intermediate goods producers. The latter buy capital goods from capital goods producers and combine them with labor to produce intermediate goods. These goods are sold to competitive monopolistic final goods producers and supplied on the goods market. Banks are restricted by capital requirements, such that their equity determines the maximum level of loans. When producers default on their loans, banks' equity deteriorates, and the total amount of intermediated funds shrinks, impairing investment and production.

3.2.1 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 by holding cash (M) or deposits (D). Their utility function includes habit formation for consumption. The households' (aggregate) maximization problem can be written as:

$$\max\ E_t \sum_{i=0}^{\infty} \beta^i \left\{ ln(C_{t+i} - hC_{t+i-1}) - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\}, \tag{3.1}$$

where h is the habit parameter, χ the (dis)utility weight of labor, and ϕ the Frisch elasticity of labor supply. I assume that households pay a certain share M^*/C^* of their consumption in cash. Additionally, holding cash is costly, such that households seek to avoid holding cash above this share, which I model via a quadratic cost function in the budget constraint:

$$\begin{aligned} C_t + D_t + M_t + T_t = w_t L_t + \Pi_t^C + \Pi_t^F + \Pi_t^B + \frac{i_{t-1}^D}{\pi_{t-1,t}} D_{t-1} \\ + \frac{1}{\pi_{t-1,t}} M_{t-1} - \frac{\psi}{2}(\frac{M_t}{C_t} - \frac{M^*}{C^*})^2, \end{aligned} \tag{3.2}$$

where w is the real wage rate, Π is the income from the ownership of capital goods producers (Π^C), final goods producers (Π^F), and banks (Π^B), and T captures lump-sum taxes. i^D is the nominal return on deposits, and π is the inflation rate. The quadratic cost function is scaled by the parameter ψ that is used to pin down the steady state share of $\bar{M}/\bar{C}$. ψ also determines households' reaction to changes in the deposit interest rate: higher values imply less substitution of deposits for cash. Households maximize their utility by choosing M, D, C, and L. From the first-order conditions, the following equations result:

$$1 = \beta\Lambda_{t,t+1}(1 + r_t^D), \tag{3.3}$$

$$1 = \beta\frac{1}{\pi_{t,t+1}}\Lambda_{t,t+1} - \frac{\psi}{C_t}(\frac{M_t}{C_t} - \frac{M^*}{C^*}), \tag{3.4}$$

$$\varrho_t w_t = \chi L_t^{\phi}, \tag{3.5}$$

where ϱ is the marginal utility of consumption:

$$\varrho_t = \frac{\frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t}}{1 - \psi\frac{M_t}{C_t^2}(\frac{M_t}{C_t} - \frac{M^*}{C^*})}, \tag{3.6}$$

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

$$\Lambda_{t,t+1} = \frac{\varrho_{t+1}}{\varrho_t}. \tag{3.7}$$

The equation are standard apart from cash costs that allow for an interest rate spread between deposits and cash and affect the marginal utility of consumption due to its impact on the optimal level of cash.

3.2.2 Banks

There is a continuum of identical monopolistic competitive banks owned by households. Each period, they pay out dividends (Π^B) based on their profits (Π). Banks use their equity (N), households' deposits (D), and funds received from the central bank to buy bonds (B^B) and acquire claims on intermediate goods producers. The aggregate value of these claims, the total value of bank loans, is denoted L^B. The expected return on loans (r^L) depends on the performance of intermediate goods producers and is realized by a transfer of any revenues or losses in the next period. Banks receive their investment in bonds and pay back households' deposits and central bank funds together with the *ex-ante* known nominal interest rates i^B, i^D, and i^{CB}.

Banks need to balance their budget constraint. To do so, in the aggregate, they either have to acquire funds through the central bank's main refinancing operations (MRO)[31] when they are short on liquidity or hold excess liquidity in the central bank's deposit facility. With well functioning financial (interbank) markets, the two options are exclusive, as there is no incentive for banks to acquire liquidity at the generally higher MRO rate when they have to store the same liquidity at the lower deposit facility rate. I introduce the variable RR^{exc} that represents banks' accounts at the central bank to capture this dynamic. Positive values can be interpreted as excess reserves, while negative values indicate refinancing through MROs.[32] In addition, banks always hold a certain fraction ϖ of deposits as the minimum reserve RR^{min}. In defining RR^{min} separately from RR^{exc}, the central bank has more policy options by setting different interest rates on minimum and excess reserves.

Banks' aggregate balance sheet can be written as:

$$N_t + D_t + CB_t = B^B_t + L^B_t + RR^{min}_t + RR^{exc}_t, \tag{3.8}$$

[31] I exclude the marginal lending facility (MLF) in this analysis as it is not relevant in times of high liquidity. Without the MLF rate, the MRO rate serves as a ceiling for EONIA rates, assuming that interbank markets are without risk and refinancing at the central bank does not imply additional costs, e.g., through collateral requirements.

[32] I choose this approach to avoid occasionally binding constraints. These constraints would be necessary to prevent negative values of excess reserves or central bank refinancing. However, this simplification limits the analysis by combining the MRO rate with the deposit facility rate into i^{CB} (see chapter 3.2.6). Note further that I do not model collateral for central bank refinancing, as, in the following analysis, reserves are abundant, and refinancing does not occur.

where CB captures additional liquidity through central bank injections like LTROs. Banks' loan business is subject to capital requirements regulation, such that the individual and aggregate loan-to-equity ratio $(L^B + (1-\Psi)B^B)/N$ should not exceed its target value ρ, where (1-Ψ) captures the risk of government bonds. Banks face quadratic costs for deviating from that target. Bonds are assumed to be a safe investment in the steady state. However, if the risk for a government default increases, bonds enter the loan-to-equity ratio weighted by the respective default probability. Further, denoting RR^{min} as ϖD, the balance sheet (3.8) can be rewritten as:

$$RR_t^{exc} = N_t + (1-\varpi)D_t + CB_t - B_t^B - L_t^B. \tag{3.9}$$

The evolution of banks' equity depends on interest expenses and interest income. Additionally, following Ulate (2021), I assume that banks pay a certain fraction ς of their equity for managerial expenses and generate μ^D revenues on every unit of deposits collected from households. These revenues might stem from account fees or commissions for further services. The first assumption is necessary to pin down the steady state value of equity, while the latter assumption determines the spread between the nominal interest rate on reserves (i^{CB}) and the bank-set interest rate on deposits (i^D). Banks' expected total funds F in the next period before the payment of managerial costs and dividends to households can be written as:

$$\begin{aligned} E_t(F_{t+1}) = {} & (1+r_{t+1}^L)L_t^B + (1+r_t^{CB})RR_t^{exc} + (1-\Psi_t)(1+r_t^B)B_t^B \\ & - (1+r_t^D - \mu^D)D_t + RR_t^{min} - CB_t \\ & - f(\frac{L^B + (1-\Psi)B^B}{N_t}, \kappa, \rho), \end{aligned} \tag{3.10}$$

where $f(\frac{L^B+(1-\Psi)B^B}{N}, \kappa, \rho) = \kappa\frac{L^B+(1-\Psi)B^B}{N}(ln(\frac{L^B+(1-\Psi)B^B}{N}) - ln(\rho) - 1) + \kappa\rho$ is the quadratic costs for deviating from the target loan-to-equity ratio (ρ). Using (3.9), we can write banks' expected profits as:

$$\begin{aligned} E_t(\Pi_{t+1}) = {} & r_t^{CB}N_t + (r_{t+1}^L - r_t^{CB})L_t^B + r_t^{CB}CB_t + (1-\Psi_t)(r_t^B - r_t^{CB})B_t^B \\ & + \varsigma N_t(\pi_{t,t+1} - 1) + (r_t^{CB} - r_t^D + \mu^D - (r_t^{CB} + \frac{\pi_{t,t+1} - 1}{\pi_{t,t+1}})\varpi)D_t \\ & - f(\frac{L_t^B + (1-\Psi_t)B_t^B}{N_t}, \kappa, \rho). \end{aligned} \tag{3.11}$$

Note that Π_{t+1} differs from $E_t(\Pi_{t+1})$ as I exclude the scenario of a government default in my analysis and — contrary to their expectations — banks always retrieve their investment in bonds.[33] This approach allows for a micro-funded spread between the deposit facility rate and bonds without assuming government defaults in every period.

Following Ulate (2021), banks pay a certain fraction ω of their realized profits as dividends to households:

$$\Pi_t^B = \omega \Pi_t. \tag{3.12}$$

This way, loan performance impacts banks' equity as losses cannot be fully transferred to shareholders. Additionally, equity is slow-moving, i.e., banks cannot obtain the optimal level of equity without frictions.

Banks' equity evolves according to:

$$N_{t+1} = N_t + (1-\omega)\Pi_{t+1} - \varsigma N_t. \tag{3.13}$$

On the deposit market, bankers act as monopolistic competitors. With ε^D as the elasticity of substitution, aggregate deposits (D) are defined as a constant elasticity of substitution (CES) composite of differentiated deposits (D_j):

$$D_t = \left[\int_0^1 D_{jt}^{\frac{\varepsilon^D - 1}{\varepsilon^D}} dj \right]^{\frac{\varepsilon^D}{\varepsilon^D - 1}}. \tag{3.14}$$

Bank j's deposits are given by:

$$D_{jt} = \left(\frac{1 + r_{jt}^D}{1 + r_t^D} \right)^{-\varepsilon^D} D_t. \tag{3.15}$$

Note that bank j cannot affect the aggregate real interest rate on deposits (r^D), and thus, from an individual bank's perspective, D is exogenous. Similarly, individual levels of loan (L_j) are aggregated via a CES function with ε^L as the elasticity of substitution between different loan sources. Bank j maximizes its profits by choosing

[33] While banks expect a potential government default, the analysis excludes this scenario. Further research could expand the model to allow for government defaults, which would explicitly give an endogenous motivation for central banks to intervene in the bond market for financial stability concerns.

