

The Reversal Interest Rate

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The reversal interest rate is the rate at which accommodative monetary policy reverses and becomes contractionary for lending. We theoretically demonstrate its existence in a macroeconomic model featuring imperfectly competitive banks that face financial frictions. When interest rates are cut too low, further monetary stimulus cuts into banks' profit margins, depressing their net worth and curtailing their credit supply. Similarly, when interest rates are low for too long, the persistent drag on bank profitability eventually outweighs banks' initial capital gains, also stifling credit supply. We quantify the importance of this mechanism within a calibrated New Keynesian model.

In most New Keynesian models, the economy can enter a liquidity trap because of an exogenously assumed zero lower bound. This assumption has been called into question since a growing number of central banks – the Swedish Riksbank, the Danish Nationalbank, the Swiss National Bank, the European Central Bank, and the Bank of Japan – have led money market rates into negative territory as a response to the Great Recession. In addition to going negative, these rates have been kept low for a long period.

This motivates the question: what is the effective lower bound on monetary policy? We suggest in this paper that it is given by the reversal interest rate, the rate at which accommodative monetary policy reverses its effect, so further cuts become contractionary for bank lending. A monetary policy rate decrease below the reversal interest rate depresses rather than stimulates the economy.

Importantly, the reversal interest rate is not necessarily zero, as commonly assumed. In our model, when the reversal interest rate is positive, say 1%, a policy rate cut from 1% to 0.9% is already contractionary. On the other hand, if the reversal interest rate is -1%, policy rate cuts remain expansionary up to that point, even if their effectiveness might be impaired.

To study the emergence of a reversal rate, we develop an infinite-horizon New Keynesian macroeconomic model with a banking sector. The model features two

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key frictions: banks have market power to set deposit rates, and bank lending is constrained by net worth. In order to highlight the mechanism that gives rise to a reversal rate, we begin by theoretically analyzing the transmission of monetary policy to bank credit supply in partial equilibrium. Following an interest rate cut, two opposing forces affect banks' net worth. On the one hand, banks make capital gains on long-term assets with fixed-rate coupon payments (the *capital gains channel*). On the other hand, as interest rates head lower, the pass-through from the policy rate to deposit rates declines, e.g., due to the presence of cash, compressing banks' profit margins (the *net interest income channel*). We theoretically demonstrate that the reversal interest rate is precisely the rate below which the net interest income effect of further interest rate cuts outweighs the capital gains effect. A reversal rate is guaranteed to exist when banks' capital gains from maturity mismatch are sufficiently small. We show that our main results depend on two empirically verifiable properties of the model: first, that banks' net interest income falls following an interest rate cut, and second, that this downturn in banks' profitability causes them to reduce lending.

We apply our theoretical framework to study the effects of "low-for-long" monetary policies in which the central bank promises to keep interest rates low for a prolonged period of time. Banks' net interest income losses cumulate every period, but the initial revaluation of their long-term assets eventually fades out as those assets mature. Consequently, a promise to keep rates low might initially stimulate bank lending but later become contractionary: as banks' net worth is drained over time, they cut back on lending due to financial constraints. We precisely characterize the conditions under which extending the period of low interest rates is bound to eventually become counterproductive.

The economics behind our results carry through in general equilibrium with sticky prices. After calibrating the model to the Euro area, we compute its full non-linear response to monetary shocks. We find in our calibration that the monetary authority's ability to stimulate bank lending on impact declines with the size of the monetary shock and reverses at an interest rate close to -1%. Given the persistence of the monetary shock, the negative effects are even more pronounced on bank lending one or two years ahead: banks' capital gains shield them from rate cuts on impact, but not later. Once the reversal rate for bank lending is crossed, the economy's reliance on bank credit – the share of firms that are bank-dependent – dictates the aggregate implications for investment and output. The reversal interest rate for aggregate output is lower, as other channels through which monetary policy operates – non-bank-dependent firms' funding costs and the inter-temporal substitution channel – remain active.

The calibrated model provides an ideal setting to study the determinants of the reversal rate for bank lending and investment. We find that the tightness of banks' capital constraints is the key determinant of the reversal rate for bank lending. Tighter net worth constraints imply that banks are forced to cut back on lending sooner following the drop in profitability caused by rate cuts, *ceteris*

paribus. In turn, the share of output produced by bank-dependent firms is an important determinant of the reversal rate for aggregate investment. A greater reliance of total output on bank-dependent firms implies a stronger transmission of bank lending to aggregate investment in general equilibrium, resulting in a higher reversal rate.

In an application of our theoretical results, we also study the consequences of “low-for-long” policies in general equilibrium. In standard New Keynesian models, it is well-known that promises to hold interest rates low for prolonged periods result in implausibly large economic stimulus (the “forward guidance puzzle”). In our model, by contrast, the stimulative effects of such announcements are smaller than in a standard model without banking frictions. Upon the announcement of the interest rate cut, agents foresee that the cut will put downward pressure on bank profits and lead to an eventual decline in lending, investment, and output; thus, the initial response of demand is weaker than in a standard model. In this sense, the reversal rate mechanism can mitigate the forward guidance puzzle.

The rest of the paper is organized as follows. Section I develops a general New Keynesian model with banking frictions that we use throughout our analysis. In Section II, we impose specific assumptions on the model’s parameters that permit us to prove analytical results regarding the response of bank loan supply to monetary policy shocks. Section III illustrates the quantitative relevance of these theoretical results in general equilibrium: we calibrate the model, present our main estimates of the reversal rate, examine the key mechanisms, and address the power of forward guidance. Section IV discusses the results and studies their robustness. Section V concludes. Proofs and supporting results are in the Online Appendix.

Related Literature. A long-standing literature developed the concepts of the “balance sheet” and “bank lending” channels of monetary policy, emphasizing the importance of the balance sheet structure and the net worth of intermediaries for the transmission of monetary policy (Bernanke and Blinder, 1988; Bernanke and Gertler, 1995). In our model, these objects are key determinants of the transmission of monetary policy. From a theoretical standpoint, our microeconomic modeling of banks stands on the shoulders of a literature formally started by Klein (1971) and Monti (1972),¹ who emphasize the importance of market power when modeling banks.

Our paper also relates to the growing literature that studies the transmission of monetary policy through banks in low-interest rate environments. Closest to our paper, in contemporaneous and independent work, Eggertsson et al. (2019) and Ulate (2021a) present models in which monetary policy is weakened when rates cross into negative territory, due to the reduction in banks’ profit margins and the resulting decline in their net worth. Other work, such as Drechsler, Savov, and Schnabl (2017); Wang (2022); and Wang et al. (2022), studies the reduced pass-through of monetary policy to bank lending when rates are low but

¹Santomero (1984) provides an excellent survey of this early theoretical literature.

positive. Our work differs from those papers in two key respects. First, our model highlights that interest rate cuts may not become contractionary until rates enter substantially negative territory – we theoretically demonstrate the existence of a reversal rate and quantitatively estimate it, whereas previous work estimates the effectiveness of interest rate cuts near the lower bound on deposit rates. Second, our theoretical framework permits us to characterize the full dynamic response of banks’ credit supply to monetary shocks, allowing us to demonstrate how “low-for-long” policies can be detrimental and address the forward guidance puzzle.

We rely on a recent empirical literature that has illustrated the effects of low- and negative-rate environments on banks’ profitability. Claessens, Coleman, and Donnelly (2018); English, van den Heuvel, and Zakrajšek (2018); Eisenschmidt and Smets (2019); and Ampudia and van den Heuvel (2022) provide evidence that banks’ net interest income and equity valuations vary with the level of interest rates, possibly in a nonlinear way. In particular, Claessens, Coleman, and Donnelly (2018) find that a 1% policy rate drop implies, on average, a net interest margin decline of 8 basis points, but that this magnitude grows as rates move lower. Altavilla, Boucinha, and Peydró (2018) document that the European Central Bank’s introduction of negative interest rates was significantly detrimental to banks’ net interest income, although increased intermediation activity as well as an improvement in the risk profile of banks’ assets helped sustain returns on assets. Evidence provided by Ampudia and van den Heuvel (2022) suggests that banks’ profitability response to interest rate cuts is non-monotonic: in normal times, interest rate cuts increase banks’ valuations, but this effect reverses in low-rate environments.

Finally, our results build on a literature showing that the profitability of banks impacts their lending activities and hence the level of intermediation in the economy. Brunnermeier and Sannikov (2014) provide a theoretical foundation where intermediaries’ profitability is key for the economy to function properly. Cavallino and Sandri (2023) obtain contractionary monetary easing in their theoretical model and explore the implications in an open economy context. Empirically, Heider, Saidi, and Schepens (2019) employ a difference-in-difference analysis using syndicated loans in the Euro area to document that banks with a high deposit base decreased their lending relative to low-deposit, wholesale-funded banks following the ECB’s decision to implement negative interest rates.² Importantly, Gropp et al. (2019) show that banks exposed to higher capital requirements decrease their risk-weighted assets instead of recapitalizing, as in our model.

I. Model

We consider a New Keynesian economy in discrete time, $t \in \{0, 1, 2, \dots\}$. The main players are households that work and consume, intermediate goods firms

²Gomez et al. (2021) offer similar evidence, by studying two groups differentially exposed to interest rate risk. The group whose profitability is affected negatively (in relative terms) by a change in aggregate interest rates decreases its lending.

that employ capital and labor to produce output, and a continuum of banks $j \in [0, 1]$ that intermediate funds from households to intermediate producers. Importantly, banks have market power in setting deposit and loan rates (and hence make profits that are later paid out to households). The presence of financial frictions will imply that bank net worth matters for lending.

As in most sticky-price models, there are also monopolistic retailers that use intermediate goods to produce differentiated varieties, which are then sold to final goods producers that aggregate those varieties to produce consumption goods and capital. Firms and banks are owned by households. A central bank implements monetary policy by setting the nominal interest rate i_t , and there is a government that issues risk-free bonds and sets taxes and transfers. The economy begins at its steady state. We study the effects of an unanticipated monetary policy announcement at $t = 0$, after which point the economy evolves deterministically.

A. Households

A household's lifetime utility is given by:

$$(1) \quad \sum_{t=0}^{\infty} \beta^t (u(C_t, C_{t-1}, H_t) + \zeta \Phi(\mathcal{L}_t)).$$

In the utility function u , C_t denotes consumption, H_t denotes hours worked, and $\beta \in (0, 1)$ is households' discount factor. We permit C_{t-1} to enter the utility function in order to accommodate habits in consumption. We assume

$$u(C_t, C_{t-1}, H_t) = \frac{(C_t - hC_{t-1})^{1-\sigma}}{1-\sigma} - \chi \frac{H_t^{1+\varphi}}{1+\varphi}.$$

As in Feenstra (1986), liquid asset holdings enter directly into households' utility.³ The function Φ specifies the utility that households derive from holding liquid savings \mathcal{L}_t , which in turn are an aggregate of deposits and cash, $\mathcal{L}_t = \mathcal{L}(D_t, M_t)$, where D_t and M_t denote real deposit and cash holdings.⁴ In order to allow for the possibility of negative interest rates, we assume that the function Φ has a satiation point \mathcal{L}^* . The parameter $\zeta > 0$ determines the scale of liquid asset demand.⁵

In each period, households choose their consumption C_t , labor supply H_t (taking the nominal wage W_t as given), and savings, which are allocated across three types of assets: deposits D_t , cash holdings M_t , and risk-free bonds B_t . Each

³More recently, Drechsler, Savov, and Schnabl (2017) and Di Tella and Kurlat (2021) have adopted similar formulations.

⁴We impose standard regularity conditions. The function Φ is assumed to be weakly increasing, concave, and differentiable. The aggregator \mathcal{L} is assumed to be homothetic, concave, differentiable, and strictly increasing in both of its arguments.

⁵We explicitly specify the parameter ζ (instead of subsuming it in the function Φ) because later on, we will study comparative statics with respect to ζ , holding Φ fixed.

household is matched with a single bank j and may deposit funds at the nominal rate $1 + i_{jt}^D$ set by that bank. However, the household may not deposit at other banks; that is, banks have market power in setting deposit rates. All banks behave identically in equilibrium, so we drop the subscript j in what follows. Cash earns a net return of zero, and bonds pay the policy rate i_t . Hence, households' budget constraint is

$$(2) \quad C_t + D_t + M_t + B_t \leq \frac{W_t}{P_t} H_t + \frac{1 + i_{t-1}}{1 + \pi_t} B_{t-1} + \frac{1 + i_{t-1}^D}{1 + \pi_t} D_{t-1} + \frac{M_{t-1}}{1 + \pi_t} + \Pi_t + T_t,$$

where P_t is the price level at t , $1 + \pi_t = P_{t-1}/P_t$ is inflation from $t - 1$ to t , Π_t denotes total dividends paid out to the household by firms and banks, and T_t denotes lump-sum transfers from the government. Households' problem is to maximize (1) subject to (2) and the non-negativity constraints $B_t, D_t, M_t \geq 0$. The solution to households' problem will determine the deposit demand function $D_t(i_t^D, i_t)$ taken as given by each bank j in period t .⁶

B. Intermediate goods firms

Intermediate goods firms are set up without funds of their own and operate for two periods. They produce goods that are sold to monopolistic retailers $k \in [0, 1]$ at a competitive nominal price P_t^I . There are two types of firms: *bank-dependent* (fraction ξ) and *non-bank-dependent* (fraction $1 - \xi$). Like households, each bank-dependent firm is matched with a single bank j and may borrow only from that bank (at nominal rate $1 + i_{jt}^L$). Non-bank-dependent firms instead borrow by issuing safe one-period bonds directly to households at the policy rate $1 + i_t$. The two types of firms operate distinct types of capital that trade at competitive real prices $Q_t^{K,b}$ and $Q_t^{K,nb}$ (respectively), but they hire from a single labor market with competitive nominal wage W_t .

