NEGATIVE RATES AND THE EFFECTIVE LOWER BOUND: THEORY AND EVIDENCE

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Abstract
With the monetary policy lower bound a re-emerging concern in some locations, we present new insights on the impact of negative policy rates. We develop a new theoretical model to match the empirical evidence on their effects. The model features a heterogeneous, oligopolistic banking sector where loan pricing is determined in part by the availability of deposit funding and in part by wholesale funding. The use of non-deposit funding ensures that the bank lending channel of negative rates remains active. We explore the impact of the policy on different types of banks: High-deposit banks may experience a fall in interest margins and profitability, which can result in reduced lending. But this is more than compensated for by greater lending from low-deposit banks. We embed this banking sector in an open-economy macroeconomic model, featuring exchange-rate and capital market transmission channels, which continue to work as normal when rates are negative. These non-bank channels, combined with general equilibrium effects and an active bank lending channel, mean that the transmission of negative rates is only somewhat weaker than the transmission of conventional policy. (JEL: E31, E52, E58, F41)

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1. Introduction

> *After the rate of interest has fallen to a certain level, liquidity preference may become virtually absolute in the sense that almost everyone prefers cash to holding a debt which yields so low a rate of interest. In this event the monetary authority would have lost effective control over the rate of interest.* Keynes (1936)

Following the recent rise and fall of inflation, many central banks have been reversing the associated increases in interest rates, in some cases to low levels. Against that backdrop, some central banks may again need to confront the question of how much monetary policy space they have to cut interest rates further if faced with a new disinflationary shock.

As Keynes noted, the existence of cash creates a lower bound on the interest rate. When he discussed the concept in the General Theory, he suggested that 'whilst this limiting case might become practically important in future, I know of no example of it hitherto'. Keynes's future is already in the past: In the 2010s, central banks in the Euro Area, Switzerland, Sweden, Denmark, and Japan implemented negative policy rates, which were successfully transmitted to market interest rates along the yield curve.

With negative policy rates no longer just a theoretical possibility, we need to consider different concepts of the lower bound.[1] There remains a 'physical lower bound' (PLB): the point at which all agents will substitute from risk-free bonds into cash, but this has been shown to be below zero.[2] Instead, when policy rates approached zero in recent years, central banks have sought to understand the location of the effective lower bound (ELB): the point at which further cuts in the policy rate no longer provide stimulus. Concerns with adverse effects of negative rates typically centre on the banking system and the idea of a 'reversal rate', defined as the rate below which accommodative monetary policy becomes contractionary for bank lending. Despite such concerns, the empirical literature on negative interest rates has come to broadly positive conclusions on transmission, including via banks.

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1. We follow the terminology used in Balloch, Koby, and Ulate (2022).

2. See Rognlie (2016) for a discussion. It remains uncertain at what point the PLB could become a severe constraint on monetary policy. Ten-year government bond yields in Germany and Switzerland have fallen to −0.9% and −1.2% at times, without adverse effects on market functioning. This suggests that the inconvenience of cash is non-trivial for large investors, even if at some point, relative rates of return would ultimately lead to large-scale substitution into cash. Possible reforms to influence the PLB were first proposed by Gesell (1916) and Eisler (1932) and more recently discussed by Buiter (2009), Agarwal and Kimball (2015) and Lilley and Rogoff (2020).

In this paper, we match the theory with the evidence. We present a comprehensive model that matches the stylised facts from the empirical literature on negative rates. The model includes a wide set of the key theoretical channels identified by the literature, while also capturing some additional channels stressed by central bank policymakers.

We summarise the large and growing empirical literature on negative rates as a set of stylised observations. First, while retail deposit rates appear constrained at or around a zero lower bound (ZLB), pass-through of negative policy rates to wholesale funding rates has been virtually full, and corporate deposit rates have also fallen below zero in some countries. Second, lending volumes have increased and lending rates have fallen, even if in many cases by less and with somewhat longer lags than in normal times. Third, results on banking sector profitability have been mixed, especially using aggregate data. Some studies have even reported small positive effects on bank profitability after cuts into negative territory. Fourth, there has been compelling evidence of heterogeneity. Some authors have found that high-deposit banks have seen lower profits and less lending relative to low-deposit banks after the introduction of negative policy rates. Fifth, importantly, beyond the transmission through the banking sector, the literature has found that broader financial market channels have worked normally and the pass-through of negative rates has been complete.

We present a model of the banking sector, which includes some key features that help it match this empirical evidence. We assume a strict ZLB on deposit rates but not on wholesale funding. We then show that if bank loans are partly deposit and partly wholesale funded, as is the case in most advanced-economy banking systems, negative policy rates are passed through partially to bank lending rates, and bank profits can increase. This intermediate setup also nests two alternative extremes, which are the source of some of the conflicting results in the literature to date. We include the mechanism in a heterogeneous oligopolistic banking sector, in which low-deposit banks compete with high-deposit banks. This heterogeneity is motivated by the empirical literature that studies differences between low-deposit and high-deposit banks.

We embed our model of the banking sector in a small open economy macroeconomic model, where banks and firms can fund their activities both domestically and in global capital markets. Funds are intermediated across borders by global financiers, similar to Gabaix and Maggiori (2015). These financiers are not subject to the zero lower bound friction. The model captures the evidence that broader financial market channels, including the exchange-rate channel of monetary transmission, continue to work as normal under negative rates.

Under plausible calibrations, we find that negative rates are effective at boosting bank lending, output and inflation. The intuition behind our results is straightforward: Negative rates above the PLB only lead to a lower bound friction on a single asset—household deposits—held by one sector of the economy. While this shuts down the intertemporal substitution channel for households, other agents can circumvent it to the extent there are substitute assets or liabilities that are unaffected. In particular, the availability of bank wholesale funding, even as a partial substitute, leads to a positive bank lending channel, although this is more muted than standard rate cuts in positive territory. Moreover, by including a more complete set of non-bank channels of transmission in our open economy model, any partial impairment of the bank lending channel becomes less important. The accompanying general equilibrium effects further strengthen the bank lending channel of negative interest rates: Stronger aggregate demand from non-bank channels increases loan demand and asset values, with positive effects on bank profitability and lending.

By modelling heterogeneous banks and non-financial firms, we can also examine the distributional effects of negative interest rates on these agents. The empirical evidence is mixed, but a number of papers find that low-deposit banks benefit from increases in their relative profitability, and lend relatively more under negative interest rates than their high-deposit counterparts. However, panel studies using cross-sectional identification are typically silent on the implications in absolute terms. In our model, low-deposit banks increase lending and receive higher profits following a policy rate cut in negative territory. The effect on high-deposit banks' lending and profits is theoretically ambiguous. If the difference in bank funding structures is sufficiently large, high-deposit banks can experience a lending reversal and falling profits due to competitive dynamics. Crucially, the effect of a policy rate cut on aggregate lending and banking industry profits remains unambiguously positive, as any reduction in high-deposit banks' lending will be more than compensated for by low-deposit banks. There are also distributional impacts for borrowing firms, as negative rates lead to an increase in capital market borrowing relative to bank borrowing.

The paper relates most closely to two sets of recent literature on negative interest rates. Our empirical discussion synthesises the findings in surveys by Tenreyro (2021), Balloch, Koby, and Ulate (2022), and Brandao-Marques et al. (2024). The general equilibrium model that we introduce relates to those in Ulate (2021), Abadi, Brunnermeier, and Koby (2023), Onofri, Peersman, and Smets (2023), and Eggertsson et al. (2024). Relative to these models, our paper makes three main contributions.

Our first contribution is to present a model of negative interest rates that matches both the aggregate and cross-sectional empirical evidence, while also being flexible enough to nest competing views. We summarise a set of empirical stylised facts on the effects of negative rates, incorporating facts on both the average and relative responses by banks. Our introduction of a model with a heterogeneous banking sector allows us to match this evidence. We also highlight that a crucial theoretical assumption driving differing findings on the bank lending channel of negative interest rates has been on the determination of banks' marginal funding cost. When the marginal cost is the deposit rate (and banks have no excess securities), then the bank lending channel shuts down at negative rates; when it is the wholesale rate, there is full pass-through. Our model nests both assumptions, but with a baseline that the marginal funding cost depends on both sources.

Second, we recast those competing views within the historical literature on the bank lending channel of monetary policy. We compare cases where the deposit rate is the marginal cost (which would be the case if banks can fund lending only through household deposits) to cases where banks have an alternative, infinitely elastic source of wholesale funding (which is instead the marginal cost). This alternative—the presence of substitute funding sources—was precisely the critique by Romer and Romer (1990) of the mechanism put forward in the original bank lending channel of Bernanke and Blinder (1988).

Evidence against the Romer and Romer (1990) assumption was, in turn, provided by Kashyap and Stein (2000), who showed, using disaggregated data, that small banks more reliant on deposit funding were more affected by monetary policy. Consistent with this, profitability and lending fall in our model for high-deposit banks relative to low-deposit banks. But crucially, both metrics rise in aggregate. While our model can therefore match the cross-sectional empirical evidence, it also serves as a reminder that this cannot provide a direct read on aggregate outcomes.

The paper's third main contribution is to embed our banking sector in an open-economy New Keynesian model, which captures a more complete set of channels than previous work. A key innovation relative to the literature to date is our inclusion of an exchange-rate channel of negative rates. We show that the presence of intermediaries that trade financial assets on global markets gives rise to similar exchange-rate dynamics from rate cuts in either negative or positive territory, so long as those intermediaries find it too costly to substitute at scale into domestic cash. Using an exchange-rate depreciation to circumvent the lower bound in this way relates to Svensson (2001)'s classic 'Foolproof Way', which proposed generating a depreciation using a price level target, rather than by cutting the nominal rate.

Our open economy model also provides a new basis for the presence of external finance available to both firms and to banks, but not subject to a zero lower bound friction. Our firms can borrow on capital markets, as in Abadi, Brunnermeier, and Koby (2023), while our banks can borrow on wholesale markets similar to Onofri, Peersman, and Smets (2023), but these measures of external borrowing are ultimately funded (at the margin) from abroad, rather than by domestic households. In addition, the model incorporates a wide set of the mechanisms explored elsewhere in the literature, including a narrowing in the deposit spread as the policy rate falls, as in Drechsler, Savov, and Schnabl (2017); links from profitability to lending, as in Ulate (2021); a signalling channel of negative rates (de Groot and Haas 2023); and general equilibrium effects, as stimulus increases aggregate demand and bank profitability and reduces non-performing loans. Since these channels tend to increase the effectiveness of negative rates, models capturing only a subset of them and their interactions are likely to understate the benefits of the policy.

The paper is organised as follows. Section 2 summarises the empirical literature on negative rates and draws out some stylised facts that a model for the transmission of negative policy rates via banks needs to account for. Section 3 explains how our work relates to recent and historical debates in the literature on negative policy rates and the bank lending channel. Section 4 presents a partial equilibrium model of an oligopolistic banking sector with heterogeneous funding structures. Section 5 examines the macroeconomic impact of negative rates by embedding the oligopolistic banking model in a New Keynesian open economy model. Section 6 provides concluding remarks.

2. Empirical Motivation: The Experience with Negative Rates

This section introduces the main empirical observations that we seek to match in our model assumptions and results. A rapidly growing literature has documented the following observations:

Empirical Observation 1. Pass-through of policy rates to household deposit rates is bounded by the ZLB. Meanwhile, corporate deposit and wholesale funding rates can fall below zero.

Many studies have documented that household deposit rates do not smoothly follow policy rates into negative territory, but tend to 'pile up' close to zero.[3] Some banks, in particular in Denmark and Germany, have charged negative deposit rates on large household deposits, but aggregate household deposit rates only fell slightly below zero in these countries. In contrast, corporate deposit rates have fallen significantly below zero in many cases, though with some reduction in pass-through (Figure 1).

The stickiness of household deposit rates at zero could reflect that cash storage and security costs are lower for households than for corporates and institutional investors. Alternatively, it could be that households become more sensitive to deposit rate differentials at very low rates, perhaps owing to money illusion or nominal loss aversion.[4]

Empirical Observation 2. At low or negative policy rates, aggregate pass-through to bank lending rates and volumes still occurs, though it is typically reduced and potentially delayed.

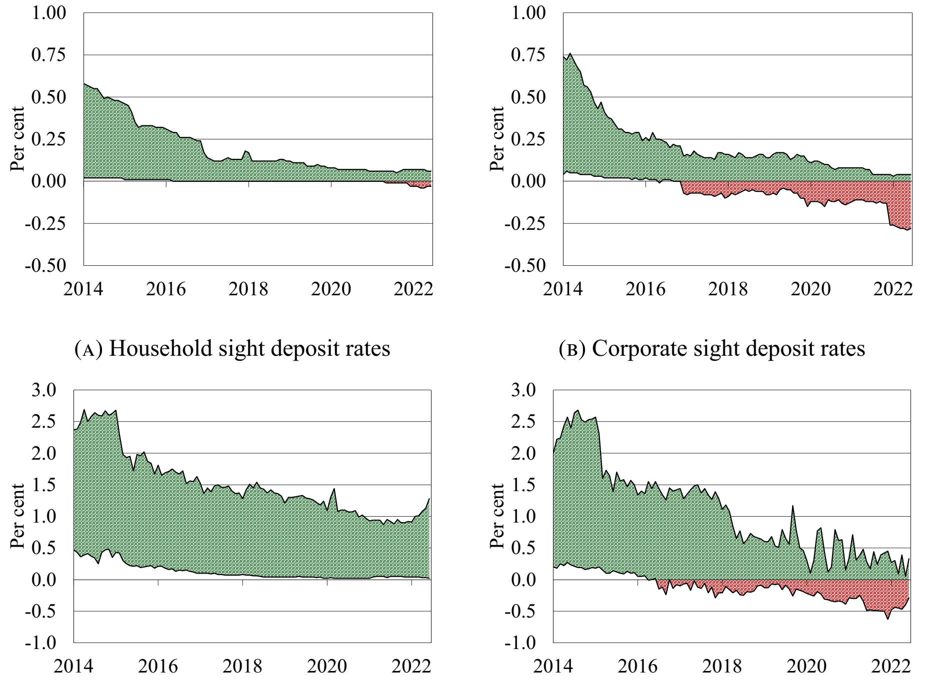
The aggregate evolution of lending rates shows that they have fallen after the introduction of negative policy rates (Tenreyro 2021; Brandao-Marques et al. 2024). While this association is consistent with positive pass-through from negative policy rates to lending rates, it does not causally identify the effect.[5] A number of empirical studies have attempted to identify this transmission, however. Most of these find positive, but often reduced or delayed, pass-through. Table 1 brings together some key findings.

Euro area estimates suggest strong pass-through to lending rates, with little evidence that pass-through was materially impaired. For some southern Euro Area countries, deposit rates were still well above zero when the ECB first cut its deposit

3. For example, Demiralp, Eisenschmidt, and Vlassopoulos (2021), Eisenschmidt and Smets (2019), and Tan (2019) for the Euro Area.

4. Abadi, Brunnermeier, and Koby (2023) suggest a model that captures this.

5. Rate cuts are often a response to economic slowdowns or recessions, so the effect of the policy rate on lending rates may be masked by adverse direct effects of demand or supply shocks on lending. In the other direction, negative rates have sometimes been used to help along recoveries rather than fight recessions, so it is also possible that falling lending rates reflect improvements in the risk outlook that would have taken place regardless.



(A) Household sight deposit rates

(B) Corporate sight deposit rates

(C) Household time deposit rates

(D) Corporate time deposit rates

FIGURE 1. Range of deposit rates across euro-area countries during the NIRP period. Source: ECB Data Portal. The figures show the ranges of effective aggregate deposit rates (percent) on new business across all euro-area countries with consistently available data between January 2014 and June 2022.

TABLE 1. Estimated pass-through from negative policy rates to lending rates.

Region	Pass-through	Source
Euro area	50%–80%	Altavilla et al. (2022)
Sweden	0%–50%	Erikson and Vestin (2019), Eggertsson et al. (2024)
Denmark	30%–40%	Adolfsen and Spange (2020)
Switzerland	0%–30%	Baeriswyl et al. (2021), Schelling and Towbin (2020)

facility to a negative rate, so it is possible that the ZLB was not yet binding (Bittner et al. 2021). But even when restricting to the experience of countries such as Germany or France, pass-through was still positive and material.

For Sweden, evidence has been mixed. Eggertsson et al. (2024) argue that pass-through to lending remained intact up to a policy rate of −0.25%, but broke down for cuts beyond that when deposit rates were at zero. In contrast, using the same data, Erikson and Vestin (2019) find delayed but ultimately material pass-through to lending rates. One difference is that Eggertsson et al. (2024) measure transmission in a tight 30-day window and hence miss any subsequent pass-through.

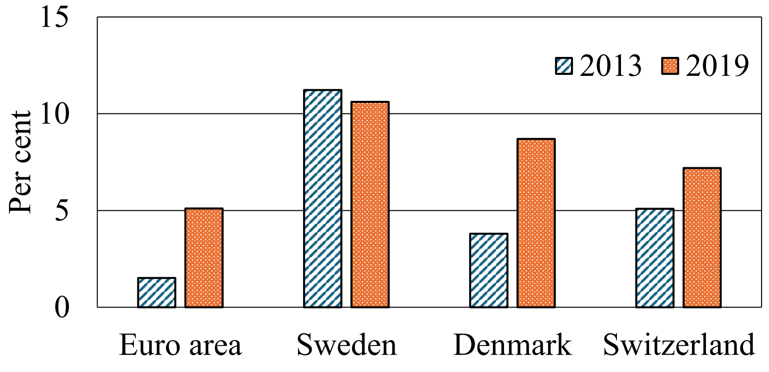


FIGURE 2. Aggregate bank return on equity. Sources: ECB Data Portal and FRED.

In Switzerland, Baeriswyl et al. (2021) estimate pass-through to 10-year mortgage rates of around 30%, as long as long-term interest rates—most relevant for such long-term lending—also fall substantially. Schelling and Towbin (2020) find evidence of fairly limited pass-through transmission and reversal for some high-deposit banks, but show that risk-taking increased to offset pressures on profitability.

Empirical Observation 3. Aggregate banking sector profitability is not necessarily adversely affected by negative policy rates, and may even improve owing to general equilibrium effects.

