

Money Markets, Collateral and Monetary Policy*

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This draft: December 2025

Abstract

We document dramatic changes in euro area interbank money markets during the financial and sovereign debt crises: unsecured borrowing declined across the euro area, while secured market haircuts on sovereign bonds increased, and bank borrowing from the European Central Bank rose in southern countries. We construct a quantitative general equilibrium model to assess the macroeconomic impact of these developments and the associated policy response. Our model features heterogeneous banks and sovereign bonds, secured and unsecured money markets, and a central bank. We compare a benchmark policy – the central bank providing collateralized lending to banks at haircuts lower than the market – with an alternative policy that maintains a constant central bank balance sheet. We show that the fall in output, investment, and capital would have been twice as high under the alternative policy.

Key words: money markets, collateral, monetary policy, central bank balance sheet

JEL code: E44, E52, E58

*We would like to thank Saki Bigio, Stefano Corradin, Nicolas Crouzet, Matthias Kaldorf, Peter Karadi, Nobuhiro Kiyotaki, John Leahy, Enrique Mendoza, Giorgio Primiceri, Victor Rìos Rull, Pedro Teles, our discussants Juliane Begenau, Nicolas Caramp, Ikeda Daisuke, Luigi Paciello, Farzad Saidi, Saverio Simonelli and Ivan Werning, and seminar participants in numerous conferences and universities for useful comments and discussions. We are grateful to Johannes Pöschl, Luca Rossi, Maksim Bondarenko, Pablo Herrero Marco, and Catalina Cozariuc for research assistance. The previous version of the paper was circulated under the title “The Macroeconomic Impact of Money Market Disruptions.” The views expressed here are those of the authors and do not necessarily reflect those of the Bank for International Settlements, the European Central Bank, or the Eurosystem.

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1 INTRODUCTION

Money markets are an important cornerstone of the financial system. Banks rely on money markets for their short-term funding, while money market rates serve as benchmark rates for the pricing of credit to firms and households. Central banks target a short-term money market rate for monetary policy. What happens in money markets, therefore, matters for the transmission of monetary policy and for the economy as a whole.

Euro area money markets underwent dramatic changes during the Global Financial Crisis and the European Sovereign Debt Crisis. We start by documenting four interrelated facts in particular. First, activity in the segment of the unsecured money market, where banks borrow and lend to each other based on trust, progressively dried out. The share of unsecured interbank transactions declined throughout the euro area, with banks substituting towards secured transactions, where borrowers must secure the loan by pledging enough securities as collateral. Second, with the onset of the European Sovereign Debt Crisis in 2010, collateral haircuts – the difference between the security price and its value as collateral – on government bonds from countries in the southern euro area increased substantially, reducing the amount banks could borrow against pledged assets.¹ Third, during this period, banks in the southern countries increased secured borrowing from the European Central Bank (ECB) eightfold. This occurred while the ECB kept haircuts on accepted collateral nearly unchanged and well below those set in the market, creating a favorable “haircut gap” between private and ECB haircuts. Fourth, household deposits exhibited a U-shaped pattern: they fell when banks borrowed from the central bank, and vice versa when the central bank borrowing waned. This pattern was more pronounced in the South, where the ECB borrowing take-up was larger.

Our goal in this paper is to understand how these money market developments impacted the real economy and the role played by policies employed by the ECB. We develop a dynamic general equilibrium model with the banking sector at its heart to lay out the mechanism and quantify the effects. As in Gertler and Karadi (2011) and Gertler and Kiyotaki (2010), banks are capital investors who can leverage their net worth by issuing deposits up to some limit. Similar to Bianchi and Bigio (2022), banks must also manage short-term deposit outflows using the interbank market. Our key innovation here is to embed additional empirically relevant

¹A haircut is expressed as the percentage deduction from the market value of collateral (e.g., 3%). While collateral offers the lender protection against counterparty default, the collateral haircut offers the lender protection against the potential loss of value due to, e.g., the cost of liquidating collateral following counterparty default, or the possibility that the issuer of the collateral defaults.

features of money markets: some banks can borrow unsecured while others only have access to secured funding, which requires posting collateral, typically government bonds. How much secured funding the bank can access depends on the asset's collateral value: the higher the asset value and the lower the haircut, the larger the available funding. In line with the euro area context, our model features one central bank but heterogeneous government bonds. Specifically, there are two regions, the “North” and the “South” each with its own government bonds and a banking sector that holds a home-biased portfolio of the bonds.

Our model, which we calibrate to euro area data, indicates that the observed money market developments had a significant impact on the macroeconomy. Various forces are at play. First, as more banks become unable to borrow unsecured and need to access interbank markets on a secured basis, more collateral is held, crowding out capital investment. This is exacerbated by more banks chasing the same collateral, which makes collateral more costly to hold. Second, when haircuts on southern government bonds rise, banks located in southern regions must source additional collateral, which further crowds out capital. Crucially, this collateral scarcity spills over to banks in the northern regions because southern banks react to the rising cost of collateral by increasing outright holdings of reserves to manage liquidity. Banks in the North, who lose reserves to those in the South, instead manage liquidity with bond collateral, driving up the cost of issuing deposits and worsening the crowding out of capital as a result. Third, the ECB policy of offering secured loans of reserves to banks with attractive collateral terms when private market haircuts abruptly rise shields the economy from money market tensions. In the absence of tensions, deposit funding is banks' cheapest funding source. However, when money markets are disrupted, managing deposit flows is costly, and central bank funding becomes an attractive funding source. The central bank funding rose to over 4% of bank assets in the South. Central bank liquidity provision injects new borrowed reserves into the banking system and mitigates collateral scarcity. The policy matters quantitatively; the adverse effect on output from higher southern private haircuts would be twice as large in the absence of this measure. As a caveat, we have excluded considerations of sovereign default risk, which has been a large driver of private haircut developments. Our focus is on what happens, absent a default.

To demonstrate these insights, we have organized our paper as follows. Section 2 provides a “bird's eye view” of our analysis. It first documents four key developments in the euro area money markets. It then presents an overview and an informal description of the model,

the forces that play out, and how they combine to generate the empirical observations. This should suffice for readers to follow the fully dynamic analysis in section 6, though a more formal analysis is needed for a deeper understanding and replicability. Section 3 therefore presents the model formally. Section 4 outlines the analysis of banks, whose behavior is at the heart of the model, and shows that all key ingredients are necessary for money market frictions to matter. Section 5 explains the calibration of the model. Section 6 presents a numerical analysis focusing on understanding the dynamic impact of the money market developments in the euro area during the financial and sovereign debt crises. Section 7 concludes.

Related literature. Our paper is related to three strands of the literature. First, it shares with numerous papers the emphasis on the role of financial frictions for the provision of credit to the real economy and for the transmission of standard and non-standard monetary policies; see, e.g., Gertler and Kiyotaki (2010), Curdia and Woodford (2011), Gertler and Karadi (2011), Del Negro et al. (2017), and Kumhof and Salgado-Moreno (2024). In our model, as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), banks face an enforcement problem and an associated constraint on leverage. In addition, banks are subject to a liquidity management constraint; see Bianchi and Bigio (2022). Notably, our model features heterogeneity across banks' access to unsecured or secured money markets. Another novel feature of our framework is that we do not require the various constraints to be binding at all times. This is a feature we share with, e.g., Mendoza (2010), Brunnermeier and Sannikov (2014), Bocola (2016), He and Krishnamurthy (2019), and Justiniano et al. (2019).

Second, our paper is related to a strand of the banking literature that is concerned with the interactions between capital, liquidity, and other regulatory requirements; see Vives (2014), Cecchetti and Kashyap (2018), and Kara and Ozsoy (2020). Vo (2021) offers a review of the literature. While our framework also features multiple constraints for banks, we do not address regulatory issues and, instead, focus on banks' liquidity management problem through interbank markets as in, e.g., Bhattacharya and Gale (1987), Flannery (1996), Repullo (2005), Freixas and Jorge (2008), Freixas et al. (2011), Martin et al. (2014), Afonso and Lagos (2015), Atkeson et al. (2015) and Heider et al. (2015). Relative to these studies, we focus on the macroeconomic implications of interbank market frictions.

Third, and closest to our work, is the literature that studies how frictions in the unsecured or secured money markets impact the macroeconomy and interact with the effectiveness of monetary policy. Our results relate to those in Bruche and Suarez (2010), who show that

freezes in the unsecured money market segment can cause large reallocations of capital across regions, with a sizable impact on output and welfare. Bianchi and Bigio (2022) develop a tractable model of bank liquidity management with an over-the-counter interbank market to study the credit channel of monetary policy. Piazzesi et al. (2019) and Arce et al. (2020) study floor versus corridor systems in a New Keynesian framework. Piazzesi and Schneider (2017) provide a model of the determination of securities prices and inflation in an economy with a layered payment system. As in our paper, the provision and allocation of collateral play a central role. Our paper contributes by considering frictions in both unsecured and secured interbank markets. In our setup, frictions in the unsecured money market segment may, in principle, be offset by an increased recourse to private secured markets or to central bank funding.²

Importantly, several recent empirical papers study the effects of the “Haircut Gap Force” of monetary policy, the difference between private market and central bank haircuts for the same collateral assets; see e.g., Drechsler et al. (2016) and Jasova et al. (2023). Our model explains and quantifies the effects of the ‘Haircut Gap Force’ in a general equilibrium model by comparing the impact of a collateralized lending policy whereby central banks’ haircuts are more favorable relative to those in the private market with the counterfactual policy of keeping the central bank balance sheet constant.

2 FACTS AND FORCES: A BIRD’S EYE VIEW

This section provides an overview of the key facts motivating our analysis and of the main forces driving our results based on the model described in section 3.

2.1 Key developments in the euro area money markets

We focus on the largest euro area countries, Germany (DE), France (FR), Italy (IT), and Spain (ES), plus Portugal (PT), for which the relevant data are available.³ We document four key observations in money markets during the period 2003-2015.

I. Decline in the share of unsecured interbank borrowing. Between 2008, the year the Great Financial Crisis erupted, and 2015, the end of our sample, the turnover in unsecured

²Altavilla et al. (2018) provide evidence that increases in interbank rate uncertainty, as observed during 2007-2009 and again during the European sovereign crisis, generate a significant deterioration in economic activity.

³Our observations are derived from several data sources, which we describe in section A of the Online Appendix.

money market borrowing decreased, while turnover in the secured money market borrowing increased. Figure 2 documents this development.⁴ Normalizing the respective turnover in the secured and unsecured money market in 2007 to 100, we observe a negative co-movement between secured (dotted line) and unsecured (bold line) turnover, as of 2008 (see two panels on the left). Importantly, the co-movement is negative in both northern European countries (DE and FR), in which sovereigns enjoyed a higher credit rating, and in the three southern European countries (ES, IT, and PT), in which sovereigns had a lower credit rating.⁵ Considering the share of unsecured borrowing in total (see panel on the right), this share declined from roughly 50% in 2005 to less than 10% in 2015, in both northern and southern European countries in our sample.

II. Bank borrowing from the ECB increased eightfold in the South. Figure 3 plots bank borrowing from the ECB as a share of bank total assets (solid line, left-hand-side scale) for the northern European countries (DE and FR) and southern European countries (ES, IT, and PT). The figure illustrates that there was no substantial increase until 2010 in bank borrowing from the ECB across both northern and southern euro area countries. Bank borrowing fluctuated in a range from 0% to 3% across countries. However, during the European Sovereign Debt Crisis, bank borrowing increased approximately eightfold for banks in the “South,” from approximately 1% to approximately 8% of their total assets.

III. Increase in haircuts on government bonds in the South. The increase in southern countries’ bank borrowing from the ECB as of 2010 (solid line in the right-hand panel of figure 3) was accompanied by the rise in interbank market haircuts on government bonds in these countries (dashed line in the right-hand panel of figure 3), while haircuts remained largely unchanged in the northern countries. Meanwhile, the ECB kept its haircut schedule for central government debt instruments largely unchanged throughout the Great Financial Crisis and the European Sovereign Debt Crisis. This was the case both for higher-rated assets (rated AAA to A-) and for lower-rated assets (rated BBB+ to BBB-).⁶

⁴Turnover is defined as the sum of all borrowing transactions in the respective money market segment over the second quarter of each year, as reported by banks participating in the ECB’s Money Market Survey.

⁵This observation suggests a substitution between unsecured and secured money market activity. Such substitution was documented empirically by Di Filippo, Ranaldo, and Wrampelmeyer (2022), who analyzed individual banks’ borrowing and lending in the unsecured and secured euro interbank markets.

⁶Marginal adjustments in haircuts on government debt were made in 2014. We note that there was a level difference in haircuts charged by the ECB between higher-rated and lower-rated debt: 2.8% versus 7.8%, respectively (haircuts on fixed coupon central government bonds in 2011, average across maturities). For simplicity, in our simulations, we keep the central bank haircuts fixed at 3%. This is not very material as what matters in the model is the variation in the haircut gap, i.e., the difference between private and central bank

IV. U-Shaped relationship between household deposits and ECB funding. Figure 4 illustrates the evolution of the share of bank borrowing from households (household deposits) in total bank assets, along with the share of bank borrowing from the ECB, again as a share in total bank assets. The figure shows that the share of bank borrowing from the household sector remained fairly stable overall but exhibited a U-shaped pattern during the onset of ECB borrowing: it fell when banks borrowed from the central bank and vice versa when the central bank borrowing waned. Importantly, this U-shape is more pronounced in the South, where ECB borrowing take-up was larger.

2.2 MODEL OVERVIEW

The economy is composed of two regions, the “North” (standing in for countries such as Germany and France) and the “South” (standing in for countries such as Spain, Italy, and Portugal), each with its own fiscal authority but one common central bank. Observations II and III show how money markets developed differently in the North than in the South. The geographical distinction in our model is not only essential to account for these observations, but it also plays a key role for the main forces driving our analysis. Our primary focus is on banks that are leveraged capital investors and face a liquidity management problem that is at the core of our model.