When an intermediate producer is born, it borrows in order to buy capital. In the second period it produces and sells output, sells back undepreciated capital, repays its debt and closes shop. Firms operate a decreasing-returns-to-scale technology using capital K_t and labor H_t , with a productivity parameter that differs across firm types. The production function for a firm of type $z \in \{b, nb\}$ is then $Y_t = A^z (K_t^\alpha H_t^{1-\alpha})^\nu$, with $\alpha \in (0, 1)$ (so that α is the capital share) and $\nu \in (0, 1)$ (capturing decreasing returns to scale).⁷ The problem faced by bank-dependent firms is

$$(3) \quad \max_{K_t, H_t} \frac{P_t^I}{P_t} \cdot A^b (K_t^\alpha H_t^{1-\alpha})^\nu + (1 - \delta) Q_t^{K,b} K_t - \frac{1 + i_{t-1}^L}{1 + \pi_t} Q_{t-1}^{K,b} K_t - \frac{W_t}{P_t} H_t,$$

⁶Due to the presence of risk-free bonds, deposit demand depends on both the deposit rate set by bank j and the policy rate, as demonstrated by (B.6) and (B.7) in the Online Appendix.

⁷With constant returns to scale, frictions in bank lending would become much less relevant. Any shortfall in investment by bank-dependent firms would be almost entirely undone by non-bank-dependent firms in equilibrium (Koby and Wolf, 2020).

where $\delta \in (0, 1)$ denotes the depreciation rate of capital. Firms' first-order conditions yield their loan demand curve $L_t(i_t^L)$, which is taken as given by banks.⁸

The problem of non-bank-dependent firms is identical to that of bank-dependent firms except for the fact that their productivity is A^{nb} , they borrow directly from households by issuing one-period risk-free bonds at the nominal rate $1 + i_t$, and they trade capital at price $Q_t^{K,nb}$.

C. Banks

Banks extend loans L_t and purchase safe, long-term government bonds B_t^L using their net worth N_t as well as by issuing deposits D_t . Their balance sheet constraint is

$$(4) \quad L_t + Q_t^B B_t^L = D_t + N_t.$$

Long-term bonds are modeled similarly to those in Hatchondo and Martinez (2009): a bond matures with probability $1/\tau$ each period (so that the expected maturity is τ) and yields a nominal payoff of 1 at maturity.⁹ The (real) bond price in period t is denoted Q_t^B . No-arbitrage implies that from $t = 0$ forward, bond returns equal the risk-free rate, $(1 + i_t)P_t Q_t^B = (1 - \tau^{-1})P_{t+1} Q_{t+1}^B + \tau^{-1}$.

Banks have market power in setting deposit and loan rates, since each household and bank-dependent firm is constrained to deal with a single bank. In each period, a bank sets a deposit rate i_t^D , a loan rate i_t^L , and bond holdings B_t^L , taking as given households' deposit demand $D_t(i_t^D, i_t)$, intermediate firms' loan demand $L_t(i_t^L)$, and the bond price Q_t^B .

Banks face two frictions in choosing the composition of their balance sheets. First, bank lending is constrained by net worth. A bank with net worth N_t that issues loans L_t incurs a cost $\Psi^L(N_t, L_t)$ that is homogeneous (of degree one), decreasing in net worth N_t , and increasing in loans L_t . The assumption that Ψ^L is homogeneous implies that loan spreads will depend on banks' loan-to-net worth ratio $\frac{L_t}{N_t}$. This cost is a smooth approximation of the types of net worth constraints typically present in macro-finance models in which bankers face moral hazard problems (Kiyotaki and Moore 1997; Bernanke, Gertler, and Gilchrist 1999). Second, it is costly for banks to lack a buffer of safe, liquid assets held against their deposits. We model this motive for banks to hold safe assets at cost $\Psi^D(Q_t^B B_t^L, D_t)$ that is homogeneous, decreasing in bond holdings $Q_t^B B_t^L$, and increasing in deposit issuance D_t . This type of cost may stem from regulation or from banks' need to mitigate fire sales of loans when facing unexpected deposit outflows (Drechsler, Savov, and Schnabl 2018; Bianchi and Bigio 2022).

In each period, banks pay out a fixed fraction $\gamma \in (\beta^{-1} - 1, 1)$ of their net worth

⁸See (A.12) in the Online Appendix for an exact expression for the loan demand curve $L_t(i_t^L)$.

⁹We assume $\tau < \frac{1}{\delta}$ to ensure that the price of bonds remains finite even as interest rates approach $-\delta$, which is the lowest value they can attain. (Otherwise, the user cost of capital goes to zero, and loan demand diverges.) We find that this parametric restriction holds in our calibration.

as dividends,¹⁰ so from $t = 0$ forward, they accumulate net worth according to

$$(5) \quad N_{t+1} = (1 - \gamma) \left(\frac{1 + i_t}{1 + \pi_{t+1}} Q_t^B B_t^L + \frac{1 + i_t^L}{1 + \pi_{t+1}} L_t(i_t^L) - \frac{1 + i_t^D}{1 + \pi_{t+1}} D_t(i_t^D, i_t) - \Psi^L(N_t, L_t) - \Psi^D(Q_t^B B_t^L, D_t) \right).$$

Banks' objective is to maximize the discounted stream of dividends,

$$(6) \quad \max_{B_t^L, i_t^L, i_t^D} \sum_{t=0}^{\infty} \beta^t \Lambda_t \gamma N_t \text{ s.t. (4), (5),}$$

where $\Lambda_t = \partial U(C_t, C_{t-1}, H_t) / \partial C_t$ denotes the household's marginal utility of consumption.

Banks enter $t = 0$ with a maturity-mismatched position, consisting of loans L^* , a quantity B^{L^*} of long-term bonds, and outstanding short-term deposits D^* (which are the quantities of loans, bonds, and deposits in the economy's long-run steady state, before the unanticipated $t = 0$ monetary policy announcement). Due to the maturity mismatch, banks experience capital gains or losses on bonds at $t = 0$, and their initial net worth is revalued to

$$(7) \quad N_0 = N^* + (1 - \gamma) \left(\frac{(1 - \frac{1}{\tau}) Q_0^B + \frac{1}{1 + \pi_0} \frac{1}{\tau}}{Q^{B^*}} - \frac{1 + i^*}{1 + \pi^*} \right) Q^{B^*} B^{L^*},$$

where N^* is steady-state net worth, Q^{B^*} is the steady-state bond price, and i^* , π^* denote the steady-state nominal rate and inflation, respectively.¹¹

D. Capital producers

There are representative capital goods producers $z \in \{b, nb\}$ that produce capital employed by bank-dependent and non-bank-dependent firms, respectively. Capital producers use the output of the final goods producer as an input. Capital in sector z sells at (real) price $Q_t^{K,z}$ in competitive markets. An investment of I_{t+1}^z in sector z at time t yields $(1 - \Xi(I_{t+1}^z / I_t^z)) I_{t+1}^z$ units of capital at $t + 1$, where $\Xi(\cdot)$ is a convex adjustment cost function. The problem faced by capital producers is

$$(8) \quad \max_{I_t^z} \sum_{t=0}^{\infty} \beta^t \Lambda_t \left(Q_t^{K,z} I_{t+1}^z (1 - \Xi(\frac{I_{t+1}^z}{I_t^z})) - I_{t+1}^z \right).$$

¹⁰The fixed-dividend assumption makes certain that banks do not drive leverage costs to zero by borrowing from households. This is consistent with the empirical evidence in Gropp et al. (2019). Repullo (2020) shows that our results would change if banks could flexibly issue equity: in the calibration section, although we do not allow for flexible issuance, we do assume banks receive periodic equity injections.

¹¹For simplicity of notation, we have assumed the steady-state price level is $P^* = 1$.

E. Standard New Keynesian ingredients

There is a continuum of monopolistic retailers $k \in [0, 1]$ that produce using intermediate goods purchased in competitive markets (using a linear production function). Their price-setting is subject to Rotemberg (1982) adjustment costs (parameterized by $\theta > 0$). There is a representative final goods producer that aggregates retailers' differentiated varieties (using a CES production function with elasticity of substitution $\varepsilon > 1$) and sells output at a competitive nominal price P_t .¹²

The government supplies long-term bonds elastically and sets lump-sum transfers (or taxes) T_t in each period in order to be able to repay interest to bondholders. The central bank makes an unanticipated announcement of its monetary policy at $t = 0$, under which it sets the nominal rate according to a rule

$$(9) \quad i_t = i(Y_t, \pi_t, i_{t-1}, \epsilon_t^{mp}),$$

where $\{\epsilon_t^{mp}\}$ is an unanticipated sequence of monetary shocks whose value is realized at $t = 0$ (since we assume perfect foresight). For our theoretical results, we will assume that the central bank employs a simple monetary policy rule meant to capture a negative shock to the interest rate. In our calibration, by contrast, we assume that the central bank follows a conventional Taylor rule. Both policy rules can be written in the general form (9).

II. Bank loan supply and the reversal rate

In this section, we present analytical results demonstrating the existence of a reversal rate for loan *supply* in our model. Specifically, we hold the loan and deposit demand functions fixed at their steady-state values, and we characterize the impulse response of bank credit supply for a given interest rate cut at $t = 0$. We provide conditions under which an interest rate cut beyond a certain point can be contractionary for credit supply at the margin. Finally, we apply our results to study the dynamic effects of monetary shocks and the effects of “low-for-long” monetary policies. All results are proven in Online Appendix B.

A. Setting

In order to prove sharp analytical results, we impose assumptions on some of our model's parameters. First, we assume that prices are fully rigid (i.e., we take the limit as price adjustment costs θ go to infinity). This permits the central bank to control the real rate, which we assume is set according to the policy

$$(10) \quad i_t = \begin{cases} i & 0 \leq t \leq T \\ i^* & t > T \end{cases},$$

¹²See Online Appendix A.1 for a detailed description of retailers and final goods producers.

where the economy's long-run natural rate is $i^* = \beta^{-1} - 1$ and $i < i^*$. That is, the central bank announces an unanticipated interest rate cut at time $t = 0$ until time T , at which point the interest rate returns to its natural level. Given the announced sequence of interest rates, bond prices satisfy

$$(11) \quad Q_t^B = \frac{1}{\tau} \sum_{s=0}^{\infty} \left(\prod_{r=0}^s \frac{1}{1+i_{t+r}} \right) \left(1 - \frac{1}{\tau}\right)^s \quad \text{and} \quad Q^{B*} = \frac{1}{\tau} \frac{1+i^*}{1+\tau i^*}.$$

Second, we assume that banks face a simple *capital constraint* on their lending, $L_t \leq \psi^L N_t$, and a *liquidity constraint* on their deposit issuance, $Q_t^B B_t^L \geq \psi^D D_t$.¹³ Banks' capital constraint requires that lending not exceed a multiple ψ^L of net worth.¹⁴ Banks' liquidity constraints require that their holdings of safe, liquid bonds exceed a fraction ψ^D of deposit issuance.

Third, we fix the loan and deposit demand curves at their steady-state values. Formally, in the loan demand equation derived from (3), we fix the price level $P_t = 1$ (since prices are fully rigid) and hold real wages W_t , the price of intermediate goods P_t^I , and the price of capital $Q_t^{K,b}$ at their steady-state values W^* , P^{I*} , and $Q^{K,b*}$, yielding a typical downward-sloping loan demand curve $L^*(i_t^L)$ that is time-invariant. Loan demand depends only on the loan rate, since bank-dependent firms do not substitute from loans to bonds when loan rates rise. Instead, in our model, this substitution takes place at the aggregate level: in general equilibrium, an increase in loan rates (all else equal) causes bank-dependent firms to reduce investment, putting downward pressure on the price of capital and allowing non-bank-dependent firms to profitably invest more.