B_j, and r_j^D and the share of profits it demands for loans.[34] From the first-order conditions, the following equations result:

$$r_t^B = \frac{1+r_t^{CB}}{\Psi_t} - 1 + (1-\Psi_t)\kappa(ln(\frac{L_t^B + (1-\Psi_t)B_t^B}{N_t}) - ln(\rho)) + spread, \tag{3.16}$$

$$1 + r_t^D = \frac{\varepsilon^D}{\varepsilon^D - 1}(1 + r_t^{CB} + \mu^D - (r_t^{CB} + \frac{\pi_{t,t+1} - 1}{\pi_{t,t+1}})\varpi), \tag{3.17}$$

$$1 + r_{t+1}^L = \frac{\varepsilon^L}{\varepsilon^L - 1}\left[1 + r_t^{CB} + \kappa\left(ln\frac{L_t^B + (1-\Psi_t)B_t^B}{N_t} - ln\rho\right)\right]. \tag{3.18}$$

Equation (3.16) states that banks choose B^B such that the expected real return on bonds equals the real return on excess reserves, including the opportunity cost for holding bonds instead of lending to comply with the capital requirement regulations. Note that if $\Psi = 1$, then $r^B = r^{CB}$. For this simple case, if $r^B > r^{CB}$, banks will increase their bond holdings, thereby either increasing funds from the central bank's lending facilities or decreasing excess reserves. As the bond interest rate is determined on the bond market, this increase in demand leads to an increase in r^B until $r^B = r^{CB}$. The parameter *spread* is used for some policy experiments below to create a steady state difference in the remuneration of bonds and reserves. It might resemble an exogenous liquidity or risk premium. Equation (3.17) describes the real interest rate on deposits, while equation (3.18) defines the relationship between loans and the expected real return on loans. As all banks are identical, I drop the j subscript from r^D and L^B.

Note that the level of excess reserves does not appear in these equilibrium conditions, i.e., the optimal loan level, the optimal interest rate on deposits, and the optimal amount of bonds are not directly affected by the amount of excess liquidity in the banking sector. Instead, these variables are determined by interest rate spreads above the deposit facility rate. Intuitively, this result reflects that banks cannot control the level of total reserves in the system and therefore take it as given. This observation has two important implications. First, the supply-driven provision of additional reserves in times of ample liquidity automatically leads to excess reserves

[34] The rationale and the exact derivation for loans can be found in Ulate (2020).

as banks' optimal behavior is unaffected. Second, the central bank does not lose control over monetary aggregates as its ability to steer the loan volume rests solely on the deposit facility rate and is independent of excess reserves.

While excess reserves do not affect the equilibrium conditions above, they have a potentially strong impact on bank profitability when deposit interest rates are constrained by an ELB. Furthermore, it is crucial to understand how the additional reserves are provided. When the central bank buys assets, i.e., bonds (PSPP) or shares of intermediate goods producers (CSPP), this purchase has an impact on the value and expected return of these assets, which lowers interest rate margins and further depresses bank profitability.

3.2.3 Intermediate Goods Producers

Intermediate goods producers receive funds from banks and — with active CSPP — from the central bank, 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 final goods market.

The timing is as follows. At the beginning of period t, 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 determine the price of capital. Lower capital prices disincentivize the build-up of capital by capital goods producers and thus, 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:

$$Q_t K_{t+1} = Q_t S_t, \tag{3.19}$$

where QS is the total amount of funds intermediate goods producers receive from banks L^B and the central bank $CSPP$:

$$Q_t S_t = L_t^B + CSPP_t. \tag{3.20}$$

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

$$Y_t^M = A_t (U_t \xi_t K_t)^{\alpha} L_t^{1-\alpha}, \tag{3.21}$$

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 (3.22) and labor demand (3.23):

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta'(U_t) \xi_t K_t, \tag{3.22}$$

$$P_t^M (1-\alpha) \frac{Y_t^M}{L_t} = W_t, \tag{3.23}$$

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^L can be written as:

$$r_t^L = \frac{[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta(U_t)] \xi_t}{Q_{t-1}} - 1. \tag{3.24}$$

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 great financial crisis.

3.2.4 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 at Q. The creation of new capital goods is subject to (flow) adjustment costs. Capital producers' profits are transferred in each period to households. Gross capital goods created are defined as I and net investment I^N as the difference between I and refurbished capital goods $I^N = I - \delta(U)\xi K$. $\bar{I}$ denotes the steady state level of investment.

Capital goods producers maximize the sum of their discounted profits:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left[(Q_{t+i} - 1) I_{t+i}^N - f\Big(\frac{I_{t+i}^N + \bar{I}}{I_{t-1+i}^N + \bar{I}} \Big) (I_{t+i}^N + \bar{I}) \right], \tag{3.25}$$

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:

$$Q_t = 1 + f(\cdot) + \Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} \Big) f'(\cdot) - E_t \beta \Lambda_{t,t+1} \Big(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}} \Big)^2 f'(\cdot). \tag{3.26}$$

Hence, in the steady state $\bar{Q} = 1$, while changes in the level of investment increase production costs and, consequently, the price of capital. Capital producers' profits are given by:

$$\Pi_t^C = (Q_t - 1) I_t^N - \frac{\eta_i}{2} \Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} - 1 \Big)^2 (I_t^N + \bar{I}). \tag{3.27}$$

Note that capital evolves according to the following equation:

$$K_{t+1} = \xi_t K_t + I_t^N. \tag{3.28}$$

3.2.5 Final Goods Producers

Final goods producers are also owned by households. They buy intermediate goods, repackage 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, the total output Y is defined as a CES composite of differentiated final goods:

$$Y_t = \left[\int_0^1 {Y_{ft}}^{\frac{\varepsilon - 1}{\varepsilon}} df \right]^{\frac{\varepsilon}{\varepsilon - 1}}. \tag{3.29}$$

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

$$Y_{ft} = \Big(\frac{P_{ft}}{P_t} \Big)^{-\varepsilon} Y_t, \tag{3.30}$$

$$P_t = \left[\int_0^1 {P_{ft}}^{1-\varepsilon} df \right]^{\frac{1}{1-\varepsilon}}. \tag{3.31}$$

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 can 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:

$$\max E_t \sum_{i=0}^{\infty} \gamma^i \beta^i \Lambda_{t,t+i} \Big[\frac{P_t^*}{P_{t+i}} \prod_{k=1}^{i} (\pi_{t+k-1,t+k})^{\gamma_\pi} - P_{t+1}^M \Big] Y_{ft+i}. \tag{3.32}$$

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

$$P_t = [(1-\gamma)(P_t^*)^{1-\varepsilon} + \gamma(\pi_{t-1,t}^{\gamma_\pi} P_{t-1})^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}}. \tag{3.33}$$

Thus, the retail price level is a weighted average of adjusted and non-adjusted prices. Final goods producers' aggregate profits are given by:

$$\Pi_t^F = (P_t - P_t^M) Y_t^M. \tag{3.34}$$

3.2.6 Central Bank

The central bank sets the nominal interest rate on both its deposit facility and main refinancing operations i^{CB} according to a standard Taylor rule without interest rate smoothing (Gertler and Karadi, 2011). As banks are homogeneous, RR^{exc} is either positive or negative for all banks at a given time t. Thus, in the model, i^{CB} is either the main refinancing rate or the deposit facility rate, but never both at the same time. Based on my calibration, RR^{exc} will never be negative. Hence, i^{CB} is always the deposit facility rate.

$$i_t^{CB} = \bar{i}^{CB} + \kappa_\pi \pi_t + \kappa_{y_{gap}} y_{gap,t}, \tag{3.35}$$

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), I use the negative value of the price markup as a proxy for the output gap.

Apart from setting interest rates, the central bank conducts unconventional monetary policy by buying shares of intermediate goods producers ($CSPP$) and bonds ($PSPP$) from banks. The central bank chooses its shares Z in total loans to intermediate goods producers (Z^C) and bonds (Z^B) in response to changes in the loan premium and the bond premium, respectively.

$$Z_t^C = \bar{Z^C} + \Upsilon^C E_t[ln(\frac{1+r_{t+1}^L}{1+r_t^{CB}}) - ln(\frac{1+\bar{r}^L}{1+\bar{r}^{CB}})], \tag{3.36}$$

$$Z_t^B = \bar{Z^B} + \Upsilon^B E_t[ln(\frac{1+r_t^b}{1+r_t^{CB}}) - ln(\frac{1+\bar{r}^b}{1+\bar{r}^{CB}})], \tag{3.37}$$

where

$$Z_t^C = \frac{CSPP_t}{Q_t S_t}, \tag{3.38}$$

$$Z_t^B = \frac{PSPP_t}{B_t}. \tag{3.39}$$

With this modeling approach, the underlying assumption is that the central bank can choose its two available unconventional monetary policy tools with different goals in mind. $CSPP$ is designed to reduce volatility in asset prices and support the economy in times of scarce funding. Specifically, the additional funds for intermediate goods producers will reduce capital costs, which leads to additional investment and faster economic recovery after a shock. $PSPP$ affects the bond market by reducing risk and, thus, the costs for government debt. High risk levels of government default are a substantial threat to financial stability, which gives a reason for the central bank intervention.