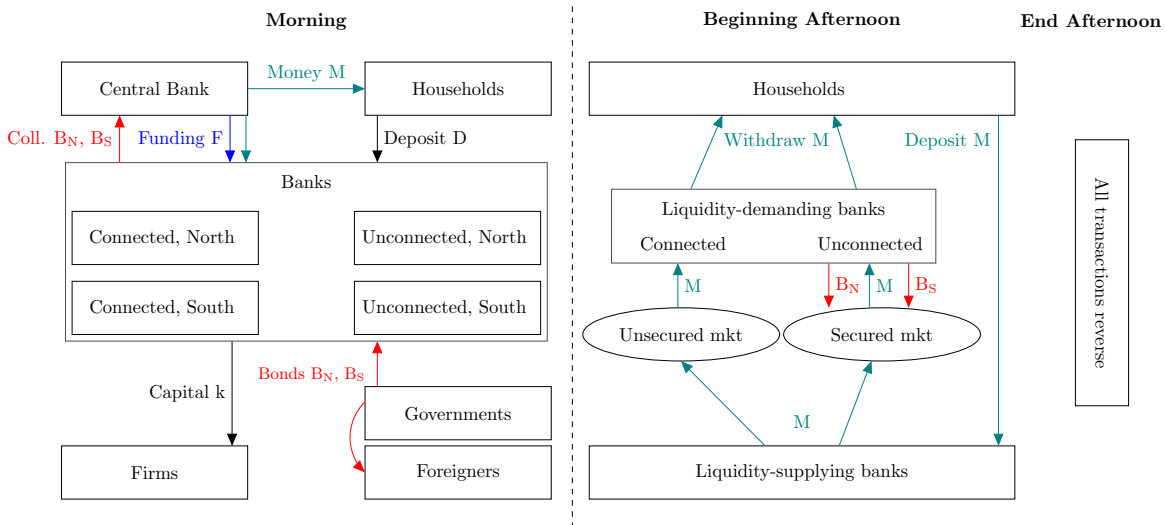


Figure 1: Model Overview

haircuts. It is this difference that widened dramatically in southern European countries during the European Sovereign Debt Crisis.

Figure 1 provides an overview of the model. Each period in the model is subdivided into a “morning” and an “afternoon”. Although all markets are open in the morning, only interbank markets are open in the afternoon. Decisions in the morning must anticipate liquidity needs in the afternoon. In the spirit of backward induction, we, therefore, first describe the latter.

In the afternoon, depositors reshuffle their deposits, making withdrawals from some banks and depositing with the other banks (as in Bianchi and Bigio (2022)). This is a simple way of formulating randomly arising payments from some consumers to others, using their deposit accounts. Banks with payment outflows can borrow from banks with payment inflows via the interbank money market to service withdrawals.

We imagine that banks can be part of bank networks of partner banks that offer mutually favorable borrowing arrangements, e.g., due to repeated interactions. We describe such banks as “connected” to a network. We incorporate the favorable borrowing arrangements by assuming they do not need to post collateral when borrowing from other banks in their network, i.e. they can access the unsecured money market. In contrast, “unconnected” banks, i.e. banks outside such networks, can only borrow from other banks by pledging bonds in a secured (repo) market. Rather than modeling networks and the repeated interaction explicitly, we assume that the network type ν of a bank is “connected”(c) or “unconnected”(u).⁷ For simplicity, we assume that the network type is drawn iid each period, with a bank being “connected” according to some exogenous probability ξ_t and “unconnected” otherwise.⁸ Defining these two types is a novel and essential element in the model. It helps us capture the structural shift towards banks relying on the unsecured rather than the secured money market and acting as “unconnected” in the data, as shown in observation I above.

The pledged bonds in the interbank market are subject to a haircut $(1 - \tilde{\eta}_t)$: When banks pledge one unit of collateral, they receive $\tilde{\eta}_t$ units of interbank loans. Haircuts can vary between the two regions, as shown in observation III. In the interest of model clarity, we impose their evolution as an exogenous variable rather than also modeling sovereign default fears and market disruptions as their root cause. Reflecting the well-known home bias in domestic sovereign bond holdings, we assume that banks in the “North” use northern government bonds and banks in

⁷Several reasons may explain why some banks have access to the unsecured money market. These include profitability, leverage, and liquidity position, and network relationships with other banks. We abstract from these considerations and assume an exogenous probability of being “connected” or “unconnected”, which reflects at any point in time the aggregate turnover observed in the unsecured and secured market segments.

⁸In our model, the bank’s type (connected vs. unconnected) is re-drawn each period rather than being a permanent type. There are two reasons for this. First, if they were permanent types, connected banks would grow and crowd out unconnected banks entirely due to their competitive advantage. Second, it makes the model tractable by not having to track the type as a state variable.

the “South” use southern government bonds as collateral for secured loans. This is a crucial feature of our model that allows us to capture rising haircuts observed in the “South” only and their impact on southern banks. We assume that the region of the banks is drawn iid in each period.⁹

At the end of the afternoon, the deposit reshuffling is reversed and the short-term interbank money market loans are repaid so that banks exit the period with the same portfolio that they had at the beginning of the afternoon.

In the morning, banks learn their connectedness type (connected or unconnected) and their region (North or South). They then make their portfolio decision. On their liability side, they have two ways of financing aside from their own net worth: household deposits D and funding F from the central bank. On their asset side, they can invest in firm capital k , in government bonds, i.e., B_N for North banks and B_S for South banks, and in reserves M . Unconnected banks may buy bonds in the morning, anticipating needing them as collateral in the secured market in the afternoon, as described above. Alternatively, they can acquire reserves in the morning, either directly on the market (“money” M) or via loans F from the central bank, collateralized with government bonds. For our benchmark policy specification, we allow banks to borrow from the central bank at constant haircuts $1 - \eta$, even when private sector haircuts $1 - \tilde{\eta}_t$ increase.¹⁰ Under our alternative policy, the central bank maintains a constant supply of reserves. Connected banks do not need to anticipate afternoon liquidity needs because, in the event of a deposit withdrawal, they obtain within-afternoon unsecured loans on the interbank market to cover it. They invest in bonds or reserves only if their returns are attractive relative to investing in firm capital.

The bonds are supplied by the North and South governments and traded in the government bond market, in which the foreign investors, who have an elastic demand, also participate. The presence of foreign investors helps the model to smooth out bond demand fluctuations that arise from the banking sector. In addition, banks decide whether to raise additional funding from the central bank in exchange for bonds as collateral. Finally, “unconnected” banks decide on the amount of reserves M and bonds B_N or B_S to bring to the afternoon to cover for possible deposit withdrawals.

⁹The reasons are similar to the reasons for assuming the iid nature of the connectedness: it simplifies the model and avoids driving out the less profitable southern banks entirely unless one also explicitly models country-specific firms and capital markets.

¹⁰Central bank haircuts on pledged bonds are a standard feature and policy tool for lending to banks via repurchase agreements. This is presumably done to cover the risk and cost of selling the collateral if things go wrong and the bank does not repay the loan, but we do not model that explicitly.

The choice of a bank portfolio involves trade-offs. Holding reserves instead of bonds to cover for the possibility of withdrawals in the afternoon foregoes the interest banks could earn on bonds. However, if private sector haircuts are large, relatively more bonds need to be held, which crowds out profitable capital investment by banks. Alternatively, banks could use central bank loans instead of deposits as a funding source. This becomes attractive if the gap between private sector and central bank haircuts is sufficiently large.

This interplay of trade-offs and market interactions generates the main forces that help our model explain the data. Aside from the impact of leverage well known from models building on Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), the market for collateral (bonds, money) gives rise to four forces that are novel to the analysis here.

1. **Capital Crowding Out:** suppose the banking sector needs to hold more collateral assets. This can be due to a higher share of unconnected banks or to a lower quality of existing collateral (e.g., higher private haircuts on bonds). As banks have limits on leverage, this crowds out productive capital investment.
2. **Bond-Reserves Substitution:** when there is an increase in collateral scarcity, banks pay a higher *collateral premium* in equilibrium, i.e., they forego more interest investing in bonds relative to capital. If the premium is high enough, banks may find it optimal to switch from bonds to reserves to manage liquidity. This helps mitigate the loss in bank profitability.
3. **North-South Liquidity Spillover:** when both regions hold reserves, there are strong spillovers of collateral scarcity across regions. For example, suppose that the South experiences a drop in the collateral quality of its bonds. In response, unconnected banks in the South rebalance to reserves as a way to manage liquidity. However, the reserves must come from other banks unless the central bank steps in, i.e., unconnected banks in the North, which, therefore, must rebalance from reserves to collateral assets for liquidity needs. As a result, banks in the North end up facing a collateral scarcity issue as well.
4. **Haircut Gap:** the gap between the private market and the central bank haircut is what we call the “haircut gap”. If the gap is large enough, banks will start to use the central bank as a source of funding since high private haircuts make managing afternoon deposit flows costly. In addition, by lending new reserves, the central bank increases

the aggregate supply of reserves for banks. This reduces collateral scarcity across the monetary union by alleviating collateral shortages.

Armed with these four forces, we can now tell the story through the lens of our model of how observed changes in interbank markets impacted the real economy and understand the role played by central bank funding.

In light of observation I, we assume that there is a gradual permanent increase in the share of unconnected banks. As a result, more banks must hold bonds as collateral, reducing capital investment in the long run via the Capital Crowding Out Force. The increased need for bonds drives up the collateral premium so much so that banks substitute toward reserves to manage liquidity needs for the afternoon (Bond-Reserves Substitution Force). Overall, less capital investment and higher collateral premia make banks less profitable which, through the usual leverage constraint channel of Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) amplifies the effects of the transition.

Given observation III, we assume a temporary rise in southern bond haircuts starting around 2010. This exacerbates the collateral shortage and the scramble for reserves in the South, as described by the bank-reserves substitution force. This shortage spills over to northern banks due to the North-South Liquidity Spillover Force, causing all banks to switch out of capital more aggressively. However, with the benchmark policy specification, southern banks wishing to escape the punishing private market haircuts can now borrow from the central bank instead, posting southern bonds at unchanged and relatively favorable haircuts, as described by the Haircut Gap Force. As a result, banks substitute deposits for central bank funding. Our model therefore reproduces observation II and observation IV for the South. Reducing collateral scarcity across the union weakens the North-South Liquidity Spillover Force and, ultimately, the Capital Crowding Out Force and, thus, the drop in output. The central bank policy is important: without the central bank lending facility, which fully satisfies banks' demand for reserves as long as they pledge enough collateral, the output drop caused by the rise in haircuts would be twice as large.

This completes the informal description of our model and the key forces. A reader might proceed to the results of the fully dynamic analysis in section 6 at this point. However, a more formal description and analysis in the following two sections will be needed for a deeper understanding and replicability.

3 THE MODEL

Time is discrete and infinite. There is no aggregate uncertainty. Each region, denoted by $j \in \{N, S\}$, is of size s_j , where $s_N + s_S = 1$. An overview of the timing is available in Online Appendix B. Nominal variables are denoted with upper case, while real variables are denoted with lower case.

3.1 The household

In each region, there is a continuum of identical households. Since taxes are the same in the two regions, households are identical, so we eliminate the subscript j .

Households arrive in period t with cash, M_{t-1}^h , and bank deposits D_{t-1}^h that are remunerated at the gross return R_{t-1}^d . Households also earn wages from labor supplied, net of proportional taxes paid, $(1 - \tau_t) W_t h_t$. Assets and post-tax wages are then used to finance consumption, $P_t c_t$, along with savings allocated to deposits, D_t^h , and money, M_t^h . The budget constraint of the household is then given by

$$M_t^h + D_t^h = M_{t-1}^h + R_{t-1}^d D_{t-1}^h + (1 - \tau_t) W_t h_t + \phi N_t + \Pi_t^{CP} - P_t c_t \quad (1)$$

where N_t is the total net worth of banks and ϕ is the share paid as dividends, so that ϕN_t are the bank dividends paid to the bank-owning households.

The household chooses $c_t > 0$, $h_t > 0$, $D_t^h \geq 0$, $M_t^h \geq 0$ to maximize the objective function

$$\max \sum_{t=0}^{\infty} \beta^t \left[u(c_t, h_t) + v\left(\frac{M_t^h}{P_t}\right) \right] \quad (2)$$

subject to the budget constraint (1).¹¹ We assume that households derive convenience from their money holdings, reflected as “money-in-the-utility.”

3.2 Final goods firm

A representative final-good firm rents capital k_{t-1} and hires labor h_t to produce a homogeneous final-output good y_t according to the production function

$$y_t = k_{t-1}^\theta h_t^{1-\theta}. \quad (3)$$

¹¹As a functional form, we assume that, $u(c_t, h_t) = \log(c_t) - \frac{h_t^{1+\zeta}}{1+\zeta}$, and $v(m_t^h) = \frac{1}{\chi} \log(m_t^h)$.

It receives revenues $P_t y_t$, pays wages $W_t h_t$ and pays rent $P_t r_t k_{t-1}$ to banks who are the capital owners.

3.3 Capital-producing firms

The competitive capital-producing firms use k_{t-1} units of old capital and invest i_t in units of consumption goods to produce

$$k_t = (1 - \delta)k_{t-1} + \Phi\left(\frac{i_t}{k_{t-1}}\right)k_{t-1} \quad (4)$$

units of new capital that are sold at the real price Q_t^k , i.e. in units of the date- t consumption good, to capital-owning banks. Each firm is a price-taker, maximizing profits

$$\max_{i_t \geq 0, k_{t-1} \geq 0} Q_t^k k_t - \tilde{Q}_t^k k_{t-1} - i_t \quad (5)$$

subject to (4), where $\Phi'(\cdot) > 0$, $\Phi''(\cdot) < 0$, $\Phi(\delta) = \delta$ and $\Phi'(1) = 1$, where δ is the depreciation rate, and \tilde{Q}_t^k is the date- t post-rental real price for old capital, i.e., in units of the date- t consumption good.¹² Since (4) has constant returns to scale, capital-producing firms make zero profits i.e.

$$Q_t^k k_t = i_t + \tilde{Q}_t^k k_{t-1} \quad (6)$$

Given the price of capital, the nominal return realized at time t for investing in a unit of capital at time $t - 1$ is given by

$$\begin{aligned} R_t^k &= \frac{P_t}{P_{t-1}} \frac{r_t + \tilde{Q}_t^k}{Q_{t-1}^k} \\ &= \frac{P_t}{P_{t-1}} \frac{r_t + Q_t^k \frac{k_t}{k_{t-1}} - \frac{i_t}{k_{t-1}}}{Q_{t-1}^k} \end{aligned} \quad (7)$$

where (7) exploits the aggregated versions of (4) and (6) to substitute out \tilde{Q}_t^k ¹³

¹²As a functional form, we assume that $\Phi(x) = a_1 x^{1-\zeta} + a_2$, where $a_1 = \delta^\zeta / (1 - \zeta)$ and $a_2 = -\delta\zeta / (1 - \zeta)$. The parameter ζ controls the degree of convexity in the capital adjustment cost function.