The effects of negative policy rates on aggregate bank profitability have tended to be modest.[6] During the transition from low interest rates to negative interest rates in the 2010s, aggregate bank return on equity (ROE) fell only slightly in Sweden, increased slightly in Switzerland, and increased significantly in the Euro Area and Denmark (Figure 2). While that may reflect factors unrelated to the level of the policy rate, most empirical studies come to relatively benign conclusions on the causal effect of negative rates on bank profits as well. For instance, Lopez, Rose, and Spiegel (2020) find small effects on bank profitability across countries. Specifically for the euro area, Boucinha, Burlon, and Kapp (2020) and Altavilla, Boucinha, and Peydro (2018) find that the ECB's negative interest rate policy has increased bank lending without material adverse effects on bank profitability. Studies by Albertazzi, Nobili, and Signoretti (2016), Bräuning and Wu (2017), and Tan (2019) come to similar conclusions. For Japan, Hong and Kandrac (2018) find that markets initially priced an adverse effect of

6. It is worth noting that the studies cited here are mainly concerned with the transition from low interest rates to negative interest rates. That transition is also the focus of our analysis in Sections 4 and 5. The earlier transition from high interest rates to low interest rates compressed deposit spreads in many jurisdictions, but our focus is specifically on the effects of negative interest rate policies compared to a zero interest rate policy.

negative rates on banks, but in the event, profitability actually increased more for the banks that markets had deemed most exposed.[7]

The modest effects of negative interest rates on bank profitability found in the literature are likely to partly reflect general equilibrium effects. While negative rates will have at best neutral and possibly adverse effects on banks' net interest margins, they can raise loan demand and reduce loan defaults, both of which can boost bank profitability compared to the counterfactual of a zero interest rate policy.

Another important reason for the findings of positive transmission of negative policy rates to lending, and the lack of large adverse effects on bank profits, is that while the zero lower bound has affected household deposits, it has not been seen to apply to wholesale funding or corporate deposits (Rostagno et al. 2021). The rates on a large part of banks' funding sources can continue to adjust downward when the policy rate is cut below zero, leaving space for at least partial pass-through to lending rates without adverse effects on profitability.

The typical bank in the Euro Area, Sweden, Denmark, and Switzerland has a significant reliance on funding sources that are not constrained by the ZLB (Figure 3). Consistent with the empirical evidence, this suggests that banks should be able to afford at least partial pass-through of policy rate cuts below zero to lending rates without a reduction in overall profitability.

Empirical Observation 4. Negative interest rates can have heterogeneous effects on different types of banks. A number of papers find evidence that low-deposit banks expand lending relative to high-deposit banks, though this result is not universal.

Much of the empirical evidence on negative interest rates comes from panel data, which is able to use bank-level variation to identify causal impacts. While this evidence can be harder to interpret at the aggregate level, it gives us further empirical facts that we can match using our heterogeneous bank model.

There is consistent evidence that high-deposit banks can come under relative profitability pressure in negative rate environments. Given the evidence for a ZLB on household deposit rates, it is intuitive that high-deposit banks may not be able to both maintain profitability and expand lending as much as low-deposit banks. There is also evidence, however, that some high-deposit banks are able to offset this pressure by expanding risky lending.

Studies by Heider, Saidi, and Schepens (2019), Amzallag et al. (2019), Eggertsson et al. (2024), and Basten and Mariathasan (2018) all find that high-deposit banks expand lending by less than low-deposit banks when the policy rate falls below zero. But this result is not universal: Altavilla et al. (2021), Demiralp, Eisenschmidt, and

7. Some papers, such as Borio, Gambacorta, and Hofmann (2017) and Claessens, Coleman, and Donnelly (2018), find moderate adverse effects of low and negative rates on bank profits. But these papers are subject to the critique in Altavilla, Boucinha, and Peydro (2018): Without controls for expected macroeconomic conditions, regressions of bank profits on the policy rate will be biased because policy rates tend to be cut when the economic outlook deteriorates, which will directly reduce bank profits regardless of the interest rate level.

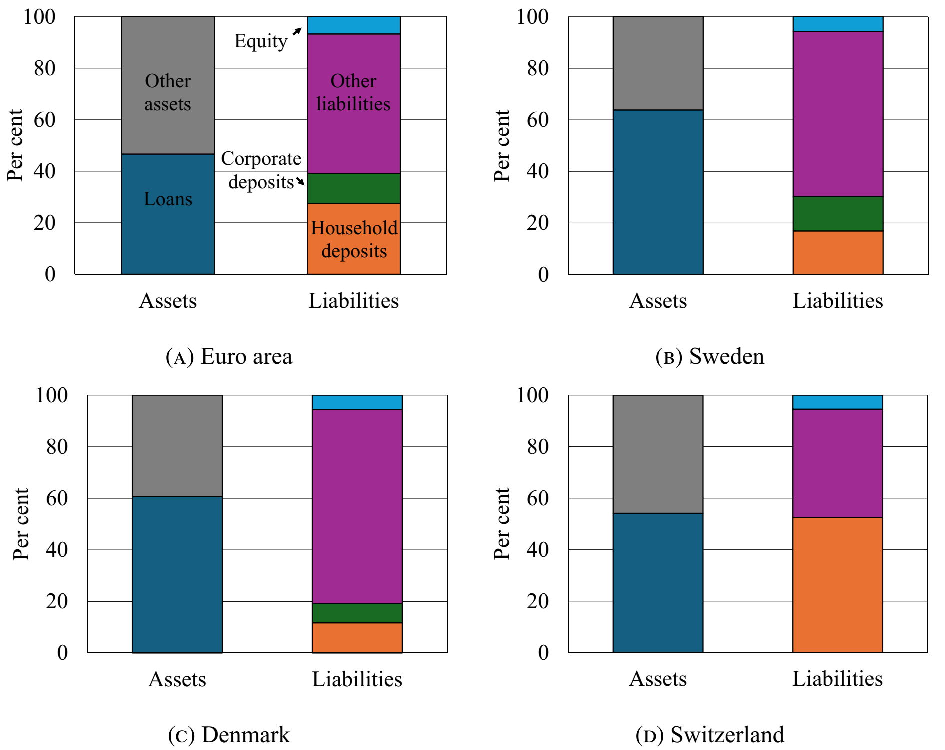


FIGURE 3. Aggregate consolidated bank balance sheets. Source: Consolidated banking data from the ECB Data Portal and Swiss National Bank. The figure is based on annual end-of-year data, averaged over 2014 to 2019. For Switzerland, the chart shows an average of monthly data for domestically focused banks between 2014 and 2019. Loans refers to loans to households and non-financial corporations only. The Swiss panel shows total customer deposits in the bottom liability bar, which combines both the household and non-financial corporate deposit bars shown in the other panels.

Vlassopoulos (2021), Bottero et al. (2019), Schelling and Towbin (2020), and Hong and Kandrac (2018) find that high-deposit banks actually lend relatively more than low-deposit banks when rates are cut below zero, while Adolfsen and Spange (2020), Bittner et al. (2021), Klein (2020), and Arce et al. (2023) find no significant relationship between the degree of deposit funding and subsequent lending behaviour.

Empirical Observation 5. Broader financial market channels of transmission tend to work normally and do not appear to be constrained by a lower bound.

In countries that have implemented negative policy rates, a wide range of market interest rates have turned negative. These include short-term interbank lending rates (Figure 4), government bond yields, and some corporate bonds (Arteta et al. 2016). A number of studies have found that transmission from policy rates to longer-term yields

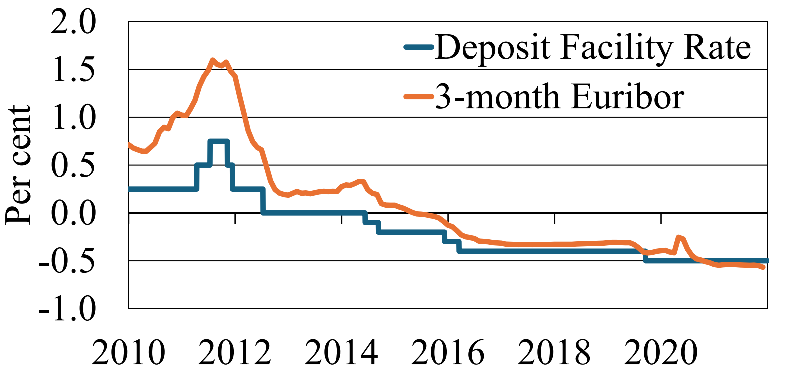


FIGURE 4. ECB deposit facility rate (DFR) and 3-month Euribor. Source: ECB Data Portal.

may actually strengthen in negative territory (Rostagno et al. 2025),[8] and other studies have found strong and largely unchanged transmission to exchange rates and equity prices.[9]

Financial market channels that go beyond bank lending are an important part of monetary policy transmission, in particular in small open economies and more so the less bank-reliant an economy is. For example, Tenreyro (2021) reported a Bank of England estimate of non-bank channels accounting for a third to two-thirds of the total medium-term impact on output from policy rate changes in the UK, and half to three-quarters of the impact on inflation. These channels matter for assessing the effectiveness of negative policy rates both as part of the transmission mechanism, but also because stimulus provided through these channels has general equilibrium effects on bank lending, where positive effects on aggregate demand boost bank profitability, including by reducing non-performing loans.

The banking model we develop in Sections 4 and 5 attempts to match these empirical observations. One simplification in the model is that we do not allow banks to choose the riskiness of their loan portfolio. This prevents us from matching the potential channel by which high-deposit banks resort to increased risk taking in response to the pressure that negative policy rates put on their profitability. Our model also abstracts from possible interactions between negative rates and quantitative easing (QE).[10]

8. See also Bräuning and Wu (2017) and Rostagno et al. (2025). Grisse, Krogstrup, and Schumacher (2017) similarly find evidence that transmission of rate cuts to long rates is stronger the closer the proximity to the perceived lower bound, perhaps due to signalling to the market that the floor on policy rates is lower than previously thought.

9. See, for example, Bräuning and Wu (2017) and Eisenschmidt and Smets (2019).

10. For example, Rostagno et al. (2025) find that negative rates are likely to improve the effectiveness of QE by pushing down on the perceived lower bound on the policy rate, which opens up additional space for

3. Relation to Past Debates on Negative Rates and the Bank Lending Channel

In this section, we set out in more detail how our model assumptions relate to some of the competing views in the literature. We first discuss a key source of differing results in some of the important recent theoretical papers modelling negative interest rates. We then discuss how these assumptions are closely related to the older debate on the original bank lending channel of monetary policy.

The banking sector in our model builds on the textbook Monti–Klein framework.[11] When banks have access to wholesale finance in this model, lending and deposit taking are separable, and hence the transmission of negative policy rates to lending rates should be unaffected by the ZLB on deposits as long as wholesale funding rates continue to reprice with the policy rate. However, taken literally, an implication of this model is that the deposit market would disappear as soon as the policy rate falls below the deposit rate.

Recent papers have therefore taken two different approaches to adapt the Monti–Klein model in order to generate more realistic model dynamics. Some break the separability between lending and deposit taking. For example, Eggertsson et al. (2024) study the transmission of negative rates in a model of a perfectly competitive banking system. The deposit rate is always the marginal funding cost for banks in this model, and hence separability is broken. The result is that pass-through to lending rates breaks down once the ZLB on deposits binds, and can turn negative depending on the bank's overall balance sheet structure and exposure to interest rate risk.

Others maintain separability but force banks to accept any deposits that are supplied at the ZLB. Losses from deposit taking reduce profitability and can lead to reduced pass-through and, in the extreme, lending reversal via a capital constraint or leverage costs. For instance, in Ulate (2021), pass-through to lending rates remains complete, except to the extent that reductions in profitability weigh on bank lending via leverage costs. This paper finds that in general equilibrium, pass-through from negative policy rates to lending rates should be between 60% and 90%, while bank profitability falls materially. In another example, Repullo (2020) maintains separability between lending and deposit taking, and hence pass-through from negative policy rates to lending rates is unaffected by the ZLB on deposits. Reversal could occur in this model, but only in the extreme sense that banks shut down entirely due to mounting losses from deposit taking. Up to that point, banks will continue to fully pass-through policy rate cuts to lending rates.[12]

QE to reduce longer-term interest rates. Sims and Wu (2021) set out a model that studies the interaction of QE and NIRP, but with intermediaries that are unable to hold non-deposit liabilities.

11. See Monti (1971), Klein (1971).

12. Abadi, Brunnermeier, and Koby (2023) develop a model of local monopoly banks that features a reversal rate for the bank lending channel. In this model, banks are subject to both capital and liquidity constraints. Depending on which constraint binds, separability could be broken as in Eggertsson et al. (2024), or maintained as in Ulate (2021).

Our model takes a middle ground between these two approaches. We break Monti–Klein separability by assuming that banks prefer (or are required) to fund loans with a minimum amount of retail deposits. This also implies that banks' profit-maximising behaviour can be approximated by concepts such as average cost pricing or net interest margin targeting. The resulting model dynamics are able to explain well the empirical evidence from countries with negative policy rates.

Our intermediate approach also means that our model is able to nest alternative extreme assumptions by varying the deposit requirement. The assumptions above make clear that a crucial determinant of the impact of changes in deposit supply is the extent to which there are elastically available alternative sources of funding. At one extreme, banks fund all lending only using deposits, and the deposit rate is the marginal funding cost. Naturally this means that a ZLB on deposit rates shuts down the bank lending channel of monetary policy. At the other extreme, elastically available wholesale funding can perfectly substitute for deposits, and the marginal funding cost is pinned down by the policy rate, and lending is little affected by the ZLB.

Those competing views relate closely to historical debates of the traditional bank lending channel of monetary policy. In the original bank-lending channel, set out by Bernanke and Blinder (1988), banks funded all loans using reservable deposits—one of the extremes set out above. This model assumption was challenged by Romer and Romer (1990), who suggested that changes in deposit supply could be offset by substituting into market-based funding, essentially making the opposite extreme assumption. Later work, for example by Kashyap and Stein (2000), argued in favour of the traditional bank lending channel in a less extreme form, motivated by cross-sectional empirical evidence of imperfect substitution between deposits and other funding sources. This debate closely parallels a key assumption underlying the different effects of negative interest rates across models. Our intermediate approach is similar to an assumption of imperfect substitution across funding sources.

The most closely related paper to our modelling approach, which similarly emphasises wholesale finance, is Onofri, Peersman, and Smets (2023). In this model, banks' access to wholesale finance stems from the assumption that households have a preference for holding some amount of investment fund shares even when those carry negative nominal returns. This assumption not only opens up the bank lending channel, but also re-establishes the intertemporal substitution channel for the transmission of negative policy rates.

In our model, households will not hold any negative-yielding assets in equilibrium. Banks in our model have access to wholesale finance through a group of global financiers. These financiers do not hold cash due to safety concerns or inconvenience costs. Hence, financiers will hold negative-yielding assets in equilibrium. They can raise finance in domestic and international bond markets, and they issue wholesale finance to banks as well as to a subset of intermediate goods firms with direct capital market access. Financiers are partly financed by domestic households away from the zero lower bound. But as bond rates turn negative, households will switch into zero-yielding cash or deposits, shutting down the intertemporal substitution channel.

4. The Effective Lower Bound in a Banking Model

This section develops a model for the transmission of negative policy rates to bank lending. Building on the canonical Monti–Klein bank with access to wholesale funding, we introduce a deposit funding constraint that breaks the separability between lending and deposit taking. We then explore the transmission of negative rates in a heterogeneous Cournot oligopoly.

The bank is financed through a combination of equity, wholesale finance, and household deposits. The empirical evidence suggests that only household deposits are subject to a zero lower bound, while other sources of finance can carry negative nominal returns.

The banking model in this section is a partial equilibrium model. In particular, we treat the loan demand function as exogenous. We also focus on the effect of policy rate cuts from zero into negative territory, starting from a position where the deposit spread has already been compressed to zero. The general equilibrium model developed in Section 5 will endogenise loan demand, and also feature a steady-state deposit spread that is compressed as the policy rate is cut towards and eventually below zero.

4.1. A Funding-Constrained Bank at the ELB

Consider a local monopoly bank faced with a downward-sloping loan demand $L(i_L)$ and an upward-sloping deposit supply $D(i_D - i)$. We discuss firms' loan demand and households' deposit supply in detail in Section 5. For the partial equilibrium analysis in this section, we assume constant semi-elasticity throughout to obtain clean expressions for monetary policy transmission to lending rates.

The bank can borrow in wholesale funding markets at the policy rate i and is subject to a capital requirement, $\psi L \leq K$, which will always be binding because the required return on capital exceeds the interest rate by $\rho > 0$. If the bank is not subject to any further constraints on its balance sheet structure, we can write its problem as

$$\max_{L,D} \ \pi = (i_L - i - \psi\rho)L + (i - i_D)D.$$

The lending problem is separable from the deposit-taking problem. Consequently, a zero lower bound on the deposit rate i_D would have no effect on lending decisions, as the bank would continue to fully pass through any policy rate cut to the lending rate,

$$\frac{di_L}{di} = 1.$$

However, the bank would also exit the deposit-taking business at the ZLB because $(i - i_D)D < 0$ for all $D > 0$ when $i < 0$ and $i_D = 0$. To avoid such a breakdown of the deposit market, ZLB models that maintain separability between lending and deposit taking, such as Repullo (2020) and Ulate (2021), assume that banks cannot turn depositors away but have to accept whatever deposit supply is offered at the ZLB. In such models, the policy rate is the marginal funding cost, and pass-through to lending rates remains complete. Meanwhile, bank profitability falls sharply due to large losses from deposit taking. That fall in profitability can ultimately reduce transmission to lending depending on the nature of capital or leverage constraints. But as set out in Section 2, the empirical evidence does not suggest that aggregate bank profitability has been significantly affected by negative policy rates.

Alternatively, one could break separability by restricting banks' ability to rely on sources of finance that are not subject to the ZLB. In that case, the deposit rate is the marginal funding cost, and hence pass-through to lending at the ZLB will in general be zero, but could turn negative depending on banks' overall balance sheet structure and assumptions on capital constraints or leverage costs. However, as discussed in Section 2, banks do rely significantly on funding sources that are not constrained by the ZLB, and aggregate pass-through to lending rates has generally been positive.

Our approach is to break separability, but in a way that implies that the bank's marginal funding cost is a weighted average of the deposit rate and the policy rate. This will result in muted but positive pass-through to lending and broadly neutral effects on bank profitability. We also assume that the bank can turn away unwanted excess deposits at the ZLB. For example, there is evidence from countries with negative policy rates that banks do so by raising account fees, offering negative deposit rates to new customers, and charging negative rates to existing customers above certain thresholds.

We introduce a constraint which requires the bank to fund at least a certain fraction of its loans through deposits,

$$\varphi L \leq D, \quad \varphi \in (0, 1).$$

We can think of this constraint as capturing regulatory rules or banks' preferences over their balance sheet structure and business models. Alternatively, one could think of this as a reduced-form approach to capture complementarities between lending and deposit taking. Explicitly modelling such complementarities, which are ultimately behind the fact that lending and deposit-taking tend to be done by the same institutions, would also break Monti–Klein separability.[13] Finally, our approach could be motivated by an observation that in practice some banks depart from profit maximisation and resort to average cost pricing or net interest margin targeting. They may use such rules of thumb or heuristics because they lack sufficient information about the demand curves for their many differentiated products to carry out marginal cost pricing as envisaged by standard microeconomic theory.

