R-stars Across the Atlantic - The Role of Policy Expectations*

Mátyás Farkas†

International Monetary Fund

Zoltán Jakab‡

International Monetary Fund

Jesper Lindé‡‡

International Monetary Fund and CEPR

PRELIMINARY, PLEASE DO NOT CITE OR CIRCULATE

7TH OF JANUARY, 2026

Abstract

We study how policy expectations affect the estimated natural rate of interest (r^*) for the United States and the euro area. To discipline policy expectations, we incorporate information on future policy rates and long-term yields in episodes where Fed and ECB forward guidance were crucial, including the effective lower bound and the post-COVID episodes. Importantly, we find that the estimated rise in r^* during the post-Pandemic period is substantially larger than in an otherwise standard identical specification that omits yield-curve observables. This implies that the post-COVID tightening of the monetary policy stance was not as large as standard r^* models imply, which helps explain why economic activity did not slow much when nominal policy rates were raised dramatically in 2022 to fight inflationary pressures. In our model, yield-curve information pins down anticipated policy innovations and alters r^* estimates and the thus stance of monetary policy. We conclude that it is crucial to account for policy expectations when gauging the stance of monetary policy during this period.

Keywords: Natural Rate of Interest; Bayesian inference; DSGE Model; Monetary Policy Stance, Convenience Yield, Forward Guidance.

JEL codes: C110, E170

Disclaimer: The views expressed herein are those of the authors and should not be attributed to the IMF, its Executive Board, or its management.

---

* We thank Tobias Adrian, Roberto Billi, Allan Dizioli, Tom Holden and seminar participants at the IMF and seminar participants at the "IMFS Conference on Monetary and Financial Stability" at the Goethe University in November 2025 for very helpful comments and discussions. We are grateful for Marco Del Negro and colleagues at the Federal Reserve Bank of New York for help with data.

† mfarkas@imf.org

‡ zjakab@imf.org

‡‡ jlinde@imf.org

1. Introduction

The natural rate of interest, or r^*, plays a central role in monetary policy as both a short-run indicator of stance and a long-run anchor for interest rate expectations. r^*, is the real interest rate that equates savings and investments when output is at potential and inflation is stable. The concept—tracing back to Wicksell—provides a key guidepost for monetary policy: it represents the level of the policy rate that would prevail once business-cycle shocks dissipate. Central banks use estimates of r^* to gauge whether their policy stance is stimulative, neutral, or restrictive. A misperception of r^* can lead to systematic policy errors, as the central bank may inadvertently provide too much or too little accommodation over the long run.

For most of the four decades before the COVID-19 pandemic, estimates of r^* across advanced economies declined markedly (Laubach Williams, (2006); Holston et al. (2014); Del Negro et al. (2017)). The pandemic and its aftermath have sparked a debate about whether r^* has begun to rise materially. Recent papers (Baker et al. (2023); IMF (2023); Brand (2024)) for the United States and the euro area suggest that r^* has increased to pre-pandemic levels, though uncertainty bands are wide. We revisit the potential drivers of r^* through a modified version of a state-of-the-art canonical DSGE model by Del Negro et al. (2017).

First, we document that including yield curve information alters our r^* estimates relative to standard models, which do not account for policy expectations. Second, our higher r^* estimates imply that policy stance was not tightened nearly as much during the post-COVID rate-hike as measured compared to an unchanged baseline. Third, we show that the neo-Fisherian impact of forward guidance, also termed as the *"forward guidance reversal puzzle"* (Carlstrom et al. 2022), drives our results. Forward guidance shocks can mimic convenience yield shocks and accounting for policy expectations improves the identification of r^*. Lastly, using the estimated models, we quantify the exorbitant privilege the US enjoyed compared to the euro area. From a policy perspective, this suggests caution in interpreting movements in r^* estimates.

Forward guidance and any persistent change in expectation formation embed persistent nominal expectations into the economy, effectively introducing moving-average dynamics that shift the structure of DSGE models from a backward-looking restricted VAR form into a more complicated VARMA form. As a result, distinguishing between persistent policy shocks and permanent structural shifts in the natural rate becomes increasingly difficult. In other words, it is difficult to identify anticipated monetary shocks unless additional information (e.g. yield-curve information) is utilized.

Our results corroborate the evidence of increasing r^* through structural estimation. Interpretations of the rise in r^* are diverse; some view a higher r^* as a sign that the global saving-investment

balance is shifting, for instance, households drawing down precautionary savings accumulated during the pandemic, others emphasize persistent supply shocks that raised inflation and thus require higher real rates, and still others point to large fiscal deficits or geopolitical fragmentation that might sustain higher real yields. In addition, consistent one-sided monetary surprises may have cumulated into a persistent increase in the equilibrium real rate, implying an endogeneity of r^* to monetary policy (Benigno et al. (2024)). We argue, however, that a simpler mechanism might be at play; expectations on future rates affect the estimated r^*.

The remainder of the paper is organized as follows. Section 2 reviews related literature on neutral rate estimation. Section 3 describes our DSGE framework and data. In Section 4 we present our* estimates for the U.S. and euro area and give a narrative assessment on the monetary stance and why policy expectation may matter in the estimation of r^*. Section 5 demonstrates counterfactual exercises on the implications for misreading r^* changes post Covid and a measure of the exorbitant privilege of the dollar. Section 6 points to some avenues for future research and concludes.

2. Literature review

The natural rate of interest, often denoted as r^*, is defined as the real short-term rate that would prevail when the economy is operating at full potential with stable inflation (Kiley 2015). This concept dates back to Wicksell (1898), who described the natural rate as the rate "compatible with a stable price level." In modern theory, r serves as a benchmark for monetary policy (Woodford 2003) and is central to New Keynesian models: it is the real interest rate that aligns consumption and investment decisions with potential output. However, r^* cannot be directly observed and must be inferred from data. Lubik and Matthes (2015) emphasize that the natural rate is "fundamentally unobservable" and can only be estimated via structural assumptions.

Laubach and Williams (2003) operationalized this by modeling r^* as a latent state in a simple macro model of inflation, output, and the policy rate. In their framework the real natural rate is recovered using the Kalman filter, based on observed GDP growth, inflation, and the federal funds rate. Their estimates showed a dramatic secular decline in US r^*, from about 4.5 percent in the early 1960s to roughly zero by the late 2000s. These early findings established a benchmark for the low real-rate environment that persisted in the 21st century.

Subsequent studies have refined and extended these methods. Holston, Laubach, and Williams (2017) applied the state-space approach to multiple advanced economies, finding large declines in trend output growth and r^* across the US, euro area, Canada, and the U.K. over the past 25 years. Other approaches include macro-finance models of the yield curve, which allow the equilibrium real rate and trend inflation to vary over time. For example, Bauer and Rudebusch (2017) show that treating r^* (and inflation expectations) as time-varying endpoints is crucial for explaining low bond yields and term premiums. Researchers have also used full-fledged DSGE or econometric

models. Kiley (2015) estimates r^* within a Board of Governors model using Bayesian methods, finding that econometric identification is weak but estimates still indicate a subdued equilibrium rate (around 1–2 percent in the 2010s).

In sum, a variety of estimation techniques (state-space, macro-finance, Bayesian DSGE) tend to converge on the conclusion that real neutral rates have fallen sharply in recent decades. Empirical estimates overwhelmingly document that r^* has drifted to very low levels in the United States.

Across the Atlantic, in the euro area a series of ECB studies corroborates these trends, finding a "protracted fall" in the neutral rate driven by demographics, waning productivity, and increased risk aversion following the financial crisis (Ciccarelli et al. (2018); Brand and Mazelis (2019, 2024). Fiorentini and Tambalotti (2018) document "a rise and fall of the natural interest rate for several advanced economies" with a peak reached in the 1980s and secular decline. Rachel and Summers (2019) estimate that neutral real rates in the industrialized world have dropped by roughly 300 basis points since the 1970s, largely due to shifts in global savings and investment propensities.

Literature offers several explanations for the long-term decline in r^*. Demographic shifts are frequently cited: aging populations tend to raise savings and reduce investment demand, pushing real rates down. Structural factors such as aging, weak productivity, and higher persistent mark-ups (Ciccarelli et al. (2018)), as well as heterogeneity and fiscal dominance (Angeletos et al. (2024)) have been associated with a secular decline.[1]

A wide range of structural forces were implicated in this secular decline. Factors that raise desired saving or reduce investment all put downward pressure on the neutral rate. Prominent examples include slower potential growth, population aging, rising inequality, shifts in risk aversion, and persistent global saving gluts financed by emerging markets. Demographic trends such as longer retirements and lower dependency ratios tend to boost aggregate saving. Higher inequality concentrates income in the hands of wealthy households with high saving propensities. Greater risk aversion and an increased demand for safe assets simultaneously depress investment and the return required on savings. In the years after the Global Financial Crisis (GFC), many observers pointed to a worldwide excess of desired saving over investment (a "global saving glut"), which, alongside a surge in demand for safe assets, drove real interest rates down globally. Other studies link a low r^* to weaker productivity growth, a slowdown in investment-specific technical progress, or persistently high markups. Platzer and Peruffo (2022) show that secular drivers, like inequality, demographic change, and slowdown in productivity account for a decline in r^*, with growing public debt being the major counteracting force. In contrast, proponents of the fiscal theory of the price level argued that large fiscal deficits could keep r^* low by raising expected future inflation. Lastly, we note an alternative r^*, the fiscal r^* (the real rate required to stabilize government debt)

[1] Bulíř and Vlcek (2024) deals with open economy aspects of r^* estimation in emerging markets using semi-structural models and found that real exchange rate movements can alter estimates.

show that monetary-fiscal gaps can affect r^*. For a recent review on the decline and the structural drivers of r^* see the WEO (2023).

Another strand of research focuses on an increased demand for safe, liquid assets. Del Negro et al. (2017) construct a model with safety and liquidity premia, finding that a rising safety and liquidity premium for US Treasuries has been a key factor keeping the equilibrium real rate low. In related fashion, global "savings glut" hypotheses (Caballero and Farhi (2017); Bernanke (2023)) attribute the low r^* to excess desired savings worldwide. Rachel and Summers (2019) in particular argue that secular increases in savings rates (e.g. from retirement systems, wealth inequality) and subdued investment demand explain most of the decline in neutral rates.

3. The DSGE model

As a starting point of our analysis, we present the updated re-estimation of the New York Fed's medium-scale DSGE model (Del Negro et al. (2017)) for the United States, and our estimation for the Eurozone. By explicitly incorporating forward guidance and convenience yield shocks, these models provide a refined estimate of post-pandemic r^* in both regions. Our model treats the convenience yield —the premium investors assign to safe and liquid assets — as a crucial driver of the natural real rate. High demand for safety and liquidity compresses the real return on government bonds, lowering r^*.

Our structural model of the US and Euro Area r^* reflects both observed data and policy expectations by accounting for anticipated monetary shocks. The structural model allows safety asset and liquidity channels to be disentangled from the effects of forward guidance based on their impact on r^*, where the former often mimic permanent movements in the natural rate, while forward guidance is assumed to be neutral to the natural rate.

Our DSGE model provides a structured framework to shed light on the interaction between unconventional monetary policy and real interest rate dynamics in the post-GFC, post-pandemic macroeconomic landscape.

Del Negro et al. (2017)'s DSGE model is a medium scale DSGE model which is based on the New Keynesian model with financial frictions used in Christiano, Motto, and Rostagno (2014) and Del Negro, Giannone, and Schorfheide (2015). The core of the model is the Smets and Wouters (2007) model, a neo-classical DSGE featuring sticky prices and wages, allowing for backward inflation indexation, habit formation in consumption, investment adjustment costs, variable capital utilization and fixed costs in production. The model also includes financial frictions, as in the financial accelerator model developed by Bernanke, Gertler, and Gilchrist (1999), following the model of risk shocks of Christiano, Motto, and Rostagno (2014). The model accounts for forward guidance in monetary policy by including anticipated policy shocks as in Laséen and Svensson (2011).