We proceed analogously for deposit demand by fixing households' deposit demand curve $D^*(i_t^D, i_t)$, which depends on the deposit rate and the policy rate, at its steady-state level. In order to suppress general equilibrium effects, we hold households' total savings constant and derive deposit demand from households' optimal portfolio allocation across bonds, deposits, and cash given interest rates i_t^D and i_t . Deposit demand in the steady state can be derived as the solution to the problem¹⁵

$$(12) \quad \max_{B_t, D_t, M_t} \zeta \Phi(\mathcal{L}(D_t, M_t)) + \beta \Lambda^* ((1+i_t)B_t + (1+i_t^D)D_t + M_t) \\ \text{s.t. } B_t + D_t + M_t \leq S^*, B_t, D_t, M_t \geq 0,$$

where Λ^* denotes the household's marginal utility of consumption in steady state and S^* denotes its steady-state savings. In this formulation, deposit demand

¹³The capital constraint can be derived from a cost function $\Psi^L(L_t, N_t)$ that is equal to zero when $L_t \leq \psi^L N_t$ and infinite otherwise. An analogous cost function can be used to derive the liquidity constraint.

¹⁴For simplicity, we take ψ^L large enough that the net worth constraint does not bind in steady state, and we take ψ^D small enough that the liquidity constraint does not bind when the household is satiated in liquid assets.

¹⁵Here we use the fact that with fixed prices, inflation is equal to zero.

depends separately on the deposit rate and the policy rate (rather than just on the deposit spread $i_t - i_t^D$) because of the presence of cash.

Banks solve (6) with the household's discount factor held constant at its steady-state level Λ^* , taking as given the loan and deposit demand curves $L^*(i_t^L)$ and $D^*(i_t^D, i_t)$, the sequence of interest rates (10), and bond prices Q_t^B . Banks' initial net worth N_0 is determined according to (7), with the initial bond price Q_0^B and the steady-state bond price Q^{B*} given by (11).

B. Definition of the reversal rate

In this setting, we will be interested in studying the impulse response of lending (i.e., credit supply) to the policy rate cut (10). Until noted otherwise, we hold the length of the policy shock T fixed and consider the response of bank lending to different initial interest rates i . We let $L_t(i)$ denote bank lending at time t (in partial equilibrium) when the interest rate is cut to $i < i^*$ at $t = 0$. We define the *time- t reversal rate* to be the interest rate below which further cuts are contractionary for lending at time t .

DEFINITION 1: A *time- t reversal rate* is the highest interest rate i_t^{RR} such that $L_t(i)$ is increasing in i for all $i < i_t^{RR}$.¹⁶

The reversal rate relates to the *marginal* effect of an interest rate cut on lending. If i_t^{RR} is the time- t reversal rate, then if the central bank cuts rates to some $i < i_t^{RR}$, lending at time t is less than it would have been if the bank had cut rates only to i_t^{RR} . However, it may still be the case that time- t lending $L_t(i)$ under this policy is greater than lending in the economy's long-run steady state, so that the *total* effect of the rate cut on lending is still positive.

Note that the reversal rate is permitted to depend on the horizon t of the impulse response function. That is, in principle, it is possible that decreasing the policy rate below i may be contractionary for lending at some time t while at the same time stimulating lending at some other time s . In Section II.D, we will provide conditions under which the reversal rate is increasing as a function of the horizon, so that if an interest rate cut is contractionary for time- t lending at the margin, then it is also contractionary for lending at all times $s > t$.

C. The bank's problem

We now solve the bank's problem in the setting of Section II.A. By holding loan and deposit demand constant, we will be able to isolate the effect of the monetary policy shock (10) on bank credit supply and theoretically provide conditions under which a reversal rate exists.

¹⁶Formally, $i_t^{RR} = \sup\{\tilde{i} : L_t(i) < L_t(i') \forall i < i' \leq \tilde{i}\}$. Note that under our definition, if a time- t reversal rate exists, then it is unique.

The bank's problem (6) reduces to choosing long-term bond holdings B_t^L as well as loan and deposit rates i_t^L, i_t^D to maximize net interest income period-by-period.¹⁷ In this environment, given that the loan and deposit demand curves are static, a bank's net interest income in a period depends only on its net worth N_t and the policy rate i_t .

$$(13) \quad NII(N_t, i_t) = \max_{B_t^L, i_t^L, i_t^D} i_t Q_t^B B_t^L + i_t^L L^*(i_t^L) - i_t^D D^*(i_t^D, i_t)$$

s.t. (4), $L^*(i_t^L) \leq \psi^L N_t$, $Q_t^B B_t^L \geq \psi^D D^*(i_t^D, i_t)$.

The solution to the bank's problem (13) can be written in compact form as

$$(14) \quad i_t^L = \underbrace{i_t}_{\text{Marginal cost}} + \underbrace{\frac{1}{\varepsilon_t^L}}_{\text{Mark-up}} + \underbrace{\lambda_t + \mu_t}_{\text{Constraints}},$$

$$(15) \quad i_t^D = \underbrace{i_t}_{\text{Marginal benefit}} - \underbrace{\frac{1}{\varepsilon_t^D}}_{\text{Mark-down}} + \underbrace{(1 - \psi^D)\mu_t}_{\text{Liq. constraint}}.$$

Here, ε_t^L and ε_t^D denote the semi-elasticities of loan and deposit demand with respect to i_t^L and i_t^D , respectively.¹⁸ The terms λ_t and μ_t represent the Lagrange multipliers on the bank's net worth and liquidity constraints, respectively. When the constraints are slack, loan (deposit) rates are set to the policy rate i_t plus a mark-up (minus a mark-down); when they bind, rates are determined by the constraints.

When banks are unconstrained, (14) and (15) illustrate that monetary policy is transmitted to credit supply through the standard *bank lending* channel of monetary policy. A decrease in i_t , the return on bonds, reduces banks' opportunity cost of lending, so they offer lower loan rates to borrowers, increase their lending activity, and finance this lending by setting lower deposit rates.

We will be particularly interested in the case in which banks' net worth constraints bind. In this regime, their lending is fully determined by their net worth, $L_t(i) = \psi^L N_t(i)$. The standard bank lending channel of monetary policy is therefore shut down. Instead, monetary policy is transmitted to banks' credit supply through two channels by which interest rate cuts affect banks' net worth: a *capital gains channel* and a *net interest income channel*. A rate cut announced at $t = 0$ leads to a revaluation of assets initially held on bank balance sheets. Since banks enter with a maturity mismatch, an interest rate cut has an unambiguous positive

¹⁷We prove this fact in Online Appendix B.1.

¹⁸Specifically, $\varepsilon_t^L = -\frac{L^{*'}(i_t^L)}{L^*(i_t^L)} \Big|_{i_t^L}$ and $\varepsilon_t^D = \frac{1}{D^*(i_t^D, i_t)} \frac{\partial D^*(i_t^D, i_t)}{\partial i_t^D} \Big|_{(i_t^D, i_t)}$.

effect on bank net worth through the capital gains channel. On the other hand, it is possible for a policy rate cut to depress banks' net interest income, thereby reducing their net worth. For instance, when rates are in negative territory, it is difficult for banks to fully pass on rate cuts to their depositors, who have the option to hold cash.¹⁹

The case in which banks are liquidity-constrained is quite similar and less empirically relevant – banks have tended to hold excess liquidity even in countries with negative rates. We therefore postpone discussion of this regime to Online Appendix B.1.

D. Existence of the reversal rate

The discussion above suggests that when banks are constrained, an interest rate cut can trigger a reversal in bank lending if the deterioration of banks' interest income outweighs the effect of capital gains, $dN_t(i)/di < 0$. Figure 1 illustrates that under these conditions, we can expect that a reversal rate will exist: interest rate cuts eventually depress banks' net worth enough to constrain their lending. Until banks become constrained, rate cuts stimulate lending. Past that point, further cuts reduce net worth and credit supply. The following proposition provides a characterization of the reversal rate in line with this logic.

PROPOSITION 1 (Characterization): *Suppose i is the highest interest rate satisfying the following two properties:*

- 1) *The net worth constraint binds (or both constraints bind) at t for all $i' \leq i$;*
- 2) *Time- t net worth is increasing in the interest rate, $\frac{dN_t(i)}{di} > 0$, for all $i' < i$.*

Then i is the time- t reversal rate i_t^{RR} .

It is worth pointing out that this characterization of the reversal rate says nothing about whether the reversal rate should be positive or negative. Indeed, in our calibration, we find that even though the reversal rate for short horizons is negative, it is possible for the reversal rate at long horizons to be slightly positive.

Applying the Envelope Theorem to banks' problem (13), the effect of a change in interest rates on net interest income NII_t at time t , holding net worth fixed, is

$$(16) \quad \frac{\partial NII(N_t, i_t)}{\partial i_t} = Q_t^B B_t^L + (i_t - i_t^D) \frac{\partial D^*(i_t^D, i_t)}{\partial i_t}.$$

Intuitively, an interest rate cut reduces the interest income that banks receive from their bond holdings. However, it can also generate an inflow of deposits:

¹⁹See, for instance, Bech and Malkhozov (2016), Eggertsson et al. (2019), or Eisenschmidt and Smets (2019), who document a collapse in pass-through to deposit rates when the policy rate enters negative territory.

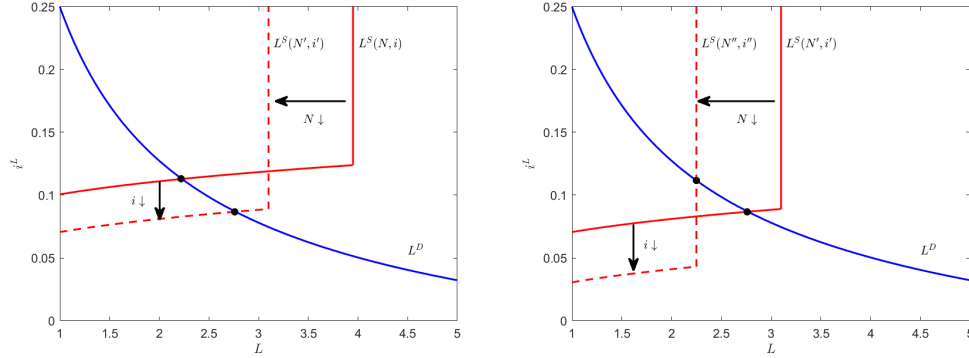


FIGURE 1. ILLUSTRATION OF THE REVERSAL MECHANISM. LEFT PANEL: THE POLICY RATE IS CUT FROM $i = 0.03$ TO $i' = 0.01$. BANK NET WORTH IS REDUCED FROM N TO N' , BUT BANKS REMAIN UNCONSTRAINED, SO CREDIT SUPPLY INCREASES. RIGHT PANEL: THE POLICY RATE IS CUT FURTHER FROM $i' = 0.01$ TO $i'' = -0.01$. BANK NET WORTH IS REDUCED FROM N' TO N'' , AND BANKS BECOME CONSTRAINED, *reducing* CREDIT SUPPLY.

bonds become less attractive relative to deposits, so households are encouraged to deposit at the bank ($\partial D^*(i_t^D, i_t)/\partial i_t < 0$). The bank can then decrease its deposit rate without fearing an erosion of its deposit base, allowing it to maintain its interest margins. When this substitution effect is weak enough, a reduction in i (holding net worth fixed) is guaranteed to reduce bank net interest income, meaning that rate cuts exert downward pressure on bank net worth through the *net interest income channel*.

In fact, in our setting, the presence of cash implies that the substitution from bonds to deposits is shut down when the policy rate is sufficiently low.

LEMMA 1: *There exists \underline{i} such that deposit demand is independent of the policy rate, $\frac{\partial D^*(i_t^D, i_t)}{\partial i_t} = 0$, for all $i_t \leq \underline{i}$.*

When $i < 0$, at least, households no longer hold bonds, since cash delivers a higher return. Households then do not substitute into deposits from bonds following a policy rate cut. Therefore, when interest rates are low enough, a further interest rate cut is guaranteed to decrease banks' net interest income: banks' income from their bond holdings is reduced, but they cannot pass lower rates on to depositors without losing some of their deposit base.²⁰

LEMMA 2: *Banks' net interest income is increasing in the policy rate i_t (holding net worth N_t fixed) when rates are sufficiently low: $\frac{\partial NII(N_t, i_t)}{\partial i_t} > 0$ for all N_t and*

²⁰If firms could substitute from loans to bond funding, there would be an additional effect: a decrease in the policy rate would cause a substitution away from loans and into bonds, *decreasing* bank profitability.

$$i_t \leq \underline{i}.^{21}$$

We can then decompose the effect of an interest rate cut on bank net worth into the part attributable to the capital gains channel and the part attributable to the interest income channel. To this end, define $N_t(N_0, i)$ to be bank net worth at time t when the bank's initial net worth is N_0 and the policy rate is cut to i .²² Initial net worth N_0 is itself a function of i , determined by (7) and (11). Then

$$(17) \quad \frac{dN_t}{di} = \underbrace{\frac{\partial N_t}{\partial N_0} \frac{dN_0}{di}}_{\text{Capital gains}} + \underbrace{\frac{\partial N_t}{\partial i}}_{\text{NII}}.$$

With this decomposition, it is possible to prove two simple facts.