Away from the ZLB, the funding constraint may or may not be binding. At the ZLB, deposit taking is a loss-making line of business. The bank will then only take deposits to the extent necessary to support lending, and hence the funding constraint will bind, $\varphi L = D$. This allows us to write the bank's problem at the ZLB as

$$\max_{L} \ \pi = (i_L - (1 - \varphi)i - \psi\rho)L,$$

13. See, for example, Freixas and Rochet (2008), chapter 3.

which implies the following expressions for optimal lending and for the lending rate:[14]

$$L = -\frac{i_L - (1-\varphi)i - \rho\psi}{i_L^{'}}, \qquad i_L = (1-\varphi)i + \rho\psi + \frac{1}{\varepsilon}. \tag{1}$$

The ZLB on deposit rates reduces the transmission from the policy rate to the lending rate, but pass-through remains positive as long as loans are at least partially wholesale funded,

$$\frac{di_L}{di} = 1 - \varphi \geq 0. \tag{2}$$

As we argued in Section 2, this is the empirically relevant case for aggregate banking sectors in many countries.

4.2. A Heterogeneous Oligopoly at the ZLB

The Monti–Klein model of a local monopoly bank can easily be reinterpreted as a model of imperfect Cournot competition between a finite number N of banks.

To begin, consider N identical banks engaged in Cournot competition. At the ZLB, $i_D = 0$ and the funding constraints are binding, that is,$\varphi L_n^* = D_n^*\ \forall\ n$. A Cournot equilibrium of this banking industry is given by $(L_n^*)_{n=1,\ldots,N}$ such that for every n, L_n^* maximises the profit of bank n, taking the volume of loans, and hence deposits, of all other banks as given. That is, for every n, L_n^* solves

$$\max_{L_n} \left[i_L \left(L_n + \sum_{m \neq n} L_m^* \right) - (1-\varphi)i - \psi\rho \right] L_n.$$

There is a unique symmetric equilibrium, in which each bank sets $L_n^* = L^*/N$. The equilibrium lending rate is characterised by

$$i_L(L^*) = (1-\varphi)i + \psi\rho + \frac{1}{N \cdot \varepsilon}.$$

The only difference to the case of a monopoly bank is that the markups, which stem from the banks' market power, are now scaled by the number of banks N. For $N \to \infty$, mark-ups disappear and we obtain the perfect competition allocation.

At the ZLB, pass-through to lending rates is the same regardless of the number of banks in the market,[15]

$$\frac{di_L}{di} = 1 - \varphi.$$

14. We define $\varepsilon \equiv -L^{'}/L$, the (by assumption constant) semi-elasticity of loan demand.

15. Note that this result depends on our simplifying assumption of constant semi-elasticity. Under constant elasticity, for instance, pass-through does depend on the intensity of competition, as, for example, Freixas and Rochet (2008) discuss.

An important concern about negative policy rates is that they could affect banks differently according to their business models. In particular, banks whose business model relies more extensively on deposit funding are more heavily exposed to the ZLB friction than low-deposit banks, and could thus come under competitive pressure. To study this, consider n_1 banks subject to $\varphi_1 L_{1,j} \leq D_{1,j}$ and n_2 banks subject to $\varphi_2 L_{2,k} \leq D_{2,k}$, with $0 < \varphi_1 < \varphi_2 < 1$. That is, banks of type 2 are more deposit-reliant than banks of type 1. At the ZLB, the problem for bank j of type 1 is:[16]

$$\max_{L_{1,j}} \left(i_L \left(L_{1,j} + \sum_{m \neq j} L^*_{1,m} + \sum_k L^*_{2,k} \right) - (1-\varphi_1) i \right) L_{1,j}.$$

The problem is identical for banks with the same funding constraint, so a symmetric solution requires

$$L_{1,1} = \ldots = L_{1,n_1} = -\frac{i_L - (1-\varphi_1)i}{i'_L}, \quad L_{2,1} = \ldots$$
$$= L_{2,n_2} = -\frac{i_L - (1-\varphi_2)i}{i'_L}. \tag{3}$$

Note that $i'_L < 0$, so for the high-deposit banks to participate ($L_{2,k} > 0$), their net interest margin must be positive, $i_L - (1-\varphi_2)i > 0$. With $i < 0$, a negative net interest margin would require a sufficiently negative aggregate lending rate. A negative lending rate could still deliver a positive margin for the low-deposit banks, so in principle it could arise in our model. Hence, there will be a threshold for the policy rate below which the high-deposit banks exit.[17] We will assume that high-deposit banks' participation constraint is fulfilled.

Differentiating optimal lending with respect to the policy rate yields

$$\frac{dL_{1,j}}{di} = \frac{(1-\varphi_1)\left[(n_2+1)i'_L + n_2 i''_L L_{2,k}\right] - (1-\varphi_2) n_2 (i'_L + i''_L L_{1,j})}{i'_L \left[(n_1+n_2+1)i'_L + n_1 i''_L L_{1,j} + n_2 i''_L L_{2,k}\right]} \quad \forall j, \tag{4}$$

and similarly for banks of type 2. Given second-order conditions and constant semi-elasticity, the denominator of the above expression is positive. Thus, following a policy rate, cut each bank's lending increases in proportion to the reduction of its own funding cost and is reduced in proportion to the reduction of the competitor group's funding cost.

High-deposit banks can experience lending reversal at the ZLB purely as a result of competitive dynamics, even if their capital constraint is not binding and their funding costs fall. High-deposit banks will increase lending in response to a policy rate cut if

16. We abstract from capital constraints here to keep the algebra simple, but reintroduce leverage costs in the discussion of a heterogeneous back-book channel in Appendix G.

17. Based on our solution for the lending rate, this threshold is $i > -1/(n_1(\varphi_2 - \varphi_1)\varepsilon)$. Sensible calibrations (e.g., $n_1 = 4$, $\varphi_2 - \varphi_1 = 0.2$, $\varepsilon = 0.5$) would suggest a threshold of $i > -2.5\%$, significantly below the mildly negative policy rates that have been implemented so far.

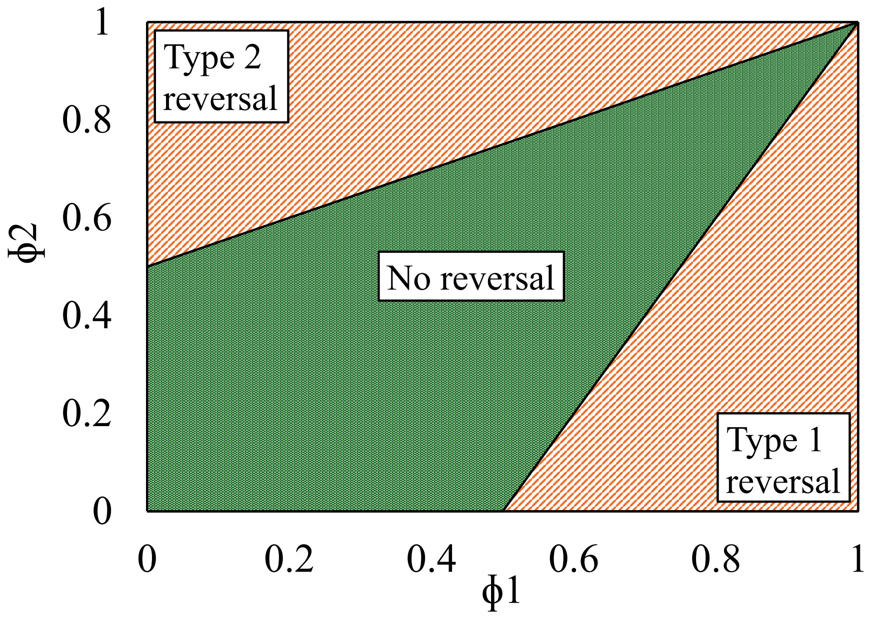


FIGURE 5. Lending reversal in a heterogeneous duopoly at the lower bond. φ_1 and φ_2 are the deposit funding shares for banks of type 1 and type 2.

and only if

$$\varphi_2 < \frac{i_L' + n_1 i_L''(L_{1,j} - L_{2,k})}{(n_1+1)i_L' + n_1 i_L'' L_{1,j}} + \frac{n_1(i_L' + i_L'' L_{2,k})}{(n_1+1)i_L' + n_1 i_L'' L_{1,j}}\varphi_1. \tag{5}$$

Figure 5 illustrates this condition for the case of a heterogeneous duopoly with a linear loan demand function. In the light shaded area where the banks' funding constraints are sufficiently similar, both banks will increase lending in response to a policy rate cut at the ZLB. In the red shaded areas where one bank is significantly more deposit-reliant than the other, the high-deposit bank will reduce lending while the low-deposit bank will increase lending.

Yet while there can be shifts in market share away from high-deposit towards low-deposit banks, there is no aggregate lending reversal. High-deposit banks may experience lending reversal, but this will always be over-compensated by low-deposit banks' expansion of lending. Provided aggregate loans are less than entirely funded by ZLB-constrained deposits, aggregate lending will always increase in response to a policy rate cut in negative territory,

$$\frac{dL}{di} = n_1\frac{dL_{1,j}}{di} + n_2\frac{dL_{2,k}}{di} = \frac{n_1(1-\varphi_1) + n_2(1-\varphi_2)}{i_L' + n_1(i_L' + i_L'' L_{1,j}) + n_2(i_L' + i_L'' L_{2,k})} < 0. \tag{6}$$

With constant semi-elasticity of loan demand, we can write an explicit solution for the lending rate as

$$i_L = \underbrace{\left(\frac{n_1}{n_1+n_2}(1-\varphi_1) + \frac{n_2}{n_1+n_2}(1-\varphi_2)\right) i}_{\text{Average loan funding cost}} + \underbrace{\frac{1}{(n_1+n_2)\varepsilon}}_{\text{Constant mark-up}}. \tag{7}$$

It is easy to see that raising the number of banks in the model while keeping the ratio of high-deposit to low-deposit banks constant will only reduce the constant markup of the lending rate over the average bank funding cost, but will not affect pass-through from the policy rate to the lending rate. So the degree of competition does not affect monetary policy pass-through.[18] Following a policy rate cut at the ZLB, pass-through to lending rates will be equal to the average reduction in funding costs.

$$\frac{di_L}{di} = \frac{n_1(1-\varphi_1) + n_2(1-\varphi_2)}{n_1+n_2} > 0. \tag{8}$$

Pass-through to lending will be muted relative to transmission above the ZLB, but will remain positive as long as aggregate loans are at least partly wholesale funded.

We can write the profits of the overall banking industry as

$$\begin{aligned} \pi &= n_1\pi_{1,i} + n_2\pi_{2,j} \\ &= \left[i_L - \left(\frac{n_1}{n_1+n_2}(1-\varphi_1) + \frac{n_2}{n_1+n_2}(1-\varphi_2)\right) i\right] L = \frac{1}{(n_1+n_2)\varepsilon} L. \end{aligned} \tag{9}$$

It is clear that banking industry profits will increase following a policy rate cut in negative territory:

$$\frac{d\pi}{di} = \underbrace{0}_{\text{Delta Mark-up}} \cdot \underbrace{L}_{\text{Loans}} + \underbrace{\frac{1}{(n_1+n_2)\varepsilon}}_{\text{Mark-up } (>0)} \cdot \underbrace{\frac{dL}{di}}_{\text{Delta Loans } (<0)} < 0. \tag{10}$$

But this increase in profits is driven entirely by the increase in lending volumes. Assuming the banks re-establish target leverage in subsequent periods via retained earnings, ROE will be unaffected by the policy rate cut in the medium term. This is consistent with the common finding in the empirical literature that negative policy rates appear to have little and, if anything, marginally positive effects on aggregate profitability.

It can also be shown that the profits of low-deposit banks will always increase following a policy rate cut in negative territory, while it is ambiguous whether the profits of high-deposit banks will increase or fall.[19] The larger the difference in funding structure between the two types of banks, the more likely the high-deposit banks are to experience declining profitability.

18. Note this result depends on constant semi-elasticity of loan demand. Under other specifications, such as linear loan demand or constant elasticity loan demand, the degree of competition will affect pass-through. Yet in both of those cases, pass-through from negative policy rates to lending rates remains positive.

19. See Appendix E.

Why is there no aggregate reversal in this model? The key intuition is that because a lower policy rate will always reduce banks' funding costs, aggregate lending must increase. The banks that experience the smaller reduction in funding costs due to their heavier deposit reliance will be at a competitive disadvantage and might actually reduce lending, but that creates a profitable opportunity for other banks to expand lending. Aggregate reversal cannot be an equilibrium outcome as long as banks are at least partially wholesale funded.

Individual banks—those with high deposit reliance—can suffer lending reversal in absolute terms, however. The likelihood that a bank will experience this owing to negative rates is determined more by its relative than its absolute deposit reliance.

The dynamics of our banking model line up well with the stylised facts set out in Section 2. The model implies positive but reduced pass-through to lending rates, in line with the empirical evidence. The model also implies that aggregate banking sector profits do not fall, in line with the headline data. And the model implies that high-deposit banks can come under pressure, but that their lending response is theoretically ambiguous, consistent with the mixed findings on this in the literature.

Appendix F sets out an extension to our model in which banks can suffer short-term back-book losses when negative rates are introduced. Such losses could for example stem from floating-rate mortgages, the interest rates on which mechanically track the policy rate. At the lower bound, this could generate losses because the interest rates on household deposits that are partly funding lending cannot follow the policy rate below zero. This channel makes lending reversal on impact possible, in particular if banks are surprised by the policy and have not adjusted their hedging strategies for the possibility.

5. The Effective Lower Bound in a Macroeconomic Model

In this section we embed our banking model in a fully specified open economy macroeconomic model featuring a large number of transmission channels. Using a macroeconomic model with a wide range of channels is essential to fully measure the benefits of the policy, given the empirical finding that the non-bank channels typically continue to work as normal.

The simple intuition for why we would expect negative rates to be more effective in larger models is illustrated in Figure 6. This shows a stylised monetary transmission mechanism diagram, featuring a subset of the key channels in our model. In our model, the intertemporal substitution channel will be shut down by the ZLB on deposit rates. But reflecting the empirical evidence presented in Section 2, capital-market and exchange-rate channels will continue to operate as normal. The bank lending channel will be impaired, but only partially, given our allowance of non-deposit funding sources. Moreover, the inclusion of a complete set of non-bank channels leads to further general equilibrium effects, which determine the ultimate size of the bank lending channel.

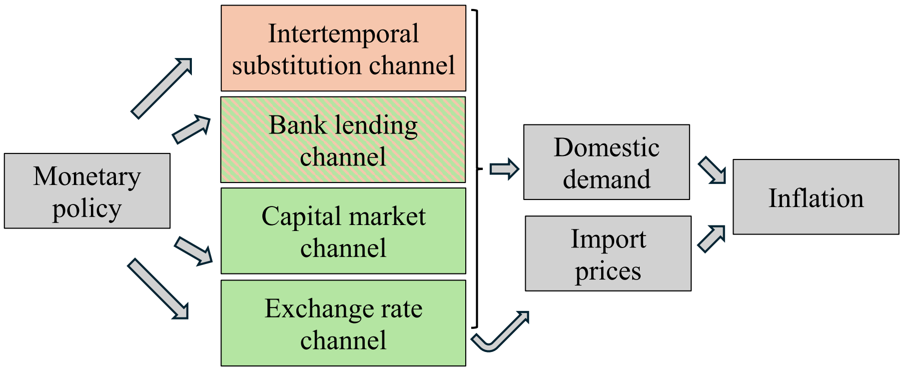


FIGURE 6. Stylised monetary policy transmission mechanism.

Compared to other papers on negative interest rates, our model places greater emphasis on the role of non-bank transmission channels, in particular by opening the economy and allowing for exchange rate effects.[20] This reflects the fact that in small open economies, bank channels of monetary policy transmission typically account for a smaller proportion of the aggregate impact. We also report the effects of negative rates on different types of banks in general equilibrium.

The model consists of households, intermediate goods firms, capital producers, retailers, a representative final goods firm, banks, financiers, a government, and a central bank. Intermediate goods firms are perfectly competitive and produce goods using labour hired from households and capital financed either by banks or by financiers. Monopolistically competitive retailers buy intermediate goods to produce differentiated varieties and set prices subject to a Rotemberg friction.[21] A representative final goods producer aggregates retailers' differentiated varieties and sells domestic output at a competitive nominal price. Perfectly competitive capital producers purchase undepreciated capital from intermediate goods firms as well as consumption goods to produce new capital, subject to an investment adjustment cost. The central bank sets the nominal interest rate following a Taylor rule. Oligopolistic banks take deposits from households, raise wholesale finance from financiers, and lend to firms. Banks are subject to leverage costs and funding constraints requiring a minimum amount of deposit finance. Within the banking sector, there is a group of high-deposit banks and a group of low-deposit banks engaged in imperfect

20. Lindé, Kolasa, and Laseen (2025) present a small open economy in which exchange rates play a key role in the transmission of negative policy rates, though without an explicit banking sector.

21. We assume producer currency pricing, as in Obstfeld and Rogoff (1995). As shown by McLeay and Tenreyro (2025), under realistic conditions, the expenditure switching channel is often of similar strength under common alternatives such as dollar invoicing. This is because dollar invoicing is typically used for homogeneous goods, whose prices tend to be flexible, with nominal rigidities arising in inputs such as sticky wages, rather than export prices. In this setting, a depreciation of the currency lowers the cost of labour and export quantities expand.

competition. Meanwhile, financiers can borrow at the policy rate as well as in international financial markets. They provide wholesale finance to banks and lend to a subset of intermediate goods firms.

5.1. Households

There is a continuum of households, each of which consumes, saves, and supplies labour. Households can save by holding cash, investing in bonds, or depositing money in banks. They also derive utility from the liquidity value of holding cash or deposits (our implementation follows Feenstra 1986). A household's lifetime utility is defined by

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[u(C_t, C_{t-1}, N_t) + \Phi(\mathcal{L}_t) \right],$$

where

$$u(C_t, C_{t-1}, N_t) = \frac{(C_t - hC_{t-1})^{1-\sigma} - 1}{1-\sigma} - \chi \frac{N_t^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} \text{ and } \Phi(\mathcal{L}_t) = 1 - e^{-\upsilon \mathcal{L}_t}.$$

C_t is consumption and N_t is labour supply, β is the discount factor, σ the inverse of the intertemporal elasticity of substitution, χ determines the importance of labour in the utility function relative to consumption, and η is the Frisch elasticity of labour supply. The parameter h allows for habit formation in households' consumption behaviour. The specific functional form chosen for liquidity benefits is not essential, provided that $\Phi'() > 0$ and $\Phi''() < 0$, which requires $\upsilon > 0$. This ensures that the marginal utility gained from an additional unit of liquidity is strictly non-negative but decreasing in the level of liquidity. We define liquidity as the sum of real deposits and real cash, $\mathcal{L}_t = (D_t + M_t)/P_t$.