As for longer-term dynamics the model features both a deterministic and a stochastic trend in productivity and allows for transitory and exogenous movements in risk premia; the inflation target is time-varying, following Del Negro and Schorfheide (2013); households preferences are non-separable in consumption and leisure; the Dixit-Stiglitz aggregator of intermediate goods has been replaced by the more flexible Kimball aggregator; we include indexation in the price and wage adjustment processes. For additional details of the model see Appendices III to V.

A central feature of the model is the explicit inclusion of convenience yield to capture movements in *r**. The convenience yield means that investors accept lower returns on Treasuries due to their safety and liquidity, which depresses the natural rate. Permanent safety and liquidity factors, as well as permanent productivity shocks, are the major factors explaining low-frequency movements in *r**. This mechanism is formalized in a modified Euler equation with a spread above the policy rate is influenced by liquidity and safety premia, capturing convenience yields $\left(b_{\mathrm{liq,t}} + \mathrm{b_{safe,t}}\right)$ as well as risk shocks following Christiano, Motto, and Rostagno (2014) ($\sigma_{\omega,t}$) exogenous bankruptcy costs ($\mu_{e,t}$) and shocks to the fraction of entrepreneurs surviving period t ($\gamma_{e,t}$):

$$\mathrm{c_t} = \frac{\mathrm{he^{-\gamma}}}{1+\mathrm{he^{-\gamma}}}\mathrm{c_{t-1}} + \frac{1-\mathrm{he^{-\gamma}}}{\sigma_c(1+\mathrm{he^{-\gamma}})}(\mathrm{R_t} - \mathrm{E_t}\pi_{t+1}) - \frac{1}{1+\mathrm{he^{-\gamma}}}(\mathrm{E_t c_{t+1}} + \mathrm{E_t z_{t+1}}) + \frac{\mathrm{he^{-\gamma}}}{1+\mathrm{he^{-\gamma}}}\mathrm{z_t} - \frac{\sigma_c - 1}{\sigma_c(1+\mathrm{he^{-\gamma}})}(\omega_L \mathrm{L_t} - \mathrm{E_t L_{t+1}}) - \mathrm{b_{liq,t}} - \mathrm{b_{safe,t}} \quad (1)$$

In other words, the Euler condition is extended with a convenience yield term, where a rising convenience yield translates to a premium that investors place on the safety and liquidity of government bonds, that "depresses the safe real rate of return": investors accept a lower return in exchange for convenience. Transitory and persistent technology shocks to arrive at Balanced Growth and to capture the link between *r** and trend growth rate. Convenience yields also enter the capital formation (entrepreneurs' optimization problem) where along with Risk shocks (Christiano et al., (2014)) Along with risk, survival and bankruptcy shocks convenience yields also enter the determination of demand for capital. Convenience yields create a wedge between the policy rate and the return on capital.

$$\mathrm{E_t}\widetilde{\mathrm{R_{k,t+1}}} - \mathrm{R_t} = \frac{\sigma_c(1+\mathrm{he^{-\gamma}})}{1-\mathrm{he^{-\gamma}}}\left(\mathrm{b_{liq,t}} + \mathrm{b_{safe,t}}\right) - \zeta_{\mathrm{spb}}\left(\mathrm{qk_t} + \bar{\mathrm{k}}_\mathrm{t}\right) + \zeta_{\mathrm{spb}}\mathrm{n_t} - \sigma_{\omega,t} - \mu_{e,t} \quad (2)$$

The above two equations imply that movements in *r** are directly driven by persistent TFP and convenience yield shocks. Liquidity premium is identified as common component in Aaa and Baa corporate yields over Treasuries. Safety premium is identified from the spread between Baa and Aaa corporate yields. Convenience yield is the sum of safety and liquidity premium.

$$\text{Government Bond Yield } Curve_\{t\} = \mathrm{E_t}\left[\mathrm{R_{t+j}}\right] \quad (3)$$

$$\mathrm{AaaSpread}_t = \overline{b_{liq}} + \ \mathrm{frac}(\lambda_{AAA} - 1)\sigma_c(1 + he^{-\gamma})1 - he^{-\gamma}{}_{\mathrm{liq},t} + \frac{1}{80}\sum_{j=0}^{79} E_t\left[b_{\mathrm{liq},t+1+j}\right] + \lambda_{AAA}\left(E_t[R_{t+1}^k] - R_t\right] \quad (4)$$

$$\mathrm{BaaSpread}_t = \overline{b_{liq}} + \mathrm{bar}b_{safe} + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + E_t[R_{t+1}^k - R_t] + + \frac{1}{80}\sum_{j=0}^{79} E_t\left[R_{t+j+2}^k - R_{t+j+1}\right] \quad (5)$$

Monetary policy is governed by a standard policy rule, amended by anticipated policy shocks.

$$\mathrm{R_t} = \rho \mathrm{R_{t-1}} + (1-\rho)\psi_1(\pi_t - \pi_t^\star) + (1-\rho)\psi_2\left(\mathrm{y_t} - \mathrm{y_t^f}\right) + \psi_3\left(\Delta \mathrm{y_t} - \Delta \mathrm{y_t^f}\right) + \mathrm{r_{m,t}} \quad (6)$$

where $r_t^m = \rho_{r^m} r_{t-1}^m + \varepsilon_{t_t^{r^m}} + E_t[r_{t+h}^m]$.

Anticipated policy shocks ($\varepsilon_t^{\mathrm{r}^{m,h}}$) are modelled as a forward MA (moving average) process, while the monetary surprise is modelled in a standard way and is denoted by $\varepsilon_t^{r^m}$.

3.2. Data and Estimation

The models were estimated with Bayesian techniques using the same data definitions and priors as Del Negro et al (2017). For the euro area we have modified steady state growth rate of the economy but otherwise employed the same priors. The sample covers the United States (1960Q1–2024Q3) and the euro area (1970Q2–2024Q3). Standard macroeconomic observables are augmented with financial spreads and long-term inflation expectations. As Del Negro et al. (2017) the model is estimated on Baa and Aaa spreads, real output growth, both gross domestic product and gross domestic income, consumption growth, investment growth, real wage growth, hours worked, inflation, measured as the GDP deflator and core inflation, the policy rate, the 10-year government bond yield, and a measure of TFP. To capture policy expectations, we include yield-curve information. The anticipated policy component was modelled as an observable during times during periods in which forward guidance is operative: at the effective lower bound and under the post-COVID policy frameworks (including AIT in the US). Outside these periods, the yield curve is left to be determined by the model. For more details see Appendices III to V. *r** is defined as the ex-ante 5 year ahead long term riskless real interest rate under flexible prices.

$$r_t^* = E_t\left[R_{t+20}^{f,real}\right] \quad (7)$$

i.e. it is the forward moving average of short term risk-free real rates of bonds providing perfect safety and liquidity services.[2]

4. *r** estimates across the Atlantic

Our estimates suggest a significant fall in natural rates after the GFC and a subsequent rise around the pandemic, regardless of the model used. The broad, often called, secular decline in natural rate is common across regions and methods, albeit there is a correction more recently, which may or may not be persistent. The key difference emerges after 2008: when policy expectations are explicitly accounted for, the estimated post-pandemic increase in r^* is materially smaller in the estimation without anticipated policy.

This result is best understood as a reallocation of explanatory weight between two persistent forces that both fit the positive inflation–rate co-movement: Without forward guidance observables, the model can rationalize the joint fall and subsequent rise in inflation and the policy rate mostly by loading more heavily on movements in convenience yields and other persistent structural forces, which by construction move r^*. With forward guidance observables during the relevant episodes, the model attributes more of the same joint behavior to anticipated policy shocks, thereby reducing the need to move r^* to fit the data. This is the central measurement result: policy expectations act as an identifying restriction on the anticipated policy component, and that restriction changes inferred r^*.

To illustrate the role of policy expectations we can also look at the output gap estimates (second row on Figure 1) and the contributions to the output gap from anticipated policy (third row of Figure 1) and convenience yield shocks (fourth row of Figure 1). The difference between the two lines is the impact of policy expectations. As the forward guidance shocks have no impact on r^* but on output gap, the difference in the r^* estimates are mostly due to the changes in the filtered convenience yield shocks and the forward guidance shocks explain the difference in output gap estimates. Figure 1, thus, shows that the inclusion yield curve observables identify convenience yield shocks that change the estimated r^*, as well as policy expectations that change the output gap estimates.

[2] We consider this as the measure of the natural rate, as the real interest with flexible prices and without any financial frictions or when constraints are binding. This should be slightly distinguished from the neutral rate which is the real policy rate when inflation is at the target and output gap is closed. The concepts often coincide but it can differ due to financial frictions.

Figure 1: DSGE estimates of *r and output gap with and without policy expectations**