The central bank transfers any profits to the government. Profits are given by:

$$\begin{aligned} \Pi_t^{CB} = (&\frac{i_{t-1}^B}{\pi_{t-1,t}} - 1)PSPP_{t-1} + r_t^L CSPP_{t-1} \\ &- (\frac{i_{t-1}^{CB}}{\pi_{t-1,t}} - 1)RR_{t-1}^{exc}. \end{aligned} \tag{3.40}$$

3.2.7 Government and Aggregation

The government receives income from lump-sum taxes (T) and central bank profit (Π^{CB}) and issues government bonds (B). It finances government spending (G) and repays last period's bond holdings, including interest payments. Its budget constraint can be written as follows:

$$T + \Pi^{CB} + B_t = G_t + (1 + r^B_{t-1})B_{t-1}. \tag{3.41}$$

For simplicity, in the baseline scenario, G and B are constant and defined as a share of steady state production.

$$G_t = \bar{G} = \frac{\bar{G}}{\bar{Y}}\bar{Y}, \tag{3.42}$$

$$B_t = \bar{B} = \frac{\bar{B}}{\bar{Y}}\bar{Y}. \tag{3.43}$$

Then, taxes can be expressed as:

$$T_t = (\frac{i^B_{t-1}}{\pi_{t-1,t}} - 1)\bar{B} + \bar{G} - \Pi^{CB}_t. \tag{3.44}$$

The bond market clears such that:

$$B_t = PSPP_t + B^B_t. \tag{3.45}$$

Banks might consider their government bond holdings as risky, i.e., they calculate a probability of government default $(1 - \Psi)$. Ψ is defined as follows:

$$\Psi_t = 1 - \Upsilon(\frac{B^B_t}{Y_t} - \frac{B^{B*}}{Y^*})^{\Omega}, \tag{3.46}$$

where Ω defines the sensitivity of Ψ to changes in the share of privately held bonds to GDP, while Υ scales the effect. Should the government expand its bond issuance above the steady state level, banks might consider the new debt level less sustainable, and thus, a government default more likely. Therefore, banks ask for higher remuneration to compensate for potential losses. By modeling the risk of government bonds this way, I create a channel for central bank intervention to stabilize the bond market. When the central bank increases its bond holdings, banks' bond holdings are ceteris paribus reduced, and banks perceive bonds as less risky.[35] Output is divided into consumption, cash storage costs, investment, investment adjustment costs, banks' managerial costs, and government expenditures. Hence, the economy-wide budget constraint can be expressed in the following manner:

$$\begin{aligned} Y_t = \; & C_t + I_t + f\Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}}\Big)(I_t^N + \bar{I}) + \bar{G} + \varsigma N_t + \frac{\psi}{2}(\frac{M_t}{C_t} - \frac{M^*}{C^*})^2 \\ & - \mu^D D_{t-1}\pi_t^{-1} - \Bigg[\kappa \frac{L_{t-1}^B + (1-\Psi_t)B_{t-1}^B}{N_{t-1}} \\ & *(ln(\frac{L_{t-1}^B + (1-\Psi_t)B_{t-1}^B}{N_{t-1}}) - ln(\rho) - 1) + \kappa\rho\Bigg] N_{t-1}. \end{aligned} \tag{3.47}$$

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

$$1 + i_t^D = (1 + r_t^D)(1 + E_t\pi_{t,t+1}), \tag{3.48}$$

$$1 + i_t^{CB} = (1 + r_t^{CB})(1 + E_t\pi_{t,t+1}), \tag{3.49}$$

$$1 + i_t^B = (1 + r_t^B)(1 + E_t\pi_{t,t+1}). \tag{3.50}$$

[35] Obviously, the reason for risk in government bonds is not primarily tied to a deviation from a certain debt level. However, this approach is a micro-founded and straightforward way of introducing spreads between the deposit facility rate and government bonds and nicely captures the idea that increased central bank activity in the bonds market facilitates debt roll-over and reduces interest rates.

3.3 Calibration

I use a total of 30 parameters, 24 of which are conventional and also used in Gertler and Karadi (2011) or Ulate (2021). I introduce additional parameters related to cash (M^*/C^*, ψ), the minimum reserve requirement (ϖ), and risk on the bonds market(B^{B*}/Y^*, Ω, Υ). Table 3.1 summarizes the calibration.

The calibration of the conventional parameters for households and the whole production sector closely follows that of Gertler and Karadi (2011). The parameters for banks are calibrated with three goals in mind. First, the baseline model should resemble the results from their analysis. Specifically, a shock to the quality of capital should increase capital costs for producers. Second, in the steady state, banks should not hold excess reserves. Third, interest rates should be low and close to the ELB. Thus, the model should loosely represent a euro area country after the great financial crisis before the advent of large-scale asset purchase programs. I calibrate the income from deposit issuance μ^D and the optimal loan-to-equity ratio ρ as in Ulate (2021). The cost parameter for violating CRR κ, managerial expenses ς, the share of bank profits paid as dividends ω, the elasticity of substitution between different loan providers ε^L, and the elasticity of substitution between deposits at different banks ε^D are calibrated to hit specific steady state targets and to determine the impact of central bank purchase programs.

I calibrate κ to 0.05. This value is above the calibration (0.0012) in Ulate (2021), but crucial for a positive effect of asset purchase programs. From equation (3.18), I can derive the following expression for the the loan-to-equity ratio:

$$ln\frac{L_t^B}{N_t} = \frac{1}{\kappa}[(1+r_{t+1}^L)\frac{\varepsilon^L-1}{\varepsilon^L} - (1+r_t^{CB})] + ln(\rho).$$

Thus, κ determines how banks adapt lending to changes in the interest rate spread between the deposit facility rate and the expected future return on lending. High values of kappa imply that banks hardly deviate from the optimal loan-to-equity ratio as specified by the CRR. Values close to zero mean that banks are less constrained by the CRR, thus, decoupling equity from lending. Hence, after a shock-induced deterioration of bank equity, there is hardly any shortfall in lending. Any corporate-sector asset purchases from the central bank would reduce the expected return and crowd-out bank lending without stimulating the economy. To avoid this scenario, I calibrate κ to 0.05, which roughly reproduces the dynamics from Gertler and Karadi (2011). Unlike Ulate (2021), I do not directly set the steady state excess reserves. Instead, the steady state is endogenously determined and depends primarily on ω and the managerial cost ς. With ω set to 0.5, I calibrate ς to 0.044 such that banks do not hold excess reserves in the steady state. Finally, I calibrate the discount factor *beta* to 0.999, such that the steady state interest rate on deposits is at 0.1% annually. The deposit facility rate is then pinned down by ϵ^D, which I set to -444, such that the deposit facility rate is at 0%. Similarly, ϵ^L is set to 135.3 such that the annual return on capital is 3%.

The additional parameters are calibrated as follows. I assume that households want to make 10% of their purchases with cash, i.e., M^*/C^* is 0.1. The scaling parameter for costs related to cash ψ is set to one. Note that for small values of ψ, households are incentivized to increase their money holdings once the nominal return on deposits is negative. With $\psi = 1$, the shift is small. The minimum reserve requirement ϖ is set to 1%, reflecting the current situation in the euro area. For bonds, I assume that the target ratio of debt-to-GDP is 60% as specified by the Maastricht criteria. Bond risk increases linearly, i.e., Ω is set to one.[36] Υ defines the elasticity of the risk factor to changes in debt-to-GDP. I set the value to 0.05, such that a debt-to-GDP ratio of 120%, i.e., twice as high as defined by the Maastricht criteria, leads approximately to a 12.5 annualized percentage point increase in the bond yield. Note that this is not representative of the average euro area country but is meant to analyze the abstract case of an increase in government bond risk.

[36]Note that this is also a technical assumption. As the model is linearized around the steady state by a first-order approximation, any non-linearities in this function will be lost. However, this simplification is not critical, as the focus of this analysis is qualitative rather than quantitative.

Table 3.1: Parameter calibration

Households			
β	Intertemporal Discount Factor	0.999	0.1% Deposit Rate
h	Habit Parameter for Consumption	0.815	GK
ψ	Scaling Parameter Cash Costs	1	See Above
χ	Relative Utility Weight of Labor	3.409	GK
ϕ	Inverse Frisch Elasticity of Labor Supply	0.276	GK
M^*/C^*	Optimal Cash to Consumption Ratio	0.1	See Above
Banks			
ρ	Loan-to-Equity (CRR)	9	Ulate
ε^D	Elasticity of Substitution between Deposits	-444	0% Deposit Facility
ε^L	Elasticity of Substitution between Loans	135.3	3% Return on Capital
ω	Share of Bank Profits payed as Dividends	0.5	Shock Impact
ς	Managerial Expenses	0.044	Shock Impact
Y	Minimum Reserve Requirement	0.010	ECB Regulation
μ^D	Income from Deposit Issuance	0.0025	Ulate
κ	Cost Parameter for CRR Violation	0.05	See Above
Intermediate Goods Producers			
α	Capital Share	0.330	GK
ζ	Elasticity of Marginal Depreciation	7.200	GK
δ_i	Steady State Depreciation Rate	0.025	GK
Capital Goods Producers			
η_i	Elasticity of Investment Adjustment Costs	1.728	GK
Final Goods Producers			
ε	Elasticity of Substitution between Goods	4.167	GK
γ	Calvo Parameter	0.779	GK
γ_π	Price Indexation of Inflation	0.241	GK
Central Bank and Government			
κ_π	Taylor Rule Inflation Coefficient	1.5	GK
$\kappa_{\underline{y}_{gap}}$	Taylor Rule Output Gap Coefficient	-0.5/4	GK
$\bar{G}/\bar{Y}$	Steady State Share of Gov. Expenditures	0.2	GK
B^{B*}/Y^*	Sustainable Level of Gov. Debt	0.6	Maastricht Criteria
Ω	Curvature Gov. Risk	1	Linear Approximation
Υ	Scaling Factor Gov. Risk	0.05	See Above
$\bar{B}/\bar{Y}$	Steady State Share of Gov. Debt	0.6	Maastricht Criteria

3.4 Experiments

The following simulations focus on the effects of unconventional monetary policy in connection with excess liquidity in the banking sector.[37] I start with a comparison of three different shocks to present the mechanisms of the model: a PSPP shock, a CSPP shock, and a liquidity shock. I choose these three shocks to distinguish the mechanisms of the different unconventional policies from the effects of a simple liquidity injection. Additionally, I highlight the effects of PSPP for countries with risk in the bonds market.

In a second step, I conduct a crisis experiment by shocking the economy with an unexpected 1% drop in the quality of capital. This scenario mimics a financial crisis as the drop in the quality of capital reduces the worth of banks' assets and their equity. I first compare the effects of government loans to intermediate goods producers financed by additional government debt to a CSPP program conducted by the central bank with newly created base money. The main difference between these two programs is that liquidity in the banking sector is either absorbed by additional bonds or increased by central bank purchases. This distinction is only relevant if there is a spread between the remuneration on bonds and excess reserves. Without the spread, both policies are equivalent.

In a third step, I repeat this exercise for a periphery country, where government intermediation financed by bonds increases government default risks and risk premia. In this scenario, a PSPP program can help stabilize bond interest rates. If the central bank is willing to purchase all additional government bonds, the scenario is mainly identical to a central-bank-financed CSPP scenario.