The households' budget constraint can be written as

$$C_t + \frac{D_t}{P_t} + \frac{M_t}{P_t} + \frac{B_t}{P_t} = \frac{W_t}{P_t} N_t + \Pi_t - T_t + \frac{1 + i_{t-1}^D}{1 + \pi_t} \frac{D_{t-1}}{P_{t-1}} + \frac{1}{1+\pi_t} \frac{M_{t-1}}{P_{t-1}} + \frac{1 + i_{t-1}}{1 + \pi_t} \frac{B_{t-1}}{P_{t-1}}.$$

D_t, M_t and B_t are, respectively, the nominal amounts of bank deposits, cash, and bonds that households hold in period t. W_t is the nominal wage, Π_t are total dividends paid to the household by firms, financiers, and banks, T_t are lump sum taxes, P_t is the price level in period t, and inflation $\pi_t = P_t/P_{t-1} - 1$ is defined as the change in the price level between period $t-1$ and period t.

Because households derive the same liquidity value from cash and deposits, they will hold no cash whenever deposits pay a positive rate, and would hold no deposits were banks to offer a negative rate on deposits. Hence, the existence of physical cash will enforce a zero lower bound on the bank deposit rate, $i^D \geq 0$.

When the policy rate is above zero, households will hold a mix of deposits and bonds, and they will make intertemporal consumption-savings decisions based on the policy rate following a standard Euler equation,

$$1 = \beta \mathbb{E}_t \left[\frac{\rho_{t+1}}{\rho_t} \frac{1 + i_t}{1 + \pi_{t+1}} \right],$$

where ρ_t is the marginal utility of consumption in period t.

Combining this with the first-order condition with respect to deposits, we can write the household's inverse deposit supply function $i^D(D)$ as

$$i_t^D = i_t - \mathbb{E}_t \left[\frac{(1 + \pi_{t+1})\upsilon}{\beta \rho_{t+1}} \right] e^{-\upsilon \frac{D_t}{P_t}}. \tag{11}$$

The liquidity benefit of deposits generates a spread between the policy rate and the deposit rate, which will be positive in steady state when the policy rate is above zero ($\bar{i} - \bar{i}_D > 0$). When the policy rate falls below zero, the deposit spread turns negative ($i_t - i_t^D < 0$) due to the lower bound on the deposit rate ($i_t^D \geq 0$). Households will then strictly prefer bank deposits or cash to bonds and hold none of the latter.[22] This means that the Euler equation governing the households' intertemporal decision that applies to all possible levels of the policy rate is

$$1 = \beta \mathbb{E}_t \left[\frac{\rho_{t+1}}{\rho_t} \frac{1 + \max\{\mathrm{i_t}, 0\}}{1 + \pi_{t+1}} \right]. \tag{12}$$

The intertemporal substitution channel shuts down at the lower bound because the household makes consumption-savings decisions purely based on the zero deposit rate. Households will not hold any negative-yielding assets in equilibrium. Nevertheless, the policy rate can be cut below zero and will continue to transmit to the bond rate and to the exchange rate. That is due to the existence of financiers, who will hold negative-yielding assets in equilibrium.

Finally, the economy is open to trade in final goods. Domestic households consume a constant elasticity of substitution aggregate of domestic and foreign goods, with elasticity of substitution η^F. This implies period t households' demand for the domestic and the foreign good of

$$C_t^H = (1 - \gamma) \left(\frac{P_t^H}{P_t} \right)^{-\eta^F} C_t \qquad \text{and} \qquad C_t^F = \gamma \left(\frac{P_t^F}{P_t} \right)^{-\eta^F} C_t,$$

where P_t^H is the price of the domestic good, P_t the consumer price index (CPI), and γ a trade openness or home bias parameter. Foreign households have the same preferences, giving rise to a symmetric demand for exports of home final goods.

22. Note that households are indifferent between bank deposits and cash at the lower bound. In our model, the deposit amount at the lower bound will be pinned down by banks' funding constraint.

5.2. Financiers

There is a perfectly competitive group of global financiers, similar to Gabaix and Maggiori (2015). We think of these as global banks that intermediate across borders, and as such, they have access to reserve accounts at both home and foreign central banks. They provide wholesale finance to banks, trade in international bond markets, and directly finance a subset of intermediate goods firms. In contrast to households, financiers do not have access to deposit insurance, and we assume that they do not hold physical cash due to its inconvenience and safety concerns. Hence, they will hold negative-yielding assets in equilibrium when the policy rate falls below zero.[23] Financiers can raise bond finance in both domestic and international markets.[24] In equilibrium, their balance sheet constraint is

$$WF_t + HF_t + e_t HF_t^* + L_t^C = E_t^C + B_t + e_t B_t^*,$$

where WF_t is wholesale finance provided by financiers to banks, L_t^C is direct lending from financiers to intermediate goods firms with capital market access, and E_t^C is financiers' equity. B_t is domestic bond finance, HF_t is holdings of domestic central bank reserves, B_t^* is international bond finance denominated in foreign currency, and HF_t^* is foreign central bank reserves, while e_t is the nominal exchange rate denominated as the price of one unit of foreign currency expressed in terms of domestic currency. Financiers elastically supply wholesale finance to banks at the policy rate i_t. We assume that they must hold a non-negative total stock of (domestic and foreign) reserves ($HF_t + e_t HF_t^* \geq 0$), which forces them to seek international bond financing to replace reductions in domestic funding.

Financiers' lending to intermediate goods firms with capital market access is also perfectly competitive, but subject to two frictions. First, lending to firms generates operating costs, which we calibrate so that financiers' lending rate matches the bank lending rate in steady state. Second, financiers' lending to firms is subject to leverage costs. This is to ensure that financiers' credit provision cannot fully undo the financial frictions stemming from the banks in equilibrium, discussed in more detail later in the section. The resulting rate at which firms with direct capital market access can borrow is

$$i_t^C = i_t + \mu_F + \kappa \left(\frac{L_t^C}{E_t^C} - \psi \right),$$

where μ_c is the operating costs parameter, $\kappa > 0$ captures leverage costs, and ψ is a leverage target.

As well as capital market lending, financiers maximise the real discounted stream of profits from their bond market activities, reserve holdings, and wholesale funding,

23. As discussed in Section 2, this is in line with the empirical evidence for the mildly negative policy rates considered in this paper.

24. In our baseline calibration, 20% of their steady-state financing is domestic while 80% comes from abroad.

given by,

$$\mathbb{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \Bigg[\frac{WF_{t+s} + HF_{t+s} - B_{t+s}}{P_{t+s}} \frac{1 + i_{t+s}}{1 + \pi_{t+s+1}} + s_{t+s+1} \frac{HF^*_{t+s} - B^*_{t+s}}{P^*_{t+s}} \frac{1 + i^*_{t+s}}{1 + \pi^*_{t+s+1}} - s_{t+s} \frac{\kappa_B}{2} \left(\frac{B^*_{t+s}}{P^*_{t+s}} - \overline{B^*} \right)^2 \Bigg],$$

where $\Lambda_{t,t+s}$ is the households' stochastic discount factor, P^*_t the foreign price level, $\pi^*_t = P^*_t / P^*_{t-1} - 1$ the foreign inflation rate, and i^*_t the exogenous foreign interest rate. The real exchange rate is $s_t = e_t P^*_t / P_t$, and κ_B is an adjustment cost on gross foreign currency debt, which leads to a risk premium on international borrowing, as in Schmitt-Grohé and Uribe (2003).

The reserves constraint will always bind with equality when foreign debt is above its steady state value. Substituting out the term in domestic assets using the balance sheet constraint, and taking the first order condition with respect to foreign debt, (also indexing $P^*_t = 1 \ \forall t$ and hence $\pi^*_t = 0$), yields the uncovered interest parity condition

$$\mathbb{E}_t \left[\frac{1 + i_t}{1 + \pi_{t+1}} \right] = \mathbb{E}_t \left[(1 + i^*_t) \frac{s_{t+1}}{s_t} \right] + \kappa_B (B^*_t - \overline{B^*}).$$

When foreign debt is at its steady state level, the risk premium term drops out and any departure from interest rate parity would be met with infinitely large changes in asset positions (we assume that financiers face leverage costs only on their market lending activities). Because the ZLB friction does not apply to financiers, this UIP condition continues to apply as normal for policy rates below zero.[25]

5.3. Intermediate Goods Firms

There are two types of intermediate goods producers, which differ solely in how they raise finance to purchase capital. In particular, a fraction $1 - \lambda$ of firms borrow from financiers (type $z = c$), while the larger proportion λ borrow from banks (type $z = b$). There is a separate capital market for each type of intermediate goods firm, but they hire labour from a single labour market, as in Abadi, Brunnermeier, and Koby (2023).

Intermediate goods firms purchase new capital K^z_{t-1} from capital producers at a real price q^z_{t-1} in period $t - 1$ for production in period t. Capital K^z_{t-1} and labour N^z_t hired from households are used to produce the intermediate good Y^z_t based on a constant returns to scale Cobb–Douglass production function,

$$Y^z_t = A_t \left(\xi_t K^z_{t-1} \right)^{\alpha} N^{z,1-\alpha}_t .$$

25. For tractability, we assume that financiers transfer profits to domestic households as lump-sum transfers.

The term ξ_t is an exogenous capital quality shock as in Gertler and Karadi (2011). The intermediate good is sold to retailers at a nominal price P_t^m. In period $t-1$, bank-reliant firms need to take out L_{t-1}^B units of loans to finance the purchase of new capital at price q_{t-1}^b from capital producers,

$$L_{t-1}^B = q_{t-1}^b K_{t-1}^b.$$

Banks as well as financiers offer one-period loan contracts, so the gross real loan interest payment that firms have to make at the beginning of period t is $(1+i_{t-1}^z) \times L_{t-1}^z/(1+\pi_t)$. Hence, an intermediate firm's period t real profit is accounted for by product sales revenue, the revenue from selling undepreciated capital back to capital producers, wage costs, and the gross real loan interest payment,

$$\Pi_t^z = \frac{P_t^m}{P_t} Y_t^z + q_t^z \xi_t (1-\delta) K_{t-1}^z - w_t N_t^z - \frac{(1+i_{t-1}^z) L_{t-1}^z}{(1+\pi_t)},$$

where w_t is the real wage. Firms will choose capital K_t^z and labour N_t^z to maximise the sum of expected discounted future profits. They take all prices as given because they operate in a perfectly competitive industry. The resulting first-order conditions with respect to labour is standard. The first-order condition with respect to capital is

$$\mathbb{E}_t \Lambda_{t,t+1} \left[\frac{P_{t+1}^m A_{t+1} \alpha \xi_{t+1} (K_t^z)^{\alpha} (N_{t+1}^z)^{1-\alpha}}{P_{t+1}} + q_{t+1}^z (1-\delta) \xi_{t+1} - \frac{(1+i_t^z) q_t^z}{1+\pi_{t+1}} \right] = 0. \tag{13}$$

This condition implies that firms adjust their demand for capital, and consequently their demand for loans, to equate the expected marginal product of capital and the expected user cost of capital, where the latter consists of the gross cost of borrowing minus the expected resale value of undepreciated capital.

5.4. *Capital Producers*

Perfectly competitive capital producers purchase undepreciated capital $(1-\delta)\xi_t K_{t-1}^z$ at the real price q_t^z from intermediate goods firms and I_t^z units of the aggregate consumption bundle, which includes both the domestic good and the foreign good, to produce new capital k_t at the end of period t,

$$K_t^z = I_t^z + (1-\delta)\xi_t K_{t-1}^z.$$

The new capital is then sold back to intermediate goods firms of either type at the real price q_t^z. Old capital can be converted one-to-one into new capital without cost. However, capital producers incur a quadratic investment adjustment cost $f(I_t^z/I_{t-1}^z) = (\kappa^I/2) \times (I_t^z/I_{t-1}^z - 1)^2$, where $\kappa^I > 0$, when using the final consumption bundle as the input to produce new capital (Christiano, Eichenbaum, and Evans 2005). For each type of intermediate goods firm, capital producers will choose the gross investment level I_t^z to maximise the sum of expected discounted future profits stemming from the sales revenue of new capital net of input and adjustment costs. The first-order condition with respect to I_t delivers the real price of capital for each type of intermediate goods firm:

$$q_t = 1 + \frac{\kappa^I}{2}\left(\frac{I_t^z}{I_{t-1}^z} - 1\right)^2 + \kappa^I \frac{I_t^z}{I_{t-1}^z}\left(\frac{I_t^z}{I_{t-1}^z} - 1\right) - \kappa^I \mathbb{E}_t\left[\Lambda_{t,t+1}\left(\frac{I_{t+1}^z}{I_t^z}\right)^2\left(\frac{I_{t+1}^z}{I_t^z} - 1\right)\right].$$

5.5. Retailers and Final Goods Firm

A representative final goods firm aggregates differentiated varieties supplied by monopolistic retailers to produce output, which it sells at the competitive price P_t^H. Monopolistic retailers purchase intermediate goods in a competitive market from both types of intermediate goods firms. They costlessly transform intermediate goods into differentiated varieties of retail goods, using a linear production function. Retailers set their prices subject to Rotemberg (1982) adjustment costs, such that their problem gives rise to a New Keynesian Phillips curve. The full set of equilibrium equations is given in Appendix C.

5.6. Banks

Banks have access to wholesale finance at the policy rate i_t and offer one-period deposit and loan contracts. Each bank's balance sheet consists of reserves (H_t) and loans (L_t) on the asset side, and equity (E_t), deposits (D_t), and wholesale finance (WF_t) on the liability side,

$$H_t + L_t = E_t + D_t + WF_t.$$

Wholesale finance is supplied elastically by financiers, and the total monetary base, consisting of domestic currency reserves held by banks and financiers and currency held by households ($H_t + HF_t + M_t$), is supplied by the central bank following an exogenous law of motion. Banks are endowed with a starting amount of equity and are subject to quadratic leverage costs for deviations of the loan-to-equity ratio from a target ψ, $(\kappa/2)(L_t/E_t - \psi)^2 E_t$. A quadratic cost of this type is a standard modelling device to capture the important role of bank capital in a tractable way.[26] In addition, each period a fraction ζ of nominal bank net worth is used up operating the bank.[27]

26. See for example Gerali et al. (2010), Campbell (1987), Drechsler, Savov, and Schnabl (2021), and Ulate (2021).

27. This fraction is calibrated such that there is a well-defined level of bank equity in steady state. Equivalently, one could interpret the dividend distribution parameter ω to be calibrated based on a given operating cost parameter ζ. See Ulate (2021).

These assumptions imply that we can write the nominal resources that bank j will have at its disposal next period as

$$S_{j,t+1} = (1 + i_t - \zeta)E_{j,t} + \left(i_t^L - i_t\right) L_{j,t} + \left(i_t - i_t^D\right) D_{j,t} - \frac{\kappa}{2}\left(\frac{L_{j,t}}{E_{j,t}} - \psi\right)^2 E_{j,t}.$$

The total nominal resources in the bank at the end of the period have to either be paid as dividends or be retained as equity, $S_{j,t+1} = E_{j,t+1} + DIV_{j,t+1}$. To capture a notion of slow-moving capital, we assume that banks cannot frictionlessly obtain the optimal amount of equity. In particular, banks are not allowed to decide their dividend distribution policy. This is to prevent them from issuing negative dividends after shocks to immediately regain their optimal level of equity, which would render equity irrelevant. Instead, each bank j will mechanically pay a fraction $1 - \omega$ of its net profits $X_{j,t}$ out as a dividend, $DIV_{j,t+1} = (1 - \omega)X_{j,t+1}$, where, following Ulate (2021), net profits are defined as total profits net of managerial costs and inclusive of an adjustment for inflation,

$$X_{j,t+1} = i_t E_{j,t} + \left(i_t^L - i_t\right) L_{j,t} + \left(i_t - i_t^D\right) D_{j,t} - \frac{\kappa}{2}\left(\frac{L_{j,t}}{E_{j,t}} - \psi\right)^2 E_{j,t} - E_{j,t}(1 - \zeta)\pi_{t+1}.$$

The inflation adjustment is chosen simply to obtain a cleaner expression for the law of motion of bank equity. The remaining fraction ω of $X_{j,t+1}$ will remain inside the bank, such that $E_{j,t+1} = E_{j,t}(1 - \zeta)(1 + \pi_{t+1}) + \omega X_{j,t+1}$. Dividing this equation by the price level in period $t + 1$ yields the law of motion for real bank equity,

$$\frac{E_{j,t+1}}{P_{t+1}} = (1 - \zeta)\frac{E_{j,t}}{P_t} + \omega\frac{X_{j,t+1}}{P_{t+1}}.$$

Turning to a key distinguishing feature of our banking model, banks are subject to a funding constraint that requires a minimum share of deposit funding,

$$D_{j,t} \geq \varphi_j L_{j,t}. \tag{14}$$

This constraint ensures that banks continue to take deposits at the lower bound. When the policy rate is negative, the deposit spread becomes negative ($i_t - i_t^D < 0$), and hence profit-maximising banks would cease to take deposits ($D_t = 0$) in the absence of any further constraints. As discussed in Section 4, there are several potential motivations for such a constraint, including regulations, complementarities between lending and deposit taking, and concerns about maintaining relationships with an existing customer base. Given the funding constraint, banks will continue to take deposits at the lower bound, even though deposit taking by itself becomes a loss-making line of business. However, banks will ration households' deposit holdings at the lower bound. We see this feature of our model as consistent with the evidence that some banks tried to fend off unwanted deposits during the NIRP period, including by raising deposit fees and offering negative rates above certain thresholds and to new customers.

To understand the implications of the funding constraint, consider first a version of our model without such a constraint. Lending and deposit taking would be separable, as in the baseline Monti–Klein model with wholesale finance. Each bank j would then set an optimal level of deposits D_j to maximise profits from deposit taking,

$$\Pi_{j,t}^{D} = \left(i_t - i_t^D \left(D_{j,t} + \sum_{m \neq j} D_{m,t} \right) \right) D_{j,t},$$

taking into account the deposit taking decisions of all other banks and the elasticity of households' deposit supply to the deposit rate. Assuming a symmetric solution, this implies

$$i_t^D = i_t - \frac{\partial i_t^D}{\partial D_t} \frac{D_t}{\mathcal{N}}.$$

Defining the elasticity of households' deposit supply to the deposit rate as

$$\varepsilon_t^D := \frac{\partial D_t}{\partial i_t^D} \frac{1 + i_t^D}{D_t}$$

we can write the unconstrained deposit rate as

$$i_t^D = \left[\frac{\mathcal{N} \varepsilon_t^D}{\mathcal{N} \varepsilon_t^D + 1} \right] (1 + i_t) - 1.$$

This is the familiar solution of a simple Cournot problem. As the number of banks $\mathcal{N}$ increases, the deposit spread converges to zero. Similarly, if households placed no value on the liquidity benefits of deposits, their deposit supply would be perfectly elastic ($\varepsilon^D \to \infty$) and hence the deposit spread would vanish. But in an oligopolistic setting with a limited number of banks and less than perfectly elastic household deposit supply, there will be a deposit spread $i - i^D > 0$, which makes deposit taking a profitable line of business for banks.