¹³This follows Uhlig (1990). Alternatively, one can follow Bocola (2016) where capital producers simply take k_{t-1} as given and optimise investment. Using this generates very similar results. We prefer our fully competitive setup.

3.4 Fiscal policy

For simplicity, we consider a single government issuing claims to two types $j \in \{N, S\}$ of bonds, one per region.¹⁴ Each period, the government purchases a fixed amount of goods, g^* . It finances expenditures with public debt, seigniorage transferred from the central bank, and tax revenues.

Government debt consists of two long-term bonds with geometrically decaying payoffs, $\bar{B}_{j,t}$, one per region. Each bond is only purchased by banks of that region as well as foreign investors and the central bank. The assumption that only banks of region j hold bonds of region j captures the well-documented home bias of banks in Europe. At the beginning of period t , the government has claims to $\bar{B}_{j,t-1}$ units of outstanding nominal debt of type j . One unit of such a claim represents a promise to the sequence of nominal payments $\{\kappa, \kappa(1 - \kappa), \kappa(1 - \kappa)^2, \dots\}$, which begins with κ units at period t and then decays at the common geometric rate $1 - \kappa$. The government pays the current coupon on outstanding debt $\bar{B}_{j,t-1}$ at t and issues $L_{j,t}$ new units of debt, resulting in debt

$$\bar{B}_{j,t} = (1 - \kappa)\bar{B}_{j,t-1} + L_{j,t} \quad (8)$$

We assume that the government issues bonds to leave the amount of aggregate real debt constant, $\bar{B}_t = P_t b^*$, where b^* is a parameter and $\bar{B}_t = \bar{B}_{N,t} + \bar{B}_{S,t}$. Total issuance is allocated to each bond in shares equal to the size of each region, s_j , implying that $L_{j,t} = [P_t - (1 - \kappa)P_{t-1}]s_j b^*$.

At time t , bonds of region j trade at nominal price Q_t^j per unit. They pay off κ nominal units and $1 - \kappa$ units of a region- j bond in $t + 1$ per unit of a bond today, for a grand total of $\kappa + (1 - \kappa)Q_{t+1}^j$ in nominal terms. Therefore, the nominal return is

$$R_{t+1}^j = \frac{\kappa + (1 - \kappa)Q_{t+1}^j}{Q_t^j} \quad (9)$$

¹⁴The dynamics of bond prices in response to shocks is a key driver of banks' leverage position and liquidity needs. The assumption of a single government issuing two distinct bonds ensures that the price of each bond, Q^j , differs depending on collateral quality, as reflected by the haircuts charged in the interbank market. We could alternatively model fiscal policy as conducted by two separate fiscal authorities indexed by $j \in \{N, S\}$, where each authority issues a domestic bond $\bar{B}_{j,t}$. The two formulations are equivalent under the additional assumption that the governments impose a common level of income taxes and balance the budget through cross-country lump sum transfers. The equivalence is derived in Online Appendix C.

This implies the relationship

$$Q_t^j = E_t \left[\frac{\kappa + (1 - \kappa)Q_{t+1}^j}{R_{t+1}^j} \right] \quad (10)$$

which one could telescope out to write Q_t^j as the sum of discounted future payoffs in the usual manner. For the analysis, though, the returns R_{t+1}^j must be calculated from the endogenously determined prices Q_t^j and Q_{t+1}^j as in equation (9) rather than the other way around. I.e., there is no easy way to apply the standard discounted-sum approach to obtain the bond prices.

The government receives seigniorage S_t from the central bank and sets proportional taxes on labor income, τ_t , ensuring the budget balances. The budget constraint is given by

$$P_t g^* + \kappa \bar{B}_{t-1} = \tau_t W_t h_t + Q_t^N L_t^N + Q_t^S L_t^S + S_t \quad (11)$$

3.5 The central bank

The central bank (CB) has a variety of policy instruments at its disposal, reflecting the expansion of policy tools in recent times. Of particular interest in this paper is the policy in which the central bank offers one-period collateralized loans of reserves to private banks. This can be quite attractive for banks, as reserves are important for managing deposit withdrawals they may face. Of course, the take-up depends on the terms of the loan, the conditions of banks, and the economy.

The set of central bank policy tools is the following:

1. **Collateralized Loans to Banks:** The central bank sets the terms of collateralized one-period loans to banks, given by the interest rate and collateral haircuts. We denote the interest rate on central bank loans by R_t^F while the discount price of loans to banks is defined as $Q_t^F \equiv 1/R_t^F$. Central bank loans are collateralized, with banks pledging region-N or region-S bonds as collateral to secure the loans. The central bank applies a haircut (that is, a reduction) to the value of the pledged collateral that determines how much a bank can borrow. For example, if a region- j bond is worth 1 euro but is given a haircut of 3% at time t , the bank can only borrow 0.97 euros. Haircuts on region- j bonds are policy parameters set by the central bank, denoted $1 - \eta_t^N$ and $1 - \eta_t^S$ for region- N and region- S , respectively. In our example, the 3% haircut is therefore $1 - \eta_t^j = 0.03$ while $\eta_t^j = 0.97$ is the value of the collateral after the haircut. The ECB kept its haircuts fairly

stable during the European Sovereign Debt Crisis, despite considerable fluctuations of private sector haircuts. We model this by setting the central bank's haircut choice at a constant throughout, $1 - \eta_t^S = 1 - \eta_t^N \equiv 1 - \eta$.¹⁵ Having set the terms of the collateralized loans, (Q_t^F, η) , the central bank satisfies any bank demand for central bank loans. That is, given policy choices (Q_t^F, η) , the take-up by the banking sector, \bar{F}_t , is a choice variable of banks.

2. **Bond Holdings Policy:** The central bank sets the quantity $B_{j,t}^C$ of bonds held outright (rather than as collateral for bank loans) of each region $j \in \{N, S\}$, where the superscript C denotes the bond holdings of the central bank. Throughout, we assume that the central bank holds a constant real stock of debt, b^C , split across regions according to each region's size.¹⁶ In other words

$$B_{j,t}^C = s_j P_t b^C \quad \text{for each } j \in \{N, S\} \quad (12)$$

This implies that central bank purchases at the beginning of each period are set to replenish the real stock after redemptions and inflation.¹⁷

3. **Money Supply Rule:** The central bank decides on the supply of money, \bar{M}_t , available to the private sector. This is held as reserves by banks and as currency by households. Throughout, we assume the following money supply rule:

$$\bar{M}_t = \bar{M}_{t-1} \pi_t + Q_t^F \bar{F}_t - \bar{F}_{t-1} \quad (13)$$

In other words, absent central bank loans to banks, the money supply is constant in real terms. The last two terms combined reflect additional reserves provided to banks via central bank loans in period t : banks repay the liabilities \bar{F}_{t-1} of the previous period and obtain new loans with face value \bar{F}_t , getting funding in the amount of $Q_t^F \bar{F}_t$, where Q_t^F is the discount price of central bank loans.

¹⁵The ECB's haircut schedule features a differentiation according to the credit quality of securities pledged as collateral, resulting in slightly higher haircuts charged on lower-rated sovereigns versus higher-rated sovereigns. The main theme in our analysis, however, is the emphasis on the much larger haircuts imposed by the private sector rather than on the much smaller differentiation among securities in the central bank's haircut schedule.

¹⁶The ECB conducted targeted asset purchases during the 2010-2014 period under the so-called "Securities Markets Programme." Those purchases were intended to ensure depth and liquidity in malfunctioning segments of the bond markets. However, such purchases were sterilized and did not affect central bank liquidity outstanding. They are, therefore, not the focus of our study.

¹⁷In particular, you can show that $\Delta B_t^C = b^C P_t (1 - (1 - \kappa) P_{t-1} / P_t)$.

Finally, the flow budget constraint of the central bank is given by

$$\begin{aligned} \bar{M}_t - \bar{M}_{t-1} = & S_t + Q_t^F \bar{F}_t + Q_t^N B_{N,t}^C + Q_t^S B_{S,t}^C \\ & - R_t^N Q_{t-1}^N B_{N,t-1}^C - R_t^S Q_{t-1}^S B_{S,t-1}^C - \bar{F}_{t-1} \end{aligned} \quad (14)$$

where the terms related to the central bank loans to banks, \bar{F}_t and \bar{F}_{t-1} , are as explained in the previous paragraph and where R_t^j is the nominal return from holding government bonds of region $j \in \{N, S\}$ defined in equation (9). S_t is the seigniorage of the central bank, which is the net proceeds from asset allocations that are transferred to the government.¹⁸

We focus on the impact of a monetary policy operation allowing banks to borrow from the central bank at favorable haircuts during crises. Therefore, we compare two policies: benchmark (CO) vs. alternative (CB). The idea here is that the benchmark describes collateralized lending operations during the Great Financial Crisis (GFC) and the European Sovereign Debt Crisis, whereas the alternative reflects monetary policy pre-GFC. In particular:

CO Policy (*Collateralized Operations*) : $\eta = 0.97$

CB Policy (*Constant Balance Sheet*) : $\eta = 0$

Under CO policy, the central bank haircut is set constant at the pre-GFC private market level of 3% or $1 - \eta = 0.03$. This can become quite an attractive policy for banks if private haircuts increase substantially. In this case, banks may find it optimal to obtain collateralized loans from the central bank so that \bar{F}_t can exceed zero. In contrast, under the CB Policy, banks have no incentive to borrow from the central bank as their collateral has zero value. In this case, the size of the central bank balance sheet is constant at $\bar{F}_t = 0$. Regarding the interest rate on central bank loans, in our numerical analysis, we set it equal to the average interest rate on central bank loans that prevailed over the 2008-2014 period (that is, during and after the GFC) in the euro area (see Section 5 for details).

3.6 Banks

There is a continuum of banks (“lenders”) $i \in [0, 1]$. They are owned by households that are perfectly diversified across banks. Choices in the previous period result in the net worth of a bank at the beginning of the period. Subsequently, their network type and region are drawn.

¹⁸We have not included interest on reserves in this version of the model to avoid the extra notation and issues arising from such an inclusion. It was of no relevance during the euro area European Sovereign Debt Crisis and thus the theme at hand, but it could be important to include it in future extensions for other applications.

We assume that both are iid across time and banks to ensure the existence of a non-trivial steady state. Banks then make choices regarding assets and liabilities in the morning, subject to a leverage constraint and, crucially, a liquidity constraint. The latter ensures they have sufficient liquidity to manage any possible deposit withdrawals in the afternoon.

3.6.1 The morning

In the morning, the date- t type of each bank is uncovered as the result of two iid shocks. First, the network type ν is drawn. Bank i is connected (“ $\nu = c$ ”) with probability ξ_t and unconnected (“ $\nu = u$ ”) with probability $1 - \xi_t$. Unconnected banks will need to pledge bonds in the afternoon in order to borrow in the secured money market, while connected banks can borrow in the afternoon in the unsecured market without posting collateral.

Second, the region j is chosen. With probability (“size”) s_N , a bank is located in $j = N$ (“North”), and with probability $s_S = 1 - s_N$ it is located in $j = S$ (“South”). In each region j , banks can trade and hold only the bond issued by their own government, $B_{j,t}$. Deposit and credit markets are integrated.

Knowing their network type and region, banks then choose their portfolio of assets and liabilities and pay dividends. We assume that dividends are a constant fraction ϕ of net worth. The bank collects nominal deposits ($D_{i,t}$) and accesses nominal secured loans from the central bank at face value ($F_{i,t}$). The ex-dividend net worth plus liabilities are then allocated to capital ($k_{i,t}$), nominal bonds ($B_{i,t}$), and nominal reserves ($M_{i,t}$).