Finally, I address the role of an ELB for deposit interest rates. As the ELB in some circumstances keeps deposit interest rates above the profit-maximizing rate for bankers, their profits decrease. Additionally, suppose deposit interest rates stay above a certain lower bound. In that case, households are less likely to hold cash instead of deposits, increasing the amount of excess reserves in the banking sector relative to the unconstrained case.

[37] I conduct the simulations using Dynare (Adjemian et al., 2011) and implement occasionally binding constraints via OccBin (Guerrieri and Iacoviello, 2015).

3.4.1 Liquidity Injection, CSPP and PSPP

As the model features no incentives to hold reserves voluntarily, e.g., as a liquidity buffer (Primus, 2017), banks only hold excess reserves involuntarily due to exogenous factors. Here, the central bank (almost)[38] solely determines the level of excess reserves with their unconventional policy measures.

Recall that excess reserves are defined as:

$$RR_t^{exc} = N_t + (1 - \varpi)D_t + CB_t - B_t^B - L_t^B.$$

As equity, deposits, and central bank injections are not (directly) set by banks, they can only alter excess reserves by changing the level of lending or bond holdings. However, profit-maximizing banks cannot change their level of bond holdings, as a reduction would increase bond yields, which would lead banks to increase their holdings again. The same reasoning can be applied to lending: if banks adapt lending, the change in available funds adjusts the expected return on loans, adapting loan supply. Thus, banks have no incentive to change the aggregate level of excess reserves.

Both lending and bonds can be targeted by a central bank policy via CSPP and PSPP respectively. It is crucial to note that these programs affect excess reserves because the purchases are conducted with new money, i.e., because the monetary base increases. Consider, in contrast, a purchase of government bonds, which the central bank finances by issuing bonds to households. As the supply of government bonds is limited, banks' bond holdings decrease, which would ceteris paribus lead to an increase in excess reserves. However, as the central bank now offers bonds to households, households decrease their bank deposits by just as much as the central bank spent buying bonds, leaving total reserves unchanged. Therefore, excess

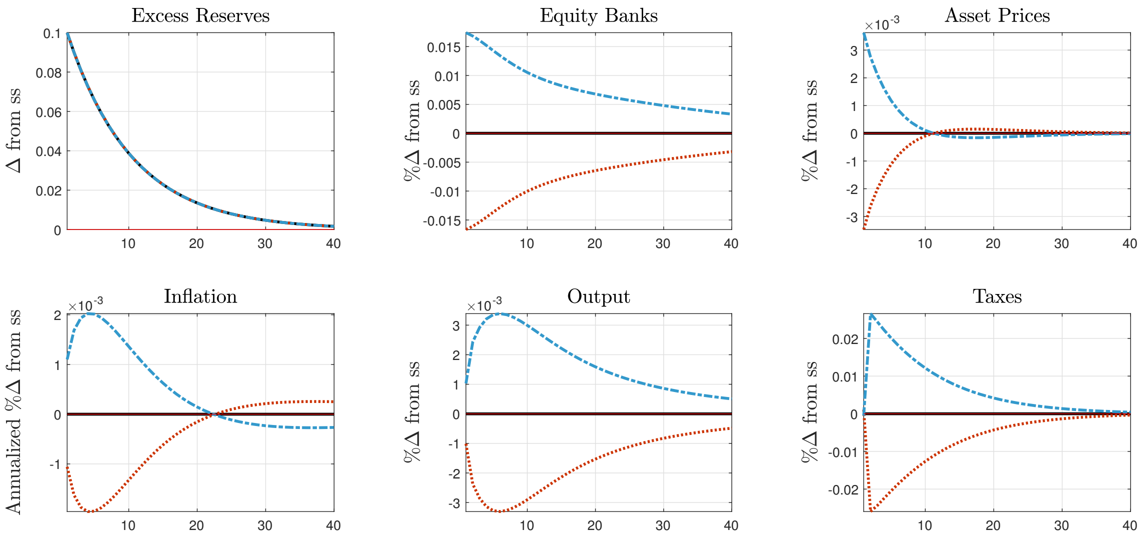
[38] As households can reduce central bank money in the banking sector by holding more cash, an ELB on deposit interest rates might lead to another involuntary accumulation of excess reserves that is not directly caused by central bank interventions. For an analysis of the role of the ELB see Section 3.4.3

reserves are hardly affected with a 1% minimum reserve requirement.[39] From the central bank's perspective, the bond purchases are financed with reserves, which initially increases total reserves in the economy. In issuing bonds, though, it absorbs the additional reserves back into its balance sheet, leaving total reserves and excess reserves unchanged. Thus, in this model, excess reserves primarily arise due to an expansion of the central bank's balance sheet when the central bank creates new money, i.e., reserves, without providing assets.

The resulting excess reserves have an ambiguous effect on banks' profitability, lending, or the economy. To highlight this feature, I first analyze a liquidity injection shock, where the central bank directly lends additional reserves to banks. Then, I turn to a CSPP and a PSPP shock.

Liquidity Injection Shock

Figure 3.2: Comparison of liquidity injection shocks under different steady state deposit facility rates.



Liquidity Shock with $\bar{r^{cb}} = 0$ Liquidity Shock with $\bar{r^{cb}} < 0$ Liquidity Shock with $\bar{r^{cb}} > 0$

[39]This feature of the model is possible, as I include the balance sheet of every sector. However, as deposits generate the monetary benefit μ^D and managerial costs are not paid to any sector in the model, excess reserves are not entirely fixed. Another source of variation is the amount of cash households hold. By holding more or less cash, households can alter the level of central bank money in the banking sector and directly affect excess reserves. However, as ψ is relatively high in my calibration, households hardly adapt cash holdings to changes in the interest rate.

Figure 3.2 compares a liquidity shock for three models with different steady state deposit facility rates — below, equal to, or above zero. The liquidity shock is set to 0.1 and has a persistence of 0.9.[40] It affects the variable CB, i.e., the central bank lends a certain amount of reserves to banks. Intuitively, this policy resembles a conventional refinancing operation. Here, banks do not pay any nominal interest for the injection and accept it for the sake of argument. The injection is conducted with new money, such that both the central bank balance sheet and banks' total reserves expand. The resulting higher excess reserves have substantially different implications in the three scenarios.

First, consider the case where the deposit facility rate is at zero (black line). As excess reserves increase, they do not affect banks' profitability because banks pay just as much for the injection as storing the money at the central bank. The level of excess reserves is, thus, irrelevant for both the financial and the real side of the economy.

Second, consider the case where the deposit facility rate is below zero (red line). While banks do not pay any interest for the injection, they have to store the additional liquidity at the central bank, where they face a negative interest rate. As described above, they cannot simply avoid this accumulation of excess reserves by changing the level of loans or bond holdings due to CRR and the limited availability of bonds and lending opportunities. Additionally, if they were to increase lending, the additional money in circulation would inevitably end up in banks' equity or with households who would receive this money in the form of bank dividends, wages, and profits from non-financial firms and hold it as bank deposits. Both equity and deposits would increase excess reserves close to their initial level, albeit slightly below due to increased minimum reserves requirements. As the central bank's supply primarily drives the level of excess reserves, banks have to accept the penalty rate, which decreases their profits. Bank equity falls, lending is reduced, and asset prices drop. Investment and expected future output decrease, leading households to lower labor supply. Output and prices fall. This dynamic is also amplified by a tax reduction, leading households to reduce labor. The central bank earns revenue for

[40] Note that the size and persistence of the shock are chosen to match the shock in the following exercise. As the purpose is solely to assess the effects of excess reserves qualitatively, the shock size and persistence are not of interest.

storing banks' excess reserves and transfers these to the government, which uses any revenues to decrease taxes.

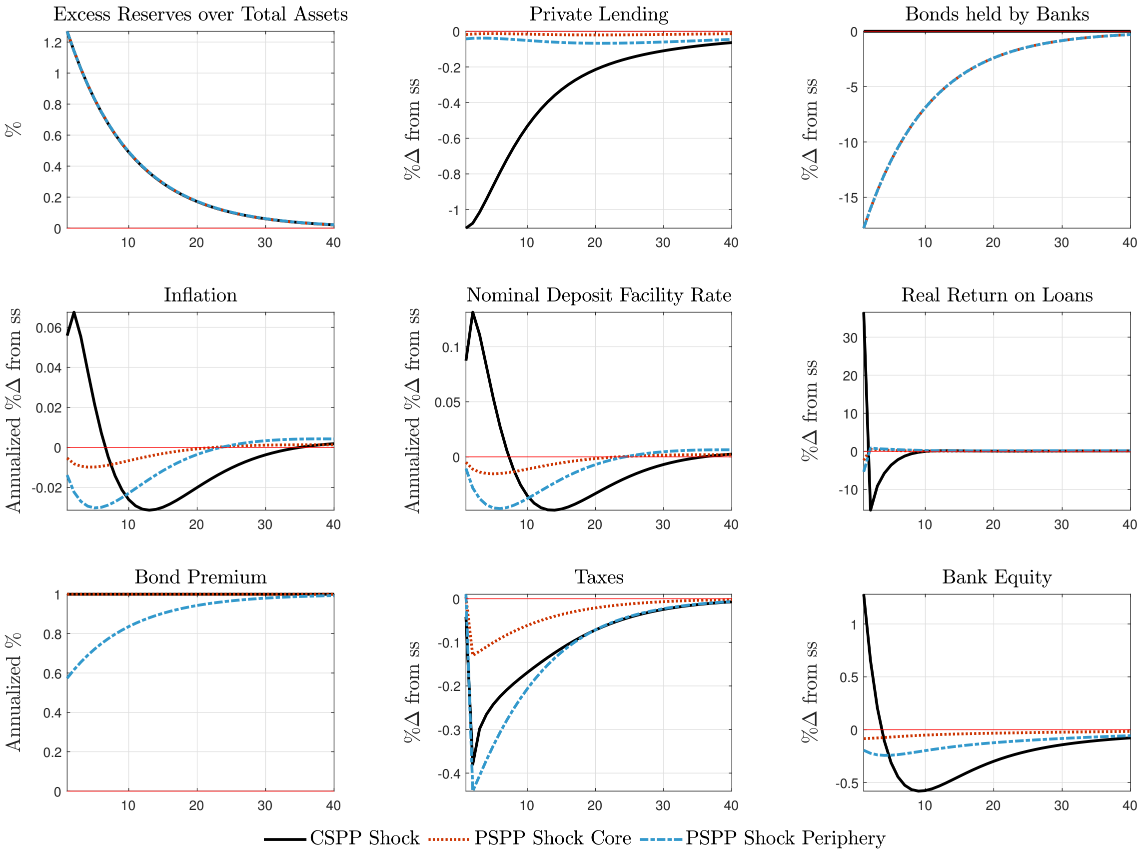
Third, consider the case where the deposit facility rate is above zero (blue line). As banks do not pay any interest for the injection but can deposit the money at the central bank at a positive real rate, their profits grow in the following period. As a result, dividend payments to households and banks' equity increase, leading to a future rise in lending. In anticipation of these future developments, households adapt their level of labor today, leading to higher production while banks expand their lending activities. Prices increase, and the central bank reacts by raising the nominal interest rate on excess reserves. This increase makes it more attractive for banks to hold excess reserves instead of lending, reducing economic activity and lowering inflation. Banks' profits decrease slowly back to the steady state. Note that the increase in banks' profits is paid for by the central bank in the next period. The central bank transfers any profits or losses to the government, which balances its budget constraint by adjusting taxes. In the end, households pay for the injection and the resulting profits for banks.