In contrast to the partial equilibrium analysis in Section 4, the elasticity of household deposit supply to the deposit rate, ε_t^D, is now endogenous to the model. We can obtain it by log-linearising and rearranging equation (11), which yields

$$\widetilde{D}_t = \left[\frac{P_t}{\upsilon D_t} \right] \left(\tilde{\pi}_{t+1} - \tilde{\rho}_{t+1} - \frac{\upsilon D_t}{P_t} \widetilde{P}_t - \frac{1 + i_t}{i_t - i_t^D} \tilde{i}_t \right) + \left[\frac{P_t}{\upsilon D_t} \right] \left(\frac{1 + i_t^D}{i_t - i_t^D} \right) \tilde{i}_t^D,$$

where $\widetilde{X}_t = (X' - X_t)/Xt$. We assume that banks internalise only the direct effects of changes in the deposit rate on household deposit supply. Consequently, the relevant elasticity of deposit supply that affects banks' decision making is given by the terms in front of $\tilde{i}_t^D$, that is,

$$\varepsilon_t^D := \frac{\partial D_t}{\partial i_t^D} \frac{1 + i_t^D}{D_t} = \frac{P_t}{\upsilon D_t} \frac{1 + i_t^D}{i_t - i_t^D} = \frac{P_t}{\upsilon D_t} \frac{\beta \rho_{t+1}}{(1 + \pi_{t+1})\upsilon} e^{\upsilon \frac{D_t}{P_t}} \left(1 + i_t^D \right),$$

which implies

$$\frac{\partial D_t}{\partial i_t^D} = \frac{P_t}{\upsilon \left(i_t - i_t^D\right)}.$$

Substituting this expression into the first-order condition from banks' unconstrained deposit-taking problem and evaluating the resulting equation at the steady state yields

$$\bar{D}|_{\varphi=0} = \frac{\mathcal{N}}{\upsilon}.$$

We calibrate the liquidity benefit such that the funding constraint binds in the steady state ($\bar{D} = \varphi \bar{L} > \mathcal{N}/\upsilon$). That is, the constraint will force banks to operate with a greater degree of deposit funding than they would choose if lending and deposit taking were separable. Given that deposit funding becomes less attractive to banks at the lower bound, the funding constraint will continue to bind when interest rates fall towards and below zero. The relevant equation determining the deposit rate then becomes

$$i_t^D = \max\left\{ i_t - \frac{(1+\pi_{t+1})\upsilon}{\beta \rho_{t+1}} e^{-\upsilon\varphi L_t}, 0 \right\}. \quad (15)$$

Turning now to banks' lending decisions, banks will take the binding funding constraint into account. When the policy rate is away from the lower bound, this has only minor implications for the pass-through of policy rate cuts to lending rates, because the deposit rate tends to move with the policy rate. But as the policy rate approaches and falls below zero, the deposit spread is compressed and eventually turns negative, and banks will reduce pass-through to lending rates.

Our model features imperfect Cournot competition between two different types of banks, which differ solely in their funding constraints. There is a group of low-deposit banks and a group of high-deposit banks, whose funding constraint parameters are

$$0 < \varphi^{low} < \varphi^{high} < 1.$$

There are $\mathcal{N}^z$ banks of each type, with $z \in \{high, low\}$. Each bank j takes the quantities of loans chosen by all other banks $m \neq j$ as given and chooses its loan quantity $L_{j,t}$ to maximise the sum of the present discounted value of future dividends,

$$\mathbb{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} DIV_{j,t+s},$$

subject to the balance sheet constraint, funding constraint and leverage costs discussed above. Substituting the funding constraint for bank j of type $z \in \{high, low\}$ into the expression for X_t^j yields

$$DIV_{j,t+1} = (1-\omega)\left[i_t E_{j,t} + \left(i_t^L \left(L_{j,t} + \sum_{m \neq j} L_{m,t} \right) - (1-\varphi^z) i_t - \varphi^z i_t^D \right) L_{j,t} \right.$$
$$\left. - \frac{\kappa}{2} \left(\frac{L_{j,t}}{E_{j,t}} - \psi \right)^2 E_{j,t} - E_{j,t}(1-\zeta)\pi_{t+1} \right],$$

where $i_t^L(.)$ denotes the inverse loan demand function, which depends on L_t and therefore on $L_{j,t}$. Consequently, each bank has some control over the equilibrium loan interest rate by choosing its loan quantity $L_{j,t}$.

Suppose first that there was a single type of bank. Taking the first-order condition with respect to $L_{j,t}$, and assuming a symmetric equilibrium $L_{j,t} = L_t/\mathcal{N}$, yields the following condition for aggregate bank lending:

$$L_t = \frac{E_t}{\kappa} \left[\frac{\mathcal{N}\varepsilon_t^L - 1}{\mathcal{N}\varepsilon_t^L} \left(1 + i_t^L\right) - (1-\varphi)(1+i_t) - \varphi\left(1 + i_t^D\right) + \kappa\psi \right],$$

and equivalently the following condition for the aggregate lending rate:

$$i_t^L = \left[\frac{\mathcal{N}\varepsilon_t^L}{\mathcal{N}\varepsilon_t^L - 1} \right] \left((1-\varphi)(1+i_t) + \varphi(1+i_t^D) + \kappa \left(\frac{L_t}{E_t} - \psi \right) \right) - 1.$$

The term in square brackets reflects a markup due to imperfect competition. Note that when the number of banks approaches infinity ($\mathcal{N}^z \to \infty$), this term tends to 1. Hence, the model nests perfect banking competition as a special case. The lending rate is set as a markup over the marginal funding cost, which is a weighted average of the policy rate and the deposit rate (reflecting the funding constraint), adjusted for leverage costs. It is evident from this equation that pass-through from the policy rate to the lending rate will continue when the policy rate falls below zero, though it will be reduced when the deposit rate hits the ZLB.

Loan demand in our model stems from the need of intermediate goods firms to raise finance to purchase capital. Hence, we can obtain the elasticity of loan demand to the lending rate from the first-order conditions of bank-reliant firms. Log-linearising equation (13) and rearranging yields

$$\widetilde{K}_t^b = -\frac{1}{1-\alpha} \frac{\mathbb{E}_t\left[\frac{(1+i_t^L)q_t^b}{1+\pi_{t+1}}\right]}{\mathbb{E}_t MPK_{t+1}} \left(\tilde{i}_t^L + \tilde{q}_t - \mathbb{E}_t(1+\tilde{\pi}_{t+1}) \right) + \mathbb{E}_t \widetilde{N}_{t+1}^b + \mathbb{E}_t \widetilde{\Omega}_{t+1}, \quad (16)$$

where $\widetilde{X}_t := (X' - X_t)/X_t$ denotes the percentage deviation from the period t value, MPK_{t+1} is the marginal product of capital, and $\tilde{\Omega}_{t+1}$ collects other effects from exogenous shocks and aggregate prices.

We assume that banks understand and internalise the effects of their individual lending decisions on the aggregate lending rate, as well as the direct effects of the aggregate lending rate on firms' capital and loan demand. Banks do not internalise wider indirect effects through the labour market or aggregate prices. Consequently, the relevant elasticity of loan demand that affects banks' decision-making is given by the terms in front of $\tilde{i}_t^L$ in equation (16).[28] We define this price elasticity of market loan demand with respect to the lending rate as

$$\varepsilon_t^L := -\frac{\partial L_t}{\partial i_t^L}\frac{1+i_t^L}{L_t} = \frac{1}{1-\alpha}\frac{\mathbb{E}_t\left[\frac{(1+i_t^L)q_t^b}{1+\pi_{t+1}}\right]}{\mathbb{E}_t MPK_{t+1}} = \frac{1}{1-\alpha}\left(1+\frac{\mathbb{E}_t\left[q_{t+1}^b(1-\delta)\xi_{t+1}\right]}{\mathbb{E}_t MPK_{t+1}}\right), \tag{17}$$

where the final equality uses the first-order condition with respect to capital (13).

One could argue that banks should internalise a wider or even the full set of general equilibrium effects on loan demand. As shown by Li (2021), allowing for more internalisation dampens the amplification of shocks caused by imperfect banking competition. This would complicate the analysis without materially affecting our key results. Our main interest in this paper is the difference between two different monetary policy responses to a recession, rather than the dynamics of the recession itself. Hence, the precise extent to which imperfect banking sector competition amplifies economic fluctuations in general is not of first-order importance for our study.[29]

Now consider two types of banks which differ solely in their funding constraints, $0 < \varphi^{low} < \varphi^{high} < 1$. Assuming a symmetric equilibrium where banks of the same type make the same lending decisions, $L_{j,t}^z = L_t^z/\mathcal{N}^z$, we can express the lending rate as

$$i_t^L = \left[\frac{\mathcal{N}^z\varepsilon_t^L}{\mathcal{N}^z\varepsilon_t^L - \frac{L_t^z}{L_t}}\right]\left((1-\varphi^z)(1+i_t) + \varphi^z\left(1+i_t^D\right) + \kappa\left(\frac{L_t^z}{E_t^z} - \psi\right)\right) - 1.$$

Note that this expression must hold for either type of bank $z \in \{high, low\}$. Hence, these equations, in conjunction with $L_t = \mathcal{N}^{high} \times L_{i,t}^{high} + \mathcal{N}^{low} \times L_{j,t}^{low}$, pin down both the aggregate lending rate i_t^L and the lending volumes by both types of bank.

In the model presented so far banks are not exposed to loan default risks. This assumption would shut down one of the channels through which monetary policy loosening can benefit banks. Expansionary monetary policy can, by reducing funding costs, boosting demand and raising prices, mitigate any increase in non-performing loans that results from a recession. In our model, negative rates are expansionary, including through bank lending, even without this non-performing loan effect (Appendix D). But to illustrate the potential effects of monetary policy on banks

28. Given bank-reliant firms' loan demand $L_t^B = q_t^B K_t^B$ and the assumption that banks do not internalise the impact of changes in the loan rate on aggregate prices such as q_t^B, the elasticity of loan demand is equivalent to the capital demand elasticity.

29. It is also worth noting that the structure of our banking system is not crucial to the macro-dynamics of our model. We have chosen a Cournot banking sector for consistency with the analysis presented in Section 4 and to study differential effects of negative rates on high-deposit banks and low-deposit banks. But a version of our model with a standard homogeneous banking sector engaged in monopolistic competition results in very similar dynamics for output and inflation as in our baseline model in response to both a zero interest rate policy and a negative interest rate policy.

through this channel, we enrich our model by assuming that banks' loan returns are stochastic. In particular, banks absorb any profits or losses of the intermediate goods firms they lend to. These profits are zero in expectation, so this assumption does not affect the banks' lending decisions. Bank j's net profit $X_{j,t+1}$ becomes

$$X_{j,t+1} = i_t E_{j,t} + \left(i_t^L - i_t\right) L_{j,t} + \left(i_t - i_t^D\right) D_{j,t} \\ -\frac{\kappa}{2}\left(\frac{L_{j,t}}{E_{j,t}} - \psi\right)^2 E_{j,t} - E_{j,t}(1-\zeta)\pi_{t+1} + \frac{NPL_{t+1}}{L_t} L_{j,t},$$

where

$$NPL_{t+1} = \underbrace{p_{t+1}^m Y_{t+1}^b - w_{t+1} N_{t+1}^b + q_{t+1}^b (1-\delta)\xi_{t+1} K_t^b - \frac{(1+i_t^L)L_t}{1+\pi_{t+1}}}_{\text{profit/loss of bank-financed intermediate goods firms}}.$$

Following the adverse demand shock we study, intermediate goods firms make material losses, which the banks have to absorb. Because banks cannot frictionlessly re-establish optimal leverage, the resulting reduction in bank equity will reduce bank lending. Monetary policy loosening can mitigate this effect by reducing the losses incurred by intermediate goods firms and hence limiting the non-performing loan problem.

An effect of this type is implicit in models with a banking sector based on Gertler and Karadi (2011), such as Ulate (2021). In those models, banks are always the residual claimant on intermediate goods firms, and hence they routinely experience gains and losses due to stochastic loan returns. Our setup allows us to switch this effect off to confirm that negative rates would remain expansionary even in the absence of a non-performing loans channel of monetary policy. Our baseline results with the NPL channel switched on are similar to those one would obtain from a version of our model in which banks are the residual claimants on intermediate goods firms, as in Gertler and Karadi (2011).

5.7. *Market Clearing*

Total domestic output Y_t is divided between household consumption of the domestic good C_t^H, investment using the domestic good I_t^H, government consumption G_t, and exports XP_t

$$Y_t = C_t^H + I_t^H + G_t + XP_t.$$

The economy is open to trade in final goods, with the foreign good used for both consumption and investment purposes. Access to the international bond market is intermediated by the group of financiers described above. We postulate that foreign demand for the domestic good is symmetric to domestic demand for the foreign good, such that exports can be expressed as $XP_t = \gamma^* \left(P_t^H/(e_t P_t^*)\right)^{-\eta_F} C_t^* = \gamma^* tot_t^{\eta_F} Y_t^*$, where Y_t^* is a measure of foreign demand that follows an exogenous autoregressive process, and γ^* is a trade openness parameter. Provided that the domestic economy is sufficiently small relative to the foreign economy, the price of the foreign good coincides with the foreign CPI adjusted by the exchange rate, $P_t^F = e_t P_t^*$. We can then write export demand as a function of the terms of trade, that is, the ratio of the price of imports to the price of exports, $tot_t = P_t^F / P_t^H$.

The economy's trade balance is the difference between exports and imports. It equals the current account in our model, which must equal the financial account balance,

$$TB_t = s_t(HF_t^* - B_t^*) - s_t(1 + i_{t-1}^*)(HF_{t-1}^* - B_{t-1}^*) + s_t \frac{\kappa_B}{2} \left(B_t^* - \overline{B^*}\right)^2 + \Pi_t^{HF^*},$$

where we assume that financiers' unexpected profits or losses on foreign debt holdings are distributed lump sum to domestic households, but profits or losses on foreign reserve holdings ($\Pi_t^{HF^*} \equiv HF_{t-1}^*(1 + i_{t-1}^*)(s_t - E_{t-1}s_t)$) are returned to foreign households, along with adjustment costs on foreign debt. By combining the balance of payment condition with the market clearing condition for the domestic good, we can write the national account identity as

$$GDP_t = \frac{P_t^H}{P_t} Y_t = C_t + I_t + P_t^H G_t + TB_t.$$

The domestic CPI is defined as the price of one unit of household consumption, and can be written as

$$P_t = \left[(1-\gamma) P_{H,t}^{1-\eta^F} + \gamma P_{F,t}^{1-\eta^F}\right]^{\frac{1}{1-\eta^F}}.$$

Market clearing also requires that bank lending equals the value of bank-reliant firms' capital ($L_t = q_t^B K_t^B$), where total bank lending is the sum of high-deposit and low-deposit banks' lending ($L_t = L_t^L + L_t^H$), and that lending by financiers equals the value of capital-market financed firms' capital ($L_t^C = q_t^C K_t^C$). Labour market clearing requires that the labour supplied by households equal the labour demand by both types of firms ($N_t = \lambda N_t^B + (1-\lambda) N_t^C$), and aggregate output and investment are given by $Y_t = \lambda Y_t^B + (1-\lambda) Y_t^C$ and $I_t = \lambda I_t^B + (1-\lambda) I_t^C$, where $\lambda \in [0, 1]$ is a measure of the economy's bank reliance.

5.8. *Monetary Policy and Shocks*

Monetary policy is set by a Taylor rule with interest-rate smoothing,

$$i_t = (1-\rho_i)(\bar{i} + \varphi_\pi(\pi_t - \bar{\pi})) + \rho_i i_{t-1} + \varepsilon_t^i, \tag{18}$$

where ε_t^i is an exogenous monetary policy shock. The central bank will follow this rule except in the regime where there is a lower bound on the policy rate, in which case it simply sets a zero policy rate whenever the Taylor rule would call for a negative policy rate. The presence of interest-rate smoothing in the rule will lead to a signalling channel of negative rates, as in de Groot and Haas (2023).[30] The model also contains

30. See Section 5.10.

standard technology, government consumption, and international demand and interest rate shocks, as well as a capital efficiency shock.

5.9. *Calibration*

The full calibration of our model is set out in the appendix. Three parameters warrant a brief discussion.

First, we set the funding constraint parameters, which are key to the dynamics of our model, to $\varphi^{low} = 0.5$ and $\varphi^{high} = 0.7$. An average φ of 0.6 is broadly consistent with the aggregate ratios of bank loans to ZLB-constrained deposits across a number of European countries as shown in Figure 3. The results of our analysis are quantitatively but not qualitatively sensitive to the choice of φ. A higher φ will be associated with more muted pass-through of negative policy rates to lending rates. Lending reversal occurs only for $\varphi > 1$, for which there is no empirical support in aggregate.[31]

Second, we set banks' share in overall financial intermediation to $\lambda = 0.8$. Again, our results are quantitatively but not qualitatively sensitive to the choice of λ. The smaller λ, the less important banks are in the overall monetary policy transmission mechanism, and hence the smaller the effect of the ZLB friction on macroeconomic dynamics. The choice of $\lambda = 0.8$ is suggestive, but broadly informed by World Bank data, which suggests that banks' share in total credit granted to the private sector ranges from just under 60% in the US to over 90% in the euro area (Martín Fuentes, Di Vito, and Leite 2023).

Third, we set households' liquidity preference parameter to $\upsilon = 0.67$, which delivers a steady state deposit spread of around $\bar{i} - \overline{i_D} = 0.5\%$. Given the structure of our model, the size of this spread will affect the point at which pass-through from policy rates to bank lending rates is reduced as the policy rate approaches zero from above. But the size of the steady-state deposit spread has no material effect on the transmission of negative policy rates in our model. Once the policy rate is zero, the deposit spread will have been fully compressed to zero. Any further policy rate cuts then reduce banks' funding costs according to their degree of wholesale funding $(1 - \varphi^z)$, which is the main determinant of the remaining strength of the bank lending channel at the lower bound in our model.

5.10. *Results*

To study the dynamic effects of negative policy rates on the economy, we simulate an adverse demand shock (to government spending) that is sufficiently large to drive the deposit rate to the ZLB. We can solve a version of the model without any non-negativity constraints on interest rates using traditional methods. We then solve the model with a ZLB on the bank deposit rate based on the methodology described in Guerrieri and Iacoviello (2015) to solve models with occasionally binding constraints.