LEMMA 3: *The strength of the capital gains channel, $\frac{\partial N_t}{\partial N_0} \frac{dN_0}{di}$, approaches zero as either:*

- *The horizon $t \rightarrow \infty$, or*
- *Steady-state bond holdings $B^{L*} \rightarrow 0$ (holding steady-state net worth N^* fixed).²³*

This result captures the fact that the capital gains channel is less relevant (1) when considering bank net worth far in the future (after some long-term bonds mature), or (2) when banks' initial bond holdings are small. Banks' initial capital gains are largely irrelevant in determining their net worth far in the future, and when banks do not initially have a significant maturity mismatch, the revaluation of their assets triggered by an interest rate cut is limited.

On the other hand, when an interest rate cut decreases banks' interest income, then the effect of an interest rate cut through the net interest income channel is to reduce bank profitability and net worth at all future dates.

LEMMA 4: *The effect captured by the interest income channel, $\frac{\partial N_t}{\partial i}$, is positive whenever $i < \underline{i}$ (defining \underline{i} as in Lemma 1) and $t < T$.*

Lemmas 3 and 4 can be used to establish sufficient conditions for the existence of a reversal rate.

PROPOSITION 2 (Existence for small maturity mismatch): *There exists \underline{B}^L such that whenever banks' steady-state bond holdings are $B^{L*} \leq \underline{B}^L$, a time- t reversal rate exists for all $0 < t \leq T$.*

²¹The threshold \underline{i} is defined in Lemma 1.

²²Formally, $N_t(N_0, i)$ is the net worth at time t of a bank that begins at $t = 0$ with net worth N_0 and solves (13) in each period, taking as given the interest rate sequence (10), the sequence of bond prices Q_t^B given by (11), and the loan and deposit demand schedules $L^*(i^L)$, $D^*(i^D, i)$.

²³Specifically, we consider a fixed value of steady-state net worth N^* and take B^{L*} to zero in (7), which determines banks' initial net worth N_0 .

PROPOSITION 3 (Existence for long horizons): *There exists \underline{T} such that when the length of the policy shock (10) is $T \geq \underline{T}$, a time- t reversal rate exists for all $t \in [\underline{T}, T]$.*

That is, there exists a time- t reversal rate whenever banks' initial bond holdings are sufficiently small or when the horizon t considered is sufficiently long. From Lemmas 3 and 4 it is clear why this should be the case. As interest rates are cut into negative territory, intermediation booms and banks lever up to their constraints. However, their profit margins are compressed. For a small initial maturity mismatch, or long horizons, the capital gains channel is weak. The interest income channel dominates, so a further interest rate cut drags down bank net worth at time t , which then causes a *reduction* in aggregate lending.

The logic underlying our existence results also highlights a property of the *dynamic* response of bank credit supply to monetary shocks. Since the capital gains channel becomes weak relative to the net interest income channel at long horizons, an interest rate cut can stimulate lending in the short run while causing a contraction in lending in the long run. In our model, this can occur if the time- t reversal rate i_t^{RR} is increasing in t , e.g. if $i_t^{RR} < i < i_{t+s}^{RR}$.

Of course, this argument assumes that bank lending is limited by net worth. Hence, we assume liquidity demand is large enough that banks are capital-constrained rather than liquidity-constrained: deposit demand is sufficient to ensure banks always have ample funds to invest in safe bonds.

LEMMA 5: *There exists $\underline{\zeta}$ such that if the liquidity demand parameter $\zeta \geq \underline{\zeta}$, then banks' liquidity constraints are slack in each period t for any interest rate i announced by the central bank at $t = 0$.*

As long as reversals in lending are triggered by banks' net worth constraints, the time- t reversal rate is increasing as a function of t .

PROPOSITION 4 (Dynamics of the reversal rate): *Suppose $\zeta \geq \underline{\zeta}$. If a time- t reversal rate $i_t^{RR} < \underline{i}$ exists for some $t < T$, then i_{t+1}^{RR} exists and is (weakly) greater than i_t^{RR} .*

Proposition 4 implies that a central bank that attempts to stimulate lending in the long run cannot infer the success of its policy from the short-term response of bank credit: an initially stimulative interest rate cut can eventually backfire, reducing total lending over the horizon considered. In Section III, we demonstrate that this result is borne out quantitatively as well.

E. "Low-for-long" monetary policies

A key question facing a central bank attempting to stimulate the economy is whether to implement "low-for-long" monetary policies, promising extended periods of low interest rates. This consideration has become especially relevant in the past decade, as inflation and demand have at times remained stubbornly

below target. In this section, we study the implications of low-for-long interest rate environments for bank credit supply and provide conditions under which they can be contractionary in the long run.

We again consider monetary policies of the form (10). Up until this point, we have held the length of the shock T fixed and considered comparative statics with respect to the level of the policy rate i . In this section, instead, we consider comparative statics with respect to T with i held fixed. We now make the dependence on T explicit and let $L_t(i, T)$ denote lending at time t when the central bank announces that it will set interest rate i until time T . Our interest is in characterizing how the impulse response of bank credit supply, $L_t(i, T)$, depends on T .

In our model, a low-for-long policy can compress banks' interest margins and drain their net worth. Therefore, if interest rates are held at i , banks' lending can eventually contract if their net interest income at that level of rates is insufficient to permanently sustain the steady-state level of lending L^* , as implied by the following inequality:

$$(18) \quad NII(N, i) \leq \frac{\gamma}{(1-\gamma)\psi^L} L^* \quad \forall N \leq N^*.$$

This inequality is guaranteed to hold if banks' net worth constraints are sufficiently tight (ψ^L is low), or if their dividend payout rate γ is sufficiently high. Moreover, it will tend to hold when banks' profitability is low, e.g., if loan and deposit demand are elastic enough.

Our main result on the effect of low-for-long policies is then:

PROPOSITION 5 (The effects of low-for-long rates): *Fix $i < i^*$, and suppose that (18) holds when the policy rate is i . Then there exists \underline{T} such that if $T > \underline{T}$, $L_t(i, T) < L^*$ for all $t \in [\underline{T}, T]$.*

Simply put, as the horizon of the interest rate cut is extended, eventually there comes a point at which bank lending contracts. Unlike our previous results, which were about the *marginal* effects of monetary stimulus, Proposition 5 implies that the *total* effect of the stimulus is contractionary (in the sense that lending eventually falls below its steady-state level).²⁴

The intuition is straightforward: extending the length of the interest rate cut further and further has diminishing returns in terms of capital gains at $t = 0$. By contrast, extending the interest rate cut decreases banks' net worth at future dates through the net interest income channel (and this effect does not weaken with the horizon T). Therefore, at some point, the loss of interest income outweighs the initial capital gains, causing banks to become constrained and resulting in

²⁴We characterize the policy's effect on total lending because the marginal effects of extending the length T of the policy rate cut vary with the horizon t considered: increasing T always increases lending at sufficiently short horizons through the capital gains channel, whereas it can decrease lending at longer horizons.

a contraction of lending. When banks face financial constraints, “low-for-long” policies are bound to eventually become counterproductive.

In our calibration, inequality (18) holds for low values of i , so low-for-long policies indeed eventually become contractionary for bank lending. General equilibrium effects imply that such policies will lead to a recession and a reduction in aggregate investment as well. This prediction stands in stark contrast to standard New Keynesian models, in which promises to keep interest rates low for extended periods provide implausibly strong stimulus (the forward guidance puzzle). In Section III.E, we therefore demonstrate that when embedded in a quantitative model, our mechanism dampens the power of forward guidance.

F. Discussion of assumptions

Our model embeds several particular assumptions about the form of loan and deposit demand, so it is natural to wonder the extent to which the results generalize beyond the specific setting considered here.

In order to address this question, we consider the partial equilibrium problem of a monopolistic bank (13) that faces arbitrary loan and deposit demand functions of the form $L^*(i^L, i)$ and $D^*(i^D, i)$ (rather than the ones implied by our model). We assume that both demand schedules satisfy standard regularity conditions,²⁵ and that loan demand $L^*(i^L, i) \rightarrow \infty$ as $i^L \rightarrow -\delta$ (guaranteeing that loan demand becomes arbitrarily large as the user cost of capital approaches zero, as in standard macroeconomic models).

All of our main analytical results follow from imposing two additional properties on top of these basic assumptions.

PROPERTY 1: *When the policy rate is low enough, further interest rate cuts decrease banks’ net interest income. There exists \underline{i} such that for all N and $i < \underline{i}$, $\frac{\partial NII(N, i)}{\partial i} > 0$.*

PROPERTY 2: *Banks’ net worth imposes a constraint on their lending: they face a capital constraint $L_t \leq \psi^L N_t$ with $\psi^L \in (0, \infty)$.*

Note that the liquidity constraint, $\psi^D > 0$, is not essential. In our model, it aids only in proving Property 1, since a reduction in i reduces banks’ interest income from their bond holdings.

As we demonstrate in Online Appendix B.2, if the loan and deposit demand functions satisfy Property 1 and there is a net worth constraint on bank lending (Property 2), then analogues of Propositions 2 and 3 hold: a reversal rate exists for sufficiently long horizons or when banks’ bond holdings are small enough. That is, the existence of the reversal rate depends only on the fact that interest rate cuts in negative territory reduce bank profits and therefore lending as well. These properties also suffice to prove an analogue of our low-for-long result,

²⁵See Online Appendix B.2.

Proposition 5. For these reasons, our model’s main results should be interpreted as providing predictions that could be expected to hold in a much more general class of economies that are consistent with the observed behavior of bank profits and lending. Proposition 4 additionally requires a condition on deposit demand that we describe in further detail in the Online Appendix, which implies banks are not liquidity-constrained in equilibrium.

Importantly, both of the key properties have empirical support. There is broad agreement in the literature that, at least during the recent period of low rates in Europe, decreases in interest rates have had adverse effects on bank’ net interest margins (Alessandri and Nelson 2015; Borio, Gambacorta, and Hoffmann 2017; Claessens, Coleman, and Donnelly 2018). More consequential is the assumption that bank net worth is an important determinant of lending, which has been the subject of some debate. Heider, Saidi, and Schepens (2019), for instance, demonstrate that when rates entered negative territory, banks that were more reliant on deposits (and therefore experienced a greater decline in profits) reduced their lending volumes relative to other banks, but they also increased their risk-taking. Bittner et al. (2022) find that net worth was a key driver of lending for Portuguese banks during the period of negative rates as well. Other papers, such as Bräuning and Wu (2017) and Wang (2022) have found that lending volumes respond positively to further monetary accommodation when rates are low, but these results are not inconsistent with our proposed mechanism: in the model, interest rate cuts can increase bank net worth even in negative territory through the capital gains channel.

III. Quantitative Evaluation

In this section, we investigate the quantitative relevance of our theoretical mechanisms and demonstrate that the reversal rate is also present in general equilibrium. We begin by describing our calibration strategy. Our theoretical model is somewhat stylized, so in this section we also outline the adjustments to our model needed to better match the data. Then, we analyze the economy’s response to monetary policy shocks in order to provide an estimate of the reversal rate. Finally, we illustrate the implications of our “low-for-long” result for the power of forward guidance.

A. Solution concept

We solve the model under perfect foresight, following an unanticipated monetary policy shock at $t = 0$. Our solution algorithm (implemented in Dynare) finds the full nonlinear solution of the corresponding system of equations and thus does not rely on perturbation methods. This is important because our economy inherently features large non-linearities and non-monotonicities.

B. Calibration strategy

We calibrate our model to the Euro area, where negative interest rates were first implemented in 2014. We set the length of a period to one quarter.

Conventional parameters: Several of the parameters in our model have conventional values in the DSGE literature. These are the preference parameters (σ, h, φ) , technology parameters (δ, α) , the parameters (ε, θ) describing the elasticity of substitution across monopolistic retailers' goods and the cost of adjusting their prices, and the parameters of the Taylor rule we will specify. The parameter values are summarized in Table 1, and Online Appendix C.2 provides sources for the value of each parameter.

TABLE 1—CONVENTIONAL DSGE PARAMETERS.

Parameter	Description	Value
σ	IES parameter	1
h	Habit formation	0.62
φ	Inverse Frisch elasticity	2
δ	Capital depreciation	0.025
α	Capital share	0.36
ε	Retail price elasticity	3.9
θ	Rotemberg cost	70.7
ϕ^π	Taylor rule inflation coefficient	2.74
ρ^{mp}	Taylor rule persistence	0.93

Households: It remains to calibrate two of households' conventional preference parameters: the subjective discount factor β and the disutility of labor χ . We set $\beta = 0.995$ to match a real interest rate of 2% per annum, and we set $\chi = 0.41$ as a normalization so that households work a quarter of their available time in the economy's steady state.