In summary, involuntary excess reserves have an ambiguous effect on the economy. It is crucial to know how the central bank creates additional base money to understand its impact on bank profitability. In this exercise, the central bank injects the money by crediting the money to banks at no cost. Thus, the deposit facility rate is the spread banks earn or lose from the policy. However, the central bank can also buy assets on the market, thereby effectively limiting the supply of these assets for banks. Then, banks' profitability depends on the interest rate spread between the assets they sell to the central bank and the deposit facility rate. The following section analyzes two such purchase programs.

CSPP and PSPP Shocks

In this section, I highlight the different effects of two central bank purchase programs on the model economy: the purchase of private bonds (CSPP) and public bonds (PSPP). The latter purchase program is analyzed in two steps where I first assume that the PSPP does not affect risk premia on bonds, which resembles the scenario in a euro area core country. I then relax this assumption to capture the

Figure 3.3: CSPP shock vs. PSPP shock for Core and Periphery



scenario for a periphery country. Figure 3.3 presents IRFss for these scenarios. For this exercise, I assume that the core and periphery countries have the same initial debt-to-GDP ratios and the same initially positive bond premia to ensure that steady states are identical.[41] I assume that government bonds in a core country are always perceived as safe investments, and thus, changes in the privately-held government-debt-to-GDP ratio do not affect bond interest rates. This assumption is especially important for the PSPP shock that substantially alters the debt composition for governments. In an exemplary periphery country, this assumption is relaxed, such that bond purchases from the central bank decrease the premium on

[41]The interest rate spread between bonds and the deposit facility is set to 0.25% to avoid a negative bond premium. Due to the linearity of Equation (3.46) central bank bond purchases might reduce the bond premium below 0. A negative premium would imply that bond interest rates are below the interest rate on the deposit facility. In this case, banks had no reason to invest in bonds. I exogenously implement a spread in the steady state that the central bank can reduce in the peripheral country to avoid this scenario. The comparison is just for highlighting the mechanism of PSPP and is not supposed to resemble specific countries.

bonds. Both shocks are equal in size (0.1) and persistence (0.9).

The CSPP shock directly increases the amount of intermediate producers' debt held by the central bank. A 0.1 shock implies that the central bank buys roughly 2% of steady state shares in intermediate production. The PSPP shock directly increases the amount of government debt held by the central bank. Here, the 0.1 shock implies that the central bank acquires about 20% of total government debt. Note that all three shocks generate the same accumulation of excess reserves, even though they trigger substantially different dynamics in the model. Again, this highlights that excess reserves are not accumulated voluntarily by the banking sector but are determined by the central bank. The remuneration for loans and bond holdings, i.e., the respective counterparts in banks' balance sheets for the two purchase programs, is above the deposit facility rate. Thus, using the argument developed in the last section, bank profitability decreases for both programs.

First, consider the CSPP shock (black line). Similar to the liquidity shock, banks receive additional liquidity that they deposit with the central bank. However, now, the liquidity is not simply injected by the central bank. Instead, the central bank buys shares in intermediate goods production. The central bank might do so by directly buying shares from producers or buying from banks on the secondary market. In both cases, the results are identical. In the former case, the additional demand for shares increases asset prices, such that banks reduce their demand due to the lower expected return on loans. In the latter case, banks use the revenues from selling their shares in intermediate goods production to the central bank to grant additional loans, thereby increasing asset prices until lending is no longer profitable. In both cases, the central bank intervention reduces interest rates on loans and crowds out private bank lending.

The additional demand for shares also temporarily boosts the real return on capital, which leads to an increase in banks' equity. As the central bank decreases the amount of liquidity in the next period, asset prices fall, leading to lower returns on capital and lower profits for banks. Combined with increasing managerial costs due to higher equity levels, lower profits reduce banks' equity below its steady state in the following periods.

Recall that the parameter κ determines banks' reaction to the expected return on capital. Low levels of κ decouple lending from equity as the CRR are less binding. The central bank purchases would decrease the expected return on capital and crowd out bank lending, such that asset prices barely change. However, with my calibration, banks are reluctant to lower lending, i.e., the central bank intervention does not one-to-one crowd out bank lending and, thus, impacts interest rates on loans. Then, a higher loan supply leads to higher prices for capital and an increase in equity, followed by a stronger reverse effect in the following periods, when asset purchases decrease. Initially, higher asset prices lead to increased capital goods production and higher expected future output. Households adapt to these expectations, and labor, output, and prices rise. To offset the inflationary effect of its policy, the central bank increases the deposit facility rate, further decreasing private lending. Unlike in the injection experiment, households do not pay for banks' initial profits. Instead, taxes drop as the positive real return on capital leads to profits for the central bank.

Second, consider the PSPP shocks (red and blue line) where the central bank buys government bonds. The core and periphery country models only differ in Υ, which is set to 0 and 0.01, respectively.

As the supply of government bonds is assumed to be fixed for this exercise, banks reduce their total bond holdings. The additional liquidity from the central bank purchase results in excess reserves on their balance sheets. Again, it is not important whether the central bank directly buys bonds from the government or indirectly from banks. Note that, in the absence of an interest rate spread between bonds and the deposit facility, for a core bank, this policy means just a change of assets with identical remuneration and does not lead to any disruptions. However, if we assume such a spread initially, banks' profitability decreases.[42]

Consider the scenario for banks in the core country (red line), where central bank purchases do not affect the spread. By buying bonds with an interest rate higher than the deposit facility rate, the central bank reduces banks' profits by exchanging

[42] As banks are perfectly competitive in the bonds market, the equilibrium interest rate represents the lowest rate profit-maximizing agents are willing to accept. Here, the central bank determines the volume of bonds it wants to buy independent of the current yield offered by the government. The initially higher demand depresses yields such that banks reduce their bonds by exactly as much as the central bank wants to buy. In sum, total demand and yield are unaffected as the central bank crowds out private investors.

a better-paying asset (bonds) with a worse-paying asset (reserves). As a result, in the following periods, bank equity drops, and lending is reduced. Asset prices drop, further deteriorating bank equity, and capital production decreases. In anticipation of the coming recession, households reduce labor, which reduces output and prices. Note that taxes drop as bond interest payment is now partially paid to the central bank that transfers any profits directly back to the government. In summary, the intervention causes effects in relation to the spread between bonds and the deposit facility rate. When the bond rate is close to or equal to the deposit facility rate, which is true for most government bonds in the euro area, the purchase itself has little to no impact.[43]

This result depends on the assumption that central bank purchases do not affect bond yields. While this assumption might be reasonable for a core country like Germany, where bonds are highly liquid and considered to be risk-less, it does not fit empirical evidence for periphery countries (see, e.g., Andrade et al., 2016). Central bank purchases on the bonds market during and after the sovereign debt crisis significantly reduced bond yields by lowering uncertainty and facilitating debt rollover. Assuming that PSPP can affect bond yields, the results substantially change. Consider the scenario for a periphery country (blue line), where the PSPP shock additionally reduces the premium on bonds. While the central bank again attenuates banks' profits as described above, it also reduces profits by shrinking the profitability of holding the remaining bonds. This additional reduction deteriorates bank equity further and amplifies the effects described for the core country.