The bank’s balance-sheet constraint at the end of the morning is, therefore, given by

$$P_t Q_t^k k_{i,t} + Q_t^j B_{i,t} + M_{i,t} + \phi N_{i,t} = D_{i,t} + Q_t^F F_{i,t} + N_{i,t}, \quad (15)$$

Banks face a variety of additional constraints on their portfolio choice in the morning. Firstly, the collateral constraint at the central bank requires loans not to exceed the value of the bonds pledged, adjusted by the central bank’s haircut. In equilibrium, banks will pledge just enough collateral to make the collateral constraint at the central bank bind. This is because any extra bonds can instead be used as collateral in the secured money market in the afternoon, or alternatively, the funds used to buy extra bonds can instead be invested in at least as profitable capital in the morning. We impose that the “just enough” collateral constraint holds, even if banks are indifferent, i.e., for all types of banks,

$$F_{i,t} = \eta_t Q_t^j B_{i,t}^F. \quad (16)$$

Given the face value of central bank loans $F_{i,t}$, the bank obtains central bank funding in the amount of $Q_t^F F_{i,t}$.¹⁹

Second, bonds pledged at the central bank are constrained to be non-negative but also to not exceed the amount of bonds acquired in the morning,

$$0 \leq B_{i,t}^F \leq B_{i,t}. \quad (17)$$

Third, banks face a leverage constraint. As in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), we assume there is a moral hazard constraint in that bank managers may run away with a fraction λ of their assets at the end of the morning. Let $V_{i,t}$ be the value of a bank at the end of the morning after the type of the bank is known, deposit claims are issued, central bank funding is accessed, and assets are purchased, but before dividends are paid. At this point, the banker has the option to walk away with a fraction λ of the assets and transfer them back to the household. They will decide to do so if the value of the bank itself, $V_{i,t}$, is below a fraction λ of the value of the assets held. In this case, creditors will lose out as they can only recover a fraction $(1 - \lambda)$ of their investments. As a result, the following leverage constraint must be satisfied for depositors to be willing to deposit with the bank:

$$\lambda \left(P_t Q_t^k k_{i,t} + Q_t^j B_{i,t} + M_{i,t} \right) \leq V_{i,t} \quad (18)$$

Finally, there are non-negativity constraints for investing in capital, deposits, cash, bonds, and for financing from the central bank, for any bank i :

$$k_{i,t} \geq 0, D_{i,t} \geq 0, M_{i,t} \geq 0, B_{i,t} \geq 0, F_{i,t} \geq 0. \quad (19)$$

3.6.2 The afternoon

In the afternoon, banks face a liquidity management problem, as in Bianchi and Bigio (2022). At the beginning of the afternoon, they experience idiosyncratic liquidity shocks. A bank with end-of-morning deposits $D_{i,t}$ experiences a shock $\omega_i D_{i,t}$. Negative (positive) ω_i denotes incoming (outgoing) payments. Here, $\omega_i \in [-\omega^{\max}, \omega^{\max}]$ is a random variable, which is iid across banks and is distributed according to $F(\omega)$, where $\omega^{\max} \in [0, 1]$ is a parameter. Payment shocks average out across all banks, so that total deposits remain unchanged. The liquidity

¹⁹In the aggregate, the difference between the new period t loans, $Q_t^F \bar{F}_t$, and the $t - 1$ central bank loans repaid, \bar{F}_{t-1} , represent additional reserves provided to the banking sector via central bank loans, as per Equation (13).

shocks are exactly reversed at the end of the afternoon and thus create only a temporary need for liquidity at banks with $\omega_i > 0$. These shocks are a simple way to capture random payments between depositors.

We add to the Bianchi and Bigio (2022) structure the distinction between “connected” and “unconnected” bank types. Connected banks can borrow unsecured in the afternoon interbank market. We think of connected banks as operating in a network of banks mutually trusting each other, such that collateral is unnecessary. By contrast, unconnected banks must secure interbank borrowing with bonds. Payments between banks are settled using reserves acquired in the morning (outside money) or using interbank loans (IOUs, inside money), which are either unsecured or secured by government bond collateral (e.g., a repo). Unsecured IOUs can only be issued by connected banks. Unconnected banks have to collateralize their IOUs. When the liquidity shocks are reversed at the end of the afternoon, the interbank loans are repaid.²⁰ The assets and liabilities of a bank at the end of the afternoon are unchanged compared to its assets and liabilities at the beginning of the afternoon.

In the secured market, we assume that a lending bank imposes a private-sector haircut $0 \leq 1 - \tilde{\eta}^j \leq 1$, with $j \in \{S, N\}$. We allow for haircuts to differ between regions for different reasons, including the rational assessment of the market on the default risks of the underlying bonds. We sidestep modeling those reasons and instead treat the haircuts as exogenous. The borrowing bank then pledges the amount $(B_{i,t} - B_{i,t}^F)$ of bonds, as it can only pledge the portion that has not yet been pledged to the central bank. Taking literally, there is no risk of bond default here against which this haircut is insuring the lender. This is to keep the model simple. Every bank can lend unsecured to any connected bank or secured to any bank if they so choose.²¹ We impose that the within-afternoon interest rate on interbank loans is zero.²²

²⁰We follow a long tradition in the banking literature of focusing on the role of interbank money markets in smoothing out idiosyncratic liquidity shocks, as in Bhattacharya and Gale (1987) and Allen and Gale (2000). Although analytically convenient, in reality, interbank relationships may exhibit more persistent patterns, some banks being structural borrowers and others structural lenders in interbank markets (Craig and Ma (2022)).

²¹Implicitly, we are assuming that the discount window of the central bank is not open in the afternoon, i.e., that banks need to obtain central bank reserves, if any, in the morning in anticipation of possible liquidity shocks in the afternoon. This captures the fact that the discount window is rarely used for funding liquidity needs, and these liquidity transactions happen “fast,” compared to central bank liquidity provision.

²²This can be justified if some banks hold positive reserves $m_{i,t} > 0$: in that case, there is an excess supply of interbank loans (payment inflows plus morning reserves) compared to the demand for interbank loans (payment outflows). The market-clearing interbank rate then must fall to the price of the alternative storage technology for keeping reserves, i.e., to zero. If no banks wish to hold positive reserves in the morning, supply and demand for interbank loans are equal across various interest rates. We pick the lowest one, compatible with the storage alternative, implicitly assuming that the borrowing banks have all the bargaining power. Alternatively, a minimum reserve requirement could be introduced so that $m_{i,t} > 0$ always.

Bankruptcy is not allowed. Hence, if bank i is unconnected, it must make sure it has enough reserves brought over from the morning and/or enough unpledged collateral to be able to cover the maximum possible afternoon payment outflows, $\omega^{\max} D_{t,i}$. In other words, an unconnected bank i must satisfy

$$\omega^{\max} D_{i,t} \leq M_{i,t} + \tilde{\eta}_t^j Q_t^j (B_{i,t} - B_{i,t}^F). \quad (20)$$

We denote (20) as the unconnected bank’s “afternoon constraint.”²³ Given that all liquidity shocks reverse at the end of the afternoon, the only impact of the afternoon is that unconnected banks need to plan ahead of time in the morning to make sure they have enough reserves or collateral in the afternoon. An overview of the timing of bank decisions is shown in figure B.1 of the Online Appendix.

3.7 Price setting

We assume that prices are determined one period in advance. In particular, we have that

$$\pi_t = \pi_{t-1}^e \quad (21)$$

In other words, inflation in the next period is already pre-determined at π_t^e . It endogenously adjusts to ensure that the money market clears. For our perfect foresight experiments, the only restriction this imposes is that the inflation rate at the time of the shock does not respond.

3.8 The rest of the world

We assume that a share of the stock of government bonds is held by the rest of the world, and that foreign investors have an elastic demand for those bonds.²⁴

²³We assume that banks will always find defaulting on the payments worse than any precautionary measure they can take against it, and thus rule out payment caps and bank runs by assumption. Alternately, one might interpret the absence of bankruptcy as the result of vigilant regulators.

²⁴We introduce an elastic demand for the foreign sector for two reasons. First, foreigners are significant holders of euro area government bonds. In our model, foreign investors are equivalent to all residual bond holders who are neither banks nor the central bank, which we calculate as 64% for 2015 using data from the ECB’s Statistical Data Warehouse. Second, their demand responds to price changes, where the elasticity measure is taken from pre-Public Sector Purchasing Programme rebalancing data from Kojen et al. (2021) (see Section 5 for more details on the calibration).

We do not explicitly model the foreign sector. Instead, we assume that foreign investors have demands for bonds issued in region j , $B_{j,t}^w$, which react to movements in the real return,

$$\frac{B_{j,t}^w}{P_t} = \alpha \left(1 + \frac{1}{\varrho} \log \left(\frac{E_t \left[\frac{R_{t+1}^j}{\pi_{t+1}} \right]}{r^j} \right) \right) \quad (22)$$

where $\varrho > 0$, $\alpha \geq 0$, $\frac{R_{t+1}^j}{\pi_{t+1}}$ is the real one-period holding return on the bond from t to $t+1$, and r^j is the real rate of return on bond j in the baseline calibrated steady state. Notice that if $\varrho = 0$, the bond demand is infinitely elastic. In that case, the real return is fixed, and foreign holdings take whatever value is needed to clear the bond market.

The flow budget constraint of the foreign sector is

$$P_t c_t^w = R_t^N Q_{t-1}^N B_{N,t-1}^w + R_t^S Q_{t-1}^S B_{S,t-1}^w - Q_t^N B_{N,t}^w - Q_t^S B_{S,t}^w \quad (23)$$

where c_t^w is the foreign-investor consumption of the homogeneous good produced in the union. The right-hand side is the negative of the net investment of foreign investors in domestic bonds, that is, the flow out of the financial account, while the left-hand side is the corresponding trade balance.

4 UNDERSTANDING BANKS

The decision problem of households and firms is standard. The full optimality conditions are reported in Online Appendix D. The key to the model is the decision problem of the banks.

4.1 Aggregating across banks

Recall that $V_{i,t}$ is the value of bank i , at the end of the morning, after the type of the bank is known and assets are purchased but before dividends are paid. It is the nominal price a household would be willing to pay for that bank before dividend payments, taking into account the future randomness of net worth due to the future type draws. It is given by

$$V_{i,t} = E \left[\sum_{s=0}^{\infty} \beta^s \frac{u_c(c_{t+s}, h_{t+s})}{u_c(c_t, h_t)} \frac{P_t}{P_{t+s}} \phi N_{i,t+s} \right] \quad (24)$$

Regardless of their size, we assume that all banks behave competitively and take prices as given. Due to the linearity of the objective function and all the constraints, the problem of

a bank is linear in net worth.²⁵ Therefore, the distribution of net worth between banks and, thus, its prior history, does not matter for aggregate allocations.

Equation (24) can be rewritten recursively. Define $\bar{V}_{i,t}$ as the value of bank i in the morning, before the type draw for t is known. It is given by

$$\bar{V}_{i,t} = E_t[V_{i,t}] = \psi_t N_{i,t} \quad (25)$$

for some factor ψ_t which gives the value of a marginal unit of net worth of a bank in the morning, before a bank's type is known, and where the expectation reflects the connection type and region draw.

This implies that

$$\int_0^1 \bar{V}_{i,t} di = \psi_t \int_0^1 N_{i,t} di \quad (26)$$

which gives the value of a marginal unit of net worth at the beginning of period t , for the aggregate banking sector.

Given the linearity of the bank problem, it suffices to analyze the problem of a bank with average net worth N_t of network type ν and in region j . Note that connected banks make the same choices regardless of their region, since the region only matters for unconnected banks in the afternoon. Letting $N_{\nu,j,t+1}$ denote the resulting net worth for each type (ν, j) of bank when starting out with average net worth N_t , and knowing $N_{c,N,t+1} = N_{c,S,t+1} \equiv N_{c,t+1}$, average net worth in $t+1$ is then

$$N_{t+1} = \xi_t N_{c,t+1} + (1 - \xi_t) (s_N N_{u,N,t+1} + s_S N_{u,S,t+1}) \quad (27)$$

Define $\tilde{V}_{\nu,j,t}$ as the value of a bank with average net worth, network type ν , and located in j at the end of the morning, after distributing dividends. We have

$$V_{\nu,j,t} = \phi N_{\nu,j,t} + \tilde{V}_{\nu,j,t} \quad (28)$$

where

$$\tilde{V}_{\nu,j,t} = \beta E_t \left[\frac{u_c(c_{t+1}, h_{t+1})}{u_c(c_t, h_t)} \frac{P_t}{P_{t+1}} \psi_{t+1} N_{\nu,j,t+1} \right] \quad (29)$$

with net worth $N_{\nu,j,t+1}$, resulting from the investments of period t , given by

$$N_{\nu,j,t+1} = R_{t+1}^k P_t Q_t^k k_{\nu,j,t} + M_{\nu,j,t} + R_{t+1}^j Q_t^j B_{\nu,j,t} - R_t^d D_{\nu,j,t} - R_t^F Q_t^F F_{\nu,j,t} \quad (30)$$

²⁵The arguments for linearity of the bank problem are given in Online Appendix E.

Equation (29) makes use of equation (25) because a bank of type (ν, j) at time t is valued at time $t + 1$ at $\psi_{t+1}N_{\nu,j,t+1}$. As a result, (28), (29), and (30) deliver a recursive formulation of (24).

In the morning, after the type is known, bank i chooses $k_{\nu,j,t}$, $B_{\nu,j,t}$, $B_{\nu,j,t}^F$, $F_{\nu,j,t}$, $D_{\nu,j,t}$, $M_{\nu,j,t}$ to maximize $V_{\nu,j,t}$, subject to the leverage constraint

$$V_{\nu,j,t} \geq \lambda \left(P_t Q_t^k k_{\nu,j,t} + Q_t^j B_{\nu,j,t} + M_{\nu,j,t} \right),$$

the budget constraint

$$P_t Q_t^k k_{\nu,j,t} + Q_t^j B_{\nu,j,t} + M_{\nu,j,t} + \phi N_{\nu,j,t} = D_{\nu,j,t} + Q_t^F F_{\nu,j,t} + N_{\nu,j,t},$$

the central bank funding constraints

$$\begin{aligned} F_{\nu,j,t} &\leq \eta_t Q_t^j B_{\nu,j,t}^F \\ 0 &\leq B_{\nu,j,t} - B_{\nu,j,t}^F, \end{aligned}$$

the non-negativity constraints

$$M_{\nu,j,t} \geq 0, B_{\nu,j,t} \geq 0, F_{\nu,j,t} \geq 0, D_{\nu,j,t} \geq 0, k_{\nu,j,t} \geq 0, \quad (31)$$

and the afternoon constraint for unconnected banks

$$\omega^{\max} D_{\nu,j,t} \leq M_{\nu,j,t} + \tilde{\eta}_t^j Q_t^j (B_{\nu,j,t} - B_{\nu,j,t}^F). \quad (32)$$

The problems above are linear programming problems, maximizing a linear objective subject to linear constraints. So, the solution is either a corner solution or there will be indifference between certain asset classes, resulting in no-arbitrage conditions. The optimality conditions are reported in Online Appendix E. The definition of the equilibrium and the full system of the equilibrium conditions are reported in Online Appendices F and G, respectively.

4.2 The essential nature of the afternoon and leverage constraints

So far, we have assumed the existence of a leverage constraint for each bank type and an afternoon constraint for the unconnected bank types. We show that both constraints are necessary for changes in ξ or $\tilde{\eta}^j$ to matter for the equilibrium.

4.2.1 A model with no leverage constraint

Suppose there is no leverage constraint for any bank, but unconnected banks face an afternoon constraint. The following proposition ensures that shocks to $(\xi, \tilde{\eta}^j)$ do not matter.