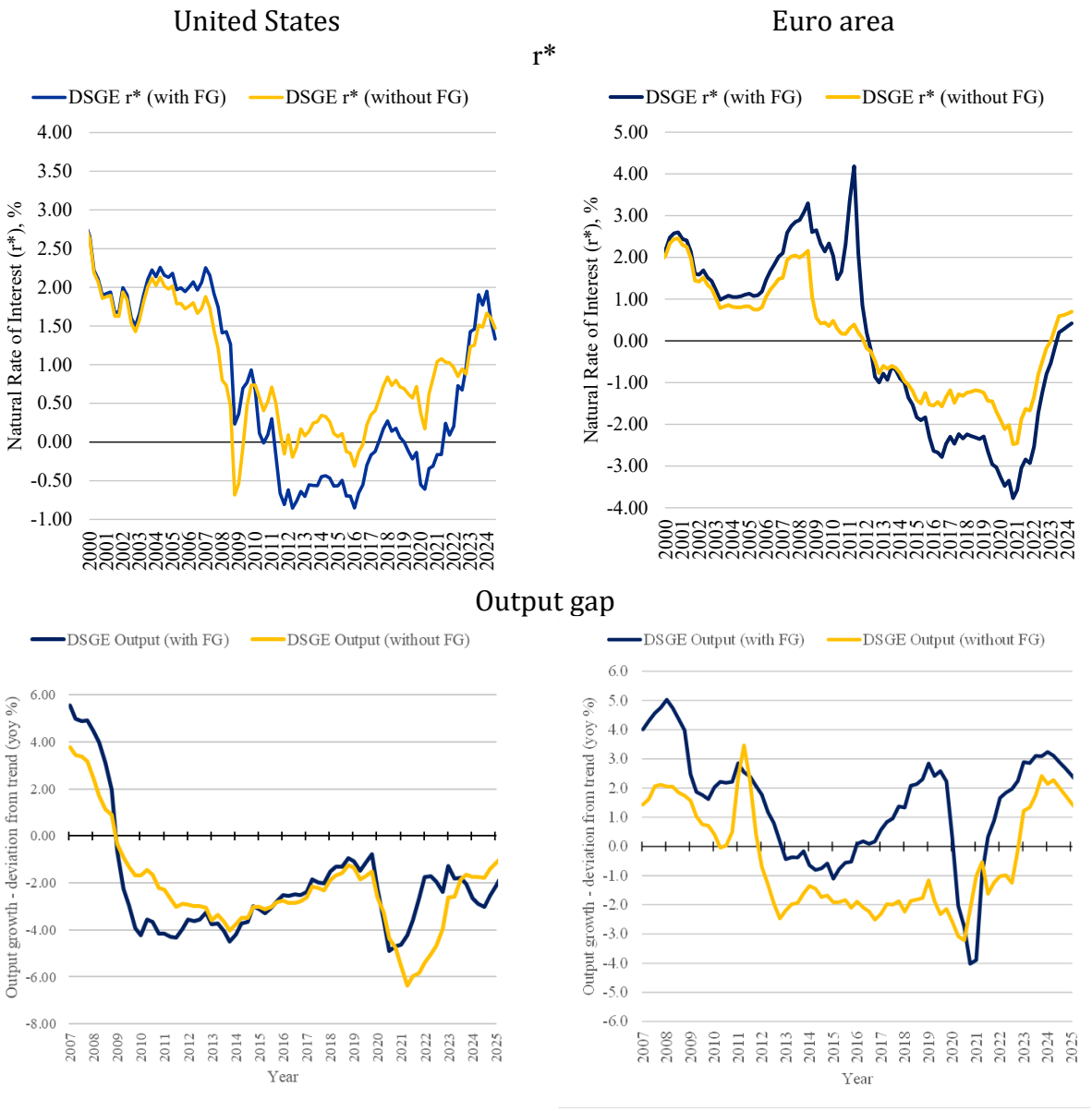
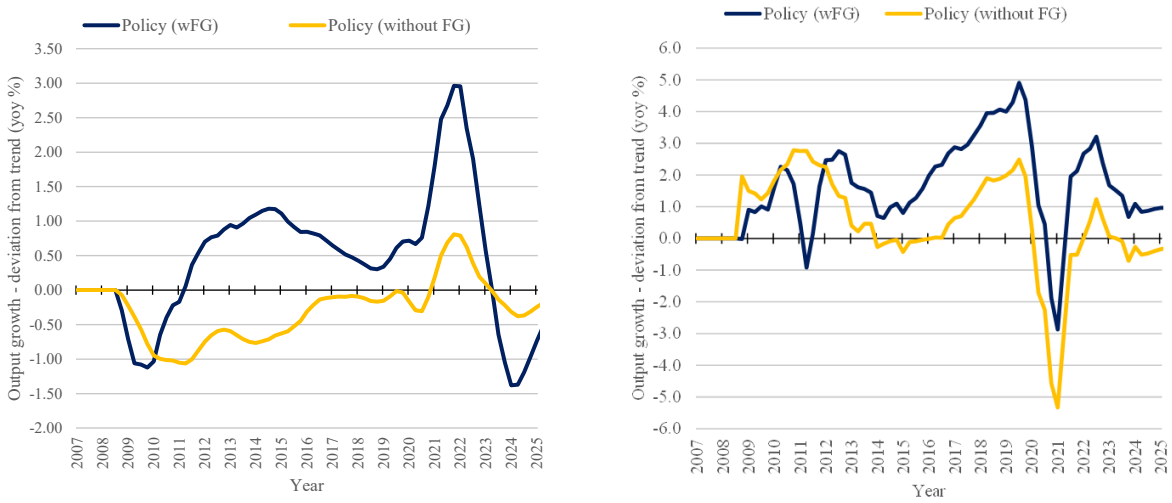
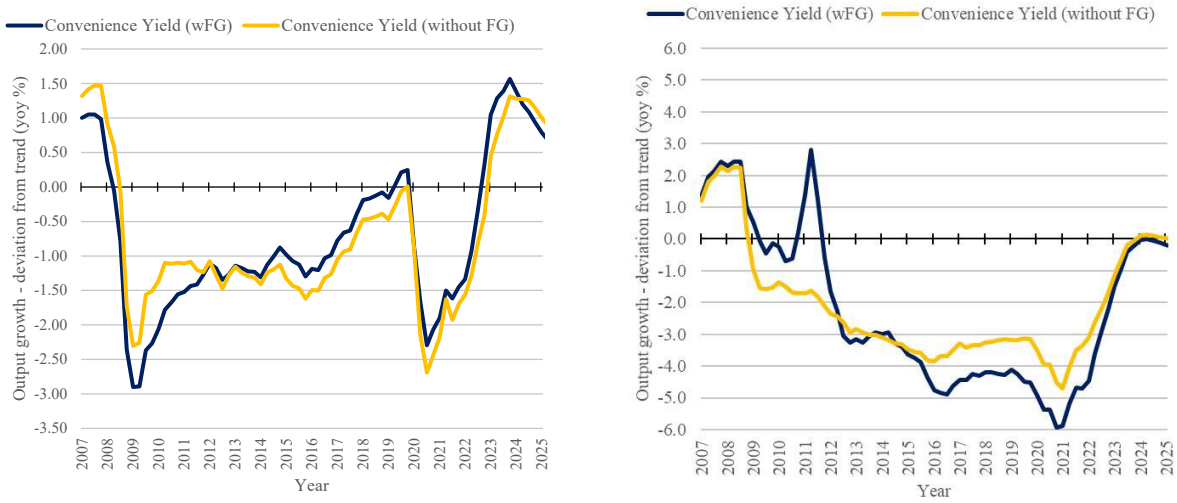


Figure 1 (cont.) Role of forward guidance and convenience yields in output gap with and without policy expectations

Contribution of FG on output gap



Contribution of convenience yield shocks on output gap



Source: IMF staff calculations.

4.1 A narrative of monetary stance

As discussed above we augmented the DSGE observables with term-structure of policy expectations from the OIS curve. Figure 2 plots the policy rate path, the yield curve data, up to 6 quarters ahead, used in estimation, and the smoothed monetary innovations and stacked anticipated shocks by horizon. We distinguish surprise, contemporaneous policy shocks from anticipated, forward guidance, shocks at fixed horizons (h=1,…,6 (FG1-FG6)). In the panel below we plot the raw structural shock series.

On Figure 2 one can observe that in both regions following the initial cuts the years after the GFC was accompanied by positive, tightening contemporaneous monetary policy shocks, and markets first expected a normal, V-type recession. This is reflected in the steep yield curves until 2011.

Figure 3 shows that filtered raw shock across the Atlantic. They enable to tell us a narrative of the nature of anticipated policy shocks. Note that if their cumulative effect is positive monetary policy is restrictive, or restricted by the ELB, compared to the reaction function. If the cumulative effect is negative, we call it an expansionary monetary policy.

In the US the GFC caused a sharp downturn in output. This is reflected in the negative contribution of monetary policy (see Figure 3 left panel). Anticipated policies even pointed toward tightening. This could capture the public sentiment of overly inflationary effects of QE at the time. Then forward guidance, lower for longer, gained a dominant role and for almost ten years they were effectively offsetting the constrained nature of monetary policy shocks at the ELB. Short spell of taper tantrum and the lift-off from the ELB in the US had marginal output and inflationary effect, reflecting that systematic policy was followed. During the COVID-19 pandemic both surprise and anticipated policies became expansionary. There are confounding factors at play. The Fed introduced a new monetary framework, average inflation targeting, unprecedented fiscal expansion and corporate spreads (safety premia) did not increase as in other recessionary episodes. More recently the withdrawal of accommodative policy led to a positive co-movement between policy rates, inflation, and r^*. This reduced the effectiveness of monetary tightening, and in part contributed to the surge in inflation. We argue that this channel is new.

Figure 2: Policy rate and Expectations

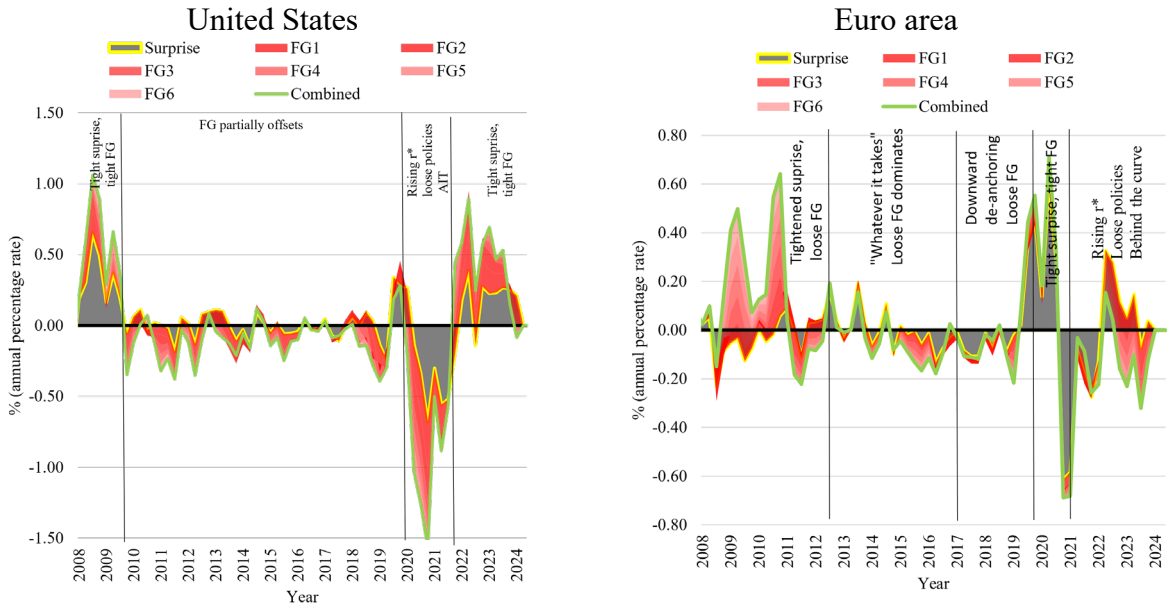


Notes: Expected policy rates are shown for the periods when the Effective Lower Bound (ELB) was binding or when new monetary framework was (Average Inflation Targeting for the US) introduce
Sources: IMF staff calculations, Fred database, Federal Reserve Bank of New York, Haver Analytics.

In the euro area, the relative importance of surprise and anticipated policy shocks had a different trajectory. In general, the euro zone faced less constraints on the short-term policy rate, because r^* was lower than in the US. Despite a temporary rise in 2011-12 the markets did not expect it to continue so anticipated policy offset monetary tightening from the surprise channel. After the

unfolding of the euro zone debt crisis anticipated policy shocks became more dominant, following the "whatever it takes" by Mario Draghi. Despite the gradual run-off of the Eurosystem balance sheet until 2015, anticipated policy was expansionary overall monetary policy remained accommodative. In 2016 the reinvigorated large scale asset purchases created an additional shortage of safe assets, lowering *r** to deeply negative territories, and creating an accommodative environment even at the ELB.

Figure 3: Raw policy shocks in the DSGE models



Notes: Surprise (contemporaneous) and anticipated innovations at horizons h = 1,2, … 6 (FG1-FG6). Anticipated shocks are orthogonalized, scale-free structural innovations.
Sources: IMF staff calculations, Fred database, Federal Reserve Bank of New York, Haver Analytics.

During the COVID-19 Pandemic, 2020-2021, both surprise and anticipated policy became constrained; leading to a stronger tightening than in the US, reflecting a deeper ELB bind in response to Pandemic related supply disruptions, Russia's invasion of Ukraine, geopolitical tensions, energy price increases.