We must then specify the payoff $\Phi(\mathcal{L})$ that households derive from liquid asset holdings, the liquidity aggregator $\mathcal{L}(D, M)$, and the parameter ζ that scales their demand for liquid assets. We assume deposits and cash are perfect substitutes, so liquid asset holdings can be written as $\mathcal{L}(D, M) = D + M$. We make this assumption to ensure that the deposit rate behaves as it does in the data: when the policy rate i_t is positive, the deposit spread $i_t - i_t^D$ is positive as well, but when i_t goes negative, the deposit rate remains stuck at zero. The utility from liquid assets Φ has a satiation point \mathcal{L}^* , $\zeta\Phi(\mathcal{L}) = -\frac{1}{2}\zeta(\mathcal{L}^* - \min\{\mathcal{L}, \mathcal{L}^*\})^2$. The parameters ζ and \mathcal{L}^* will be calibrated to match banking data, so we specify their values when we describe the calibration of the banking sector.²⁶

²⁶Our assumption of a satiation point at \mathcal{L}^* , rather than negative returns to liquidity for $\mathcal{L} > \mathcal{L}^*$ (e.g. $\Phi(\mathcal{L}) = -\frac{1}{2}(\mathcal{L}^* - \mathcal{L})^2$), is conservative. If there were negative returns to liquid assets for $\mathcal{L} > \mathcal{L}^*$,

Finally, we make one change to the specification of households' portfolio allocation problem. To isolate our novel channel of monetary transmission through banks, aggregate demand and the investment of non-bank-dependent firms should respond to monetary stimulus exactly as they would in a conventional model. Therefore, we would like households to hold bonds and discount at the policy rate even when cash yields a higher return. This, in turn, will cause non-bank-dependent firms to discount at the policy rate, since they issue bonds directly to households. In order to allow these conventional channels to operate when rates are negative, we assume that households face an additional constraint: they may not invest more than a quantity $\bar{\mathcal{L}}$ of funds in liquid assets, so we add the constraint $D_t + M_t \leq \bar{\mathcal{L}}$ to households' problem. This constraint can be motivated by the fact that (1) it is costly to hold cash in large quantities, and (2) retail depositors are typically limited in the quantities they can deposit.²⁷ For convenience, we set the limit $\bar{\mathcal{L}}$ on liquid assets equal to the satiation point \mathcal{L}^* , so that there is not a discontinuous jump in deposit holdings when the policy rate goes into negative territory.

Intermediate goods firms: The curvature parameter ν in firms' production function is set to 0.85 to match a steady-state consumption-investment ratio of 2.7, close to the value reported by Coenen et al. (2019). We identify bank-dependent firms with small and medium enterprises (SMEs). In Eurostat data, such firms comprise 99.8% of the total universe of firms and account for 55.8% of output. Hence, we set the fraction of bank-dependent firms $\xi = 0.998$ and the relative productivity of bank-dependent firms $A^b/A^{nb} = 0.42$ to match these two targets. Since such a large proportion of firms are bank-dependent, their productivity must be significantly lower to account for the fact that non-bank-dependent firms produce a large share of aggregate output. In our sensitivity analysis in Online Appendix C.2, we show that what matters for our results is the share of output produced by bank-dependent firms rather than the fraction ξ of firms that are bank-dependent. Finally, the productivity of non-bank-dependent firms A^{nb} is normalized to one.

Banks: We begin by making an adjustment to our model of banks. In our benchmark model, we assumed for analytical convenience that banks are monopolists in both the deposit and loan markets. However, when the parameters determining aggregate loan and deposit demand are calibrated realistically, the resulting demand curves are relatively inelastic, resulting in spreads that are quantitatively too large if we maintain the assumption of complete monopoly. In order to match spreads, in our quantitative model we instead assume that banks engage in monopolistic competition: loans and deposits provided by different banks are

households would continue to scale up their deposit holdings even as rates head deep into negative territory, putting a further drag on bank profitability.

²⁷Alternatively, this constraint could be viewed as a reduced-form representation of the fact that some investors have a "preferred habitat" and save in bonds rather than deposits or cash. It is possible to micro-found this constraint by assuming that households have two types of members: "depositors" who can invest in liquid assets and "savers" who cannot.

imperfect substitutes, as in Gerali et al. (2010) and Ulate (2021a). The household has a constant elasticity of substitution across deposits issued by different banks, and they can substitute towards cash when deposit rates go negative. The household's demand for bank j 's deposits is $D_{jt} = ((1 + i_{jt}^D)/(1 + i_t^D))^{-\varepsilon^D} D_t$ if $i_{jt}^D \geq 0$ and $D_{jt} = 0$ otherwise, where D_t is aggregate deposit demand at t , $\varepsilon^D < -1$ is the elasticity of substitution across deposits provided by different banks, and $1 + i_t^D$ is the usual CES price index given the rates set by individual banks. We derive this demand curve explicitly in Online Appendix ???. The important implication of this deposit demand curve is that aggregate deposit rates cannot go negative, since cash is a perfect substitute.

We also make one additional change to banks' problem: banks earn a marginal benefit μ^D per deposit issued. This income is meant to represent benefits banks receive from issuing deposits, e.g. fees charged to depositors or the benefits of using a relatively stable source of financing. This assumption helps our model to rationalize the fact that banks continue to take deposits even when rates are deep in negative territory: by issuing deposits, banks receive the benefit μ^D and can lend the proceeds to firms, making an additional spread $i^L - i$. We set $\mu^D = 50\text{bp}$ per annum to match the fees charged by German banks during the recent period of low rates.²⁸ Under this calibration, banks are always willing to take deposits for the interest rate cuts we consider, and equilibrium deposit rates are set according to $1 + i_t^D = \max \{ \varepsilon^D / (\varepsilon^D - 1) \cdot (1 + i_t + \mu^D), 1 \}$.

Similarly, a firm's demand for loans provided by bank j is given by $L_{jt} = ((1 + i_{jt}^L)/(1 + i_t^L))^{-\varepsilon^L} L_t$. Here, $\varepsilon^L > 1$ is the elasticity of substitution across loans provided by different banks (which is the key parameter we calibrate to match loan spreads), $1 + i_t^L$ is the usual CES price index, and L_t is aggregate loan demand at t . When banks engage in monopolistic competition in the loan market, equilibrium loan rates are set according to $1 + i_t^L = \varepsilon^L / (\varepsilon^L - 1) \cdot (1 + i_t + \partial\Psi^L / \partial L_t)$.

These specifications of loan and deposit demand can be micro-founded either by (1) directly assuming that the total funds raised by a firm are a CES aggregate of the quantity borrowed from different banks or by (2) assuming that firms face a discrete choice problem and face random taste shocks that affect their costs of borrowing from each bank (as in Anderson, De Palma, and Thisse 1989). We set $\varepsilon^L = 200$ to target a loan spread of 2% in steady state, as reported by Freriks and Kakes (2021), and we set $\varepsilon^D = -275$ to target a steady-state deposit spread of 1%, computed from the ECB's MIR database.

We now calibrate the remaining parameters determining households' deposit demand and banks' balance sheet composition. First, we set banks' dividend payout ratio γ , the deposit demand parameter ζ , and the maturity of long-term bonds τ to match three targets: a steady-state net worth-to-loan ratio of 0.155 (corresponding to an average Tier-1 capitalization ratio of 15.5% reported by

²⁸See, for instance, <https://www.wsj.com/articles/banks-in-germany-tell-customers-to-take-deposits-elsewhere-11614594601>.

Altavilla, Boucinha, and Peydró 2018), a steady-state loan-to-bond ratio on bank balance sheets of 3.6, and an average maturity of bank bond holdings of 3.4 years (both documented by Hoffmann et al. 2019). Finally, we set the satiation point of liquid asset demand equal to $\mathcal{L}^* = 6.93$ in order to match the increase in the deposit-to-GDP ratio reported in the ECB’s MFI data from 2000 until 2014, which is when interest rates first went negative.

Next, we parameterize the cost functions $\Psi^L(N, L)$ and $\Psi^D(Q^B B^L, D)$ faced by banks, corresponding to their capital and liquidity constraints, respectively. We assume that the function Ψ^L is such that banks’ marginal cost of lending, $\frac{\partial \Psi^L}{\partial L}$, is a convex function of the loan-to-equity ratio $\frac{L_t}{N_t}$,

$$\frac{\partial \Psi^L(N_t, L_t)}{\partial L_t} = \kappa^L \left(\max \left\{ \frac{L_t}{N_t} - \frac{L^*}{N^*}, 0 \right\} \right)^2,$$

where $\frac{L^*}{N^*}$ is the loan-to-equity ratio in steady state.²⁹ Under this specification, banks have a loan-to-equity target ratio $\frac{L^*}{N^*}$, and they pay a convex marginal cost for deviating from that target. The parameter κ^L is set to 0.018 so that a 1 percentage point increase in banks’ target capitalization ratio $\frac{L^*}{N^*}$ results in a 28bp increase in loan rates, as estimated by Macroeconomic Assessment Group (2010).³⁰ Parameter κ^L will be key in our calibration, since it modulates the strength of banks’ capital constraints. Our focus in the quantitative model is on capital constraints, so we set $\Psi^D(Q^B B^L, D) = 0$.³¹

For our analytical results, we assumed that banks’ net worth followed a particularly simple process: they simply paid out a fixed fraction of their net worth as dividends each period. To obtain more realistic dynamics of bank net worth, we make an adjustment to the process followed by bank equity. We assume that after paying out a fraction γ of their net worth as dividends, banks additionally receive a fixed quantity of new funds \hat{N} from the household at the beginning of each period.³² This assumption allows us to separate banks’ net worth-to-asset ratio (which will be governed by the parameter γ) from the persistence of their net worth, which would otherwise be too sluggish to recover from downturns. Our assumption is therefore conservative in the sense that it prevents the model from overstating the negative consequences of interest rate cuts for bank net worth in

²⁹Ulate (2021a) uses a similar specification for leverage costs such that *total* costs are approximately quadratic around a target leverage ratio.

³⁰Specifically, let $\frac{N^*}{L^*} = 0.155$ denote our estimated value of banks’ steady-state capitalization ratio. We choose κ^L so that $0.0028 = \kappa^L \left(\frac{L^*}{N^*} - \frac{L^*}{N^* + 0.01L^*} \right)^2$, since a 1% higher target capitalization ratio would be $\frac{N^* + 0.01L^*}{L^*}$.

³¹Quantitatively, liquidity constraints are less relevant: banks in Europe held excess reserves even when rates went negative. Likewise, banks in the model continue to hold bonds when $i < 0$.

³²The process followed by bank net worth in our model is a reduced-form version of that in Gertler and Karadi (2011) or Gertler, Kiyotaki, and Prestipino (2020): in those models, a fraction of “bankers” die in each period, returning their net worth to the household, and a fraction of “workers” become bankers and bring a fixed quantity of funds into the bank. We show in Online Appendix E how to micro-found our specification in that way.

the long run. We interpret the funds \hat{N} injected into banks each period as new equity issuance, so we set $\hat{N} = 0.016$ to match a 1% annual equity issuance-to-asset ratio on bank balance sheets (consistent with the ECB's MFI data).

Capital goods producers: Capital goods producers solve Problem (8). As is typically assumed, investment adjustment costs take a quadratic form, $\Xi(I_{t+1}^z/I_t^z) = \frac{\kappa^I}{2}(I_{t+1}^z/I_t^z - 1)^2$ for $z \in \{b, nb\}$. We set $\kappa^I = 5$ so that the elasticity of investment to a change in the price of capital is $1/\kappa^I = 0.2$, as estimated by Smets and Wouters (2003) for the Euro area.

Monetary policy: Unlike in our stylized theoretical model, for our calibration exercise we assume that monetary policy follows a conventional Taylor rule with inertia. There is an unanticipated monetary shock at $t = 0$, but from that point forward, the economy is deterministic. Hence, the monetary policy rule can be written as

$$(19) \quad \frac{1 + i_t}{1 + i^*} = \left(\frac{1 + i_{t-1}}{1 + i^*} \right)^{\rho^{mp}} \left(\frac{1 + \pi_t}{1 + \pi^*} \right)^{\phi^\pi (1 - \rho^{mp})} \exp(\epsilon_t^{mp}),$$

where i^* is the steady-state policy rate (and similarly for π^*), $\rho^{mp} = 0.93$ is the persistence of the nominal rate, $\phi^\pi = 2.74$ is the Taylor rule coefficient on inflation, and ϵ_t^{mp} is the time- t monetary shock.³³ There is no uncertainty after $t = 0$, so agents learn the full sequence of shocks ϵ_t^{mp} at $t = 0$. Our benchmark results will consider only a monetary shock ϵ_0^{mp} occurring at $t = 0$, but in Section IV.D we will also discuss other types of shocks that could cause an initial interest rate displacement.