31. It is also not clear whether $\varphi > 1$ would make economic sense. While there may be banks with more ZLB-constrained deposits than loans, it is not obvious why such banks should be required to maintain their very high degree of deposit intensity throughout a negative rate period.

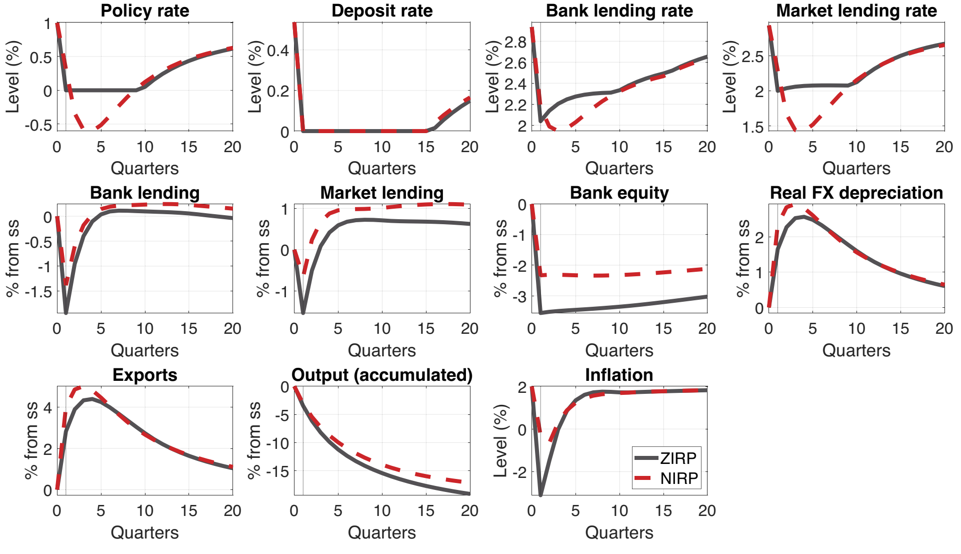


FIGURE 7. Impulse responses to an adverse demand shock. Impulse responses to a domestic demand shock top government spending. The model is simulated using the occasionally binding constraints method of Guerrieri and Iacoviello (2015). The solid lines show the IRFs for a regime with zero lower bounds on both the deposit rate and the policy rate. The dashed lines show the IRFs for a regime with a zero lower bound on the deposit rate only.

Figure 7 displays the evolution of the economy following this shock under two different regimes. In the first regime shown in the solid lines, the ZLB is binding for both the deposit rate and the policy rate. In the second regime shown in the dashed lines, the deposit rate is bounded at zero, but the policy rate can be cut below zero.

A central bank that cuts the policy rate below zero achieves better macroeconomic outcomes than a central bank that keeps the policy rate at zero, materially boosting inflation and output. That is in part because several transmission channels remain unimpaired. The economy experiences a larger exchange rate depreciation, which pushes up on inflation. And firms that can borrow directly in financial markets rather than through banks experience a significant reduction in financing costs.

At the same time, the intertemporal transmission channel shuts down because the deposit rate cannot fall below zero. Households will make intertemporal consumption choices based on the zero rate they can receive on deposits and cash, rather than on the negative policy rate. The zero deposit rate also limits the extent to which banks are able to lower lending rates, so the bank lending channel is weakened. Nevertheless, the fact that loans are only partly deposit-funded means that banks are able to pass through part of the policy rate cut to lending rates, which also results in higher loan volumes. That is, negative policy rates are expansionary through the bank lending channel, in addition to unimpaired pass-through via the exchange rate channel and the capital market financing channel.

Notably, a negative interest rate policy also mitigates the adverse effect of the recession on bank equity, relative to a zero interest rate policy. That is because the recession renders some of the banks' loans non-performing. This channel is implicit in models based on a Gertler and Karadi (2011) banking system, such as Ulate (2021), and materially affects the model dynamics. By boosting demand and pushing up prices, negative interest rates reduce the losses experienced by intermediate goods firms, which limits the extent to which loans become non-performing. This strengthens the bank lending channel. As shown in Appendix D, without this channel negative rates would be broadly neutral rather than clearly positive for aggregate bank profitability in our model.[32] Absent the non-performing loan channel, negative rates would still result in lower lending rates than under a zero interest rate policy, though bank lending volumes would not expand further. That is, negative interest rates would still be somewhat expansionary through the bank lending channel in our model, in addition to continued pass-through via the exchange rate channel and the capital market financing channel.

Figure 8 illustrates by how much the zero lower bound on the deposit rate reduces the strength of different transmission channels of monetary policy. The bars show the marginal effects of setting the policy rate at −0.5% on average over two years rather than at 0% in response to an adverse demand shock, averaged over a two-year period.[33] The Standard bars are based on a hypothetical model in which there is no lower bound on the deposit rate. This means they could also be interpreted as the results of a rate cut when the policy rate is well above the lower bound. The NIRP bars are based on the model where there is a zero lower bound on the deposit rate.

As the deposit rate has already fallen to zero before the policy rate is cut below zero, the intertemporal transmission channel shuts down fully. The bank lending channel operates at around 30% of its normal strength in terms of both bank lending rates and lending volumes. Meanwhile, the exchange rate channel and the capital market financing channel are broadly unaffected by the zero lower bound on the deposit rate.[34]

Our model suggests that in response to the demand shock studied, negative interest rates can be about 60%–70% as effective as rate cuts in positive territory at stimulating inflation and output.

32. Non-performing loans played an important role in some euro-area countries during the NIRP period but not in others.

33. The baseline for these calculations is the regime with a lower bound on both the deposit rate and the policy rate. When we compare a model with no lower bound to the model with lower bounds on both i and i_D, the resulting bars The differences would include both the marginal effects of cutting the policy rate below zero and the marginal effect of allowing the previous rate cuts from 1% to 0% to push the deposit rate below zero. Including the latter would overstate the true effects of the rate cut. We avoid this issue by setting $\upsilon = 0$ for the purposes of this exercise. This allows us to interpret these bars as the true marginal effect of cutting the policy rate below zero, compared to keeping it at zero.

34. Aggregate demand is somewhat weaker than it would be in the absence of a zero lower bound on the deposit rate, which reduces firms' financing demand. At the same time, bank lending being weaker than it would be in the absence of a ZLB on the deposit rate means that capital market-financed firms will demand somewhat more financing than they otherwise would. However, financiers' ability to extend additional loans is checked by the presence of leverage costs. The overall effect is that this channel is marginally weaker than it would be in the absence of a ZLB, but materially stronger than the bank lending channel.

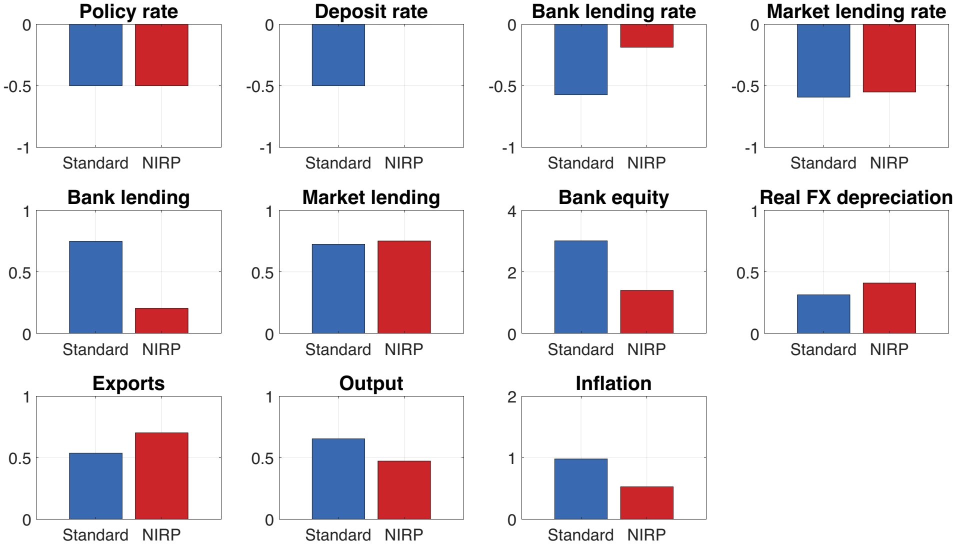


FIGURE 8. The effectiveness of NIRP compared to a standard rate cut. The chart shows the marginal effects of a policy rate path that averages -0.5% over the two years following a demand shock, compared to a 0% policy rate over the same period. The standard rate cut bars are based on the difference between the impulse responses in the model without a ZLB and the model with a ZLB on both the deposit rate and the policy rate. The NIRP bars are based on the difference between the impulse responses in the model with a ZLB on the deposit rate and the model with a ZLB on both the deposit rate and the policy rate. We average over eight quarters and standardise both sets of responses to the policy rate averaging -0.5%. The units are percentage points or percent deviations as appropriate.

A key assumption in our model is that because of the binding funding constraint, banks treat an average of the policy rate and the deposit rate as the relevant marginal funding cost for loan pricing. This results in muted but positive pass-through of negative policy rates to bank lending rates and a minor contraction in net interest margins. Some of the disagreement in the literature about the effects of negative policy rates on bank lending stems from different assumptions about the relevant marginal loan funding cost. To illustrate the possible range of outcomes depending on different assumptions, Figure 9 shows the effects of negative rates based on three different assumptions for the marginal loan funding cost, compared to a standard rate cut.[35] The NIRP (NR) bars for our baseline model are compared to two alternatives. The first (NR(i)) uses the same model and bank balance sheets, but instead assume that banks treat the policy rate i as the marginal funding cost, which is the assumption implied by the models in Ulate (2021) and Repullo (2020) (and similar to the classic Romer and Romer (1990) assumption). The second (NR(id)) instead assumes that banks treat the

35. As for Figure 8, the NIRP bars show the marginal effects of setting the policy rate at -0.5% on average over two years rather than at 0% in response to an adverse demand shock, averaged over a two-year period. The Standard bars are based on a model in which there is no lower bound on the deposit rate.

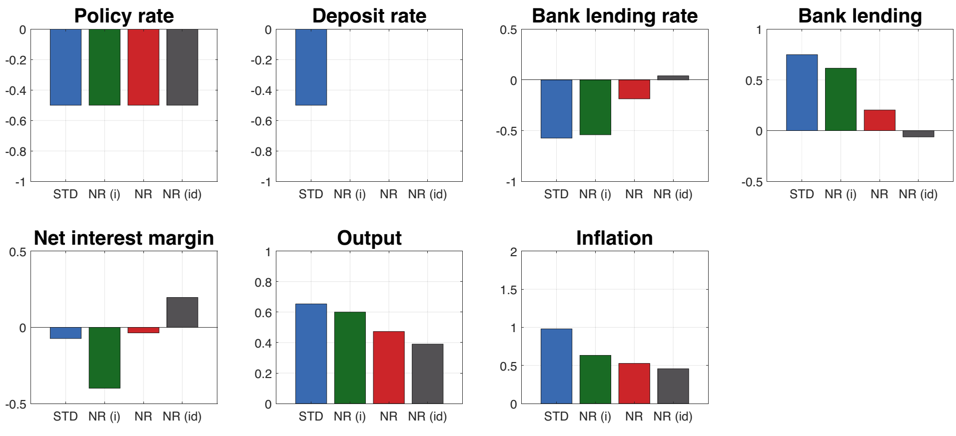


FIGURE 9. The effectiveness of NIRP compared to a standard rate cut, based on different marginal funding cost assumptions. See notes to Figure 8. The bars labelled *i* are based on a version of the model in which banks behave as if the policy rate i_t as the relevant marginal cost for loan pricing. The bars labelled *id* are based on a version of the model in which banks behave as if the policy rate i_t^D as the relevant marginal cost for loan pricing. The Standard (STD) bars and NIRP (NR) bars are identical to those in Figure 8. The NIRP bars are based on the baseline model, in which banks treat a weighted average of the policy rate and the deposit rate, $(1 - \varphi^z)i_t + \varphi^z i_t^D$, as the relevant marginal cost for loan pricing. The units are percentage points or percent deviations as appropriate.

deposit rate i^D as the marginal funding cost, as in Eggertsson et al. (2024) and similar to Bernanke and Blinder (1988).

For this experiment, we wish to highlight the role of the marginal funding cost assumption, so we opt to hold the rest of the model fixed, including the structure of banks' balance sheets. In the two alternative variants, banks continue to hold the same shares of wholesale and deposit funding, but price as if they use only one source (at the margin).[36]

Negative rates remain expansionary for output and inflation under all of these assumptions. If banks were to hypothetically treat the wholesale rate as their marginal funding cost, the bank lending channel would be stronger than in our baseline model. Assuming that banks continue to fund themselves partially using deposits—as has been the case in the data—this would be at the cost of a large fall in banks' net interest margins. But the empirical evidence discussed in Section 2 suggests that the impact on net interest margins is more modest than implied by this version of the model. If banks treat the deposit rate as the marginal funding cost, the bank lending channel shuts down, reducing the overall effectiveness of negative rates relative to our baseline model. But as long as banks were continuing to use wholesale funding, then under this assumption, banks' net interest margins would actually increase. The empirical evidence suggests that the bank lending channel has been stronger than implied by

36. An alternative experiment would be to vary the funding constraint parameter φ^z. Setting $\varphi^z = 0$ implies that the wholesale funding cost is the marginal cost, while $\varphi^z = 1$ implies that it is the deposit rate. This experiment would also change the structure of bank balance sheets, so the effect of negative rates on average funding costs would therefore differ across the three cases.

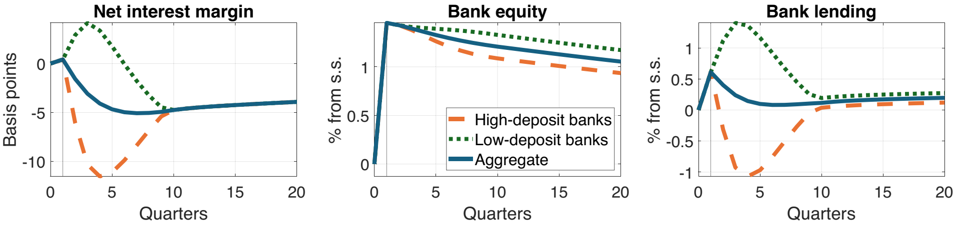


FIGURE 10. The effects of NIRP on high-deposit and low-deposit banks. These charts are based on the impulse responses to a domestic demand shock to government spending. They show the difference between the IRFs for the regime with a ZLB on the deposit rate only and the IRFs for the regime with a ZLB on both the deposit rate and the policy rate. The model is simulated using the occasionally binding constraints method of Guerrieri and Iacoviello (2015).

this assumption, while effects on net interest margins have been at best neutral rather than positive. Our baseline model with funding-constrained banks can deliver muted but positive pass-through to bank lending together with a modest adverse effect on net interest rate margins. Depending on macroeconomic circumstances, the latter can be more than compensated by the mitigating effects of NIRP on non-performing loans, such that the overall effect of negative rates on aggregate banking sector profitability can become modestly positive.

Figure 10 illustrates the effects of a negative interest rate policy on the two types of banks in our baseline model. The analysis in Section 4 suggested that negative rates could lead to lending reversal for high-deposit banks, but not for the aggregate banking sector. That is also the case in the full general equilibrium model. Aggregate bank lending is consistently higher under a negative interest rate policy than under a zero interest rate policy (the solid line on the right panel). Within that, high-deposit banks extend somewhat fewer loans than they would have if the policy rate had remained at zero (the dashed line). But this is more than offset by the additional loans extended by low-deposit banks (the dotted line).

The banks' lending decisions reflect primarily the different evolution of their funding costs due to the lower bound on the deposit rate. High-deposit banks experience a smaller reduction in funding costs than low-deposit banks. That means high-deposit banks experience a larger fall in their net interest margin (the dashed line on the left panel) than low-deposit banks (the dotted line). Meanwhile, bank equity increases for both types of banks. That reflects monetary policy mitigating losses due to non-performing loans. But high-deposit banks (the dashed line) see a smaller increase in equity than low-deposit banks (the dotted line), reflecting differences in net interest income.

6. Conclusion

We have presented a model that can match the effects of policy rate cuts in negative territory documented in empirical studies. First, our model assumes in line with the empirical evidence that household deposit rates are bounded by the ZLB. Second, given this ZLB friction, our model predicts muted but still positive pass-through from policy rate cuts below zero to bank lending rates and corresponding increases in lending volumes. Third, aggregate banking sector profitability is not adversely affected. It may even increase relative to the counterfactual of a zero interest rate policy. Fourth, high-deposit banks may experience a fall in net interest margins and a relative fall in profitability, which can result in them reducing their lending. But this is more than compensated by the additional loans extended by low-deposit banks. Fifth, other channels of monetary policy transmission via capital markets and the exchange rate work normally, with the resulting general equilibrium effects further supporting bank profitability and lending.

Overall, our results suggest that the monetary policy transmission mechanism of negative rates may only be somewhat weaker than rate cuts in positive territory. At least in small open economies, they can be expected to provide stimulus when required to meet the inflation target.

Appendix A: Empirical Data

This appendix sets out the data sources for Figures 1–4.

Figure 1 shows cross-country ranges of effective aggregate deposit rates (percent) on new business across all euro-area countries with consistently available data between January 2014 and June 2022. All data are from the ECB Data Portal. The household sight deposit rates in the top left panel have the series key MIR.M.XX.B.L21. A.R.A.2250.EUR.N, where XX is the country key. The non-financial corporate sight deposit rates in the top right panel have the series key MIR.M. XX.B. L21.A.R.A. 2240.EUR.N. The household time deposit rates in the bottom left panel have the series key MIR.M.XX.B.L22. A.R.A.2250.EUR.N, and the non-financial corporate time deposit rates in the bottom right panel have the series key MIR.M.XX.B.L22.A. R.A.2240.EUR.N.

Figure 2 shows aggregate bank ROE in 2014 and 2019. For the euro area, Sweden, and Denmark, the data are from the ECB Data Portal. The series keys are CBD2.A.XX.W0.11._Z._Z._Z._Z._Z._Z.PC, where XX is the country key (U2 for the euro area, DK for Denmark, and SE for Sweden). The data for Switzerland are from FRED and have the series key DDEI06CHA156NWDB.