Proposition 1 (no leverage constraint) *Consider the model described in Section 3 but without a leverage constraint. Consider two values for the sequence of parameters $(\xi_t, \tilde{\eta}_t^N, \tilde{\eta}_t^S)$, indexed by A and B , and fix all other parameters. If there is an equilibrium for $(\xi_{t;A}, \tilde{\eta}_{t;A}^N, \tilde{\eta}_{t;A}^S)$, then there is an equilibrium for $(\xi_{t;B}, \tilde{\eta}_{t;B}^N, \tilde{\eta}_{t;B}^S)$, where all aggregate quantities are the same.*

The proof is in Online Appendix I. Intuitively, without a leverage constraint, banks are fully unconstrained, so they invest in capital until all risk-adjusted returns of assets and liabilities held are the same. Consequently, this model is isomorphic to households investing in capital themselves directly without any banks: shocks to characteristics of the interbank market are irrelevant.

4.2.2 A model without afternoon constraint

Suppose that banks in region j face a leverage constraint but that there is no afternoon constraint for unconnected banks. The following proposition ensures that shocks to $(\xi, \tilde{\eta}^j)$ do not matter.

Proposition 2 (no afternoon constraint) *Consider the model described in Section 3 but without an afternoon constraint for unconnected banks. Then the equilibrium is independent of any shocks to $(\xi, \tilde{\eta}^j)$.*

Intuitively, without the afternoon constraint, the two bank types are identical. Therefore, any movement in ξ does not affect the equilibrium because adjusting the shares between identical banks has no impact. In addition, $\tilde{\eta}^j$ disappears from the optimization problem of banks. Banks do not need to post collateral, as they all have access to unsecured markets. As a result, bonds have no collateral value for banks and so will only be held by them in equilibrium if they exhibit no collateral premium.

4.3 Analyzing the bank problem

Armed with this setup for banks, we now take a step back and analyze a simplified static model to help us understand the portfolio choice of banks and how central bank policy interacts with

it. To do this, we make the simplifying assumption that there are no aggregate shocks. Thus, the returns on assets and liabilities are known with certainty, and banks choose a portfolio that maximizes the return on net worth subject to the constraints.

We remove the time subscript and make two assumptions that always hold in the fully dynamic numerical analysis: (i) $R^k > R^j$ and (ii) $R_d < R_F$. Banks will then only borrow from the central bank if it offers additional advantages. There are no such advantages for connected banks as they never need collateralized funding when they have access to unsecured markets. Connected banks invest entirely in capital as bond returns are lower. In the afternoon, they use unsecured funding to cover temporary deposit withdrawals. Therefore, their portfolio choice in the morning is

$$D_{c,j} = \frac{V_{c,j}}{\lambda} - (1 - \phi) N \quad \text{and} \quad Q^k k_{c,j} = \frac{V_{c,j}}{\lambda}$$

However, understanding the portfolio choice of unconnected banks in the morning requires deciphering how banks optimally plan to cover deposit withdrawals in the afternoon, given their decision on $D_{u,j}$ and $F_{u,j}$ in the morning. As dictated by the afternoon constraint, banks can do so by either using money ($M_{u,j}$) or IOUs collateralized with bonds ($B_{u,j}$). Which of the two the bank holds depends on the ‘‘collateral premium’’ for bonds, Λ^j , equaling ²⁶

$$\Lambda^j = \frac{R^k - R^j}{\tilde{\eta}^j}. \quad (33)$$

Intuitively, to issue $(1/\omega^{\max})$ of deposits, a bank must hold $(1/\tilde{\eta}^j)$ units of bonds. The cost Λ^j of doing so is the returns forgone from having to invest $(1/\tilde{\eta}^j)$ units in bonds instead of capital. By the same logic, if a bank uses money to back $(1/\omega^{\max})$ deposit units, the returns forgone are $R^k - 1$. There are three cases:

$$M_{u,j} = \begin{cases} 0 & \text{if } \Lambda^j < R^k - 1 \\ \in [0, \omega^{\max} D_{u,j}] & \text{if } \Lambda^j = R^k - 1 \\ \omega^{\max} D_{u,j} & \text{if } \Lambda^j > R^k - 1 \end{cases} \quad B_{u,j} = \frac{F_{u,j}}{Q^j \tilde{\eta}^j} + \frac{1}{Q^j \tilde{\eta}^j} (\omega^{\max} D_{u,j} - M_{u,j}) \quad (34)$$

If $\Lambda^j > R^k - 1$, money is a cheaper source of collateral than bonds. Thus, money is used exclusively to satisfy the afternoon constraint. Conversely, if $\Lambda^j < R^k - 1$, only bonds are used, while if $\Lambda^j = R^k - 1$, then any bond-money mix is optimal. Note also that additional

²⁶In Online Appendix H, we show that the collateral premium is strictly positive if the afternoon constraint is binding or unconnected banks are collateral-constrained in their borrowing from the central bank.

bonds must be held as collateral for any central bank funding, at a haircut η , as bonds are the only acceptable collateral for the central bank.

We can now understand how the bank chooses between the two funding sources: deposits ($D_{u,j}$) and central bank funding ($F_{u,j}$). An additional unit of deposits earns X_d :

$$X_d = R_k - R_d - \omega^{\max} \min \{R_k - 1, \Lambda^j\} \quad (35)$$

The first term, $R_k - R_d$, is the return earned if the bank invests the deposit unit in capital. The final term reflects the fact that banks cannot invest all in capital, but must hold collateral to back the deposit unit. This is costly because of the forgone returns, as explained above. The min operator is a result of choosing the least-cost type of collateral: bonds or money.

Conversely, an additional unit of central bank funding earns X_f :

$$X_f = R_k - R_f - \frac{\tilde{\eta}^j}{\eta} \Lambda^j \quad (36)$$

Here, the collateral cost is without a min operator because bonds must be posted to the central bank. The term $\tilde{\eta}^j/\eta$ is because the central bank applies its own haircut, $1 - \eta$, not the private haircut ($1 - \tilde{\eta}^j$), to the bond collateral.

Now, suppose that $\max\{X_d, X_f\} > 0$. The bank will then access funding until the leverage constraint binds because more funding enhances portfolio returns. In other words, $(D_{u,j}, F_{u,j})$ is such that

$$D_{u,j} + F_{u,j} = \frac{V_{u,j}}{\lambda} - (1 - \phi)N \quad (37)$$

To determine the allocation between deposits and central bank funding, the bank compares X_d and X_f . If $X_d > X_f$, then $F_{u,j} = 0$, while if $X_d < X_f$, then $D_{u,j} = 0$. If $X_d = X_f$ any non-negative $(D_{u,j}, F_{u,j})$ combination satisfying (37) is optimal.²⁷ If $\max\{X_d, X_f\} \leq 0$, it is optimal for the bank to invest only its net worth in capital and not use other funding sources.

The scenario in which $\max\{X_d, X_f\} > 0$ always prevails in the numerical analysis. Here, we can already make two key observations. First, a lower $\tilde{\eta}$ reduces the returns on deposit issuance because it requires banks to hold more costly collateral instead of capital. Second, central bank policy matters: lowering R_f and/or raising η makes central bank funding more attractive and can make $X_f \geq X_d$, especially if banks are facing high private haircuts ($1 - \tilde{\eta}^j$).

²⁷In the fully dynamic numerical analysis, it is always the case that $X_d \geq X_f$ as central bank funding is never made sufficiently attractive such that $X_d < X_f$. That is why we focus on the cases where $D_{\nu,j} > 0$.

5 CALIBRATION

5.1 Parameters

This section describes the calibration of the model parameters to euro area data. A period is one quarter. Table 1 provides the values for all parameters. Here, we describe the key choices.

We focus on cases where banks choose to raise deposits and extend loans, that is, we focus on equilibria where $D_{\nu,j,t} > 0, k_{\nu,j,t} > 0$ for all ν and j . However, we explicitly allow for corner solutions for $M_{\nu,j,t}, B_{\nu,j,t}$ and $F_{\nu,j,t}$.

One central parameter that captures unconnected banks' liquidity management constraints is ω^{\max} . We calibrate it using the information embedded in the liquidity coverage ratio (LCR) - a prudential instrument that requires banks to hold high-quality liquid assets (HQLA) in an amount that allows them to meet 30 days of liquidity outflows under stress. We implicitly assume here that regulators can estimate with high precision the 30-day outflows in a period of stress. We therefore calibrate ω^{\max} so that the maximum amount of liquidity demand in the model, $\omega^{\max} D_{t,u}$, is equated to the observed holdings of HQLA. More specifically, we use the European Banking Authority report from December 2013 (European Banking Authority (2013)), which provides LCR data for 2012Q4 and covers 357 EU banks from 21 EU regions. We take ω^{\max} to be the ratio of aggregate HQLA over total assets, implying that $\omega^{\max} = 0.1$.²⁸

We set the fraction of government bonds repaid each period, κ , to 0.042, corresponding to an average maturity of the outstanding stock of euro area sovereign bonds of around 6 years.²⁹

We choose the parameter α of the foreign demand for bonds to match the observed share of total debt held by foreign investors (see details below). For foreign demand elasticities, we take data reported by Kojien et al. (2021) on the rebalancing of euro area government bonds by non-banks, over the period 2013Q4-2014Q4. We choose this horizon as our paper focuses on policies conducted by the ECB before the large-scale asset purchase programme began in 2015. The implied percentage change in holdings over this period was 0.5%. We calculate the

²⁸In our model, whenever the afternoon constraint binds, banks hold liquid assets in the amount of $M_u + \tilde{\eta}Q(B_u - B_u^F)$ to cover maximum afternoon withdrawals $\omega^{\max}D$. Since $F = 0$ in our calibrated steady state, and net worth is a small fraction of total liabilities, we approximate D with total assets. Alternatively, we can approximate ω^{\max} using the run-off rates on deposits, as specified in the LCR regulation (e.g., a run-off rate of 10% means that 10% of the deposits are assumed to possibly leave the bank in 30 days). Runoff rates for retail deposits typically range from 5% for stable, fully insured deposits to upward of 10% for less stable deposit funding. Our calibration of ω^{\max} at 0.1 is consistent with these rates.

²⁹Average maturity is computed as a weighted average of all maturities of euro area government bonds, with weights given by outstanding amounts in 2011. Source: Bloomberg Finance L.P. (nd), European Central Bank (nda) and authors' calculations. Bond-level data used in Andrade et al. (2016) give a similar average maturity in 2015.

percentage change in the yield of long-term euro area government bonds over the same period to be -2%, using the 10-year benchmark euro area government bond yield series (European Central Bank (ndd)). We then set ϱ to replicate the observed elasticity of foreign bond holdings with respect to changes in the real return on bonds, i.e., $\varrho = 4.097$, thus interpreting it as a demand elasticity for the purpose of our analysis. We checked the robustness to alternative values (not reported) and found similar results in our quantitative analysis.

We parameterize central bank policies as follows. For the CO policy, two key parameters must be established: the interest rate on central bank loans $R^F = 1/Q^F$ and the interest rate on collateral charged by the central bank $1 - \eta$. To determine R^F , we first calculate the average rate on ECB’s collateralized loans to banks over the 2008-2014 period, i.e., the interest rate given by the rate on the so-called Main Refinancing Operations or MRO for short, using ECB’s MMI Dataset (European Central Bank (ndc)). The average MRO rate over this period was 1.29% on an annualized basis. This implies a quarterly interest rate factor of 1.003 and a value for the discount price of central bank loans of $Q^F = 1/R^F = 0.997$. We set the central bank haircut $1 - \eta$ equal to 0.03, corresponding to the private market haircuts pre-crisis and the haircuts charged by the ECB on high-quality government bonds.³⁰ This parameter constellation also ensures that banks do not take up central bank funding in the baseline steady state, which is in line with the pre-GFC data in the euro area. Pre-GFC, banks borrowed from the ECB only the amount needed to satisfy the reserve requirements, which are set to zero in our model. Under the constant balance-sheet policy, we ensure that banks do not borrow from the central bank by setting $\eta = 0$.

We treat the monetary union as composed of symmetric regions and assume that $Q^N = Q^S = Q$ and $B_N^C = B_S^C = B^C$. We calibrate the remaining six parameters to match the model-based predictions of some key variables to their empirical counterparts over the pre-crisis period 1999-2006 (see Table 2).³¹ The parameters are the share of net worth distributed by banks as dividends, ϕ , the share of assets bankers can run away with, λ , the coefficient determining

³⁰Source: LCH Ltd. (nd)).

³¹The average government expenditure to GDP ratio is computed using data for euro area (EU12) governments from Eurostat (Eurostat (nd)). The value of bank leverage is taken from Andrade et al. (2016). The share of banks’ bond holdings in total debt is set at the value reported in Kojien et al. (2021) for 2015, 23%. To compute the share of the foreign sector’s bond holdings, we first use data from the ECB’s Statistical Data Warehouse (European Central Bank (nde)) to calculate the share of central bank’s holdings in total government debt. In this item, we include not only outright purchases of government bonds, but also collateralized loans extended in refinancing operations (the main instrument through which the ECB injected liquidity in normal times). The ratio to total sovereign debt is 10%. Kojien et al. (2021) report that households hold 3% of government bonds. We then impute the remaining share to the foreign sector, which amounts to 64%. The spread between the return on capital and the return on government bonds is computed using data from ECB’s ILN database (European Central Bank (ndd)). We build average government bond yields by weighting the yields of all euro

the utility from money holdings for households, χ , the expenditure on public goods, g^* , the real stock of government bonds purchased by the central bank, b^C , and the stock of real debt in the economy, b^* . The targeted variables are: i) average ratio of government expenditure to GDP; ii) bank leverage; iii) the spread between the return on capital and the return on government bonds; iv) share of banks' bond holdings in total debt; v) share of foreign sector's bond holdings in total debt; and vi) average inflation. As Table 2 reports, the model perfectly replicates the six targeted moments and provides a good fit for two non-targeted moments: the ratios of central bank bond holdings to GDP and government debt to GDP.