C. Main results

In our main results, we seek to answer the following question: given an initial level of the interest rate, how does the economy respond to additional monetary stimulus? Specifically, we first study the effects of a marginal – minus 10 basis point – innovation ϵ_0^{mp} to the Taylor rule around the economy's steady state and report the impulse response functions. Then, we generate initial innovations of increasingly larger sizes and study impulse responses to an *additional* 10-basis point innovation to the Taylor rule. In other words, we compute three impulse responses: the IRF to a small 10-basis point shock in the vicinity of the steady state, the IRF to a large shock, and then the IRF to that large shock plus 10 basis points. We then compare the difference between the last two IRFs to the first IRF.

If we were to solve our model using a log-linear approximation, the economy's response to a 10-basis point Taylor rule innovation would be independent of the initial interest rate. Our solution method, by contrast, allows us to highlight the

³³The values of ρ^{mp} and ϕ^π are set to those estimated by the New Area-Wide Model II (Coenen et al. 2019).

TABLE 2—CALIBRATED PARAMETERS.

Parameter	Description	Value	Target
β	Time rate of preference	0.995	Real interest rate
χ	Disutility of labor	0.41	Labor hours
ν	Scale parameter	0.85	Consumption-investment ratio
ξ	Fraction of bank-dependent firms	0.998	Fraction of SMEs
A^{nb}	Non-bank-dependent firm productivity	1	Normalization
$\frac{A^b}{A^{nb}}$	Bank-dependent firm productivity	0.43	SME output share
ε^L	Elasticity of loan demand	200	Loan spread
ε^D	Elasticity of deposit demand	-275	Deposit spread
ζ	Liquid asset demand	0.0021	Loan-to-bond ratio $\frac{L^*}{B^{L^*}}$
\mathcal{L}^*	Liquid asset satiation point	6.93	2014 deposit-GDP ratio
γ	Bank dividend payout rate	0.08	Capitalization ratio $\frac{N^*}{L^*}$
\hat{N}	Bank equity injection	0.016	Equity issuance-to-asset ratio
τ	Long-term bond maturity	13.6	Bank asset maturity
κ^L	Leverage cost parameter	0.018	Elasticity of i^L to $\frac{L^*}{N^*}$
μ^D	Deposit issuance benefit	12.5bp	Deposit fees
κ^I	Capital adjustment cost	5	Elasticity of I_t to Q_t

non-linear (and possibly non-monotonic) response of aggregates to shocks as well as the dependence of the response on the level of interest rates.

Before describing our results, we point out two subtleties of our analysis. First, a reversal within our experiment necessarily applies to a particular variable at a particular horizon. For instance, our theoretical results suggest that the reversal rate for bank lending increases with the horizon t . Differently from our theoretical results, the calibrated general equilibrium model permits us to study the reversal rate for *any* aggregate quantity at any horizon. Second, given that our economy's constraints are smooth – in contrast to the constraints faced by banks in the stylized theoretical model – the economic mechanisms we highlight have consequences before aggregate variables display a full reversal, serving to dampen the effectiveness of monetary policy.

Figure 2 displays our main result. It depicts the impulse responses of bank lending and aggregate investment to an additional 10-basis point Taylor rule innovation for various initial interest rates. When the initial interest rate is greater than roughly -1%, additional monetary stimulus increases both bank lending and investment on impact, as in standard models. However, once the initial interest rate is below about -1%, this effect is reversed: monetary stimulus is contractionary for bank lending and investment. In fact, we find that the reversal rate (on impact) is -0.8% for aggregate investment and -1.3% for bank lending.

The reversal in bank lending and investment transmits to aggregate output as well. Figure 3 displays the marginal response of output to a 10-basis point Taylor rule innovation in two economies: a baseline economy in which the shock occurs in the vicinity of the steady state and an economy in which the shock occurs on top of

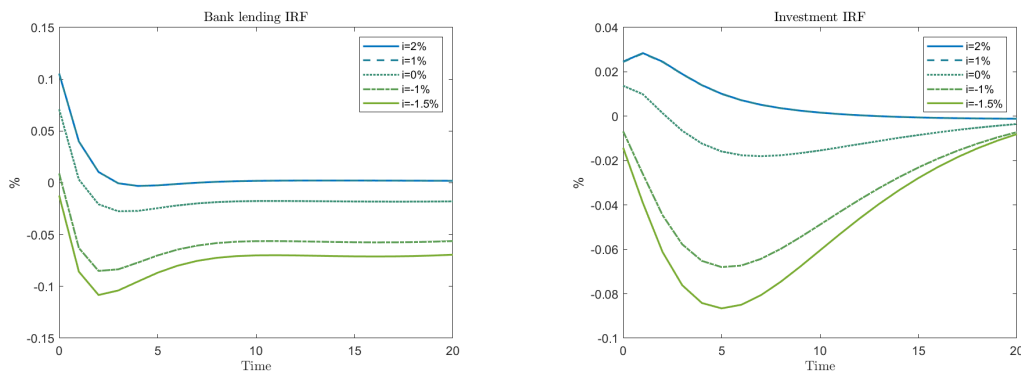


FIGURE 2. MARGINAL RESPONSES OF BANK LENDING (LEFT PANEL) AND AGGREGATE INVESTMENT (RIGHT PANEL) TO A 10-BASIS POINT TAYLOR RULE INNOVATION FOR VARIOUS INITIAL LEVELS OF THE INTEREST RATE i . THE PATH PLOTTED FOR EACH VARIABLE IS THE DIFFERENCE BETWEEN TWO IMPULSE RESPONSES: THE IMPULSE RESPONSE OF A TAYLOR RULE INNOVATION THAT WOULD REDUCE THE TIME-0 INTEREST RATE TO i , AND THE IMPULSE RESPONSE TO A TAYLOR RULE INNOVATION THAT IS GREATER BY 10 BASIS POINTS.

an innovation to the Taylor rule that, on its own, would have depressed the policy rate to -1%. When the economy begins at its steady state, the impulse response to a monetary shock is similar to that in a model without banking frictions. Once the reversal rate has been reached, however, the response of output changes substantially. Unlike investment and bank lending, the reversal in output occurs only with a four-quarter lag. An interest rate cut initially stimulates aggregate demand, boosting output. However, the reversal in investment gives rise to a gradual decline in the capital stock, reducing the economy's productive capacity and eventually depressing output.

Our quantitative results until this point have demonstrated that even when a reversal does not occur at the impact of a monetary shock, it may still occur in the future. For instance, in Figure 2, when the initial interest rate is 0%, an interest rate cut increases investment on impact but reduces it at longer horizons. Similarly, at longer horizons output experiences a reversal (Figure 3). Thus, the dynamic response predicted by Proposition 4 is also relevant in general equilibrium, and it can provide some guidance for the conduct of monetary policy. The main implication of this result is that even if an interest rate cut is initially successful at stimulating lending and investment, the effect may reverse later on.

D. The main mechanism

Near the reversal rate for bank lending, the economy's response to monetary shocks is driven by a persistent decline in bank profits and a corresponding increase in their lending costs and loan rates. Figure 4 illustrates the impulse response of banks' marginal cost of leverage and the corresponding increase in

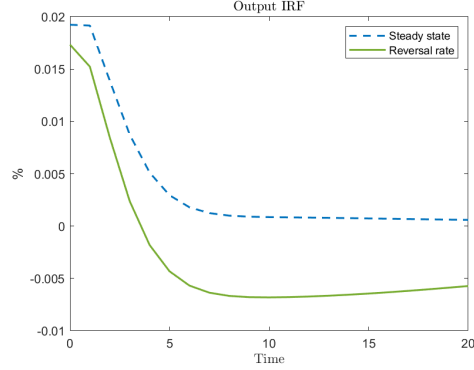


FIGURE 3. MARGINAL RESPONSE OF OUTPUT TO A 10-BASIS POINT TAYLOR RULE INNOVATION IN TWO ECONOMIES. IN THE BASELINE ECONOMY (BLUE LINE), THE SHOCK OCCURS WHEN THE ECONOMY IS AT ITS STEADY STATE. IN THE ALTERNATIVE ECONOMY (GREEN LINE), THE SHOCK OCCURS WHEN THE INITIAL INTEREST RATE IS EQUAL TO -1%.

the one-year real loan rate, $R_{t,t+4}^L = \prod_{s=1}^4 \frac{1+i_{t+s}^L}{1+\pi_{t+s}}$. Near the steady state, a negative innovation to the Taylor rule results in lower long-term loan rates, and the change in banks' leverage costs is negligible. However, near the reversal rate, the same shock actually increases loan rates due to the increase in banks' leverage costs. Due to the higher borrowing rates they face, bank-dependent firms demand less capital, reducing investment in that sector.

Bank lending $L_t = Q_t^{K,b} K_{t+1}^b$ can even decline at the impact of the shock, before any disinvestment has occurred, due to a reduction in the price of capital $Q_t^{K,b}$. To understand this result, it is conceptually useful to write bank-dependent firms' capital demand condition as an asset pricing equation,

$$(20) \quad Q_t^{K,b} = \frac{1}{R_t^L} (MPK_{t+1} + (1-\delta)Q_{t+1}^{K,b}) = \sum_{s=0}^{\infty} \frac{(1-\delta)^s}{\prod_{r=0}^s R_{t+r}^L} MPK_{t+s+1},$$

where MPK_t is the marginal product of capital for bank-dependent firms at time t and $R_t^L \equiv (1+i_t^L)/(1+\pi_{t+1})$ is the real loan rate. That is, the price of capital is equal to the discounted value of MPK_t , using the real loan rate as the discount rate. The higher discount rate on capital puts downward pressure on its price.

Figure 5 illustrates that the reversal in *aggregate* investment can be attributed to a reversal in the investment of bank-dependent firms. As their investment declines, lending shifts towards the non-bank-dependent sector, and monetary policy continues to stimulate the investment of non-bank-dependent firms. Indeed, near the reversal rate, a further interest rate cut stimulates their investment *more* than

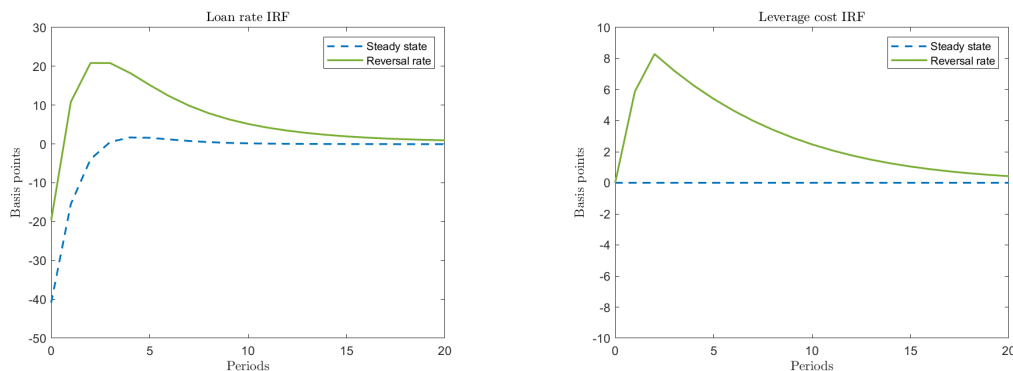


FIGURE 4. MARGINAL RESPONSE OF ONE-YEAR LOAN RATES (LEFT PANEL) AND BANK LEVERAGE COSTS (RIGHT PANEL) FOLLOWING A MINUS 10-BASIS POINT TAYLOR RULE INNOVATION IN TWO ECONOMIES. IN THE BASELINE ECONOMY (BLUE LINE), THE SHOCK OCCURS WHEN THE ECONOMY IS AT ITS STEADY STATE. IN THE ALTERNATIVE ECONOMY (GREEN LINE), THE SHOCK OCCURS WHEN THE INITIAL INTEREST RATE IS EQUAL TO -1% .

it would near the economy's steady state (due to the substitution of investment from the bank-dependent sector to the non-bank-dependent sector). Nevertheless, the net effect of an interest rate cut on aggregate investment remains negative.

It may seem surprising that despite the substitution towards investment in the non-bank-dependent sector, the reversal rate for aggregate investment is actually *higher* than the reversal rate for bank lending. The reason is that bank lending and loan rates both respond gradually over time to shocks as the capital stock and banks' net worth adjust, whereas investment is forward-looking: due to the presence of adjustment costs, it is optimal to smooth disinvestment over time. Indeed, it is clear from Figure 5 that the reversal rate for bank-dependent *investment* is actually higher than the reversal rate for aggregate investment.

E. The power of forward guidance

Following the Global Financial Crisis of 2008, when short-term interest rates were driven to zero, central banks have begun to experiment with forward guidance (i.e., promises of low rates in the future) to provide additional monetary stimulus without resorting to negative interest rates. The literature on forward guidance has encountered a major puzzle: from a theoretical perspective, promises of interest rate cuts further and further in the future have explosive stimulative effects on output in the present (Del Negro et al., 2012). On the other hand, the empirical evidence of the effectiveness of forward guidance has been mixed, and there has been no clear indication that promises of interest rate cuts in the long term are *more* effective than promises of stimulus in the present.