Figure 3 is based on consolidated banking data from the ECB Data Portal. The ratios are calculated based on annual end-of-year data, averaged over 2014–2019. Loans refers to loans to households and non-financial corporations only. The series used are total assets (CBD2.A.XX.W0.11._Z._Z.A.F.A0000. _X.ALL.CA._Z.LE._T.EUR), total equity (CBD2.A.XX.W0.11._Z._Z.A.F.LE000._X. ALL.CA._Z.LE._T.EUR), household loans (CBD2.A.XX.W0.11.S1M._Z.A.F.A1100. _X.ALL.CA._Z.LE._T.EUR), non-financial corporate loans (CBD2.A.XX.W0. 11.S11._Z.A.F.A1100._X.ALL.CA._Z.LE._T.EUR), household deposits (CBD2.A. XX.W0.11.S1M._Z.A.F.L1100._X.ALL. CA._Z.LE._T.EUR) and non-financial corporate deposits (CBD2. A.XX.W0.11.S11._Z.A.F.L1100._X.ALL.CA._Z.LE._T.EUR), where XX is again the country key (U2 for the euro area, DK for Denmark, and SE for Sweden). For Switzerland, the chart shows an average of monthly data for domestically-focused banks between 2014 and 2019, based on data from the Swiss National Bank. The Swiss panel shows customer deposits in orange, which includes both household and non-financial corporate deposits. The precise calculations are available on request from the authors.

Figure 4 shows the ECB's deposit facility rate and the 3-month Euribor rate. These are available on the ECB Data Portal under the series keys FM.D.U2.EUR.4F. KR.DFR.LEV and FM.M.U2.EUR.RT.MM.EURIBOR3MD_.HSTA, respectively.

Appendix B: Calibration

The calibration of our model is standard, following, for example, Gertler and Karadi (2011) and Ulate (2021). Table B.1 sets out the key parameters. We calibrate the model to a low steady-state policy rate of 1% so that a relatively modest shock is sufficient to push the economy to the lower bound.

TABLE B.1. Calibration of the DSGE model.

Parameter	Calibration	Description	Target or source
Households			
β	0.9975	Discount rate	1% policy rate
h	0.6	Habit formation	Standard
χ	3.5	Importance of leisure	Standard
η	1.0	Frisch elasticity	Standard
σ	2.0	Inverse Intertemporal EOS	Standard
υ	0.67	Liquidity preference	0.5% deposit spread
Firms			
α	0.33	Capital share	Gertler and Karadi (2011)
δ	0.025	Depreciation rate	Gertler and Karadi (2011)
θ	6	EOS between differentiated goods	Ulate (2021)
μ	0.75	Calvo parameter	Standard
κ^I	2.48	Investment adjustment cost	Christiano, Eichenbaum, and Evans (2005)
Banks			
ν	9	Target leverage ratio	Ulate (2021)
κ	0.0012	Leverage cost	Ulate (2021)
φ^l	0.5	Funding constraint (low)	Suggestive
φ^h	0.7	Funding constraint (high)	Suggestive
$\mathcal{N}^l$	2	# low-deposit banks	3% lending rate
$\mathcal{N}^h$	2	# high-deposit banks	3% lending rate
λ	0.8	Bank dependence	Suggestive
δ^B	0.0058	Bank managerial cost	Steady state
ω	0.1111	Earnings retention	Ulate (2021)
$\bar{H}/\bar{E}$	2	Steady state reserves/equity	Ulate (2021)

TABLE B.1. Continued

Parameter	Calibration	Description	Target or source
Government			
ψ_π	1.5	Inflation coefficient	Standard
ρ_i	0.8	Smoothing parameter	Standard
g	0.2	Steady-state G/Y	Gertler and Karadi (2011)
Open economy			
γ	0.3	Trade openness	Suggestive
η_f	1.5	Intratemporal EOS	Standard
κ_B	0.000001	Debt adjustment cost	Small
$\bar{B}^*/(\bar{B}^* + \bar{B})$	0.8	Foreign financier funding	Suggestive
$\bar{HF}^*/\bar{B}^*$	1	Foreign assets/liabilities	Equal

Appendix C: Model Equations

The equilibrium away from the zero lower bound is characterised by the relevant equations for each of the types of agents in the model. We state the equations and variables in real terms. For instance, W_t is the real wage, and D_t and L_t are real deposits and real loans. Households have an intertemporal condition for labour supply, an Euler equation, the definition of the marginal utility of consumption, and the equation pinning down the deposit rate given households' liquidity preferences, banks' funding-constrained deposit-taking decisions, and, away from the zero lower bound, zero cash holdings:

$$\chi N_t^{1/\eta} = W_t \rho_t, \tag{C.1}$$

$$1 = \mathbb{E}_t\left(\beta \frac{\rho_{t+1}}{\rho_t} \frac{(1+i_t)}{1+\pi_{t+1}}\right), \tag{C.2}$$

$$\rho_t = (C_t - hC_{t-1})^{-\sigma} - \beta h \mathbb{E}_t \left(C_{t+1} - hC_t\right)^{-\sigma}, \tag{C.3}$$

$$i_t^D = i_t - \mathbb{E}_t\left(\frac{(1+\pi_{t+1})\upsilon}{\beta \rho_{t+1}}\right) e^{-\upsilon \frac{D_t + M_t}{P_t}}. \tag{C.4}$$

Capital producers of each type $z \in \{B, C\}$ have the evolution of capital and the first-order condition for the price of capital:

$$K_t^z = (1-\delta)\xi_t K_{t-1}^z + I_t^z, \tag{C.5}$$

$$q_t^z = 1 + \frac{\kappa^I}{2}\left(\frac{I_t^z}{I_{t-1}^z} - 1\right)^2 + \kappa^I \frac{I_t^z}{I_{t-1}^z}\left(\frac{I_t^z}{I_{t-1}^z} - 1\right) - \kappa^I \beta \mathbb{E}_t\left[\frac{\rho_{t+1}}{\rho_t}\left(\frac{I_{t+1}^z}{I_t^z}\right)^2\left(\frac{I_{t+1}^z}{I_t^z} - 1\right)\right]. \tag{C.6}$$

Intermediate goods firms of each type $z \in \{B, C\}$ have the production function, labour demand, and capital demand. In addition, the elasticity of bank-dependent firms' loan demand with respect to the lending rate is relevant to the oligopolistic banks in our model.

$$Y_t^z = A_t \left(\xi_t K_{t-1}^z\right)^\alpha \left(N_t^z\right)^{1-\alpha} \tag{C.7}$$

$$(1-\alpha) P^m Y_t^z = W_t N_t^z \tag{C.8}$$

$$K_t^z = \mathbb{E}_t \left[\frac{\alpha P_{t+1}^m Y_{t+1}^z}{\frac{(1+i_t^z)q_t^z}{1+\pi_{t+1}} - q_{t+1}^z (1-\delta)\xi_{t+1}} \right] \tag{C.9}$$

$$\varepsilon_t^L = \frac{1}{1-\alpha} \mathbb{E}_t \left[1 + \frac{q_{t+1}^b (1-\delta)\xi_{t+1}}{P_{t+1}^m \alpha \frac{Y_{t+1}^b}{K_t^b}} \right]. \tag{C.10}$$

Retailers have the New Keynesian Phillips curve:

$$\begin{aligned}\left(1+\pi_t^H\right)\left(\pi_t^H - \bar{\pi}\right) = \beta \mathbb{E}_t \left[\frac{\rho_{t+1}}{\rho_t} \left(1+\pi_{t+1}^H\right)^2 \left(\pi_{t+1}^H - \bar{\pi}\right) \frac{Y_{t+1}}{Y_t} \right] \\ + \frac{\theta}{\kappa^P} \left(\frac{P_t^m}{P_t^H} - \frac{\theta - 1}{\theta} \right).\end{aligned} \tag{C.11}$$

Financiers have equations for their market lending rate, profits from real economy lending, a net worth law of motion, a balance sheet constraint and the uncovered interest parity condition, and an expression for stochastic loan returns:

$$i_t^C = i_t + \mu_C + \kappa \left(\frac{L_t^C}{E_t^C} - \psi \right) \tag{C.12}$$

$$\begin{aligned} X_t^C (1+\pi_t) = i_{t-1} E_{t-1}^C + \left(i_{t-1}^C - i_{t-1}\right) L_{t-1}^C - \frac{\kappa}{2} \left(\frac{L_{t-1}^C}{E_{t-1}^C} - \psi \right)^2 E_{t-1}^C \\ - E_{t-1}^C (1-\zeta^C)\pi_t + NPL_t^C \end{aligned} \tag{C.13}$$

$$E_t^C = (1-\zeta^C) E_{t-1}^C + \omega X_t^C \tag{C.14}$$

$$WF_t + HF_t + s_t HF_t^* + L_t^C = E_t^C + B_t + s_t B_t^* \tag{C.15}$$

$$\mathbb{E}_t \left[\frac{1+i_t}{1+\pi_{t+1}} \right] = (1+i_t^*) \mathbb{E}_t \left[\frac{s_{t+1}}{s_t} \right] + \kappa_B (B_t^* - \overline{B^*}) \tag{C.16}$$

$$NPL_t^C = P_t^m Y_t^C - W_t N_t^C + q_t^C (1-\delta) \xi_t K_{t-1}^C - \frac{(1+i_{t-1}^C) L_{t-1}^C}{1+\pi_t}. \tag{C.17}$$

Banks of each type $z \in \{L, H\}$ have a balance sheet constraint, a funding constraint, a first-order condition for lending, profits net of operating costs, a law of motion for bank net worth, non-performing loans, and the definition of the net interest margin:

$$L_t^z + H_t^z = E_t^z + D_t^z + WF_t^z \tag{C.18}$$

$$D_t^z = \varphi_t^z L_t^z \tag{C.19}$$

$$1 + i_t^L = \frac{\mathcal{N}^z \varepsilon_t^L}{\mathcal{N}^z \varepsilon_t^L - \frac{L_t^z}{L_t}} \left[(1 - \varphi^z)(1 + i_t) + \varphi^z \left(1 + i_t^D + \mu_D^z\right) + \kappa \left(\frac{L_t^z}{E_t^z} - \psi \right) \right] \tag{C.20}$$

$$\begin{aligned} X_t^z(1 + \pi_t) = {} & i_{t-1} E_{t-1}^z + \left(i_{t-1}^L - i_{t-1}\right) L_{t-1}^z + \left(i_{t-1} - i_{t-1}^D - \mu_D^z\right) D_{t-1}^z \\ & - \frac{\kappa}{2} \left(\frac{L_{t-1}^z}{E_{t-1}^z} - \psi \right)^2 E_{t-1}^z - E_{t-1}^z (1 - \zeta) \pi_t + \frac{NPL_t}{L_{t-1}} L_{t-1}^z \end{aligned} \tag{C.21}$$

$$NPL_t = P_t^m Y_t^b - W_t N_t^b + q_t^b (1 - \delta) \xi_t K_{t-1}^b - \frac{(1 + i_{t-1}^L) L_{t-1}}{1 + \pi_t} \tag{C.22}$$

$$E_t^z = (1 - \zeta) E_{t-1}^z + \omega X_t^z \tag{C.23}$$

$$NIM_t^z = i_t^L - \left(1 - \varphi^z\right) i_t - \varphi^z i_t^D. \tag{C.24}$$

We set the parameter μ_D^L to zero and calibrate μ_D^H such that in steady-state, low-deposit bank and high-deposit bank NIMs and lending are equal. This makes it easier to find the steady state without affecting the dynamics of the model. Aggregate balance sheet variables are equal to the sum of those of the individual banks: for example, $H_t = \sum_Z H_t^Z$.

Market clearing requires that the resource constraint for the domestic good and the balance of payments condition hold. The balance of payment condition makes use of the evolution of the monetary base, which, for tractability of the BOP condition, is given (with variables defined in nominal terms) by $M_t + H_t + HF_t = (1 + \pi_t) \left[M_{t-1} + H_{t-1} + HF_{t-1} \left(\mathbb{E}_{t-1} \left[\frac{1+i_{t-1}}{1+\pi_t} \right] - \kappa_B (B_{t-1}^* - \overline{B}^*) \right) \right]$; as well as the binding (nominal) financier reserves constraint ($HF_t = -e_t HF_t^*$), and an assumption that real bank reserves are constant ($\frac{H_t}{P_t} = \overline{H}$), which together imply that: $\frac{M_t}{P_t} - \frac{M_{t-1}}{P_{t-1}} = s_t HF_t^* - s_t HF_{t-1}^* (1 + i_{t-1}^*) + \Pi_t^{HF^*}$. In addition, there are a number of aggregations. Total bank loans is the sum of low-deposit and high-deposit banks' lending, capital investment by bank-reliant firms must equal total bank lending, capital investment by firms with capital market access must equal financiers' real-economy lending. Total labour supply must equal the sum of labour demand from bank-reliant and market-financed firms, and similarly for aggregate output, capital and investment:

$$Y_t = (1-\gamma)\left(P_t^H\right)^{-\eta^F}(C_t + I_t) + G_t + \gamma_f Y_t^* \left(\frac{s_t}{P_t^H}\right)^{\eta^F} \tag{C.25}$$

$$TB_t = -s_t B_t^* + s_t(1+i_{t-1}^*)B_{t-1}^* + s_t \frac{\kappa^B}{2}\left(B_t^* - \overline{B^*}\right)^2 + M_t - M_{t-1} \tag{C.26}$$

$$TB_t = P_t^H \gamma^f Y_t^* \left(\frac{s_t}{P_t^H}\right)^{\eta_F} - \gamma s_t^{1-\eta^F}(C_t + I_t) \tag{C.27}$$

$$L_t = L_t^H + L_t^L \tag{C.28}$$

$$L_t = q_t^B K_t^B \tag{C.29}$$

$$L_t^C = q_t^C K_t^C \tag{C.30}$$

$$N_t = (1-\lambda)N_t^C + \lambda N_t^B \tag{C.31}$$

$$Y_t = (1-\lambda)Y_t^C + \lambda Y_t^B \tag{C.32}$$

$$I_t = (1-\lambda)I_t^C + \lambda I_t^B \tag{C.33}$$

$$K_t = (1-\lambda)K_t^C + \lambda K_t^B. \tag{C.34}$$

Finally, we have the definition of the CPI, which we normalise to 1, and the Taylor rule:

$$1 = \left[(1-\gamma)P_{H,t}^{1-\eta^F} + \gamma P_{F,t}^{1-\eta^F}\right]^{\frac{1}{1-\eta^F}} \tag{C.35}$$

$$i_t = (1-\rho_i)(\bar{i} + \varphi_\pi(\pi_t - \bar{\pi})) + \rho_i i_{t-1} + \varepsilon_t^i. \tag{C.36}$$

In addition to the monetary policy shock, the economy can experience technology shocks, government spending shocks, capital efficiency shocks, foreign demand shocks, and foreign interest rate shocks. The relevant laws of motion are:

$$A_t = \bar{A}^{1-\rho^a} A_{t-1}^{\rho^a} e^{\varepsilon_t^a} \tag{C.37}$$

$$G_t = \bar{G}^{1-\rho^g} G_{t-1}^{\rho^g} e^{\varepsilon_t^g} \tag{C.38}$$

$$\xi_t = \xi_{t-1}^{\rho^\xi} e^{\varepsilon_t^\xi} \tag{C.39}$$

$$Y_t^* = \left(Y_{t-1}^*\right)^{\rho^y} e^{\varepsilon_t^y} \tag{C.41}$$

$$i_t^* = (1-\rho^*)\overline{i^*} + \rho^* i_{t-1}^* + \varepsilon_t^*. \tag{C.42}$$

Appendix D: Additional General Equilibrium Results

Figure D.1 shows the effects of the negative demand shock studied in Figure 7 under three different regimes. In addition to the regime with a strict zero lower bound on both the deposit rate and the policy rate (the solid lines) and the regime with a lower bound on the deposit rate only (the dashed lines), there is a third regime in which there is no lower bound at all (the dotted lines). The latter regime is how monetary policy would operate if the deposit rate could follow the policy rate at the lower bound just as it does away from the lower bound. Monetary policy would then operate more strongly through the bank lending channel, and the central bank would not have to cut policy rates as much as in the presence of the lower bound.

Figure D.2 shows the effects of the negative demand shock studied in Figure 7 under the same three regimes as in Figure D.1, but without the non-performing loan channel. Figure D.3 illustrates the marginal effects of NIRP with and without a non-performing loan channel. Bank lending rates still fall, but lending volumes are flat, and the effect on bank equity is broadly neutral. Negative rates are less powerful overall but remain expansionary, in part due to the modest fall in bank lending rates but predominantly due to the continued operation of the exchange rate channel and the capital market channel.

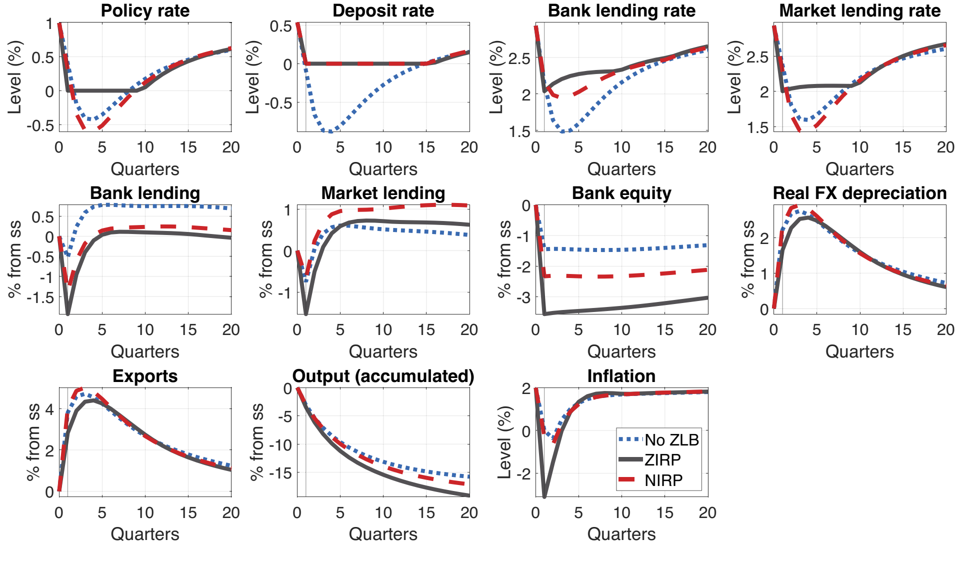


FIGURE D.1. Impulse responses to an adverse demand shock.

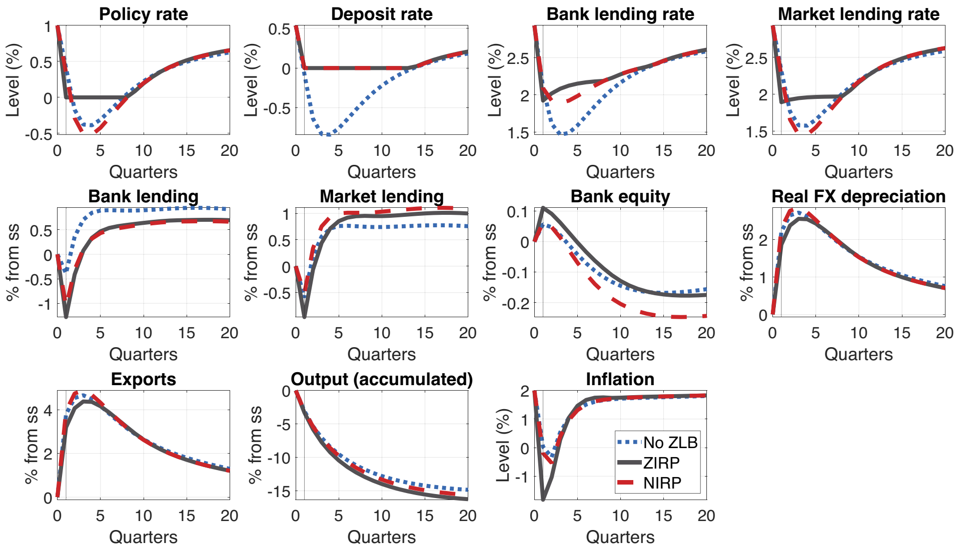


FIGURE D.2. Impulse responses to an adverse demand shock without non-performing loan channel.