5.2 Shock processes

The dynamics of the model are driven by the dynamics of the share ξ_t of “connected” banks and the private market haircut, $1 - \tilde{\eta}_t^j$.

For the baseline pre-GFC steady state, we use data from the euro Money Market Survey and obtain total turnover as the sum of the turnover in the secured and in the unsecured segments (where 2003 is the first available observation in the survey and 2007 is the last year before the Global Financial Crisis). We set $\xi = 0.42$, corresponding to the 2003-2007 average share of cumulative quarterly unsecured turnover in total. As discussed above, we set the haircuts on government bonds in private markets and at the central bank equal to each other, at $1 - \tilde{\eta}^S = 1 - \tilde{\eta}^N = 1 - \eta = 0.03$ (corresponding to a 3% haircut).

For the dynamic analysis, we assume that ξ_t and $\tilde{\eta}_t$ are constant at their benchmark steady-state levels for $t < 1$. At $t = 1$, agents learn that ξ_t follows a new and deterministic path, but assume that $\tilde{\eta}_t^j$ remains constant for $j \in \{N, S\}$.³² At $t = 13$, agents learn that $\tilde{\eta}_t^S$ also follows a new and deterministic path. We formulate these paths such that the model matches the observed evolution of the unsecured shares and private market haircuts, with $t = 1$ corresponding to the first quarter of 2009.

area government bonds, for all maturities, with the respective amounts in 2011. Average inflation is computed using quarterly changes in the HICP index taken from ECB's ICP database (European Central Bank (ndb))

³²We treat the evolution of the share of connected banks, ξ_t , as exogenous. One may instead think that the observed decline in unsecured money market lending reflects the introduction of ECB policies that injected large amounts of central bank reserves, and that those reserves simply made money market lending redundant. However, two facts documented in figure 2 are inconsistent with this argument. First, the trend decline in unsecured funding in both the North and South preceded the GFC and the ECB policies that increased reserves. Second, money markets did not become redundant; rather, the decline in unsecured funding induced a corresponding increase in secured lending.

In our model, there is a tight relationship between ξ_t and the unsecured shares within the North.³³ Therefore, we consider a process for ξ_t that matches as closely as possible the data on unsecured shares in the North.³⁴ We assume that $\log \xi_t$ converges to the new steady state ξ_∞ at a constant rate,

$$\log(\xi_t) = (1 - \rho_\xi) \log(\xi_\infty) + \rho_\xi \log(\xi_{t-1}) \quad (38)$$

where $\xi_{-1} = 0.42$ and $\xi_\infty = 0.1$. We choose ρ_ξ to minimize the squared distance between the model and the data and find a value of $\rho_\xi = 0.95$. The left panel of figure 5 compares the process (38) used in the model with the evolution of the data of the unsecured share in interbank markets in northern regions (Germany, France).

We assume that $\tilde{\eta}_t^N$ remains constant for all $t \geq 1$ and that $\tilde{\eta}_t^S$ remains constant for $t \leq 12$. From $t = 13$ onward, we assume that $\log(\tilde{\eta}_t^S)$ follows an AR(2) process in order to replicate the hump-shaped process observed in the data,

$$\log(\tilde{\eta}_t^S) = (1 - \rho_{\tilde{\eta},1} - \rho_{\tilde{\eta},2}) \log(\tilde{\eta}_\infty) + \rho_{\tilde{\eta},1} \log(\tilde{\eta}_{t-1}^S) + \rho_{\tilde{\eta},2} \log(\tilde{\eta}_{t-2}^S) + \epsilon_{\tilde{\eta}_t^S}, \quad (39)$$

where the shocks are zero, $\epsilon_{\tilde{\eta}_t^S} = 0$, except for $t = 13$. We search for $\rho_{\tilde{\eta},1}$, $\rho_{\tilde{\eta},2}$ as well as the shock $\epsilon_{\tilde{\eta}^S,13}$ in order to fit the data closely, and pick

$$\rho_{\tilde{\eta},1} = 1.65; \rho_{\tilde{\eta},2} = -0.7; \epsilon_{\tilde{\eta},13} = -0.11$$

The right panel of figure 5 compares the AR(2) of equation (39) to the data, represented as a splined interpolation through the available data points.

6 DYNAMIC RESPONSES

We now turn to the main goal of the paper: understanding the dynamic response of the real economy to the key observed money market developments and the main drivers of the response. To do this, we calculate the impulse responses of the model to the shock process

³³Intuitively, as ξ falls, there are more unconnected banks who must interact with the interbank market on a secured basis. Unconnected banks could decide to rely less on the interbank market by bringing more reserves in the afternoon. This happens in the transition paths of our shocks, but this turns out to have little effect on the secured share quantitatively, as only banks in the South, who are smaller than the North, do this. As a result, we have a tight relationship between ξ and the unsecured share in the North.

³⁴The process for ξ_t is symmetric for the North and South. This is consistent with the data, where the evolution in the unsecured shares is extremely similar across the two regions, implied by figure 2, chart on the right.

outlined in Section 5.2 that describes these developments.³⁵ After describing the experiment, we first consider the responses under the baseline monetary policy set-up where the central bank follows a policy of collateralized lending to banks (CO policy). We then compare the outcomes to a counterfactual scenario of the central bank maintaining a constant balance sheet (CB policy). We solve the model non-linearly under perfect foresight.³⁶ We frequently refer to the four forces introduced in subsection 2.2 to describe our results.

6.1 Description of Experiment

We assume that the model is at its benchmark pre-GFC steady state for $t < 1$. At $t = 1$ and corresponding to the first quarter of 2009, agents learn that ξ_t follows a new path, while at $t = 13$, they learn that $\tilde{\eta}_t^S$ follows a new path, both of which are described in Subsection 5.2 and shown in figure 5. One scenario is where only the unanticipated shock to the connected share ξ is realized at time $t = 1$. In this case, at $t = 1$, agents understand fully and with certainty that the share of connected banks ξ_t will transition to a permanently lower level in accordance with figure 5. The other scenario is where we also have the unanticipated persistent shock to $\tilde{\eta}^S$, realized at time $t = 13$. Agents in the model, from $t = 13$ onward, understand that, with certainty, $\tilde{\eta}_t^S$ will evolve according to the right-hand side of figure 5.³⁷ The difference between these two scenarios will convey the effect caused by the $\tilde{\eta}^S$ shock. Note the key difference in the characteristics of the two shocks. The shock to ξ represents a gradual transition to a permanently lower level, whereas the $\tilde{\eta}^S$ shock is a persistent but nonpermanent change in haircuts.

Figure 6 plots on the right-hand side the four empirical observations that we document, and the corresponding model counterparts under the benchmark CO policy on the left-hand side in each row: (i) secured shares in the euro area, (ii) the take-up of central bank funding as a percent of assets held by unconnected banks in the South, (iii) private haircuts on bonds issued

³⁵In Online Appendix K, we conduct some steady state comparative statics analysis where we consider what happens to the steady state when we permanently change the share of unconnected banks in the monetary union ($1 - \xi$) or the haircut on bonds issued in the South ($1 - \tilde{\eta}^S$). This helps build intuition for the main results.

³⁶We use Dynare to calculate the numerical solution. We chose the Levenberg-Marquardt mixed complementarity problem solver. This solver is more suited to models with occasionally binding constraints than the more commonly used Newton algorithm. The path to final equilibrium is imposed in finite time T , but we set the end point large enough ($T = 400$) to ensure that the economy converges to the steady state.

³⁷The shock to $\tilde{\eta}^S$ arrives at time $t = 13$ to reflect the fact that, in the data, the increase in haircuts experienced by sovereign bonds in the South occurred about three years after the beginning of the notable rise in the secured share. In addition, we adjust the estimated process slightly so that we target the evolution of $\tilde{\eta}^S$ with the constraint that there is no permanent change in $\tilde{\eta}^S$. This is to help us solve the model numerically.

in the South, and (iv) the change in deposits as a share of bank assets in the South.³⁸ Overall, the dynamic model does well in replicating all the empirical observations we documented: a rise in secured shares, a take-up of central bank funding at the peak of private haircuts, and a stable albeit U-shaped response of deposit shares. The latter two observations are explicitly not targeted. In addition, we can match the observed increase in secured shares using an appropriate process for ξ due to the tight link between ξ and secured shares in the model. Overall, this suggests that our model captures the data movements well.

Figure 7 conveys the impulse responses of key variables of interest in our two scenarios, under the benchmark CO policy: a solid line when just the shock to ξ is realized, and a dashed line when the shock to $\tilde{\eta}^S$ occurs at time $t = 13$. The thin gray vertical lines represent the time at which the $\tilde{\eta}^S$ shock is realized. The intersection with the y-axis denotes the point where the economy is in time $t = 0$, either in levels or as a percentage change from the baseline steady state. As the shift in ξ is permanent, the economy transitions to a new steady state, regardless of whether or not the $\tilde{\eta}^S$ shock occurs. The new steady state is represented by the horizontal dotted lines, which indicate the new long-run level or the percentage change from the baseline steady state.

6.2 Impact of changes in ξ only

We can gain the main intuition for the impulse responses by understanding the shift in the steady state induced by the long-run shift in the connected share ξ . The key outcome across steady states in the model is the decline in the capital stock, falling 10% on aggregate. This is due to the capital-crowding-out force described in subsection 2.2 and occurs for two reasons.

First, as ξ falls, connected banks get replaced by unconnected banks. In the baseline steady state, their balance sheets are very similar in size but differ crucially in the composition of assets held: unconnected banks need to hold collateral to satisfy their afternoon constraint. This mechanically crowds out capital investment on aggregate.

Second, each bank invests less in capital due to lower deposits. This is especially the case for unconnected banks. As the number of unconnected banks increases, the demand for collateral also increases to satisfy the afternoon constraint. This drives up the collateral premium banks pay to hold bonds and reduces the return on bonds. When this premium is high enough, the Bond-Reserves Substitution Force pushes unconnected banks to bring money rather than

³⁸See Online Appendix J for details on how we evaluate the secured share. We assume that unconnected banks cover deposit withdrawals with reserves before accessing the secured market.

bonds to the afternoon, which they can hold because an increase in the deposit rate induces households to hold less of it.³⁹ The higher cost of holding reserves, however, leads unconnected banks to downsize their balance sheets and reduce capital investment funded by deposits.⁴⁰

Notice that the capital-crowding-out force is mitigated by the presence of the foreign sector with an elastic demand curve. Foreign investors react to the decline in bond returns induced by the shock by selling some of their holdings, which increases the supply of bonds available to banks and alleviates the collateral shortage.

On aggregate, the capital stock declines at the new steady state, and investment declines by the same proportion. This depresses output as a consequence. Moreover, the two central bank policies under consideration make no difference, as ξ falls.⁴¹ If private haircuts, $1 - \tilde{\eta}^S$, remain unchanged, there is no advantage for unconnected banks to tap more collateral-intensive central bank funding, as there is no difference between central bank and private market haircuts.

However, the transition toward the steady state is far from smooth. Indeed, output and investment initially undershoot the value they reach in the new steady state, despite the share of connected banks still being far above the new steady-state level. The coming gradual decline of ξ - and thereby the gradual need for the banking sector to forgo returns in favor of holding bonds or money for liquidity reasons - lowers the value of operating a bank. This immediately causes an endogenous reduction of leverage and assets held. Moreover, as banks understand that capital investment will be crowded out in the future, the current price of capital falls. This drives down net worth and, combined with lower leverage, leads to persistently lower capital investment. Investment then gradually recovers to the new lower steady state level as the net worth of banks is replenished.⁴²

Perhaps unsurprisingly, the top left plot of figure 6 shows that a permanent fall in ξ produces a permanent rise in the secured shares. Intuitively, both bank types use only deposits as a liability source. The increasing share of unconnected banks creates a larger need to use the secured market to manage short-term deposit withdrawals. Therefore, there is a very tight relationship between ξ and the secured share. As we will see, this relationship does not

³⁹The size of the central bank balance sheet remains constant, but the composition of liabilities switches from issuing currency to households toward issuing reserves to banks.

⁴⁰Connected banks also invest less due to spillover effects. Since unconnected banks downsize their operations, the profits of unconnected banks decline. As types are re-drawn each period, connected banks each period will also have lower net worth as a consequence, and must therefore downsize operations.

⁴¹This emerges also from the steady-state analysis shown in Online Appendix K.

⁴²Note that connected banks partially counteract the decline in investment on impact as they do not suffer from higher collateral premia. However, this is not enough to prevent aggregate investment from falling.

necessarily hold if unconnected banks had an incentive to use an alternative liability source, such as central bank funding.

6.3 Impact of changes in ξ and $\tilde{\eta}$

We now investigate what happens if the economy also experiences an unanticipated persistent drop in $\tilde{\eta}^S$ at time $t = 13$, comparing the dashed-line impulse responses in figure 7 with the ξ shock-only responses in solid lines.

Bonds available to unconnected banks in the South are now worse collateral. This drives up collateral prices and makes deposit issuance more expensive, inducing banks to downsize their liabilities. Moreover, Q^S falls because these bonds are less effective as collateral, driving net worth lower. As a result of the capital-crowding-out force, capital investment by unconnected banks in the South falls.

However, unconnected banks in the South rebalance their portfolios to mitigate the effects of collateral scarcity. First, they increase the money they bring to the afternoon (Bond-Reserves Substitution Force). Second, at the peak of the rise in private haircuts, banks substitute expensive deposits with central bank funding because of the preferential haircuts the central bank charges on bonds relative to the private market (Haircut Gap Force). Indeed, this take-up is significant, equaling over 4% of total bank assets, and generates the U-shaped response of deposit shares. These are shown in the second and fourth rows of figure 6, and illustrates how our model is therefore consistent with observations II and IV. These two effects mitigate collateral scarcity and help unconnected banks in the South to reduce their investment by a smaller amount. Although unconnected banks rebalance toward central bank funding in the morning, they continue to tap into the private secured market to manage their afternoon liquidity needs, albeit to a lesser extent than before the shock. As a result, in our model, the secured share continues to rise because (i) the share of unconnected banks rises, and (ii) unconnected banks still rely heavily on the secured interbank market. We therefore replicate observation I, as we see in the first row of figure 6.