In summary, the three unconventional monetary policy interventions affect banks and their reserves differently. First, the liquidity injection increases excess reserves without directly affecting yields for bonds or shares. Its impact depends on the deposit facility rate and can be expansionary and restrictive. Second, the CSPP intervention initially increases the value of shares but decreases their future expected return, crowding out bank activity. The reduction in lending combined with an increase in excess reserves leads to lower profitability. Third, the PSPP shock switches assets on banks' balance sheets. The reduction in bond holdings is offset

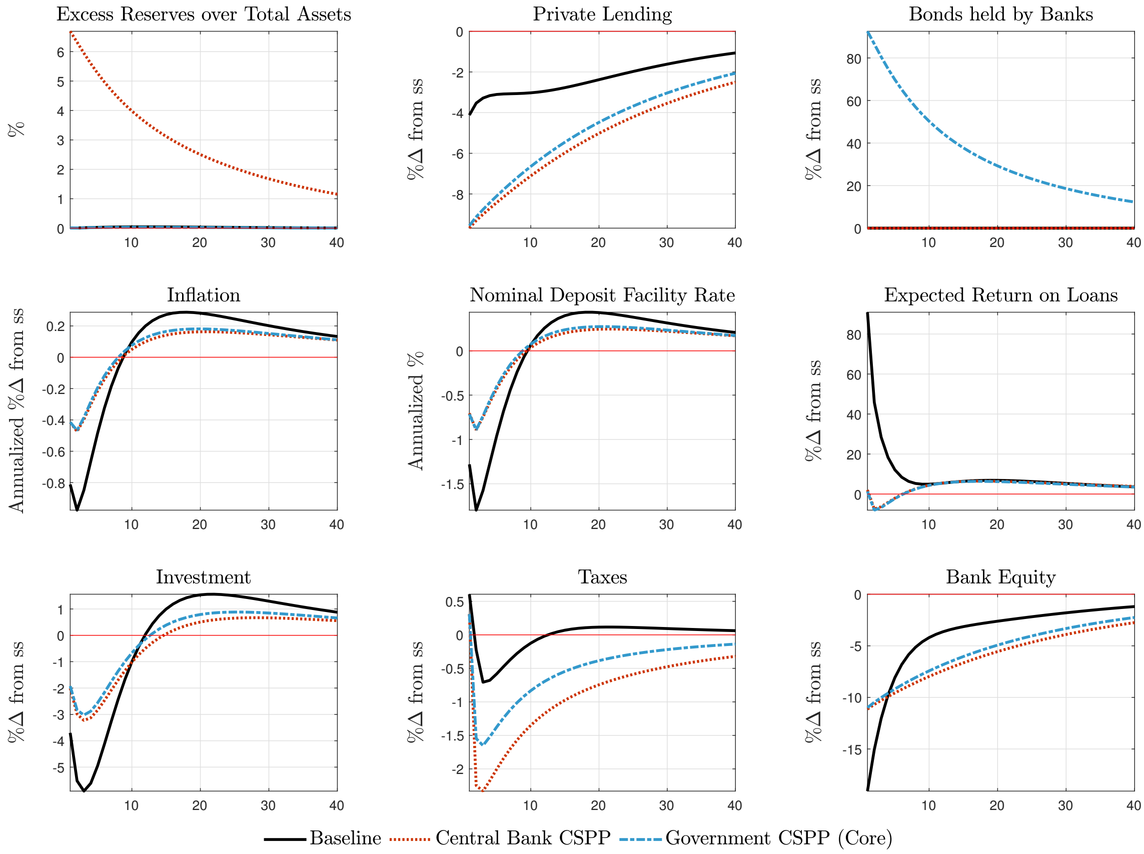
[43] As all bonds mature after one period, the model does not capture the potential positive effects of a purchase program on the value of bonds already owned by banks.

by an equally large increase in reserves. This exchange of assets does not affect bank profitability unless there is an initial difference in the remuneration of bonds and the deposit facility rate or the central bank purchases affect bond yields.
In the next section, I analyze the purchase programs as a reaction to economic disturbances. Accordingly, CSPP and PSPP are no longer shocks but are determined by rules as described in Section 3.2.

3.4.2 Crisis Experiments

In this section, I analyze the results of a shock to the quality of capital, which is used to induce a financial crisis. The unexpected reduction in the quality of capital substantially reduces banks' return on loans and deteriorates their equity. Due to the loss of equity, CRR tighten and banks decrease lending, asset prices drop, and equity declines further. Investment, capital, output, and prices drop, which leads the economy into a recession. Subsequently, the expected return on capital increases such that banks quickly recover and rebuild their equity.
The shock size is set to 0.01 with a persistency of 0.66 in a core and a periphery country. Again, both countries only differ in the calibration of Υ, which is zero for the core country and 0.05 for the periphery country. A value above zero for Υ implies that the bond premium reacts to changes in privately held government debt. In this scenario, I consider two public interventions: a government and a central bank intervention. In the former case, the government issues bonds and uses the acquired funds to buy shares of intermediate goods producers. In the latter case, the central bank buys shares by increasing its balance sheet and inserting new money in the economy, which resembles the ECB's CSPP. This way, I can disentangle the effects of public intermediation and the accumulation of excess reserves. I first analyze the shock for a core country, where the issuance of additional government bonds does not affect the bond premium. In a second step, I relax this assumption and, additionally, allow for a PSPP as a reaction to increased risk in the bond market.

Figure 3.4: Government intermediation vs. central bank intermediation (core)



Government and Central Bank Intermediation in a Core Country

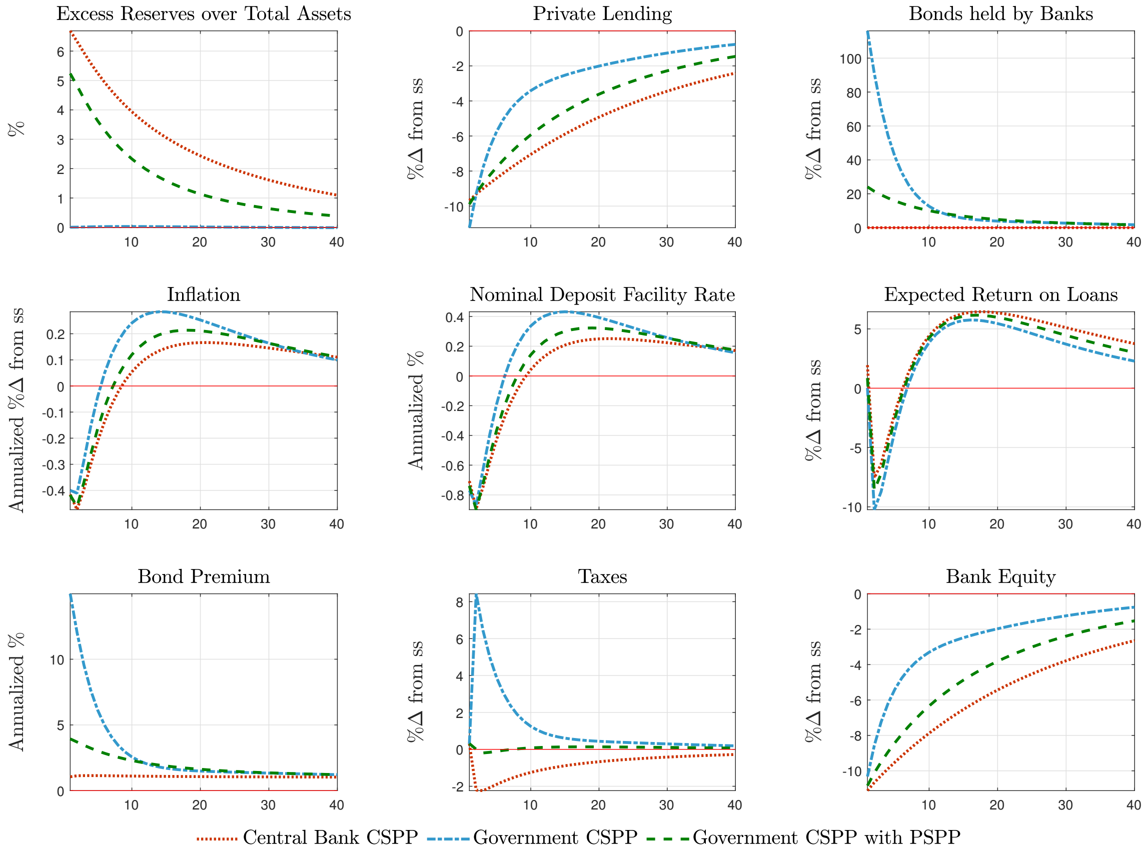
Figure 3.4 shows the effects of a quality of capital shock on a core country. The black line represents the baseline scenario, where neither the central bank nor the government conduct asset purchases. The general mechanisms and dynamics are as outlined in the prior section. The red and the blue lines represent the results for the same shock with public intermediation from the central bank and the government, respectively.

First, consider the government intermediation (blue line). The government reacts to the strong increase in the expected return on capital and the resulting investment decline by buying shares of intermediate goods producers. To raise funds for these purchases, it issues government bonds that banks buy. This way, the government effectively acts as a bank and uses funds absorbed from the banking sector to provide them as loans, which banks cannot issue due to CRR. This intervention has two important implications. First, asset prices drop less than before due to the additional demand for assets. While banks still lose equity due to the shock-induced lower production, they do not face additional losses due to the deterioration of the value of their assets. Equity drops less, and banks' lending is less restricted by the CRR. Second, as the expected return on capital is considerably lower, the government intermediation effectively crowds out private lending. With lower loan volume and smaller returns on loans, the build-up of banks' equity is markedly slowed down. Note that the changes in the level of bonds and lending do not affect excess reserves. Now, consider the central bank intermediation (red line). In this case, the purchase program is conducted by the central bank. The central bank does not issue bonds but uses additional money to buy shares, increasing overall liquidity and leading to excess reserves in the banking sector. Excess reserves over total assets reach about 6.5%, a value that fits the euro area average before the start of the PEPP (Darvas and Pichler, 2018). The central bank purchases create the same dynamics as the government purchases. However, banks now hold excess liquidity instead of bonds. As there is a constant spread between the remuneration on bonds and excess reserves, bank profitability additionally shrinks, further slowing down the recovery process. In the absence of the spread, government and central bank purchase programs are equivalent, i.e., the resulting dynamics are identical except that banks either hold additional reserves or bonds. As any central bank revenues are transferred to the government, this difference has no further implications. The build-up of excess reserves is only relevant if it reduces bank profitability. The creation of new base money does not impact M3 via the money multiplier and does not lead to inflation.

Government and Central Bank Intermediation in a Periphery Country

In this section, the increase in government debt above the 60% of gross domestic product (GDP) as defined in the Maastricht criteria worsens credit ratings. When the government increases its debt, banks consider a default more likely and charge a risk premium on government bonds. Figure 3.5 shows the simulation results of a quality of capital shock that hits a periphery country. The red line represents a central bank purchase program and is identical to the program in the core country. However, the government intermediation (blue line) differs fundamentally. With ris-

Figure 3.5: Government intermediation vs. central bank intermediation (periphery)



ing debt levels, banks reduce bond holdings due to the perceived risk. Bond prices drop, and yields increase until the bond market clears again. Initially, this mechanism leads to an increase in the bond premium to nearly 15% annually. As bonds are now risky, they are included in the CRR and ceteris paribus increase costs for lending. Lending drops further, which increases the necessary volume of government asset purchases to reduce asset price volatility. The higher yield on government bonds boosts bank profitability and substantially accelerates the recovery process after the shock. Note that the recovery process is driven by higher funding costs for the government that transfers these costs to households via taxes. Households decrease consumption and deposits and increase labor supply, further boosting recovery processes.