Our calibrated model allows us to reassess the forward guidance puzzle and the

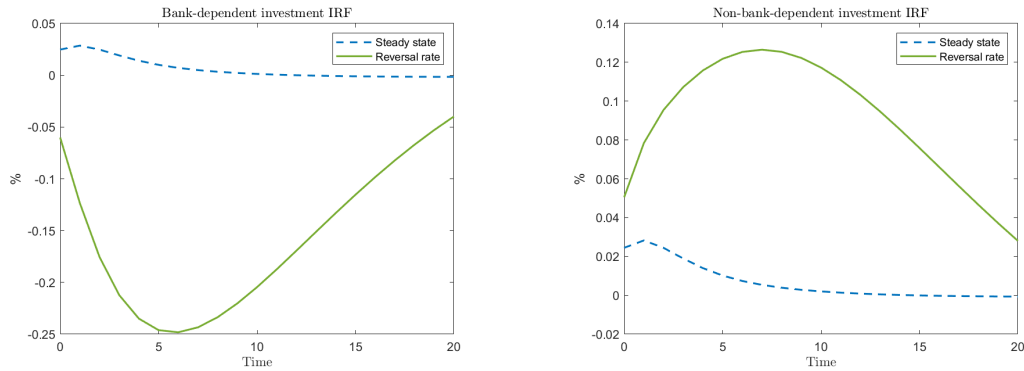


FIGURE 5. MARGINAL RESPONSES OF INVESTMENT FOR BANK-DEPENDENT FIRMS (LEFT PANEL) AND NON-BANK-DEPENDENT FIRMS (RIGHT PANEL) TO A 10-BASIS POINT TAYLOR RULE INNOVATION IN TWO ECONOMIES. IN THE BASELINE ECONOMY (BLUE LINE), THE SHOCK OCCURS WHEN THE ECONOMY IS AT ITS STEADY STATE. IN THE ALTERNATIVE ECONOMY (GREEN LINE), THE SHOCK OCCURS WHEN THE INITIAL INTEREST RATE IS EQUAL TO -1% .

effectiveness of “low-for-long” monetary policies. Intuitively, forward guidance should not be expected to be as effective in our model as it would be in the textbook New Keynesian model, in light of Proposition 5. That is, our theoretical results have shown that keeping rates low for a sufficiently long period of time will eventually have a *contractionary* effect on bank lending and investment. Thus, a policy that promises to hold interest rates down for an extended period of time should not necessarily be expected to initially produce a large economic boom, since agents will anticipate depressed investment and output in the future.

A typical forward guidance policy involves a commitment to keep the policy rate fixed at a certain level i until some date T , at which point the central bank returns to a Taylor rule. We fix the promised interest rate i at -1% , close to the reversal rate that we estimate in our benchmark results, for $T = 8$ quarters.

Figure 6 displays the impulse responses of aggregate investment and output to forward guidance in two economies: our benchmark model and an alternative “frictionless” economy in which banks do not face leverage costs (i.e., a version of our benchmark model with $\kappa^L = 0$).³⁴ The impulse response in the frictionless economy highlights the dynamics that are typically observed in standard New Keynesian models: a promise to hold interest rates down for eight quarters leads to an implausibly large boom in investment and output. At their peaks, investment and output both reach a level equal to roughly twice their steady-state values. By contrast, in our economy, these responses are only about half as large. Moreover, the forward guidance policy causes a reversal in investment to occur by the eighth

³⁴We plot the total effect of such policies (rather than the *marginal* effect of increasing T) to compare the quantitative results with Proposition 5.

quarter after its announcement.

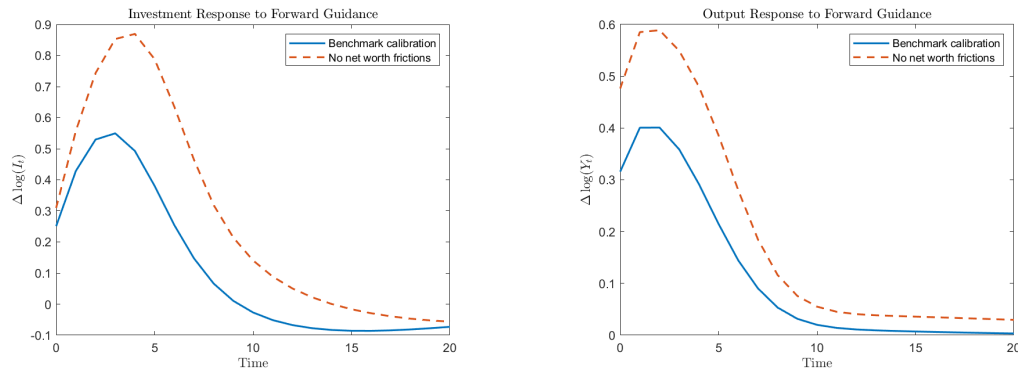


FIGURE 6. THE EFFECT OF FORWARD GUIDANCE ON BANK LENDING IN TWO ECONOMIES: OUR BENCHMARK MODEL (SOLID BLUE LINES) AND A “FRICTIONLESS” ECONOMY IN WHICH BANKS DO NOT FACE LEVERAGE COSTS, $\kappa^L = 0$ (DASHED RED LINES). THE CENTRAL BANK PROMISES TO HOLD INTEREST RATES AT -1% FOR EIGHT PERIODS BEFORE RETURNING TO A TAYLOR RULE. WE PLOT THE IMPULSE RESPONSES FOR AGGREGATE INVESTMENT (LEFT PANEL) AND OUTPUT (RIGHT PANEL) IN BOTH ECONOMIES.

In Online Appendix C.6, we show that the reduction in the power of forward guidance carries over to bank lending, consumption, and inflation as well. As expected, all variables respond explosively even to eight quarters of forward guidance in the frictionless model, whereas in our benchmark model, their responses are smaller.

Hence, our model’s novel channel of monetary policy transmission provides a mechanism to blunt the unreasonable power of forward guidance predicted by standard models. The persistent drain on bank net worth caused by “low-for-long” policies decreases investment, asset prices, and output in the long run. In turn, the anticipation of these negative long-run effects dampens the initial stimulation of the economy and the response of inflation. This mechanism should be highly relevant for central banks considering how long to hold interest rates down, since it paints a qualitatively different picture of such policies’ effectiveness: in contrast to standard theory, our model predicts that promising to hold interest rates down for longer periods can eventually turn counterproductive.

It is worth noting that the muted power of forward guidance in our model is entirely dependent on the reversal rate mechanism: it arises only because of the deterioration in bank profits, and the corresponding increase in leverage costs, when rates are cut low enough. In Online Appendix C.6, we show that for smaller prolonged interest rate cuts (e.g. from 2% to 1.5%), forward guidance in our model is just as powerful as in a standard model.

IV. Discussion and Robustness

In this section, we provide additional discussion of our main results and address the robustness of our preferred estimate of the reversal rate (-0.8% for aggregate investment in the benchmark model).

A. The model and the data

We begin by comparing our model’s predictions to some key stylized facts in the data that are related to our main mechanism. Specifically, we address (1) the response of net interest income and bank net worth to interest rate cuts, and (2) our model’s relationship to micro evidence on the response of bank lending to interest rate cuts in negative territory.

Net interest income and ROE. Our model generates a rich set of predictions for the evolution of banks’ net interest income (NII) and returns on net worth, which are key to the main mechanism. The left panel of Figure 7 illustrates the marginal response of NII (reported as a fraction of steady-state bank assets) to a 10bp interest rate cut for several initial levels of the policy rate.³⁵ When rates are positive, a -10bp Taylor rule innovation decreases NII by only about 1bp, whereas when they are close to the reversal rate, the same shock reduces net interest income by 6bp (since an interest rate cut reduces the deposit spread by approximately the same amount). We also find that banks’ returns on net worth³⁶ (over a period of one year after the shock) are decreased by 5bp when rates are initially near the reversal rate, whereas they increase by only 0.5bp when rates are initially near the steady state.

There is currently no empirical consensus on the quantitative response of NII to interest rate cuts, but studies generally agree that there is a negative effect on profitability.³⁷ In a cross-country analysis, Claessens, Coleman, and Donnelly (2018) estimate that when rates are near normal levels, a 10bp policy rate cut is associated with a 0.8bp reduction in NII (as a fraction of assets), whereas when rates are low, the same cut is associated with a 2bp reduction in net interest income. Using bank-level data from the Euro area, Borio, Gambacorta, and Hoffmann (2017) study how the marginal impact of a policy rate cut on NII depends on the *level* of the policy rate, estimating that the decrease in NII ranges from about 4bp (when rates are near 2%) to about 6bp (when rates enter negative territory). Our model’s predictions are of the same order of magnitude and also imply that the effect is stronger for lower rates. Ulate (2021a) also estimates the relationship between returns on accounting equity and the level of interest rates,

³⁵As in our original analysis, we first hit the economy with a large Taylor rule innovation, and then we apply another 10bp shock on top of the original shock. The response reported here is the marginal change in NII divided by steady state assets (at impact) resulting from the additional 10bp shock.

³⁶Formally, one-year returns on net worth from period t to $t + 4$ are defined as $ROE_{t,t+4} = \frac{Div_t + Div_{t+1} + Div_{t+2} + Div_{t+3} + N_{t+3}}{N_t}$, where Div_t is the dividend paid by a bank in period t .

³⁷See the survey by Balloch, Koby, and Ulate (2022).

finding (like in our model) that a 10bp cut in positive territory is not associated with a significant change in ROE, whereas in negative territory, the same cut leads to roughly a 5bp decline in ROE.

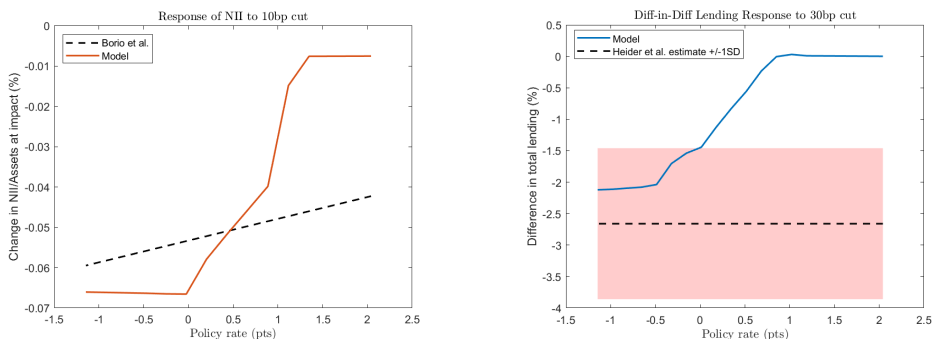


FIGURE 7. THE RED LINE IN THE LEFT PANEL PLOTS THE IMPULSE RESPONSE OF NII (AS A FRACTION OF STEADY-STATE ASSETS) TO A -10BP TAYLOR RULE INNOVATION (AT IMPACT) FOR VARIOUS INITIAL LEVELS OF THE POLICY RATE. THE DASHED BLACK LINE PLOTS THE RESPONSE ESTIMATED BY BORIO ET AL. (2017). THE RIGHT PANEL PLOTS THE IMPULSE RESPONSE OF LOG TOTAL LENDING AT THE IMPACT OF A -30BP TAYLOR RULE INNOVATION FOR THE BENCHMARK BANKS IN OUR MODEL RELATIVE TO HYPOTHETICAL BANKS WITH A 15% LOWER DEPOSIT-TO-ASSET RATIO, AS A FUNCTION OF THE INITIAL POLICY RATE.

Bank lending and the pass-through of interest rate cuts. We can also validate some the model’s predictions about individual banks’ lending behavior using micro-level evidence. Given that the compression of deposit spreads is a key mechanism by which interest rate cuts reduce banks’ interest income, several studies have compared the behavior of heavily deposit-dependent banks to banks that fund themselves primarily through other channels. Using a difference-in-difference methodology, Heider, Saidi, and Schepens (2019, henceforth HSS) study the relationship between the growth rate of a bank’s syndicated lending and its deposit-to-asset ratio. They find that:

- In the pre-2014 period (before the ECB introduced negative rates), banks’ deposit-to-asset ratios were not associated with differences in lending growth rates;
- Between June 2014 and December 2015 (during which time the ECB cut rates from zero to -30bp), a bank with a 15 percentage point higher deposit-to-asset ratio tended to have 13 percentage point lower growth in new syndicated lending.

Syndicated loans in this sample have an average maturity of about five years, so 13 percentage points lower growth in *new* lending over a period of about a year translates to roughly $13/5 = 2.6$ pp lower growth in *total* loans on a bank’s balance sheet.

We relate our model to HSS’s predictions by introducing a measure zero of “less deposit-dependent banks” whose parameters are calibrated to target a steady-state deposit-to-asset ratio that is 15pp lower than that of the banks in our benchmark model (“more deposit-dependent banks”).³⁸ Since these banks are assumed to have measure zero, their presence does not affect the equilibrium, but we can nevertheless compute their optimal loan rates and lending quantities. We then compare the marginal response of lending for more deposit-dependent and less deposit-dependent banks at the impact of a -30bp Taylor rule innovation (for various levels of the initial policy rate).