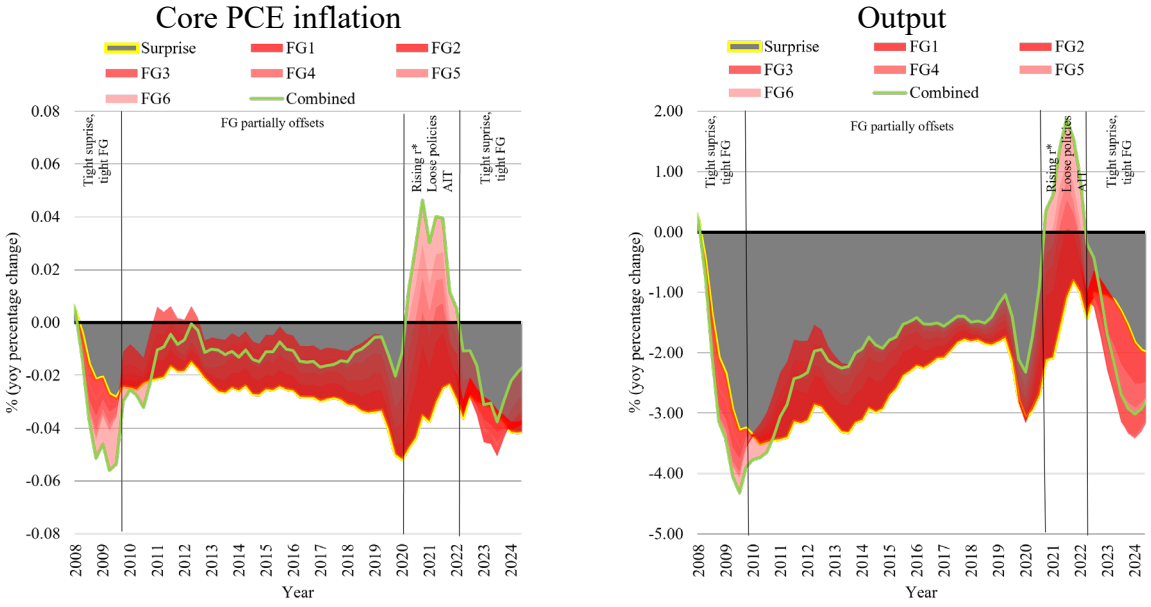
Following the pandemic surprise policy tightens and rate guidance reverses. This masks the surge in *r** and leads to a monetary policy that is inflationary. Ultimately as anticipated policy withdrawal realizes and liquidity injection is dried up, the policy rate turns neutral and then restrictive.

An alternative view of surprise vs. anticipated monetary policies can be captured by their impact on inflation and output (historical variance decomposition contributions). In both regions, anticipated easing during 2012-2019 contributes modestly and persistently to activity with limited

inflation pass-through-consistent with an ELB environment and asset-purchase, FG transmission acting primarily via term premia. During the Pandemic, 2020-2021, the ELB is hit. Following the Pandemic the joint surprise and anticipated easing raise both output and inflation. The reversal of guidance delivers contributions with the opposite sign; combined with the lift-off in short rates, the estimated r^* rises.

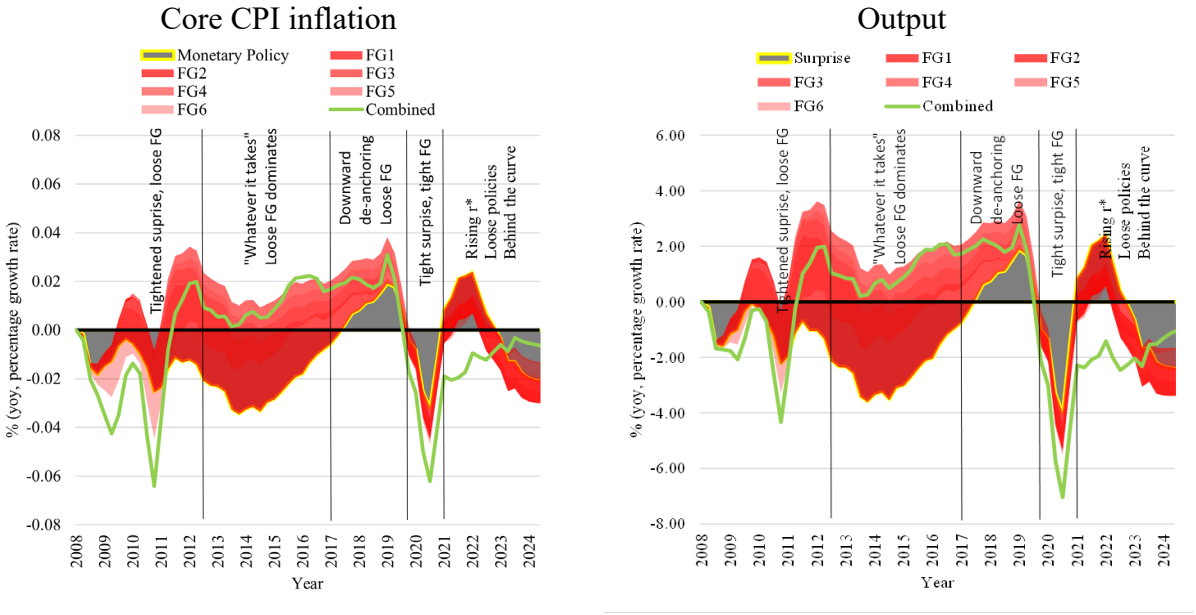
Throughout, the ELB bound, more severely in the EA, and the different mixes of unconventional policies imply different paths for the estimated r^*. The key is the positive correlation of anticipated policy and r^* estimates: when guidance and LSAPs compress long yields, the filtered r^* is lower; when guidance is withdrawn, the filtered r^* rises.

Figure 4: Contributions of surprise and anticipated policy to core PCE inflation and output in the United States



Notes: The chart shows the policy impact of the observed variable decomposition of US yoy core inflation (Fred database ID: PCEPILFE, percentage growth rate) over time.
Sources: Fred database, IMF staff calculations.

Figure 5: Contributions of surprise and anticipated policy to core CPI inflation and output in the euro area



Notes: The chart shows the policy impact of the observed variable decomposition of euro area yoy core inflation (P023SHXU@EUDATA from Haver Analytics) over time.
Sources: Haver Analytics; IMF staff calculations.

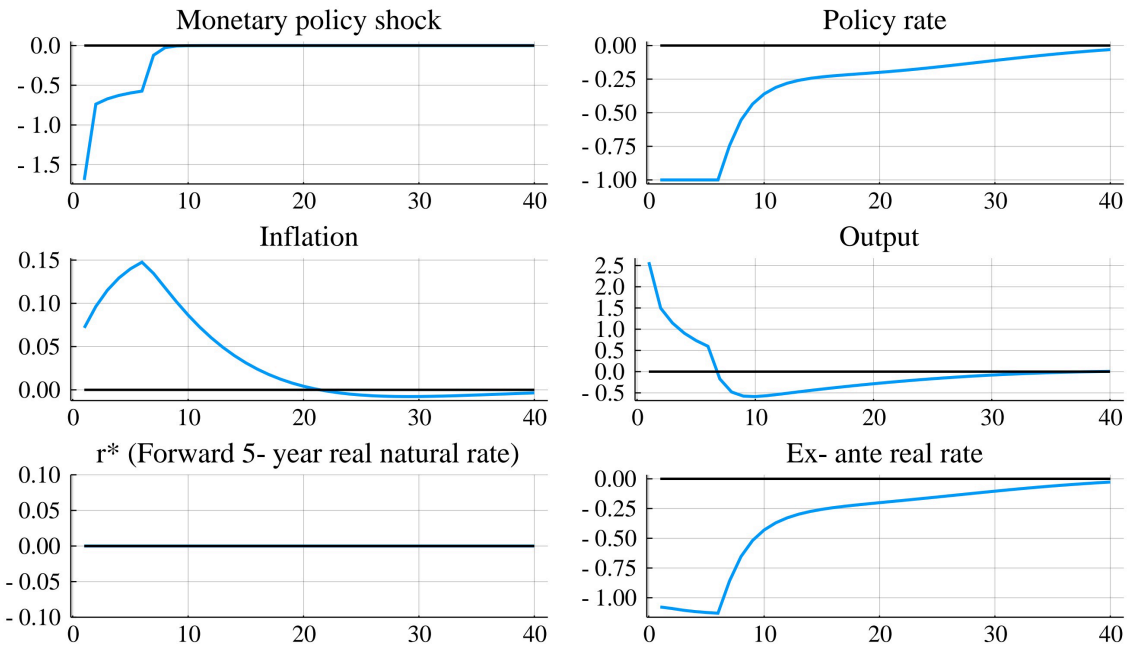
4. Forward guidance reversal puzzle and convenience yields

Depending on expectations, short term effects of monetary policy may be New Keynesian (surprise shocks, sign of policy rate and inflation/output are opposite) or Neo-Fisherian (forward guidance, lower-for-longer, scarcity etc., sign of policy rate and inflation/output opposite) (see Figure 6 and Figure 7 for the US FG model). Expectations of future ex-ante real rate increase after a prolonged monetary accommodation compress demand lowering current output and inflation.[3] Hence, surprise and anticipated policy shocks have different impact on real variables in our model. r^*, however, is unchanged in both cases. Looking at the impulse response of convenience yield (in this example anticipated policy and convenience yield are only different in unobserved r $*$. However, the anticipated monetary policy shocks' impacts are only different in the response of r^* if we compare convenience yield (in this case permanent liquidity[4]) shocks (see Figure 7 vs. Figure 8). r^*, however, is an unobservable variable of the model, posing an identification problem during estimation; without yield-curve information and information on policy expectations the model will

[3] This also holds with behavioral discounting, using Erceg et al. (2021) model, without surprise monetary shocks.
[4] Safety shocks have very similar impulse responses, so our arguments hold for them, as well.

associate policy expectations with convenience yields, and in turn, as a change in r^* in contrast to the anticipated policy expectations shocks for which r^* is unaffected. To tackle this identification issue, for each economy we have two versions of estimation. In the "*FG model*" version with policy expectations.

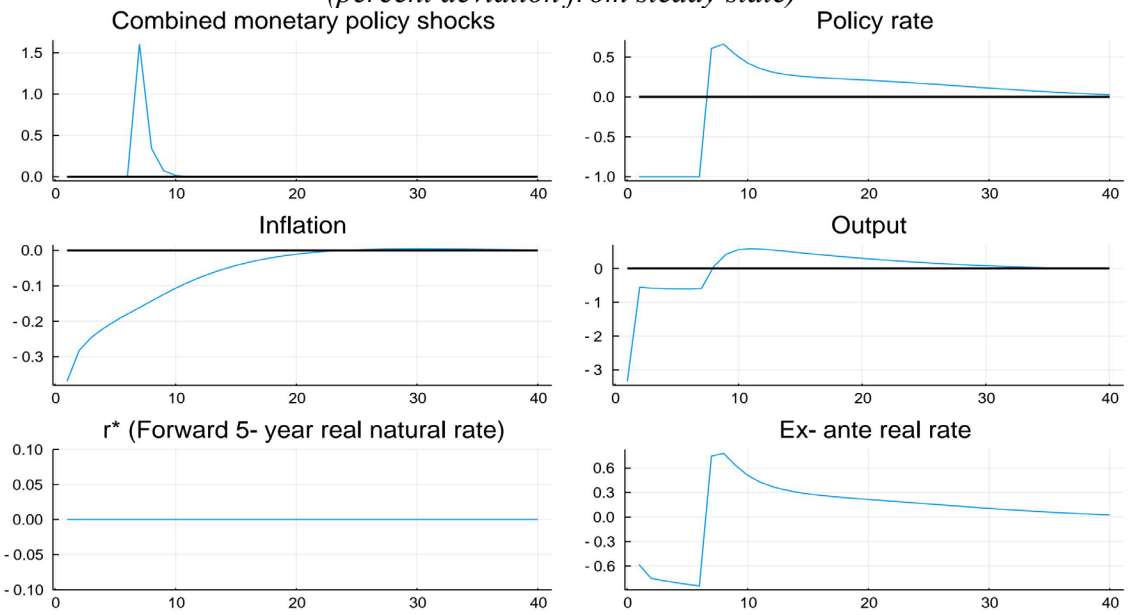
Figure 6: Interest Rate Peg with Unanticipated Monetary Policy Suprises
(percent deviation from steady state)



Notes: Inflation is defined as year-on-year percentage change, policy rate, r^* and ex-ante real rate are defined as annual percentages
Source: IMF staff calculations.