However, high government default risk poses a threat to financial stability. To mitigate this threat, the central bank might choose to buy bonds (green line).[44] Again, the central bank uses new money to buy bonds which ends up as excess reserves on banks' balance sheets. In this framework, the PSPP can be interpreted as a mechanism to switch from government to central bank intermediation. If the central bank bought all additional bonds that the government issues for its intermediation, the results would be equivalent to the central bank intermediation scenario with one exception: the central bank holds substantial amounts of government debt on its balance sheet. As the central bank transfers any profits to the government, this position does not affect government funding costs or the economy.

In this example (green line), the central bank buys roughly 80% of newly issued bonds. This intervention increases bond ratings and lowers the bond premium. Banks switch risky bonds for safe excess reserves with lower remuneration, and bank profitability decreases. As described before, the intervention not only exchanges high-paying for low-paying assets but also reduces the overall return on bonds, further decreasing bank profitability.

In summary, excess reserves are caused by central bank asset purchases funded with new money. Depending on bond premia, excess reserves can substantially decrease bank profitability and decelerate recovery processes after financial distress.

3.4.3 Excess Reserves and the Effective Lower Bound

Excess Reserves have different effects on the banking sector depending on interest rate spreads. While purchase programs mainly affect spreads between the deposit facility rate and other assets, negative interest rates and an effective lower bound on household deposit interest rates can lead to unfavorable spreads on the liability side of banks' balance sheets. Recall that, in equilibrium, the household deposit interest rate is set such that banks are indifferent to the level of deposits. Reserves from household deposits that exceed banks' funding needs are stored at the central bank. Thus, any costs or profits for receiving additional deposits are offset by the costs or profits from depositing the additional reserves at the central bank. This way, banks set the deposit interest rate with a specific fixed spread above the deposit facility

[44] Alternatively, the government could reduce its debt level by consolidating its budget. However, governments did not reduce but increased debt during the crisis, driven partly by favorable interest rates due to central bank purchases, which potentially led to fiscal dominance.

rate, regardless of the volume of deposits.

In some circumstances, banks might not be able or willing to decrease deposit interest rates below a certain level.[45] For the euro area, average household overnight deposit interest rates have stayed above zero, even though the deposit facility rate continually decreased to -0.5%. Since 2012, the spread between the two interest rates increased from zero to 0.5% (own calculations based on ECB Data).[46]

Figure 3.6: Quality of capital shock with and without an ELB on deposit interest rates

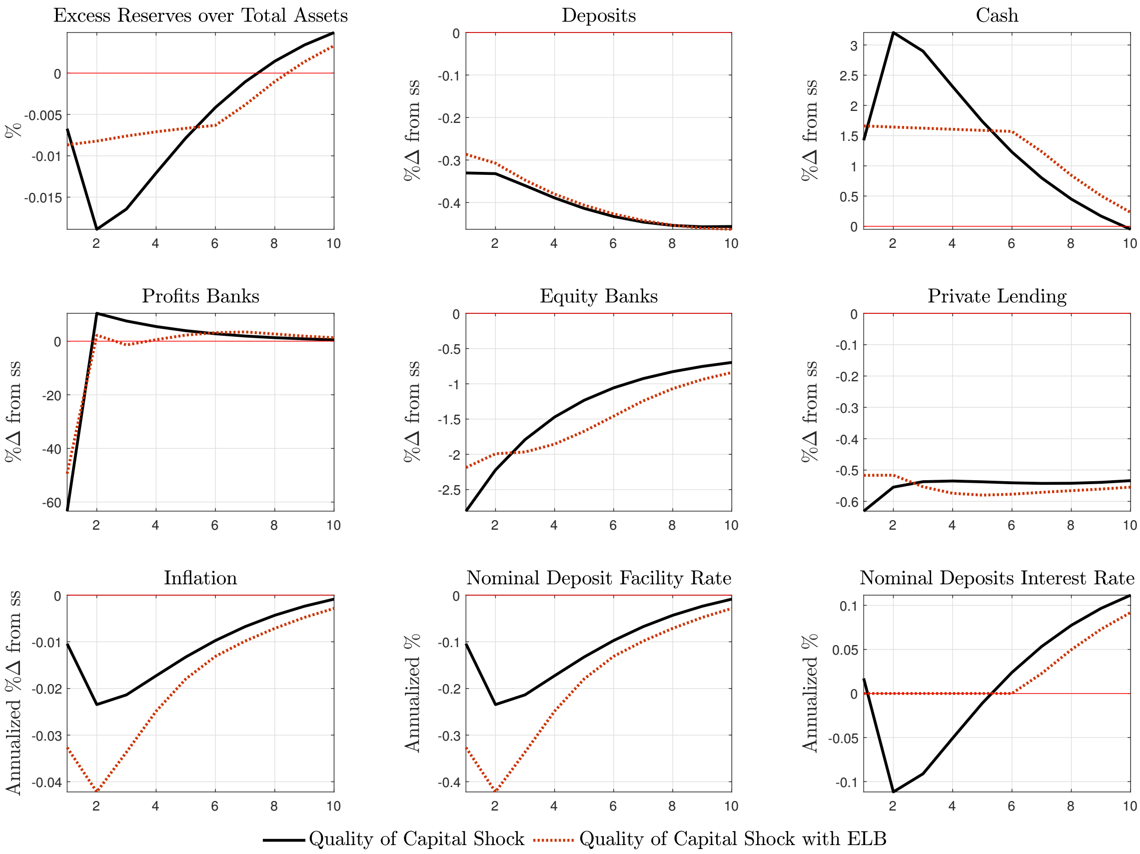


Figure 3.6 presents the simulation results of a small (0.002) shock to the quality of

[45]For an in-depth analysis of negative nominal interest rates and reasons for an ELB see Ulate (2021).

[46]While this spread exists in theory, banks have continuously increased account fees and introduced negative nominal interest rates for accounts with deposits above 50,000 euros, making the existence of a real and binding ELB doubtful. Despite that, many banks were slow to increase fees and introduce negative interest rates, which contributed to a decreasing profit margin. Thus, the ELB appears to be binding at least in the short term.

capital. The central bank reacts with changes in the deposit facility rate but does not set up any purchase programs. As before, the quality of capital shock induces a drop in the return on capital, deteriorates bank equity, and reduces lending. The reduction in lending decreases asset prices and amplifies the deterioration of equity. The central bank lowers interest rates to combat the resulting deflation. Banks offer less remuneration on household deposits, which leads to deposit interest rates below zero in the unconstrained case. Note that banks transfer any costs for holding excess reserves to households. This way, they are indifferent to any increase or reduction in deposits as described above. Households, then, have an incentive to hold cash as the additional storage costs are smaller than the loss through the negative remuneration. When households hold cash, they decrease the amount of central bank money in the banking sector, and thus, the level of excess reserves decreases.[47] The deposit interest rate cannot decrease below zero in the constrained case. Thus, banks cannot transfer the costs for their excess reserves to households, which reduces profits. Non-negative interest rates on deposits reduce incentives for households to hold cash so that the level of excess reserves in the banking sector increases. As monetary policy cannot effectively affect households' decisions, the recession is stronger with higher deflation forcing the central bank to amplify its expansive monetary policy. This reduction in the deposit facility rate also increases its spread to the deposit interest rate, further reducing bank profits. The lower deposit facility rate also increases the spread of the return on capital, positively affecting lending and asset prices. This dynamic explains the lower initial drop in bank equity.

In summary, an ELB on deposit interest rates creates an unfavorable spread between interest rates on the liability side of banks' balance sheets, which reduces their profits. Additionally, the ELB prevents households from accumulating cash as a store of value, which would reduce expensive excess reserves in the banking sector. The ELB affects both the amount of excess reserves and the profitability of banks and explains why in times of negative interest rates and high excess liquidity, deposits are an inferior source of funding.

[47] The excess reserves fall below zero. The straightforward interpretation is that banks then receive funds from the central bank, e.g., through MRO. The implicit assumption is that the deposit facility rate equals the main refinancing rate. If the main refinancing rate were higher, banks' profits would be affected, such that they would be willing to offer higher deposit interest rates once reserves fall below zero. This scenario could be modeled via regime-switching.

3.5 Conclusion

This paper establishes and analyzes a medium-sized New-Keynesian DSGE model that explicitly models involuntary excess reserves as a result of central bank asset purchases. The model features a two-tier banking sector with capital requirements regulation, a market for potentially risky short-term government bonds, and two different types of asset purchase programs.

The analysis provides several insights: First, involuntary excess reserves are a direct consequence of central bank asset purchases. With restricted lending due to capital requirements regulation and a lack of demand, banks cannot expand their activities to avoid negatively remunerated excess reserves.

Second, while excess reserves could enable banks to substantially increase their balance sheet after an economic recovery with strong and adverse implications for price stability, the central bank can use interest on excess reserves to efficiently prevent excessive lending and subsequent inflation.

Third, there is an equivalence between asset purchases financed with new money vs. bonds, as long as excess reserves and bonds are equally remunerated. However, with a positive spread between bonds and the deposit facility, asset purchases via new money worsen bank profits. Thus, the modeling approach without excess reserves, as in Gertler and Karadi (2011) or Gertler and Karadi (2018), overestimates the benefit of quantitative easing. This effect is even stronger for periphery countries where these spreads are higher.

Fourth, while excess reserves might reduce bank profits and pose a problem from a financial stability perspective, asset purchases offer strong benefits in terms of reduced price volatility. However, the impact of quantitative easing depends crucially on banks' reactions to changes in interest rate spreads, i.e., in the model on the parameter κ. If low enough, asset purchases increasingly crowd out bank activity, hardly affect interest rates, and instead primarily attenuate banks' business model.

The model should be expanded in several directions. First, as there is strong heterogeneity in excess reserves within the euro area (see Darvas and Pichler, 2018), an open economy model could provide further insights, especially relating to TARGET2 balances (see e.g. Kraus and Schiller, 2019). Additionally, excess liquidity is concentrated in relatively few banks. Thus, a model with heterogeneous banks could capture additional mechanisms.