Turning to the aggregate effect, output and investment fall because of aggregate disinvestment, mainly driven by unconnected banks in the South. This is partially counteracted by connected banks' rise in value as capital returns increase. This endogenously allows them to increase their leverage, thus investing more in capital and raising more deposits.

Quantitatively, however, a key determinant of the negative effect is the response of unconnected banks in the North, driven by the North-South Liquidity Spillover Force. These banks

do not face any shock to $\tilde{\eta}^N$ but still get impacted indirectly via higher collateral premia in the economy. Intuitively, unconnected banks in the South experience a collapse in the pledgeable value of their collateral. As a result, they move toward holding money to satisfy the afternoon constraint, thereby driving up its cost. But crucially, unconnected banks in the North already hold increased amounts of money following the ξ shock. Hence, they also pay a higher price for these holdings. This also tightens the afternoon constraint for them. Therefore, despite the increase in returns to capital and despite not being directly exposed to the private haircut shocks, they hardly change their capital investment. In other words, unconnected banks in the North face a pecuniary externality through higher liquidity costs because of the shock to collateral quality for those in the South.⁴³

The pecuniary externality is mitigated by the response of the foreign sector. The $\tilde{\eta}^S$ shock drives up the collateral premia even further – relative to the case with only the ξ shock – incentivizing foreigners to release even more bonds to the banking sector. This time, foreigners mainly sell bonds issued in the North, as they retain their collateral value and experience a larger drop in returns relative to those issued in the South. Since the collateral market is integrated, this alleviates the collateral shortage in the North and the South.

As the shock subsides and the haircuts revert back toward the pre-shock level, investment recovers, and overshoots the path absent the $\tilde{\eta}^S$ shock. The intuition is as follows. As the haircuts recover and the return to capital remains elevated, the bank now has access to favorable investment opportunities while at the same time being less constrained by collateral needs. As a result, banks can increase leverage, which causes the overshooting effect to bring capital back to its new steady state.

6.4 Comparison of impulse responses: CO policy vs CB policy

We now compare the dynamics under the benchmark policy of collateralized lending to banks (CO policy) to a counterfactual scenario of the central bank maintaining a constant balance sheet (CB policy). In the ξ -only-shock scenario, there is no difference: since central bank haircuts are the same as private-sector haircuts under both policies, banks strictly prefer not to borrow from the central bank. Therefore, figure 8 compares the dynamics resulting from the CO policy (in solid) to the dynamics resulting from CB policy (in dashed), subtracting

⁴³What is crucial here is that banks in the North and South both use reserves. If they did not, then collateral markets would be entirely segmented: banks would only be holding bonds issued within their region as a way to manage liquidity needs in the afternoon, i.e., no reserves. In this case, banks would face region-level collateral scarcity (collateral premia), which would shut down the spillover of premia across regions.

out the dynamics resulting from the ξ -only-shock scenario. Put differently, figure 8 shows the dynamics under these two policies arising from the additional $\tilde{\eta}^S$ -shock.

With figure 7, we have shown that a shock to $\tilde{\eta}^S$ has an adverse effect on output and investment and that the capital stock declines under the benchmark CO policy. As figure 8 demonstrates, the impact on the real economy is stronger under the CB policy. In particular, output and investment fall around twice as much on impact. The key difference here is the access to central bank funding under the benchmark CO policy. When $\tilde{\eta}^S$ falls, the afternoon constraint is tighter and collateral premia rise for unconnected banks in the South. If the shock is large enough, unconnected banks divert their liability sources from expensive deposits (as the afternoon constraint is tighter) to central bank funding.

We have shown that unconnected banks in the South take up central bank funding when $\tilde{\eta}^S$ is low enough because it becomes a profitable opportunity. This new supply provides new units of reserves to the banking sector on aggregate, in exchange for a unit of bond collateral. However, central bank funding is taken up precisely when the collateral value of bonds is much lower than reserves. Therefore, it reduces the tightness of the afternoon liquidity constraint.

By mitigating the increase in the collateral premium, the CO policy especially benefits unconnected banks in the North. Looking at the bottom left, capital investment $k_{U,N}$ rises under the CO policy, while it falls under the CB policy. If unconnected banks in the South access central bank funding, banks in the North also benefit indirectly by having to pay less for holding reserves. The North-South Liquidity Spillover Force now acts from the South to the North, benefiting in particular the unconnected banks located in the North, although they are not directly affected by the rise of the private-sector haircuts in the South. As a result, the drop in investment and capital is smaller. Once the drop in $\tilde{\eta}^S$ subsides, the recovery under CB policy is stronger. The larger fall on impact in investment and output under the alternative CB policy increases returns to investing in capital and thereby raises the value of operating a bank. The resulting endogenous rise in leverage then leads to a larger recovery under the alternative CB policy compared to the benchmark CO policy.⁴⁴

⁴⁴The key distinction between CO and CB policies lies in the relative scarcity of collateral. However, foreign bond demand naturally counterbalances this scarcity by increasing bond supply when the collateral premium rises. Consequently, the foreign sector supplies more bonds under the CB policy compared to the CO policy. Under a perfectly inelastic foreign bond demand, the difference between the two policies would be more pronounced.

7 CONCLUSIONS

We documented four key money market developments in the euro area during the financial and sovereign debt crises: unsecured borrowing declined across the euro area; household deposits initially shrank; in southern countries, secured market haircuts on sovereign bonds increased; and bank borrowing from the European Central Bank rose. We constructed a quantitative general equilibrium model to assess the macroeconomic impact of these developments and the associated policy response. We compared a benchmark policy, the central bank providing collateralized lending to banks at haircuts lower than the market, with an alternative policy that maintains a constant central bank balance sheet. We show that the fall in output, investment, and capital would have been twice as high under the alternative policy.

Our modeling framework features heterogeneous banks and sovereign bonds, secured and unsecured money markets, and a central bank. It can be extended to analyze the impact of many other central bank policies that go beyond changing the benchmark interest rate. We leave such extensions for future research.

Data Availability Statement The data and code used to produce the results in this article are available on Zenodo at <https://doi.org/10.5281/zenodo.17909472>.

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TABLES

Table 1: Parameter values

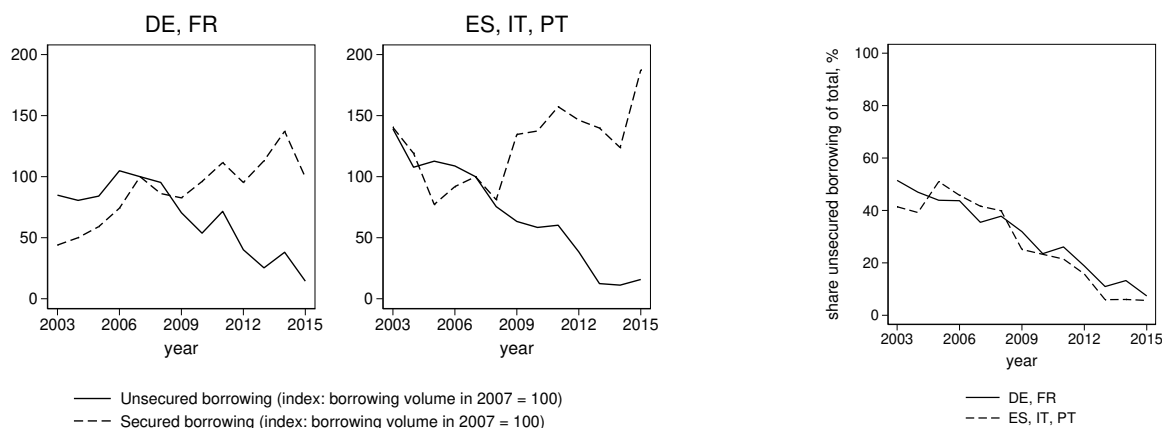
Parameter	Description	Value
θ	Capital share in income	0.330
δ	Capital depreciation rate	0.020
β	Discount rate households	0.994
ϵ	Inverse Frisch elasticity	0.400
χ^{-1}	Coefficient in households' utility	0.006
g	Government spending	0.566
κ^{-1}	Average maturity bonds (years)	5.896
ϕ	Fraction net worth paid as dividends	0.025
ξ	Fraction banks with access to unsecured market	0.420
$\tilde{\eta}$	Haircut on bonds set by banks	0.970
η	Haircut on bonds set by central bank	0.970
λ	Share of assets bankers can run away with	0.701
ω^{\max}	Max possible liquidity demand as share of deposits	0.100
α	Intercept foreign demand function	4.764
B_C	Bonds held by central bank	0.968
B^*	Stock of debt	7.443
ϱ	Parameter foreign bond demand	4.097
Q^F	Price central bank loans	0.997

Table 2: Calibration

Targeted variables	Data	Model
Govt expenditure/GDP	0.200	0.200
Bank leverage	6.000	6.000
Govt bond spread	0.013	0.013
Share bonds held by banks	0.230	0.230
Share bonds foreign sector	0.640	0.640
Inflation (annual)	0.020	0.020
Non-targeted variables	Data	Model
CB bond holdings/GDP	0.059	0.085
Govt debt/GDP	0.688	0.657

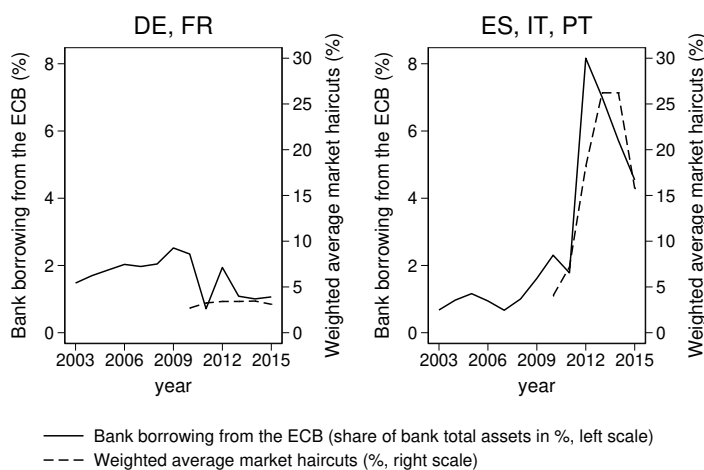
FIGURES

Figure 2: Unsecured and secured interbank borrowing



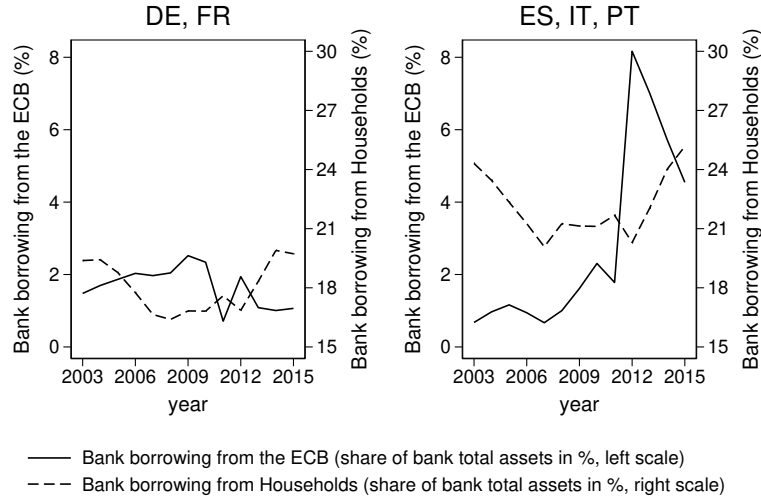
Notes: The two figures on the left present cumulative quarterly turnover of unsecured and secured interbank borrowing over 2003-2015 (the time span of the data collection), for northern (Germany, DE, France, FR) and southern (Spain, ES, Italy, IT, Portugal, PT) regions, respectively. Turnover is defined as the sum of all borrowing transactions over the second quarter of each year (the quarter in which the data were collected), reported by banks participating in the ECB’s Money Market Survey (MMS) and normalized to 100 in 2007. The MMS panel comprised 98 euro area banks. The figure on the right presents the relative share of unsecured borrowing in total, for DE and FR (solid line) and for ES, IT and PT (dashed line). Source: Euro Area Money Market Survey.

Figure 3: Bank borrowing from the ECB and market haircuts, % of total assets



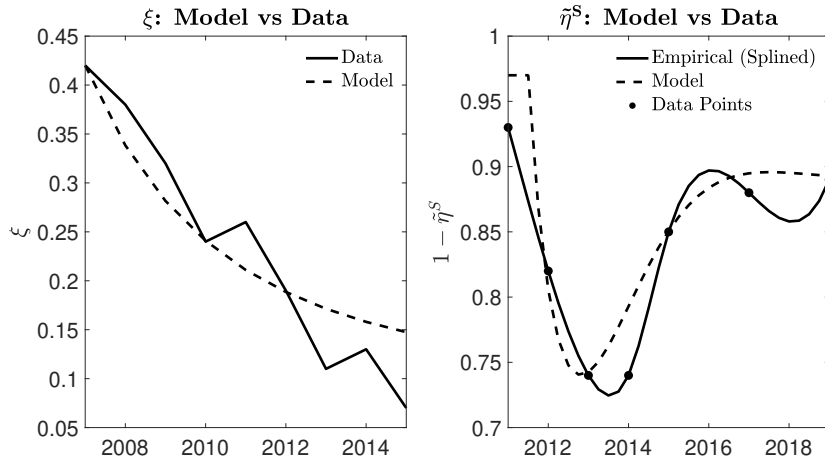
Notes: The figure presents bank borrowing from the ECB as % of bank total assets (solid line, left scale in each figure) and weighted average market haircuts in % (dotted line, right scale in each figure) over 2010-2015, for northern (Germany, DE, France, FR) and southern (Spain, ES, Italy, IT, Portugal, PT) regions, respectively. Region-level haircuts are obtained as simple averages across maturities under 30 years. Region-group-level haircuts are constructed as weighted averages across the northern (southern) regions, with weights given by the shares of the respective banking sector assets in total in 2010 (the weights are 48% and 52% for DE and FR, and 49%, 44% and 7% for IT, ES and PT, respectively). Source: ECB and LCH.Clearnet.