Figure 7: Interest Rate Peg with Anticipated Monetary Shocks

(percent deviation from steady state)

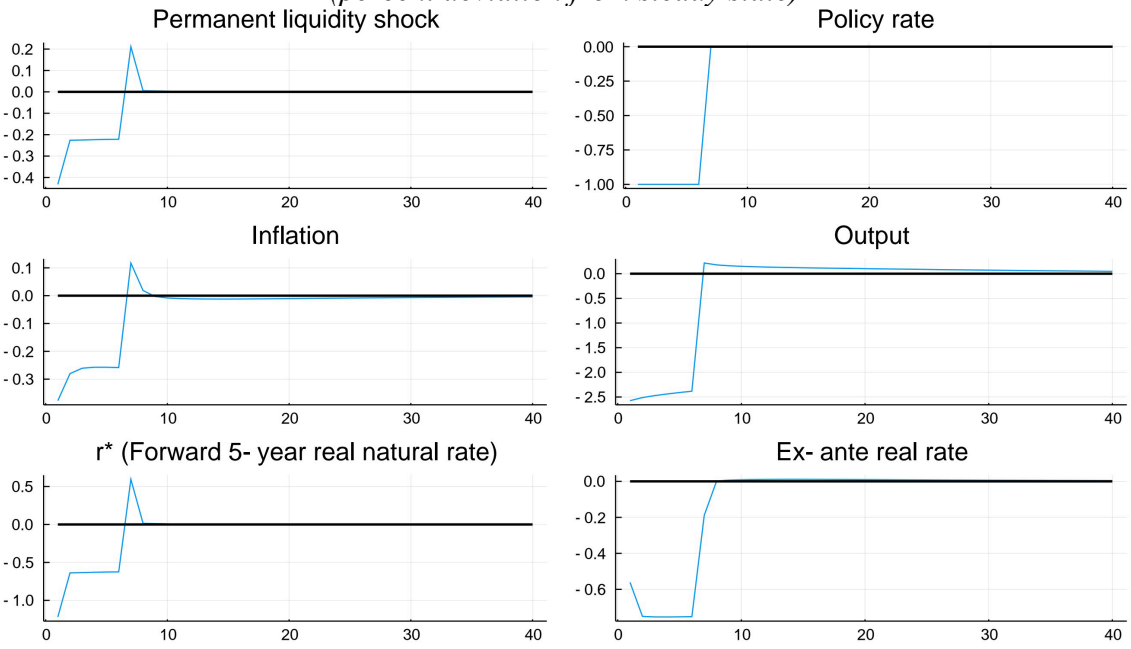


Notes: Inflation is defined as year-on-year percentage change, policy rate, *r** and ex-ante real rate are defined as annual percentages

Source: IMF staff calculations.

Figure 8: Permanent Liquidity Shocks resulting in constant policy rate for 8 quarters

(percent deviation from steady state)



Notes: The permanent safety shock has very similar IRF as a peg implemented with unanticipated monetary policy shocks. Inflation is defined as year-on-year percentage change, policy rate, *r** and ex-ante real rate are defined as annual percentages

Source: IMF staff calculations.

5. Counterfactual analysis

We have shown that convenience yield shocks and forward guidance shocks are hard to disentangle, because they have similar impacts on observables. Misidentification can lead to policy errors. Our first counterfactual exercise seeks to answer what if r^* had not risen, the second, answers the question, what if the US was exposed to the convenience yield dynamics of the euro area, that is what if the USD did not enjoy the exorbitant privilege.

5.1. What if r^* had not risen?

The exercise tries to demonstrate how the movement in the natural rate of interest may have played a role in the post-pandemic inflation episode.[5] However, even policy strategies that abstract from the level of r^* are not immune to its changes. Movements in r^* affect the stance of monetary policy not only contemporaneously but also through expectations about the future path of interest rates. As a result, uncertainty or misperception regarding the evolution of r^* can still translate into a different degree of effective accommodation than intended, particularly in an environment where forward guidance plays a central role.

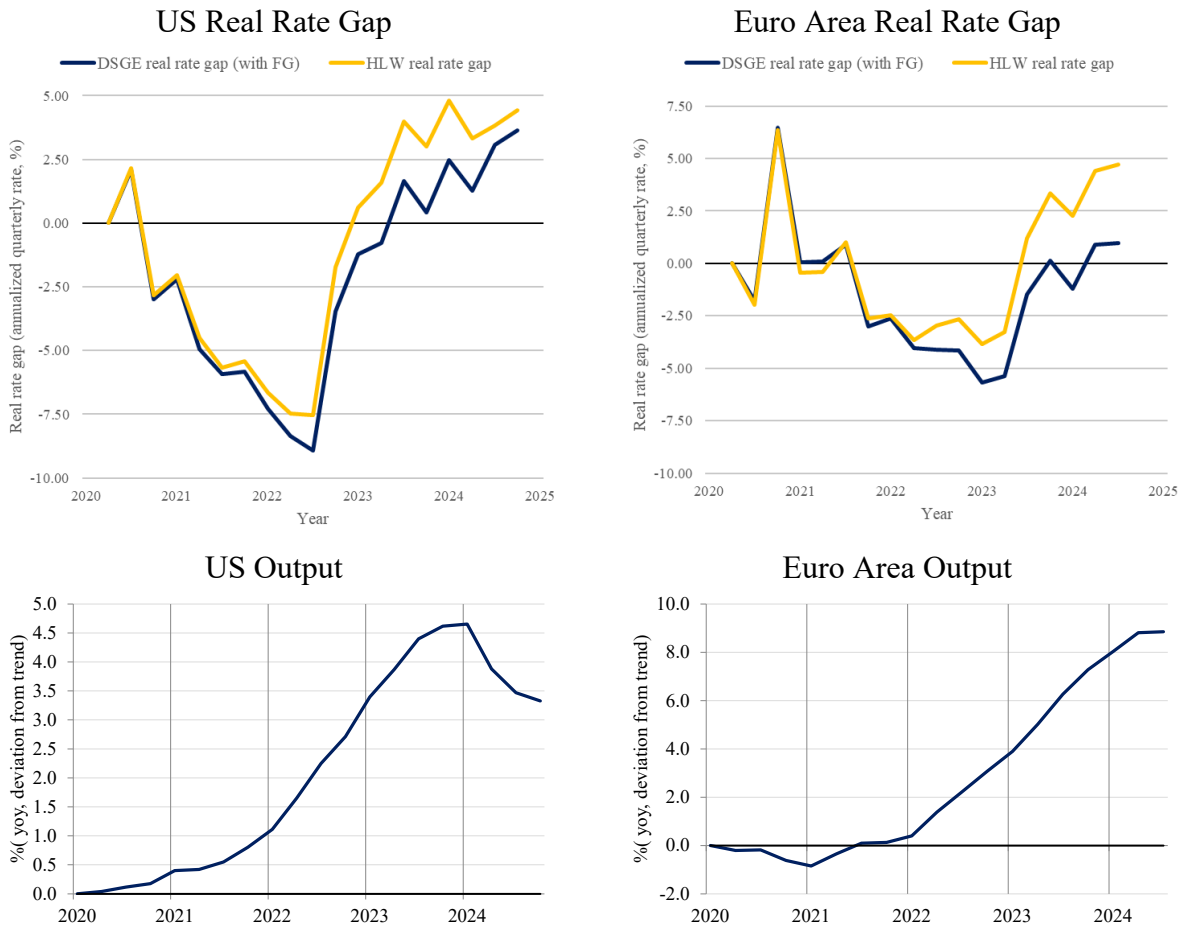
To gauge the quantitative importance of this channel, we consider a counterfactual scenario in which the change in the natural rate follows the evolution of HLW's estimates while policy follows the same path as in the data, starting from pre-Pandemic, 2020Q1 level for both the US and the euro area

The top row of Figure 9 displays the (realized) real rate gap, as a short-term measure of policy stance under alternative estimates of r^*.[6] The increase in r^* implies that the policy rate consistent with a neutral stance would have been approximately 1 to 2 percentage points higher than otherwise. Convenience-yield shocks underlying the change in r^* also have direct macroeconomic effects. In the counterfactual, they contribute to an increase of inflation by around 0.4 percentage points in the US and 0.8 percentage points in the euro area, and generate a gradual increase in output of up to 5 percent in the US and 8 percent in euro area. This large output effects translate to around 1 percentage point higher output growth in the US and 2 percentage points higher in the euro area on average.

[5] Levin, Wieland, and Williams (1998) and Orphanides and Wieland (2013), highlights the robustness of first-difference policy rules in environments where the level of the neutral rate is difficult to pin down.

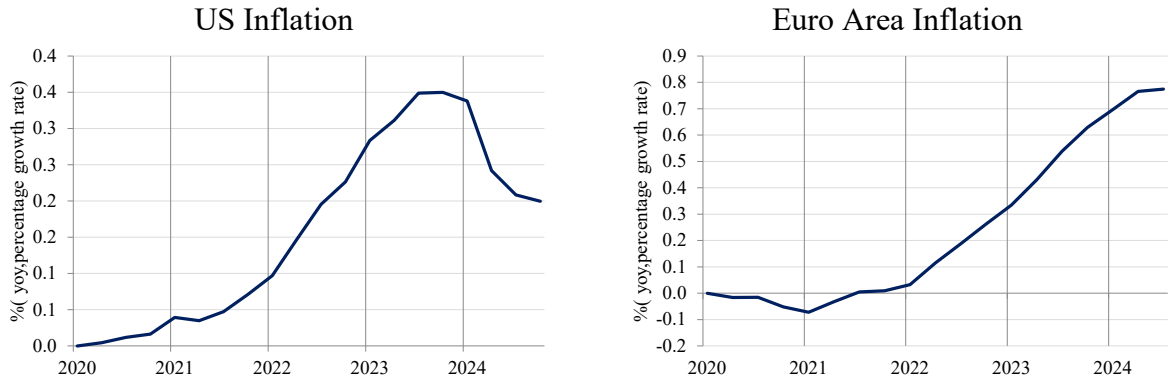
[6] We define the real rate gap as the ex-ante real rate, $rr_t = R_t - E_{t-1}[\pi_t]$, where R_t is the nominal policy rate and $E_{t-1}[\pi_t]$ is the ex-ante inflation expectation. For the DSGE we have the model implied inflation expectations. For HLW we take the realized inflation in as a proxy for the model-consistent ex-ante inflation.

Figure 9: No increase in *r: Real Rate Gaps and Counterfactual Output**



Notes: Counterfactual scenario of the US DSGE model had *r** not increased following COVID-19. We allow for all shocks to explain the change in smoothed US *r**. The counterfactual assumes *r** that of 2020Q1, depth of the pandemic would have prevailed.
Source: IMF staff calculations.

Figure 10: No increase in *r: Counterfactual Inflation**



Notes: Counterfactual scenario of the US DSGE model had *r** not increased following COVID-19. We allow for all shocks to explain the change in smoothed US *r**. The counterfactual assumes *r** that of 2020Q1, depth of the pandemic would have prevailed.
Source: IMF staff calculations.

5.2. Measuring the exorbitant privilege of the dollar

In this counterfactual exercise, we examine how US macroeconomic outcomes would have differed if the convenience yields associated with dollar-denominated assets had instead resembled those prevailing in the euro area. The exercise can be interpreted as a proxy for the macroeconomic implications of the United States benefiting from an "exorbitant privilege" in the form of lower safety and liquidity premia on its government securities[7].