Second, the model can be used to study attempts in reducing excess reserves or the burden of negative interest rates on reserves, such as the so-called two-tier system implemented by the ECB or suggestions to increase minimum reserves requirements (see Chari and Phelan, 2014).

Third, government bonds in the model mature after one period, which fails to account for the effects of changing long-term bond prices that affect banks' equity. Modeling long-term bonds opens up an additional channel for the PSPP to affect banks and help combat financial distress.

3.6 Appendix

3.6.1 Equilibrium Conditions

There are 51 variables and 51 equations. The equations are ordered by sectors.

Households

$$1 = \beta\Lambda_{t,t+1}(1 + r_t^D) \tag{3.1}$$

$$1 = \beta\Lambda_{t,t+1} - \frac{\psi}{C_t}(\frac{M_t}{C_t} - \frac{M_t^*}{C_t^*}) \tag{3.2}$$

$$\varrho_t w_t = \chi L_t^\phi \tag{3.3}$$

$$\varrho_t = \frac{\frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t}}{1 - \psi\frac{M_t}{C_t^2}(\frac{M_t}{C_t} - \frac{M_t^*}{C_t^*})} \tag{3.4}$$

$$\Lambda_{t,t+1} = \frac{\varrho_{t+1}}{\varrho_t} \tag{3.5}$$

$$\begin{aligned} C_t + D_t + M_t + T_t = {} & w_t L_t + \Pi_t^C + \Pi_t^F + \Pi_t^B + \frac{i_{t-1}^D}{\pi_{t-1,t}} D_{t-1} \\ & + \frac{1}{\pi_{t-1,t}} M_{t-1} - \frac{\psi}{2}(\frac{M_t}{C_t} - \frac{M_t^*}{C_t^*})^2 \end{aligned} \tag{3.6}$$

Banks

$$N_t + D_t + CB_t = B_t^B + L_t^B + RR_t^{min} + RR_t^{exc} \tag{3.7}$$

$$RR_t^{min} = \varpi D \tag{3.8}$$

$$\begin{aligned} \Pi_t = {} & (\frac{i_{t-1}^{CB}}{\pi_{t-1,t}} - 1)N_{t-1} + (r_t^L - (\frac{i_{t-1}^{CB}}{\pi_{t-1,t}} - 1))\rho N_{t-1} + (\frac{i_{t-1}^{CB}}{\pi_{t-1,t}} - 1)CB_{t-1} \\ & + (\frac{i_{t-1}^B - i_{t-1}^{CB}}{\pi_{t-1,t}})B_{t-1}^B + ((\frac{i_{t-1}^{CB} - i_{t-1}^D}{\pi_{t-1,t}}) + \mu^D - (\frac{i_{t-1}^{CB} - 1}{\pi_{t-1,t}})\varpi)D_t \end{aligned} \tag{3.9}$$

$$\Pi_t^B = \omega \Pi_t \tag{3.10}$$

$$N_{t+1} = N_t + (1-\omega)\Pi_t - \varsigma N_t \tag{3.11}$$

$$r_t^B = \frac{1 + r_t^{CB}}{\Psi_t} - 1 + (1-\Psi_t)\kappa(ln(\frac{L_t^B + (1-\Psi_t)B_t^B}{N_t}) - ln(\rho)) + spread \tag{3.12}$$

$$1 + r_t^D = \frac{\varepsilon^D}{\varepsilon^D - 1}(1 + r_t^{CB} + \mu^D - (r_t^{CB} + \frac{\pi_{t,t+1} - 1}{\pi_{t,t+1}})\varpi) \tag{3.13}$$

$$1 + r_{t+1}^L = \frac{\varepsilon^L}{\varepsilon^L - 1}\left[1 + r_t^{CB} + \kappa\left(ln\frac{L_t^B + (1-\Psi_t)B_t^B}{N_t} - ln\rho\right)\right] \tag{3.14}$$

Intermediate Goods Producers

$$Q_t K_{t+1} = L_t^B + CSPP_t \tag{3.15}$$

$$Y_t^M = A_t(U_t \xi_t K_t)^\alpha L_t^{1-\alpha} \tag{3.16}$$

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta'(U_t)\xi_t K_t \tag{3.17}$$

$$P_t^M(1-\alpha)\frac{Y_t^M}{L_t} = W_t \tag{3.18}$$

$$\delta_t = \delta_c + U_t^{1+\zeta} b/(1+\zeta) \tag{3.19}$$

$$r_t^L = \frac{[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta(U_t)]\xi_t}{Q_{t-1}} - 1 \tag{3.20}$$

Capital Goods Producers

$$\begin{aligned} Q_t = 1 + \frac{\eta_i}{2}\left[\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} - 1\right]^2 + \eta_i\left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} - 1\right)\left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}}\right) \\ - E_t \beta \Lambda_{t,t+1}\eta_i\left(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}} - 1\right)\left(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}}\right)^2 \end{aligned} \tag{3.21}$$

(3.22) $$I_t^N = I_t - \delta_t \xi K_t$$

(3.23) $$\Pi_t^C = (Q_t - 1)I_t^N - \frac{\eta_i}{2}\Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} - 1\Big)^2 (I_t^N + \bar{I})$$

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

Final Goods Producers

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

(3.26) $$Y_t = Y_t^M P_t$$

(3.27) $$P_t^{\pi*} = \frac{\varepsilon}{\varepsilon - 1}\frac{P_t^*}{P_t^X}\pi_t$$

(3.28) $$\pi_{t,t+1}^{1-\varepsilon} = \gamma \pi_{t-1,t}^{\gamma_\pi(1-\varepsilon)} + (1-\gamma){P_t^{\pi^*}}^{1-\varepsilon}$$

(3.29) $$P_t^* = Y_t P_t^M + \beta\gamma\Lambda_{t,t+1}\pi_{t,t+1}^{\varepsilon}\pi_{t+1,t+2}^{-\varepsilon\gamma_\pi} P_{t+1}^*$$

(3.30) $$P_t^X = Y_t + \beta\gamma\Lambda_{t,t+1}\pi_{t,t+1}^{\varepsilon-1}\pi_{t-1,t}^{\gamma_\pi(1-\varepsilon)} P_{t+1}^X$$

(3.31) $$\Pi_t^F = (P_t - P_t^M)Y_t^M$$

Central Bank

(3.32) $$i_t^{CB} = \bar{i}^{CB}\pi_t^{\kappa_\pi}\left(\frac{y_{gap,t}}{\frac{\varepsilon}{\varepsilon-1}}\right)^{\kappa_{y_{gap}}}$$

(3.33) $$Z_t^C = \bar{Z^C} + \Upsilon^C[ln(\frac{1+r_{t+1}^L}{1+r_t^{CB}}) - ln(\frac{1+\bar{r}^L}{1+\bar{r}^{CB}})]$$

(3.34) $$Z_t^B = \bar{Z^B} + \Upsilon^B[ln(\frac{1+r_t^B}{1+r_t^{CB}}) - ln(\frac{1+\bar{r}^B}{1+\bar{r}^{CB}})]$$

$$Z_t^C = \frac{CSPP_t}{Q_t K_{t+1}} \tag{3.35}$$

$$Z_t^B = \frac{PSPP_t}{B_t} \tag{3.36}$$

$$y_{gap,t} = \frac{1}{P_t^M} \tag{3.37}$$

$$\begin{aligned} \Pi_t^{CB} = & (\frac{i_{t-1}^B}{\pi_{t-1,t}} - 1)PSPP_{t-1} + r_t^L CSPP_{t-1} \\ & - (\frac{i_{t-1}^{CB}}{\pi_{t-1,t}} - 1)RR_{t-1}^{exc} \end{aligned} \tag{3.38}$$

Government and Aggregation

$$G_t = \bar{G} = \frac{\bar{G}}{\bar{Y}}\bar{Y} \tag{3.39}$$

$$B_t = \bar{B} = \frac{\bar{B}}{\bar{Y}}\bar{Y} \tag{3.40}$$

$$T_t = r_{t-1}^B \bar{B} + \bar{G} - \Pi_t^{CB} \tag{3.41}$$

$$B_t = PSPP_t + B_t^B \tag{3.42}$$

$$\begin{aligned} Y_t = \ & C_t + I_t + f\Big(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}}\Big)(I_t^N + \bar{I}) + \bar{G} + \varsigma N_t + \frac{\psi}{2}(\frac{M_t}{C_t} - \frac{M^*}{C^*})^2 \\ & - \mu^D D_{t-1}\pi_t^{-1} - \Bigg[\kappa \frac{L_{t-1}^B + (1-\Psi_t)B_{t-1}^B}{N_{t-1}} \\ & *(ln(\frac{L_{t-1}^B + (1-\Psi_t)B_{t-1}^B}{N_{t-1}}) - ln(\rho) - 1) + \kappa\rho\Bigg] N_{t-1}; \end{aligned} \tag{3.43}$$

$$\Psi_t = 1 - \Upsilon(\frac{B_t^B}{Y_t} - \frac{B^{B*}}{Y^*})^\Omega \tag{3.44}$$

$$1 + i_t^D = (1 + r_t^D)(1 + E_t \pi_{t,t+1}) \tag{3.45}$$

$$1 + i_t^{CB} = (1 + r_t^{CB})(1 + E_t \pi_{t,t+1}) \tag{3.46}$$

$$1 + i_t^B = (1 + r_t^B)(1 + E_t \pi_{t,t+1}) \tag{3.47}$$

Shocks

$$CSPPShock_t = 0.9CSPPShock_{t-1} + \varepsilon_t^{CSPP} \tag{3.48}$$

$$PSPPShock_t = 0.9PSPPShock_{t-1} + \varepsilon_t^{PSPP} \tag{3.49}$$

$$LiqShock_t = 0.9LiqShock_{t-1} + \varepsilon_t^{LIQ} \tag{3.50}$$

$$\xi_t = 1 + 0.66(\xi_{t-1} - 1) - \varepsilon_t^{\xi} \tag{3.51}$$

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