Figure 4: Bank borrowing from households and the ECB, % of total assets



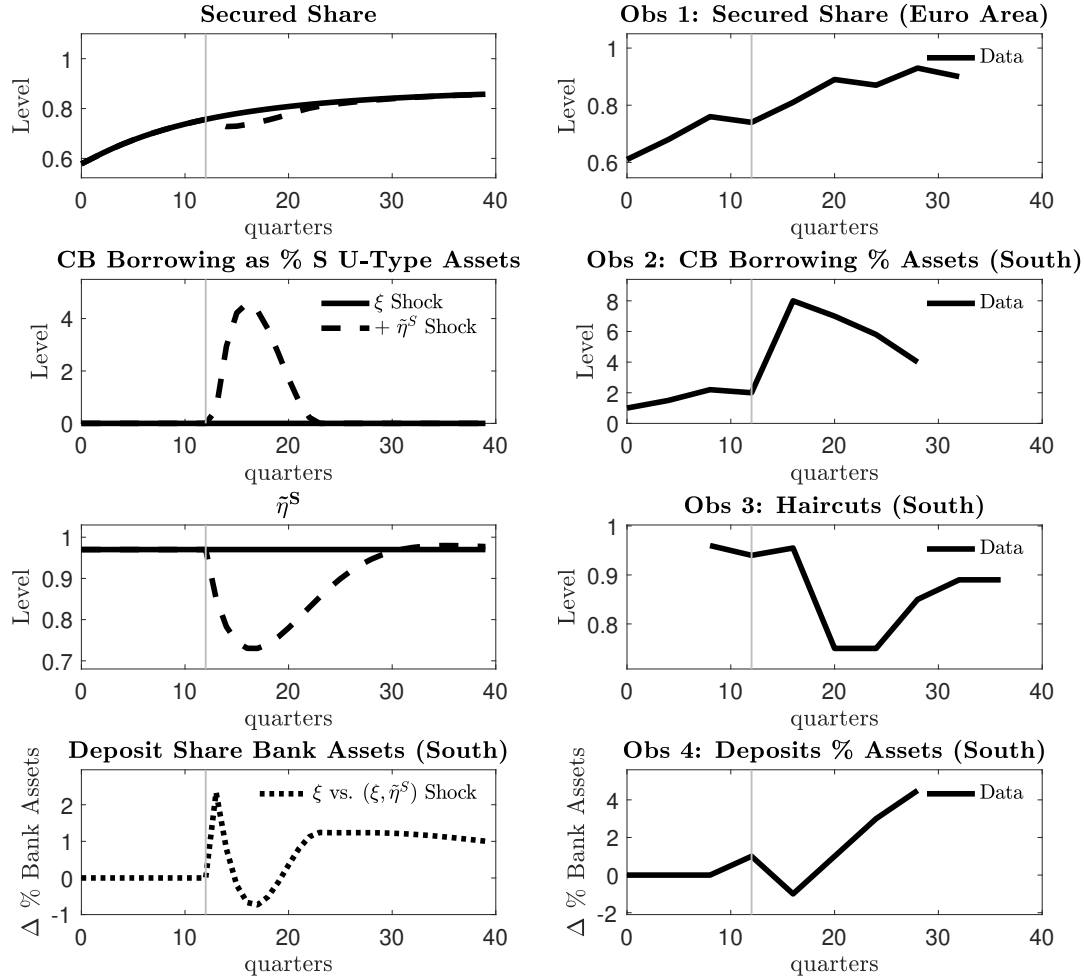
Notes: The figure presents bank borrowing from the ECB (solid line, left scale in each figure) and from households (dotted line, right scale in each figure) as % of bank total assets over 2003-2015, for northern (Germany, DE, France, FR) and southern (Spain, ES, Italy, IT, Portugal, PT) regions, respectively. Source: ECB.

Figure 5: Model vs. data: evolution of ξ and $\tilde{\eta}^S$



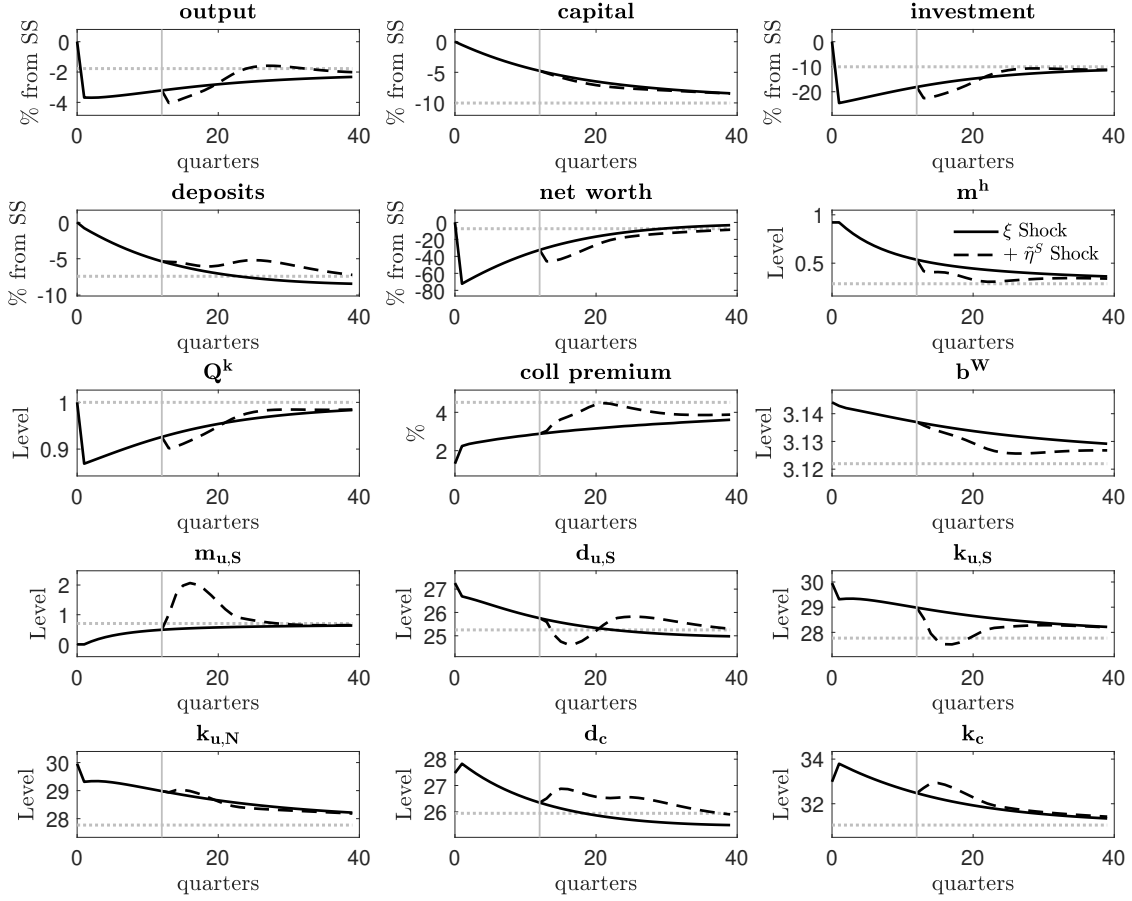
Notes: The figure shows the evolution of, on the left, the share of unsecured borrowing in total, corresponding to the share of connected banks in the model (ξ) and, on the right, the collateral value post-haircut in the South ($\tilde{\eta}^S$). The solid line is the data taken from Section 2.1, while the dashed line is the fitted model-implied evolution of these variables described in Section 5.2. The data points for $\tilde{\eta}^S$ come from the time series evolution of private market haircuts (LCH.Clearent) on southern government bonds (weighted average across Italy, Spain and Portugal), while the Model line is a spline interpolation through these points that we attempt to fit with an AR(2) process.

Figure 6: Four facts: model vs data



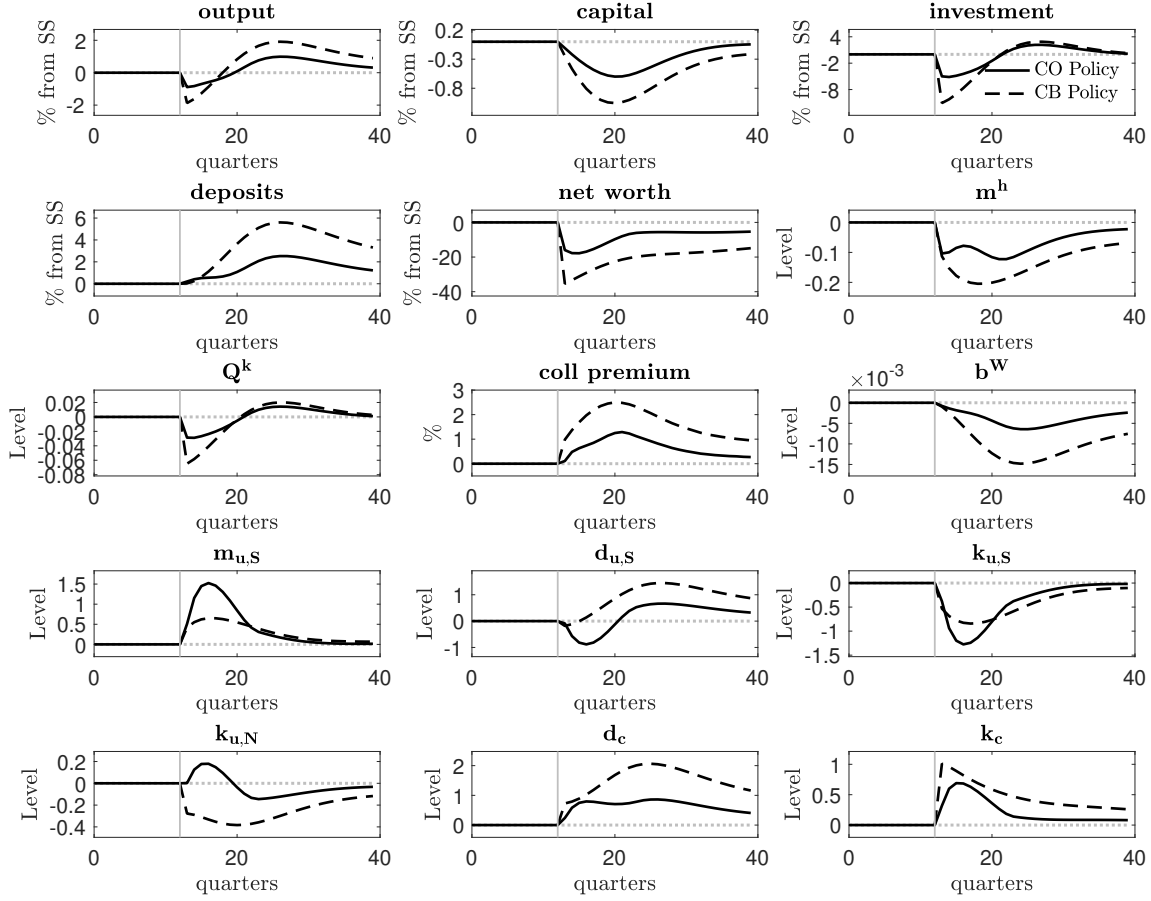
Notes: The figure compares the model outcomes on the first column to their empirical counterparts on the second column regarding the four facts documented in Subsection 2.1. The first column shows the impulse responses of key variables to exogenous shocks under CO Policy. The timing and process of the shocks in the full experiment are explained in Section 5.2. The solid lines denote the response to the permanent shock to ξ only, which occurs at time 0. The dashed lines in the top three rows denote the response of variables when there is an additional shock to $\tilde{\eta}^S$, which occurs at time $t = 13$. The dashed line in the bottom left figure denotes the response of variables when there is the combined $(\xi, \tilde{\eta})$ shock relative to the ξ shock alone. The timing of the shock to $\tilde{\eta}^S$ is conveyed by the vertical thin gray line. First row: the secured share in the interbank market. Second row: borrowing from central bank as a % of total assets held by unconnected banks in the South. Third row: process for $\tilde{\eta}^S$. Fourth row: deposits as a share of total bank assets in the South. The observations are annual, and the yellow line represents 2011.

Figure 7: Impulse responses: $\xi + \tilde{\eta}$ shock (dashed) vs. ξ shock only (solid)



Notes: The figure conveys the impulse responses of key variables to exogenous shocks under CO Policy. The timing and process of the shocks in the full experiment are explained in Section 5.2. The solid lines denote the response to the permanent shock to ξ only that occurs at time 0. The dashed lines denote the response of variables when there is an additional shock to $\tilde{\eta}^S$ that occurs at time $t = 13$. The timing of the shock to $\tilde{\eta}^S$ is conveyed by the thin gray line. The thin dotted horizontal lines indicate the permanent % change / new level of the variable in response to the permanent shock to ξ . First row: % change in aggregate output, capital, and investment. Second row: % change in aggregate deposits, bank net worth, and money held by households. Third row: price of capital, bond collateral premium (as defined in Section 4.3), and world bond demand. Fourth row: money, deposits and capital held by U-types in the South. Fifth row: capital held by U-types in the North, and deposits issued and capital held by connected banks.

Figure 8: Impulse responses: CO policy (solid) vs. CB policy (dashed)



Notes: The figure conveys the response of variables in the full experiment compared to a counterfactual where only the ξ shock occurs. In other words, it illustrates the additional effect induced by the shock to $\tilde{\eta}^S$. The timing and process of the shocks in the full experiment are explained in Section 5.2. The solid lines denote the response under CO policy, while the dashed lines denote the response under CB policy. The timing of the shock to $\tilde{\eta}^S$ is conveyed by the thin vertical gray line at $t = 13$. The thin dotted horizontal line is at zero. First row: % change in aggregate output, capital, and investment. Second row: % change in aggregate deposits, bank net worth, and money held by households. Third row: price of capital, bond collateral premium (as defined in Section 4.3), and world bond demand. Fourth row: money, deposits, and capital held by U-types in the South. Fifth row: capital held by U-types in the North, and deposits issued and capital held by connected banks.