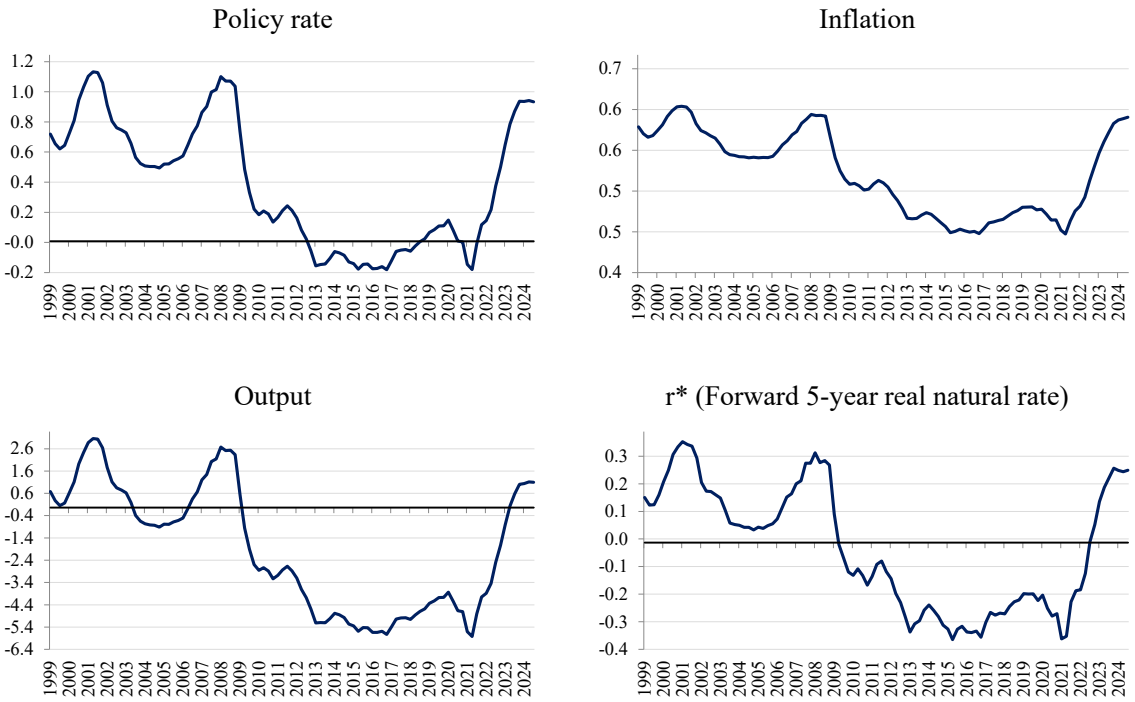
The counterfactual is implemented by targeting the observed euro area convenience-yield premia from the perspective of a US investor. Because safety and liquidity premia in the model are driven exclusively by transitory and permanent shocks, only these shocks are adjusted to match the euro area convenience-yield path, while all other structural relationships are left unchanged. Figure 11 reports the implied paths of the policy rate, inflation, output, and the natural rate.

The resulting shock realizations are persistently one-sided through the end of 2012. In the model, these shocks raise inflation and the policy rate on a sustained basis, lead to a modest increase in *r**, and depress output relative to baseline. The counterfactual also reproduces features associated with the euro area sovereign debt crisis: had similar safety and liquidity dynamics prevailed in the US, output losses would have been substantial, while inflation pressures would have remained elevated. In this environment, both *r** and the policy rate would eventually have been lower. More recently, the exercise suggests that heightened geopolitical and trade tensions may have narrowed

[7] Specifically, we construct a counterfactual US economy in which the safety and liquidity services of US dollar assets are removed, and investors require convenience yields equal to those observed in the euro area.

the historical advantage associated with the dollar's safety premium, reducing the extent to which US assets command exceptionally low convenience yields.

Figure 11: Impact of the lack of exorbitant privilege on the United States



Notes: Counterfactual scenario simulated by the US DSGE model targeting the convenience yield dynamics in the Euro Area. We allow for all shocks to match the transitory and permanent liquidity and safety spreads associated with the exorbitant privilege of the US. The counterfactual filters the observed Euro Area data for the convenience yield from the US representative agent's perspective. The filtered shock displays a persistent one-sided realization, driving inflation and policy rate persistently higher. *r** is initially rising and later falling sharply as the EA entered the fiscal crisis in 2012. Output would be on average slightly lower with the dynamics mirroring that of *r** driven by predominantly permanent TFP shocks.
Source: IMF staff calculations.

6. Conclusion

In our paper we investigate the role of policy expectations on the estimation of natural rate of interest (r*). We examine how policy expectations shape inference about the natural rate of interest. By estimating a DSGE model that incorporates forward guidance and convenience yields, we show that the estimation of a significant part of the post-2020 increase in *r** is linked to the unwinding of forward guidance. The key mechanism is a property of the forward guidance, as the expectations channels generate a positive co-movement of the policy rate and inflation in the short run. This is usually considered as an unfavorable property of DSGE models, i.e. the forward guidance reversal puzzle. We argue, however, that this puzzle becomes a feature as data on

expected policies help identifying movements in r^*. With this, we can disentangle convenience yield and productivity shocks from anticipated monetary policy shocks. Without this information, the estimation suffers from identification as these shocks have similar impulse responses for major observed macroeconomic variables but the unobservable natural interest rate. We found that when central banks in the U.S. and euro area shifted from exceptionally accommodative policies relying on forward guidance to a rapid tightening cycle, the natural rate is estimated to rise in tandem with policy rates, and inflation, reducing the tightening of monetary policy stance. A counterfactual exercise demonstrates that US benefited from the exorbitant privilege during the eurozone debt crises and that more recently this advantage has gradually faded.

It should be noted that, we do not model fiscal policy explicitly and therefore abstract from monetary–fiscal interactions. This rules out channels in which debt dynamics, fiscal risks, or regime shifts in fiscal backing influence equilibrium real rates. In our framework, the impact of LSAP's are captured indirectly through the yield curve; we therefore omit portfolio-balance and safe asset scarcity channels that can matter for the determination of r^*. A more elaborate modeling of balance sheets might add some further details. Furthermore, our monetary policy block is intentionally parsimonious. While we allow for anticipated policy shocks that capture forward guidance, we do not model explicit regime switches in policy frameworks or reaction functions. This is potentially important in the post-COVID period, when the conduct and communication of policy plausibly deviated from simple Taylor-type prescriptions. In this respect, recent developments, like Nakamura and Steinsson's Jackson Hole paper (2025), show that persistent deviations from Taylor-rule can be motivated by a shock contingent commitment. Another promising avenue would be to complement r^* with the financial-stability real interest rate, the so-called r^{**} proposed by Akinci et al (2020).

Our main message is that central banks should carefully take into account the bias in the estimation of r^* due to policy announcements.

References

Akinci, O., Benigno, G., Del Negro, M., and Queralto, A., "The financial (in) stability real interest rate", FRB of New York Staff Report, (946), 2020

Angeletos, George-Marios, Chen Lian, and Christian K Wolf, "Deficits and Inflation: HANK meets FTPL," 2024.

Bauer, Michael D. and Glenn D. Rudebusch, "Interest Rates under Falling Stars," Working Paper 2017-16, Federal Reserve Bank of San Francisco November 2017.

Baker, Katie; Logan Casey, Marco Del Negro, Aidan Gleich, and Ramya Nallamotu, "The Post-Pandemic *r**," Federal Reserve Bank of New York *Liberty Street Economics*, August 9, 2023, https://libertystreeteconomics.newyorkfed.org/2023/08/the-post-pandemic-r/

Benigno, Gianluca; Boris Hofmann; Galo Nuño Barrau and Damiano Sandri "Quo vadis, *r**? The natural rate of interest after the pandemic," BIS Quarterly Review, Bank for International Settlements, March 2024.

Bernanke, Ben and Olivier Blanchard, "What caused the US pandemic-era inflation?", Vol. 86, PIIE, Peterson Institute for International Economics, 2023.

Bernanke, Ben S, Mark Gertler, and Simon Gilchrist, "The financial accelerator in a quantitative business cycle framework," in John B. Taylor and Michael Woodford, eds., Handbook of Macroeconomics,Vol. 1, Elsevier, 1999, chapter 21, pp. 1341–1393.

Brand, Claus and Falk Mazelis, "Taylor-rule consistent estimates of the natural rate of interest", No 2257, ECB Working Paper, 2019.

Brand, Claus, Noëmie Lisack, and Falk Mazelis, "Estimates of the natural interest rate for the euro area: an update," Economic Bulletin Boxes, 2024, 1.

Bulíř, Aleš and Jan Vlcek, "The Mirage of Falling R-stars", IMF Working Papers 2024, 161 (2024).

Caballero, Ricardo J, Emmanuel Farhi, and Pierre-Olivier Gourinchas, "The safe assets shortage conundrum," Journal of economic perspectives, 2017, 31 (3), 29–46.

Christiano, Lawrence J., Roberto Motto, and Massimo Rostagno, "Risk Shocks," American Economic Review, 2014, 104 (1), 27–65.

Ciccarelli, Matteo, Eva Ortega, Benoit Mojon, and Frank Smets, "The Natural Rate of Interest: Estimates, Drivers, and Challenges to Monetary Policy," Occasional Paper 217, European Central Bank, December 2018.

Del Negro, Marco and Frank Schorfheide, "DSGE Model-Based Forecasting," in Graham Elliott and Allan Timmerman, eds., Handbook of Economic Forecasting, Vol. 2, Elsevier, 2013, chapter 2, pp. 57–140.

Del Negro, Marc P. Giannoni, and Frank Schorfheide, "Inflation in the Great Recession and New Keynesian Models," American Economic Journal: Macroeconomics, 2015, 7, 168–196.

Del Negro, M., D. Giannone, M. P. Giannoni, and A. Tambalotti (2017). "Safety, liquidity, and the natural rate of interest", Brookings Papers on Economic Activity 2017 (1), 235–316.

DSGE.jl, [Source code] (Version 1.3) https://github.com/PSLmodels/DSGE.jl, 2025.

Fiorentini, Gabriele, Alessandro Galesi, Gabriel Pérez-Quirós, and Enrique Sentana, "The rise and fall of the natural interest rate," Banco de Espana Working Paper, 2018.

Hartmann, Philipp and Frank Smets, "The European Central Bank's monetary policy during its first 20 years," Brookings Papers on Economic Activity, 2018, 2018 (2), 1–146.

Holden, Tom D, "Existence and uniqueness of solutions to dynamic models with occasionally binding constraints," Review of Economics and Statistics, 2023, 105 (6), 1481–1499.

Holston, Kathryn, Thomas Laubach, and John C. Williams, "Measuring the Natural Rate of Interest: International Trends and Determinants," Journal of International Economics, 2017, 108, S59–S75.

Holston, Kathryn, Thomas Laubach, and John C. Williams "Measuring the Natural Rate of Interest after COVID-19," Staff Report 1063, Federal Reserve Bank of New York June 2023.

International Monetary Fund (IMF), "The natural rate of interest: drivers and implications for policy", World Economic Outlook, April, Chapter 2, 2023.

Kiley, Michael T., "What Can the Data Tell Us About the Equilibrium Real Interest Rate?," FEDS Working Paper 2015-077, Board of Governors of the Federal Reserve System August 2015.

Laséen, Stefan and Lars E. O Svensson, "Anticipated alternative instrument-rate paths in policy simulations", CEPR Discussion Paper No. DP8176, 2011.

Laubach, Thomas and John C. Williams, "Measuring the Natural Rate of Interest," Review of Economics and Statistics, 2003, 85 (4), 1063–1070., 2003

Levin, A. T., Wieland, V., and Williams, J., "Robustness of simple monetary policy rules under model uncertainty", in Monetary policy rules (pp. 263-318). University of Chicago Press., 1999

Lubik, Thomas A. and Christian Matthes, "Calculating the Natural Rate of Interest: A Comparison of Two Alternative Approaches," Economic Brief 15-10, Federal Reserve Bank of Richmond October 2015.

Nakamura, E., Riblier, V., and Steinsson, J., "Beyond the Taylor rule", No. w34200. National Bureau of Economic Research, 2025

Orphanides, Anastasios, and Wieland, Volker ," Complexity and monetary policy (No. 2012/11). CFS Working Paper.2012

Platzer, Josef and Peruffo Marcel, "Secular Drivers of the Natural Rate of Interest in the United States: A Quantitative Evaluation", *IMF Working Papers* 2022, 030, 2022.