The right panel of Figure 7 illustrates our results. For each initial level of the policy rate, it plots the change in lending at impact, $\log(L_0/L^*)$, for a more deposit-dependent bank minus the change in lending at impact for a less deposit-dependent bank. Near the steady state, the lending of more deposit-dependent and less deposit-dependent banks respond approximately equally to a 30bp cut. Near the reversal rate, on the other hand, total lending growth is lower for more deposit-dependent banks, presumably because their profits suffer more from the cut. Quantitatively, our result near the reversal rate is within a standard deviation of the point estimate provided by HSS: more deposit-dependent banks’ total loans grow by roughly 2% less than less deposit-dependent banks’. It should be noted, moreover, that HSS study an interest rate cut between 0 and -30bp (instead of -80bp and -1.1%). That is, in the data the effects of deposit financing on lending behavior are, if anything, stronger than in the model.

B. Sensitivity analysis

The quantitative model provides an ideal laboratory to study the reversal rate’s determinants as well as the sensitivity of our results to the calibration strategy. In this section, we perform comparative statics experiments to study how changing parameter values affects the reversal rate for aggregate investment (on impact).³⁹ We begin by illustrating the reversal rate’s dependence on two key parameters that are closely connected to the theoretical mechanisms underlying the reversal rate: banks’ leverage cost parameter κ^L and the relative productivity A^b/A^{nb} of bank-dependent firms. Then, we discuss the remainder of our sensitivity analysis, which can be found in Online Appendix C.2.

In the model, reversals in bank lending occur when banks become financially constrained, forcing them to raise loan rates. Hence, it is natural that the leverage cost parameter κ^L , which modulates the strength of financial frictions, should be an important determinant of the reversal rate. The left panel of Figure 8 shows the dependence of the reversal rate on the increase in loan rates resulting from a

³⁸This is accomplished by giving these banks a different dividend payout ratio $\tilde{\gamma} < \gamma$ while holding all other parameters fixed.

³⁹Specifically, we perform comparative statics experiments in which we vary the value of one parameter while holding the parameters in Table 1 constant and re-calibrating the parameters in Table 2 to match the specified targets.

1% change in banks' capitalization target N^*/L^* , which is the target in the data used to calibrate κ^L . We permit this value to run from 14bp to 42bp (i.e., half to one and a half times the benchmark estimate). This is the most important target in determining the value of the reversal rate: at the lower end of this range the reversal rate is equal to roughly -1.7%, whereas at the upper end, the estimated reversal rate is approximately -0.5%. An interpretation of this result is that the reversal rate is likely to be higher in economies with more stringent bank capital requirements.

One of the main countervailing forces against the reversal mechanism in the model is the substitution of lending from the bank-dependent sector to the non-bank-dependent sector. Thus, the relative productivity A^b/A^{nb} of bank-dependent firms is key to determining the strength of the reversal mechanism in general equilibrium. The right panel of Figure 8 shows the dependence of the reversal rate on bank-dependent firms' share of output, which is the target in the data used to calibrate that parameter. As expected, the reversal rate is increasing in bank-dependent firms' share of output: when most output is produced by non-bank-dependent firms, a large negative response of bank lending to an interest rate cut is required before a reversal of aggregate investment occurs. Our results indicate, in fact, that the reversal rate is likely to be substantially lower in countries where investment is far less bank-dependent (e.g., the U.S.).

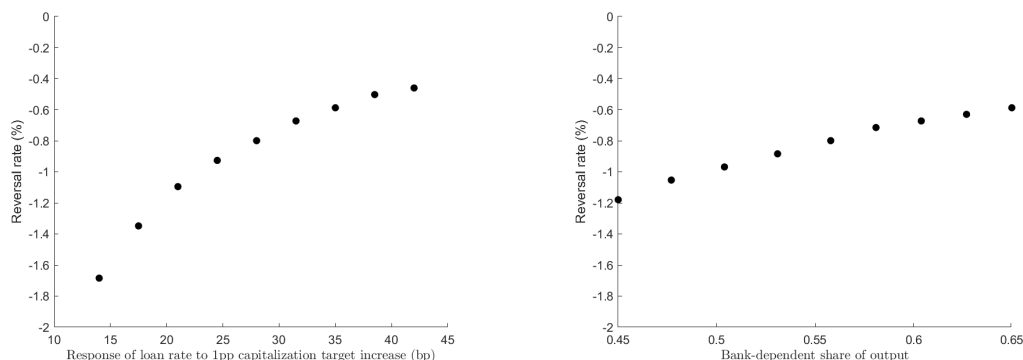


FIGURE 8. DEPENDENCE OF THE REVERSAL RATE ON THE VALUES OF THE LEVERAGE COST PARAMETER κ^L (LEFT PANEL) AND THE RELATIVE PRODUCTIVITY OF BANK-DEPENDENT FIRMS $\frac{A^b}{A^{nb}}$. THE VALUES OF κ^L ARE REPORTED AS THE CORRESPONDING INCREASE IN LOAN RATES FOLLOWING A 1% INCREASE IN BANKS' CAPITALIZATION RATIO TARGET. THE VALUES OF $\frac{A^b}{A^{nb}}$ ARE REPORTED AS THE CORRESPONDING SHARE OF OUTPUT PRODUCED BY BANK-DEPENDENT FIRMS.

As for the remainder of our sensitivity analysis, we first consider the parameters with conventional values in the literature (reported in Table 1). As we document in Online Appendix C.2, the reversal rate on impact is not very sensitive to any of these choices. For each parameter, we take a range of values considered in the

literature and plot the reversal rate for each value in that range. In each case, the reversal rate remains within a range close to our preferred estimate of -0.8%.

More important are the parameters that we calibrate to match moments in the data (reported in Table 2). Several parameters are uniquely identified by measurable bank balance sheet and interest rate moments.⁴⁰ The remaining parameters are not unambiguously identified by bank balance sheet data alone, so we report sensitivity results for those parameters as well. We report results for such parameters in Online Appendix C.2, since they are less directly related to the reversal rate mechanism.⁴¹

This sensitivity analysis allows us to draw two conclusions. First, for a reasonable range of parameter estimates, a reversal rate always exists (although it may be below -1% for the most optimistic parameter estimates). Second, given this same range of parameter estimates, one can be relatively confident that slightly negative interest rates (e.g. -0.25%) will *not* cause a reversal to occur – in our framework, a reversal tends to occur only for larger interest rate cuts. Therefore, our preferred estimate of -0.8% provides guidance similar to the picture given by our sensitivity analysis: a central bank should consider the possibility of a reversal only when rates are already substantially negative.

C. Relationship to Ulate (2021a)

Another early paper that quantifies the effects of negative interest rate policy in general equilibrium is Ulate (2021a). The paper’s static model (*without* net worth frictions) highlights the mechanisms by which, under monopolistic competition, declines in the nominal rate can lead to a decline in bank profitability but can nevertheless transmit to lending rates, even in negative territory. In this setting, Ulate finds that interest rate cuts transmit to lending rates until the policy rate reaches approximately -2.2%, at which point a “reversal” in bank lending occurs: deposits become so unprofitable that some banks stop accepting deposits entirely and contract their balance sheets. In Online Appendix B.1 we show that a similar type of reversal can arise in our model when banks hit their *liquidity constraints*. Our paper, by contrast, studies a distinct *dynamic* mechanism that works through banks’ interest income and *capital constraints* (which we view as more quantitatively relevant). Our theoretical contribution is to characterize the conditions under which, through this mechanism, an interest rate cut can be contractionary for lending *at the margin*.

After presenting theoretical results in the static model, Ulate (2021a) quantitatively assesses the strength of negative nominal interest rate policy by calibrating an infinite-horizon DSGE model with monopolistic competition among banks as well as net worth frictions in bank lending.⁴² The main quantitative experiments

⁴⁰In particular, parameters γ , ζ , and τ are pinned down in this way.

⁴¹Specifically, we report results for parameters β , μ^D , ξ , ν , \mathcal{L}^* , \tilde{N} , ε^L , ε^D , and κ^I . Importantly, the level of the reversal rate is essentially independent of the fraction of bank-dependent firms ξ .

⁴²Ulate’s net worth constraints take a slightly different form from ours: the marginal cost of lending

conducted in Ulate’s paper study the effects of negative nominal interest rates following a financial-crisis-style recession, which we do not study here. First, it is shown that an interest rate cut from 0% to a value below -1% yields an increase in lending and investment; that is, the *total* effect of the cut is stimulative. Second, the paper demonstrates that interest rate cuts between 0% and -0.5% continue to increase *welfare* at the margin.

Ulate’s results can be reconciled with ours. The total effect on lending and investment of a policy rate cut from 0% to a level below -1% is likely to be positive, since the marginal effects turn negative only at -0.8% for investment and -1.3% for bank lending. Similarly, in our calibration the marginal effect of an interest rate cut on welfare continues to be positive between 0% and -0.5%.⁴³ Our quantitative contribution is to focus on estimating the level of interest rates at which the *marginal* effects of additional cuts on *lending and investment* turn negative. As a final note, using cross-country data, Ulate estimates slightly smaller leverage costs than we do (captured by κ^L in our model). Such an estimate may in fact be more appropriate for countries like the U.S., where banks’ regulatory constraints are less binding than in the EU.⁴⁴

D. *Alternative initial shocks*

In the benchmark model, we estimate the reversal rate by first hitting the economy with a large *monetary* shock that reduces the policy rate to a low level and then studying the *marginal* response to an additional small monetary shock that reduces the policy rate by an additional 10 basis points. There is no particular reason that the initial large shock has to be a monetary shock, however – it suffices to consider *any* shock that would reduce interest rates. Therefore, we examine two additional types of large shocks in Online Appendix C.3: a shock that makes agents more patient (as in Eggertsson and Woodford, 2003) and a shock to firm productivity that reduces the natural rate. In the case of a productivity shock the estimated reversal rate is -1.1%, whereas in the case of a discount factor shock it is -0.6%. Therefore, we view our estimate of the reversal rate as being potentially applicable for a variety of initial shocks that could lower interest rates, as long as banks’ interest income behaves similarly across those scenarios.

E. *Bonds held-to-maturity*

Our benchmark model assumes that all bonds on banks’ balance sheet are “marked-to-market” when calculating bank net worth (our model’s counterpart to book equity), which is the accounting variable that determines the strength of

is linear in bank leverage rather than convex.

⁴³In general, whether interest rate cuts increase welfare at the margin depends on the type of shock that initially brought interest rates to a low level. Our benchmark model assumes that this shock is a large Taylor rule innovation. See Section IV.D for discussion of alternative initial shocks.

⁴⁴Figure (8) illustrates that lower leverage costs κ^L would indeed lead to a lower estimated reversal rate.

lending constraints. An interest rate cut initially leads to capital gains on banks' bond portfolio (the *capital gains channel*), but those bonds pay a lower interest rate $1 + i_t$ going forward (contributing to the *net interest income channel*). In reality, however, banks often designate some portion of their bond portfolios as "held-to-maturity" for accounting purposes. Changes in the market values of such bonds are not incorporated into banks' book equity, but on the other hand, these bonds continue to yield their original higher coupon payments going forward. Online Appendix C.4 extends the model to allow a realistic fraction of banks' bonds to be held-to-maturity. All of the main theoretical results continue to hold in this extension. Quantitatively the estimates of the reversal rate are quite similar as well, since the lack of capital gains approximately offsets the higher coupon payments of held-to-maturity bonds.

V. Conclusion

We have shown the conditions for the existence of a reversal interest rate, the rate at which monetary policy stimulus reverses its intended effect and becomes contractionary at the margin. Its existence relies on the net interest income of banks decreasing faster than recapitalization gains from banks' initial holdings of fixed-income assets. In a calibrated New Keynesian model, the reversal rate for aggregate investment is close to -1%. The level of the reversal rate depends on the stringency of banks' capital constraints and the economy's overall dependency on bank lending. As banks' fixed-income assets mature, their initial capital gains fade out, so "low-for-long" interest rate environments can eventually end in recessions. Our calibrated model demonstrates that this mechanism dampens the power of forward guidance.

For the sake of tractability, we have omitted other channels through which monetary policy can affect banks as well as the real economy. In particular, policies such as ECB's long-term refinancing operations could have alleviated some of the low rates' effect on bank margins. Moreover, we have omitted the explicit modeling of risk; hence, we have remained agnostic on how low rates change nonperforming loans and the associated responses in provisions. We see these as important quantitative refinements for future research. Finally, we view our results as driven by unusual surprise movements in interest rates: low-for-long and negative rates were largely unforeseen events. It remains a question whether banks can and will adjust to a permanently lower interest rate environment – for example, by increasing their maturity mismatch. The competitive landscape faced by banks could also change, with depositors growing accustomed to the possibility of negative interest rates, hence supporting banks' profitability in negative-rate environments.

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