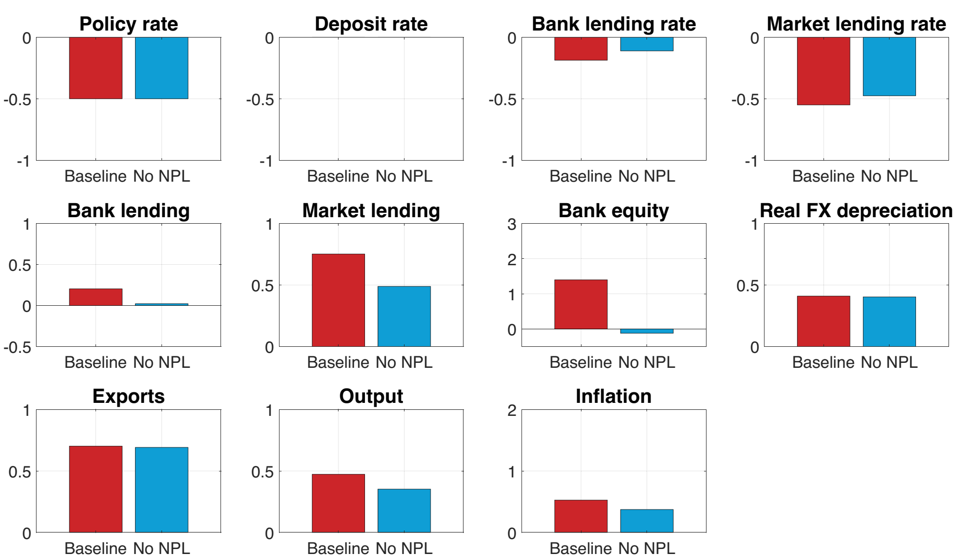


FIGURE D.3. The effectiveness of NIRP with and without a non-performing loan channel.

Appendix E: High-Deposit and low-deposit banks' profits

It can be shown that low-deposit banks will always see an increase in profits following a policy rate cut at the ZLB, while the effect on high-deposit banks' profits is theoretically ambiguous as long as $\varphi_2 < 1$:

$$\frac{d\pi_{1,j}}{di} = \underbrace{\frac{2n_2\varepsilon L}{n_1+n_2}}_{>0}\left[\underbrace{\frac{n_2}{n_1+n_2}(\varphi_1-\varphi_2)^2\varepsilon i}_{<0} + \underbrace{\frac{\varphi_1-\varphi_2}{n_1+n_2}}_{<0}\right] + \underbrace{\left[\frac{n_2}{n_1+n_2}(\varphi_1-\varphi_2)\varepsilon i + \frac{1}{n_1+n_2}\right]^2}_{>0}\underbrace{\frac{dL}{di}}_{<0} < 0,$$

$$\frac{d\pi_{2,k}}{di} = \underbrace{\frac{2n_1\varepsilon L}{n_1+n_2}}_{>0}\left[\underbrace{\frac{n_1}{n_1+n_2}(\varphi_2-\varphi_1)^2\varepsilon i}_{<0} + \underbrace{\frac{\varphi_2-\varphi_1}{n_1+n_2}}_{>0}\right] + \underbrace{\left[\frac{n_1}{n_1+n_2}(\varphi_2-\varphi_1)\varepsilon i + \frac{1}{n_1+n_2}\right]^2}_{>0}\underbrace{\frac{dL}{di}}_{<0}.$$

Appendix F: The Back-Book Channel

Our analysis has implicitly assumed that all loans and deposits are one-period assets, or equivalently, that the bank can reset the loan rate and the deposit rate on all of its outstanding loans and deposits each period. In reality, a bank's loan book will typically include some fraction of fixed-rate loans and some fraction of loans with a rate contractually set to follow the policy rate.[37] The fact that the bank cannot reset the lending rate on its entire loan book each period, while the rate on the stock of deposits does adjust each period, creates interest rate risk.

Banks typically hedge a substantial amount of this interest rate risk. But to the extent that the risk is not perfectly hedged, policy rate changes could lead to short-term 'valuation gains' or 'back-book gains/losses'. For instance, long-term fixed rate mortgages (or another asset with a fixed return) would generate a valuation gain for the bank when there is a surprise policy rate cut. In Abadi, Brunnermeier, and Koby (2023), such valuation gains provide a short-term boost to bank profitability when rates are cut below zero, making lending reversal less likely in the near term. On the other

37. Bank deposits will also typically include time deposits as well as sight deposits. For simplicity, we will assume that all deposits are sight deposits here.

hand, floating-rate products could generate a back-book loss when the policy rate is cut below zero at the ZLB.[38]

We focus on the case where some of the bank's loans automatically re-price with a change in the policy rate. At $t = 0$, the bank has chosen optimal lending L_0 given the prevailing policy rate $i_0 = 0$, and the funding constraint binds. The central bank cuts the policy rate to $i < 0$, reducing the yield on floating-rate mortgages by Δi. Away from the ZLB, this would not matter because the bank would want to pass-through most or all of the policy rate cut to lending rates anyway. But at the ZLB, the bank would optimally pass through only $(1-\varphi)\Delta i$ to i_L, and hence the 'back-book channel' reduces the bank's profitability in the near term. We capture this channel as a simple reduction in the bank's initial capital following an interest rate cut at the ZLB,[39]

$$\frac{dK_0}{di} = \beta K_0 > 0.$$

Whether this channel affects the bank's behaviour depends on how capital or leverage constraints are modelled. Based on the simple capital constraint used above, the bank would treat the back-book hit as a sunk cost, with no effect on the bank's behaviour.[40] But the empirical literature on banking finds that hits to profitability and capital can affect lending behaviour. To capture this intuition, we will assume that the bank is subject to quadratic leverage costs instead of a simple capital constraint.[41] The bank's problem becomes

$$\max_L \ \pi = (i_L - (1-\varphi)i)L - \frac{\rho}{2}\left(\frac{L}{K_0} - \psi\right)^2 K_0,$$

where K_0 is the bank's initial capital endowment, ψ is the bank's leverage target rather than its capital constraint, and ρ is a parameter that measures the bank's sensitivity to deviations from the leverage target rather than the excess cost of capital. Lending volumes and rates are now

$$L = -\frac{i_L - (1-\varphi)i + \rho\psi}{i_L' - \frac{\rho}{K_0}}, \qquad i_L = (1-\varphi)i + \frac{1}{\varepsilon} + \rho\left(\frac{L}{K_0} - \psi\right). \qquad \text{(F.1)}$$

In the medium term ($t = 2$), the bank can adjust K through retained earnings to re-establish desired leverage. In other words, following a policy rate cut at the ZLB only the reduction in funding costs survives in the medium term, and hence lending must increase, just as without the back-book channel. Leverage costs due to the back-book

38. In practice, this mechanism is not limited to floating-rate mortgages. Banks may also swap part of the fixed return into floating rates to match more closely the behavioural maturity of their deposit funding base.

39. Note this is a cash flow redistribution, so in general equilibrium we attribute a corresponding windfall gain to the household sector.

40. Except in the extreme case where the back-book hit is large enough to wipe out the bank's initial capital and force it to shut down.

41. Following, for example, Campbell (1987), Gerali et al. (2010), and Ulate (2021).

channel might dampen or even reverse transmission on impact, but over time there will be delayed pass through to lending.

In the near term, that is, in $t = 1$ following a surprise interest rate cut at the end of $t = 0$, K_0 is exogenous, so any expansion in lending in response to the rate cut will produce leverage costs. Note that leverage costs will routinely dampen monetary policy transmission in the short term, but cannot reverse it,

$$\frac{dL}{di} = \frac{1-\varphi}{2i_L^{'} + i_L^{''}L - \frac{\rho}{K_0}}. \tag{F.2}$$

The denominator is negative by the second-order condition, so a policy rate cut will always increase lending provided $\varphi < 1$. When leverage costs are prohibitively high ($\rho \to \infty$), pass-through to lending will tend towards zero, $dL/di \to 0$. That is, if banks are highly concerned with leverage and capital adequacy, for instance during a financial crisis, the monetary policy transmission mechanism could be impaired. But by itself an increase in ρ can only obstruct, never reverse, the bank lending channel.

The back-book channel, by reducing K_0, creates additional leverage costs and could in principle reverse the bank lending channel in the short run. Pass-through to lending is now

$$\frac{dL}{di} = \frac{1-\varphi-\rho\frac{L}{K_0}\beta}{2i_L^{'} + i_L^{''}L - \frac{\rho}{K_0}}. \tag{F.3}$$

Assuming that bank leverage was at target before the policy rate cut and that the rate cut is small (i.e., $L/K_0 \approx \psi$), the bank lending channel would reverse if and only if

$$\beta > \frac{1-\varphi}{\rho\psi}.$$

We discuss the calibration of the model in more detail in Section 5. But realistic parameters such as $\varphi = 0.6$, $\rho = 20$ basis points and $\psi = 10$ would imply that a one percentage point policy rate cut would need to wipe out at least 20% of initial bank capital for there to be short-term reversal.[42] This is materially larger than most estimates for the impact of rate cuts at the ZLB on bank equity values. For instance, Ampudia and van den Heuvel (2022) find that a one percentage point policy rate cut below zero would lower bank stock prices by about 8 percentage points, whereas other studies such as Altavilla, Boucinha, and Peydro (2018) and Altavilla et al. (2022) find no adverse effect on bank equity valuations at all.[43]

That said, the likelihood of near-term reversal via the back-book channel will be state-contingent. In particular, the sensitivity of bank lending to concerns about capital

42. We borrow the calibration of ρ from Ulate (2021) and ψ from Abadi, Brunnermeier, and Koby (2023), while $\varphi = 0.6$ is broadly consistent with the data in Figure 3.

43. Bank equity valuations will not only capture the back-book channel, but also possible 'valuation gains' as discussed by Abadi, Brunnermeier, and Koby (2023) and any market views on the longer-term impact of a negative policy rate on banks through various channels. But the latter should not be large given the empirical evidence on negative rates and bank profitability, and valuation gains—if significant—could be included in our model to reduce or even change the sign of the back-book channel.

adequacy, as measured by ρ, is likely to be higher during recessions and in particular during financial crises. It follows that negative policy rates are more likely to result in near-term reversal if they are implemented when banks are under stress.

Regarding the timing of possible reversal, our results differ from Abadi, Brunnermeier, and Koby (2023). There, banks are assumed to experience 'valuation gains' when the policy rate is cut, providing a temporary boost to bank profitability. These gains fade while net interest margins are permanently compressed, and hence the reversal rate 'creeps up' over time. In our model, reversal could happen on impact but not in the long run.

Finally, the back-book channel is unaffected by competition when it affects banks homogeneously. But competition will somewhat reduce the strength of the back-book channel if banks are heterogeneously exposed, leverage costs are convex, and loan demand exhibits constant semi-elasticity. For a detailed discussion, see Appendix G.

Appendix G: Heterogeneous Back-Book Effects

Consider a duopoly of identical banks with homogeneous funding constraints subject to leverage costs at the ZLB. Lending volumes and the lending rate will be

$$L_1 = L_2 = -\frac{i_L - (1-\varphi)i + \rho\psi}{i_L' - \frac{\rho}{K_{1,0}}}, \qquad i_L = (1-\varphi)i + \frac{1}{2\varepsilon} + \rho\left(\frac{L_1}{K_{1,0}} - \psi\right).$$

Again, the only difference compared to the monopoly case in equation (F.1) is that the constant mark-up of the lending rate is now smaller due to competition. Leverage costs affect the lending rate in exactly the same way as in the monopoly, given $L_1/K_{1,0} = L_2/K_{2,0} = L/K_0$ in a homogeneous duopoly. This is not straightforward to see from the resulting expression for monetary policy pass-through in a homogeneous duopoly subject to leverage costs, but the above argument implies that, subject to constant semi-elasticity of loan demand, the value of

$$\frac{dL}{di} = \left[\frac{2\left(i_L' - \frac{2\rho}{K_0}\right)}{i_L'(3i_L' + i_L''L) - \frac{2\rho}{K_0}\left(4i_L' + i_L''L - \frac{2\rho}{K_0}\right)}\right](1-\varphi) < 0$$

is unchanged from the monopoly case in equation (F.2).

Now suppose both banks are exposed to negative rates via the back-book channel, measured by β_1 and β_2. Bank 1's lending response to a policy rate cut at the ZLB will now be

$$\frac{dL_1}{di} = \frac{\left[i_L' + i_L''(L_2 - L_1) - \frac{\rho}{K_{2,0}}\right](1-\varphi) - \left(2i_L' + i_L''L_2 - \frac{\rho}{K_{2,0}}\right)\rho\frac{L_1}{K_{1,0}}\beta_1 + (i_L' + i_L''L_1)\rho\frac{L_2}{K_{2,0}}\beta_2}{i_L'(3i_L' + i_L''L_1 + i_L''L_2) - \frac{\rho}{K_1}\left(2i_L' + i_L''L_2 - \frac{1}{2}\frac{\rho}{K_2}\right) - \frac{\rho}{K_2}\left(2i_L' + i_L''L_1 - \frac{1}{2}\frac{\rho}{K_1}\right)}$$

Under constant semi-elasticity and assuming second-order conditions hold, the denominator of this expression will be positive, and the brackets in front of β_1 and β_2 will be negative. It follows that bank 1's lending response to a policy rate cut will be reduced (and potentially reversed) in proportion to its own back-book channel (β_1). But the fact that bank 2 also experiences a back-book hit—which will reduce bank 2's lending response to the policy rate cut—will increase bank 1's lending response to the rate cut. If β_2 is sufficiently bigger than β_1, it is even possible for the net back-book effect on bank 1's lending response to be positive.

This reallocation between banks nets out. Using $K_{1,0} = K_{2,0} = \frac{1}{2}K_0$, and assuming $\beta_1 = \beta_2 = \beta$ (and hence $L_1 = L_2$) to compare to the monopoly case, we can write the aggregate (near-term) lending response to a policy rate cut as

$$\frac{dL}{di} = \frac{dL_1}{di} + \frac{dL_2}{di} = \frac{2(i_L' - \frac{2\rho}{K_0})\left[1 - \varphi - \rho\frac{L}{K_0}\beta\right]}{i_L'(3i_L' + i_L''L) - \frac{2\rho}{K_0}\left(4i_L' + i_L''L - \frac{2\rho}{K_0}\right)}$$

Note that the back-book effect on $\frac{dL}{di}$ is exactly the same as in the monopoly case. That is, when the back-book hit is distributed homogeneously across banks, then the degree of competition does not affect the strength of the back-book channel.

However, when the back-book hit affects banks heterogeneously, then the aggregate back-book effect on lending will be smaller than in the monopoly case. To see this, consider two banks with the same amount of initial capital, $K_{1,0} = K_{2,0} = \frac{K_0}{2}$, which are identical in every way except that $\beta_1 = 0$ while $\beta_2 = 2\beta > 0$ (so that the aggregate back-book hit to the banking industry is the same as in the monopoly case). Now, the aggregate lending response to a policy rate cut will be

$$\frac{dL}{di} = \frac{dL_1}{di} + \frac{dL_2}{di} = \frac{2(i_L' - \frac{2\rho}{K_0})\left[1 - \varphi - \rho\frac{L_2}{K_{2,0}}\beta\right]}{i_L'(3i_L' + i_L''L) - \frac{2\rho}{K_0}\left(4i_L' + i_L''L - \frac{2\rho}{K_0}\right)}.$$

We know that the back-book hit β_2 will induce bank 2 to reduce its lending response, and more so than the monopoly bank which is hit by $\beta < \beta_2$, while it will induce bank 2 to expand lending by more than it otherwise would. Hence,

$$\frac{L_2}{K_{2,0}} < \frac{L_{Monopoly}}{K_0},$$

and so the back-book channel dampens the aggregate lending response by less in the heterogeneous duopoly than it does in the monopoly. This is a result of assuming quadratic, that is, convex, leverage costs. Bank 1 is still at target leverage immediately after its (zero) back-book hit and can hence increase lending significantly before the quadratic nature of the leverage cost function starts to bite. This can overcompensate for the fact that bank 2 might expand lending very little or even reduce it. In combination, the two banks face a smaller aggregate leverage cost penalty for any given lending expansion than they would if they had the same starting point that $\beta_1 = \beta_2 = \beta$ delivers.

Appendix H: The Back-Book Channel in General Equilibrium

Figure H.1 illustrates how a back-book channel can affect the strength of different transmission channels of negative rates. As for Figure 8, the bars show the marginal effects of setting the policy rate at –0.5% on average over two years rather than at 0% in

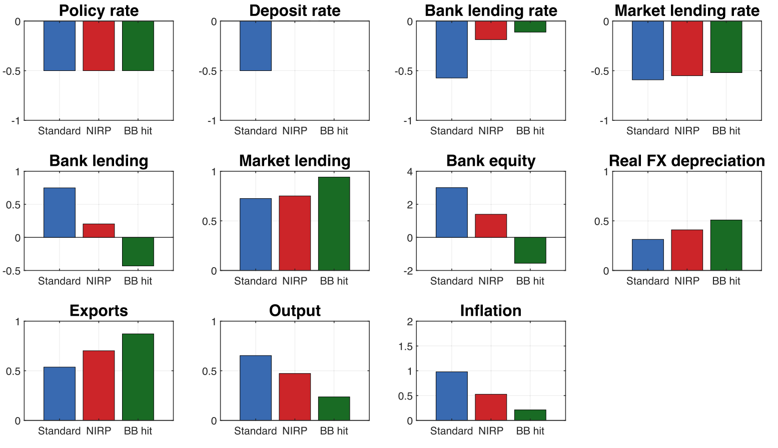


FIGURE H.1. The effectiveness of NIRP compared to a standard rate cut in the presence of a back-book channel.

response to an adverse demand shock, averaged over a two-year period. In addition to Figure 8, the green bars show the effects of NIRP when there is a back-book effect that materially reduces bank profitability during the negative rates period via back-book effects. This can lead to a reversal of the bank lending channel, reducing the overall effects of the policy rate cut on output and inflation.

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Supplementary Data

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