Rachel, Lukasz and T. D. Smith, "Secular drivers of the global real interest rate", Bank of England Staff Working Paper (571)., 2015

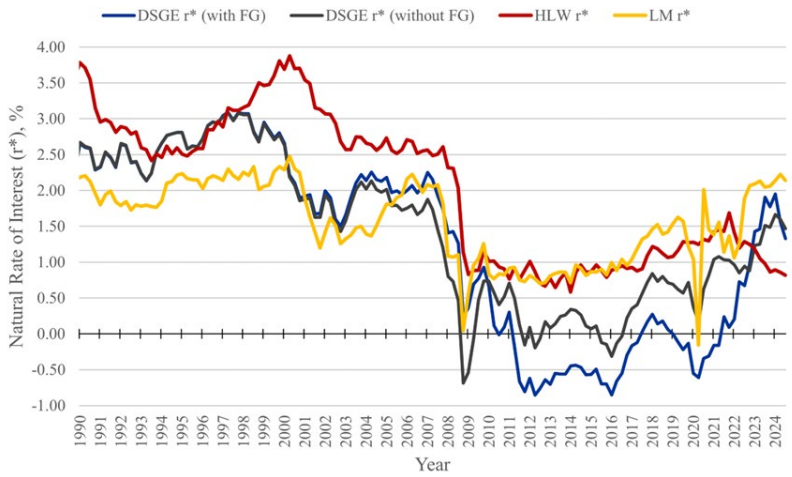
Rachel, Lukasz and Lawrence H. Summers, "On Secular Stagnation in the Industrialized World," Brookings Papers on Economic Activity, 2019, 50 (1), 1–76.

Smets, F. and R. Wouters, "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," American Economic Review, 2007, 97, 586–606. https://doi.org/10.1257/aer.97.3.586.

Woodford, Michael, "Interest and Prices: Foundations of a Theory of Monetary Policy", Princeton University Press, 2003

APPENDIX I. Comparison of DSGE estimates with other methods

Figure I.1:US Natural Rate of Interest across methods



Notes: US natural rate of interest estimated using four models: (1) a DSGE with and (2) without forward guidance (Del Negro et al. 2017), (3) Holston, Laubach, and Williams (2017) estimates and (4) Lubik and Matthes (2015) for 1990Q1–2024Q4.
Sources: Haver Analytics, Federal Reserve Bank of New York and Richmond, IMF staff calculations.

HLW provides a simple and transparent estimate of r^* by linking it directly to potential growth. This makes it widely used in policy work, but also restrictive: it attributes most of the decline in r^* to slower growth ("g") and an unexplained, other factors (a stochastic random walk - z). The Lubik--Matthes (2015) (henceforth LM) relax this restriction by estimating a time-varying Bayesian VAR with stochastic volatility. Their method is flexible allowing the likelihood to select the best fitting structure, and highlights changes in the relationship between volatility and r^* estimates. However, in its flexibility is its weakness, it remains reduced-form and offers limited guidance on which structural forces drive r^*. Lastly, both methods are one-sided, that is purely backward looking in their states.

In contrast, our DSGE model is structural and accounts for expectations. By embedding a convenience yield in the Euler equation, it shows that safety and liquidity premia can explain a large share of the changes in r^*. Compared with HLW and LM, this delivers a richer interpretation of both long-run trends and cyclical fluctuations in r^*. We will present results with and without forward guidance. Following (DelNegro2017) we denote the model consistent estimates of 5-year forward expected real natural rates as r^*.

Figure I.1 shows a common feature of the estimates that there was an overall downward trend that started with the great moderation. This is often described as secular forces being in place. These secular forces include long run developments, such as lower productivity growth and

demographic shifts. After short term rates reached the effective lower bound, both the FED as well as the ECB embarked on a large scale asset purchases. Secular forces coincided with unconventional monetary policy easing. HLW and LM only implicitly capture the impacts of these monetary policy developments. For example, in HLW estimates these developments may have been included in the unexplained random walk component (denoted as "z").

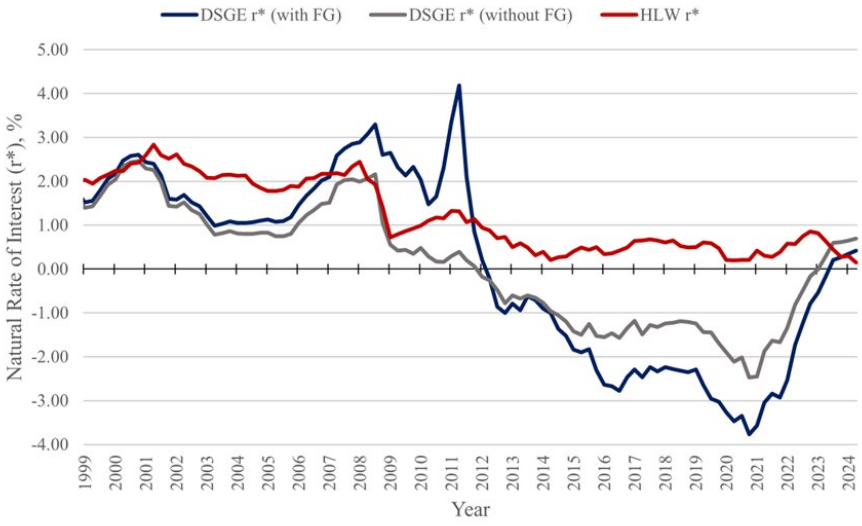
Figure I.2 compares euro area r^* estimates from New Keynesian DSGE model with forward-guidance (FG) shocks (dark blue), the same DSGE model without FG shocks (grey), and the semi-structural Holston–Laubach–Williams (HLW) measure (red).

In the early 2000s, all three measures are broadly aligned at around 2–3%, suggesting a neutral rate consistent with robust growth and well-anchored inflation expectations. However, the global financial crisis introduces sharp divergence: DSGE r^* estimates fall steeply, especially once FG shocks are included, reflecting both weaker long-run fundamentals and the role of expectations management. The HLW measure, by contrast, declines only modestly, highlighting its smoother, trend-based construction.

During the euro area sovereign debt crisis and the period of financial fragmentation (2011–2015), DSGE r^* plunges into deeply negative territory, with the FG-augmented estimate pointing to an even sharper drop. This illustrates the model's insight that in a world of persistent policy signals, elevated risk premia, and impaired transmission, the neutral rate consistent with stable inflation is far lower than what statistical filters imply. (hartmann2018european) reviewing the first 20 years of the ECB conclude that ECB policy and in particular non-standard measures were critical in offsetting downward pressures on the natural rate. Following (brand2024estimates) we stress that whilst estimation uncertainty remains high about the level of r^*, the directional change can be considered robust across estimates.

Post-pandemic, all measures show a marked rebound: DSGE r^* recovers from negative territory and by 2023–24 lies close to the HLW estimate at roughly 0–1%. This reflects the supply shocks, pandemic and Russian invasion of Ukraine, driven restructuring, elevated fiscal support, and the ECB's monetary accommodation in form of large-scale asset purchases, PEPP, targeted lending, TLTROs and forward guidance. The convergence is capturing a repeating pattern: in times of stress, structural model estimates of r^* can move sharply driven by forward looking expectations of impact of persistent shocks, that conventional one-sided filters miss. Structural DSGE approaches reveal how policy—via forward guidance and unconventional measures—not only responds to but also reshapes the trajectory of r^* through its interaction with persistent shocks.

Figure I.2 Euro Area Natural Rate of Interest across methods



Notes: The figure compares euro area *r** estimates from a DSGE model with (1) forward-guidance (FG) shocks (dark blue), (2) the same DSGE model without FG shocks (grey), and (3) the semi-structural Holston–Laubach–Williams (HLW) measure (red).
Sources: Haver Analytics; IMF staff calculations.

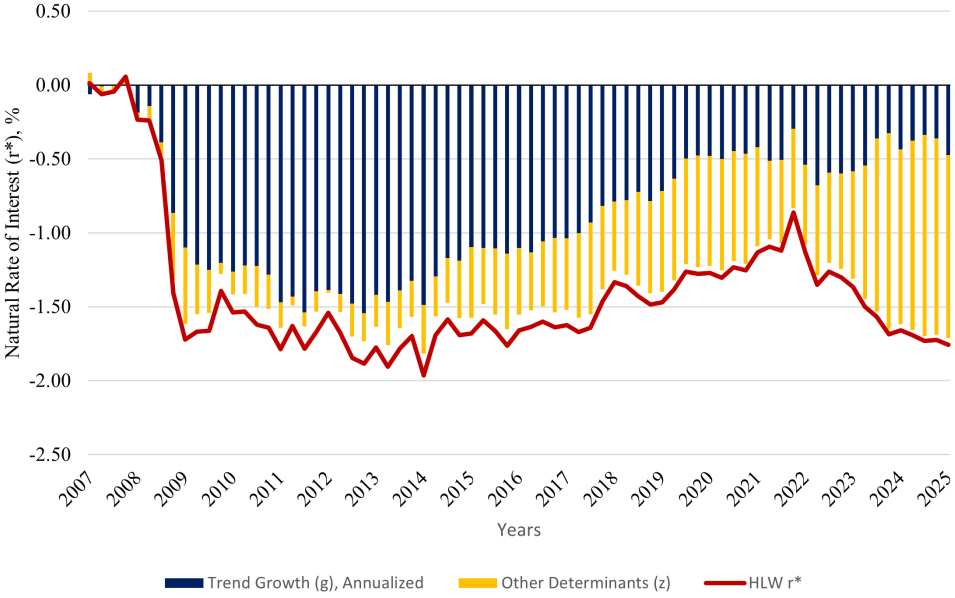
APPENDIX II. Major driving forces of r^* after the Global Financial Crises through the Pandemic

Figure II.1. presents the decomposition of changes in r^* starting from 2007 for the United States. The US HLW decomposition highlights how the natural rate of interest has been shaped since the global financial crisis. The growth component ("g") has remained modest but consistently positive, pointing to relatively resilient productivity and labor market fundamentals. The sharp fall in r^* in 2008–09 is almost entirely due to the unexplained "other" component ("z"), which may reflect heightened risk premia, deleveraging, and strong demand for safe assets, as well as any other unexplained permanent factors, such as demographics. Through the 2010s, "z" stayed deeply negative, keeping the US natural rate suppressed even as the real economy gradually recovered, before rebounding somewhat in the late 2010s and plunging again during the pandemic shock. This decomposition suggests that in the US, structural growth held up better, while financial-cycle dynamics captured by "z" explain most of the short-run variation in r^*.

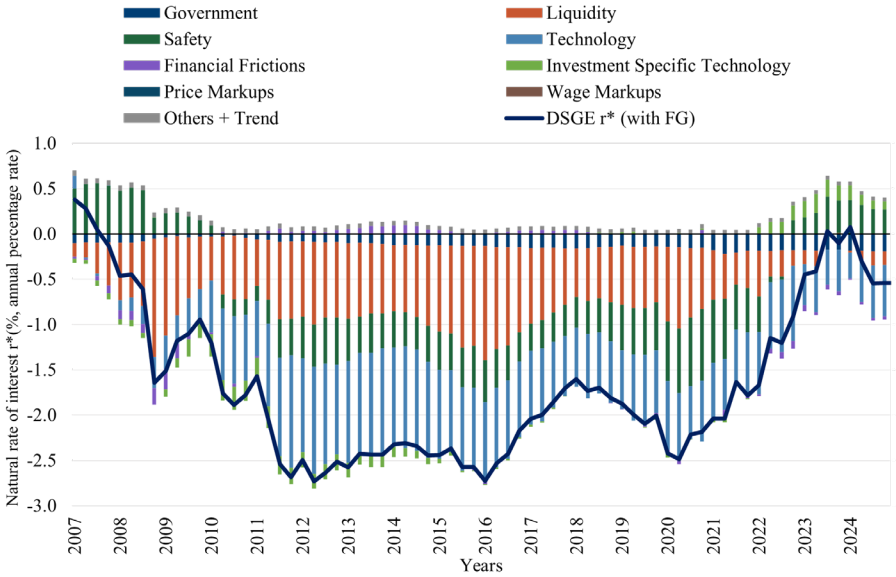
The DSGE-based decomposition with forward guidance (FG) confirms and sharpens this interpretation by linking swings in r^* to explicit shocks and policy expectations. During the Great Recession, financial (liquidity and safety shocks) and demand disturbances drove the neutral rate sharply negative, consistent with the Federal Reserve's turn to unconventional policies—large-scale asset purchases, zero lower bound policy, and forward guidance—all aimed at compressing premia and lifting the effective stance. The model shows persistently negative r^* throughout much of the 2010s, before a strong rebound in the post-pandemic period as fiscal support, reopening dynamics, and rapid tightening pushed the neutral rate temporarily higher.

Figure II.1 1: United States Natural Rate of Interest (r*) Decompositions: HLW semi-structural vs. DSGE with forward guidance

(a) HLW *r** Decomposition (US)



(b) DSGE *r** decomposition with forward guidance (US)



Notes: The figure compares US *r** estimate decompositions from (a) the semi-structural Holston–Laubach–Williams (HLW) measure, and (b)a DSGE model with forward-guidance (FG) shocks.
Sources: Haver Analytics, Federal Reserve Bank of New York, IMF staff calculations.

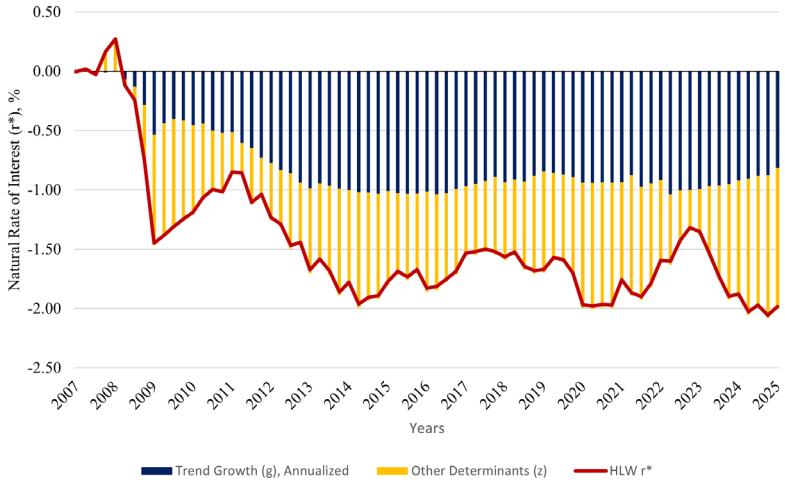
In contrast to the US, the decomposition of the HLW estimate highlights how structural growth weakness became the main driver of the natural rate's decline. The growth component ("g") fell sharply during the second wave of the sovereign debt crisis, reflecting weak productivity and demographic headwinds that amplified fiscal sustainability concerns. Since then, "g" has remained

persistently negative at around --1%, locking in a structural drag on r^*. The "Other component" ("z") receded after the acute crisis years but re-emerged as the euro area entered its "lost decade" of the 2010s, underscoring the importance of lingering fragmentation and elevated risk premia. Taken together, the HLW decomposition paints a picture of a region where structural growth headwinds, rather than cyclical shocks alone, kept the neutral rate depressed.

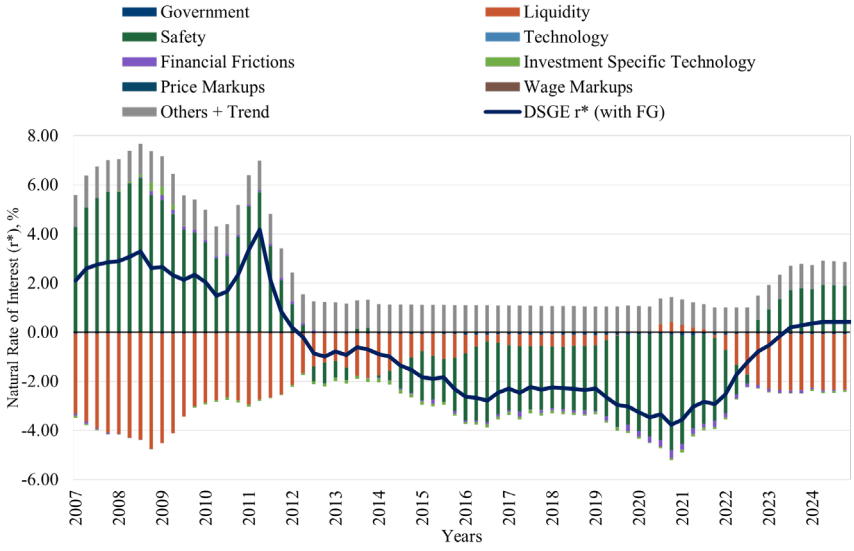
Our DSGE-based decomposition provides more detailed interpretation with the help of identified shocks and the interaction between shocks, expectations, and policy. The forward-guidance version amplifies swings in r^*, showing sharp drops during the sovereign debt crisis and deep negatives throughout the 2010s, before a recovery in the post-pandemic years. While the detailed breakdown of shocks is left for later, the broad contours resonate strongly with Hartmann and Smets' narrative: the ECB's unconventional measures—three-year LTROs, OMT announcements, asset purchase programmes, and forward guidance—were designed precisely to offset the downward pressure on r^* coming from fragmentation, risk premia, and depressed expectations. In this sense, while the HLW framework underscores structural drags from growth and fiscal sustainability, the DSGE decomposition highlights the cyclical amplification of r^* through shocks and the way monetary policy both responded to and reshaped the equilibrium rate over the euro's first twenty years.

Figure II.2 Euro Area Natural Rate of Interest (r*) Decompositions: HLW semi-structural vs. DSGE with forward guidance

(a) HLW *r** Decomposition (EA)



(b) DSGE *r** decomposition with forward guidance (EA)



Notes: The figure compares euro area *r** estimate decompositions from (a) the semi-structural Holston–Laubach–Williams (HLW) measure, and (b)a DSGE model with forward-guidance (FG) shocks.
Sources: Haver Analytics, Federal Reserve Bank of New York, IMF staff calculations.

Bringing together the U.S. and euro area evidence, one can conclude that the semi-structural HLW and our DSGE decompositions have qualitative similarities. In the HLW framework, most of the observed variation in *r** is attributed to the trend growth ("g") and the residual "z" component, which subsumes shifts in preferences, risk premia, and global savings-investment imbalances. By design, HLW leaves open the economic interpretation of the forces behind the movements in "z". The DSGE decomposition attributes the bulk of (i) persistent shocks to spreads, liquidity, and safety premia, which drive a wedge between the risk-free rate and the Euler-equation-consistent

natural rate even in a flexible-price economy; and (ii) return-on-capital shocks—both neutral and investment-specific technology—capturing secular growth. Conceptually, the former represent expectation errors in households' Euler equations, while the latter reflect structural changes in the economy's productive capacity. During the savings-glut era these forces depressed *r**; during Covid, pent-up demand and sizeable fiscal borrowing compressed safety/liquidity discounts relative to real assets, so *r** turned up even before policy lifted off, with LSAPs and guidance reinforcing the reversal.

(ii) shocks' impact in the DSGE model can be loosely translated to the trend growth rate ("g") shocks in the HLW approach. The (i) shocks - the financial spreads - moved similarly to the unexplained z component in the HLW methodology. In other words, the DSGE model suggests that most of the "other factors" in the HLW approach are explained by the safety and liquidity shocks in the DSGE model.

This richer decomposition of the DSGE model sheds light on the post-2008 decline and the post-pandemic reversal of *r**. Here, both convenience-yield terms (safety and liquidity premia) and secular technology-related forces depressed the natural rate during the "savings glut" era, consistent with subdued investment, strong demand for safe assets, and global imbalances. Yet this trend turned around following the Covid-19 shock. Pent-up demand and large-scale government borrowing compressed safety and liquidity premia relative to return on real assets, reversing a decades-long divergence. At the same time, highly accommodative unconventional monetary policy, through LSAPs and forward guidance, amplified the upward adjustment. In this setting, the tightening of monetary policy was accompanied by a rise in *r** itself, generating a non-standard dynamic where the policy rate and the natural rate moved in tandem.

APPENDIX III. The DSGE Model

In this Appendix, we present in detail the full New Keynesian DSGE model of Del Negro (2017) as implemented in *DSGE.jl*, and our extensions for both the US\ and Euro-Area exercises. We first lay out the core equilibrium conditions, with special emphasis on the safety and liquidity convenience-yield block, permanent vs. transitory shocks and the forward-guidance shock specification. We then describe our Bayesian estimation strategy and priors.

We adopt the full DSGE model of Del Negro et al (2017), estimated using the Julia code of DSGE.jl (2025), to study the evolution of the natural rate of interest (r*) in the United States and the Euro Area. This section describes the core log-linearized equations, the modeling of the convenience yield, the treatment of forward guidance shocks, and the measurement equations linking model variables to observable data. Estimation is conducted using Bayesian methods, and priors are summarized at the end.

Consumption Euler Equation

Represents intertemporal consumption smoothing under habit formation and liquidity and financial frictions. Future consumption, real interest rates, and marginal utility of wealth determine current consumption. Convenience yield assumed exogenous and identified off corporate spreads - with permanent and transitory component being driven by separate shocks.

$$c_t = \frac{he^{-\gamma}}{1+he^{-\gamma}} c_{t-1} + \frac{1-he^{-\gamma}}{\sigma_c(1+he^{-\gamma})}(R_t - \mathrm{E}_t\pi_{t+1}) - \frac{1}{1+he^{-\gamma}}(\mathrm{E}_t c_{t+1} + \mathrm{E}_t z_{t+1}) + \frac{he^{-\gamma}}{1+he^{-\gamma}} z_t - \frac{\sigma_c - 1}{\sigma_c(1+he^{-\gamma})}(\omega_L L_t - \mathrm{E}_t L_{t+1}) - b_{\mathrm{liq},t} - b_{\mathrm{safe},t}$$

In the flexible price case the equation is the same as above with flexible-price variables: $\mathrm{c}_t^{\mathrm{f}}, \mathrm{r}_t^{\mathrm{f}}, \mathrm{L}_t^{\mathrm{f}}, \mathrm{qk}_t^{\mathrm{f}}$.

Investment Euler Equation

Captures the forward-looking decision of capital accumulation, accounting for investment adjustment costs (μ_t) and Tobin's Q (q_t). It is linking current, past and expected investment through the price of capital and is directly affected by investment-specific technology shocks.

$$\mathrm{i}_t = \frac{1}{1+\beta \mathrm{e}^{(1-\sigma_c)\gamma}} \mathrm{i}_{t-1} + \frac{\beta \mathrm{e}^{(1-\sigma_c)\gamma}}{1+\beta \mathrm{e}^{(1-\sigma_c)\gamma}}(\mathrm{E}_t \mathrm{i}_{t+1} + \mathrm{E}_t \mathrm{z}_{t+1}) - \frac{1}{\mathrm{S}'' \mathrm{e}^{2\gamma}(1+\beta \mathrm{e}^{(1-\sigma_c)\gamma})} \mathrm{qk}_t + \frac{1}{1+\beta \mathrm{e}^{(1-\sigma_c)\gamma}} \mathrm{z}_t - \mu_t$$

In the flexible prices case equation has the similar form as above with flexible-price variables: $\mathrm{i}_t^{\mathrm{f}}, \mathrm{qk}_t^{\mathrm{f}}$

Financial Frictions

The financial frictions block is central to the model. It introduces credit spreads due to agency frictions subject to a set of shocks. Entrepreneurs finance investments with net worth and risky debt, the latter leading to an endogenous spread between the return on capital and the policy rate.

The spread above the policy rate is influenced by liquidity and safety premia, capturing convenience yields ($b_{liq,t} + b_{safe,t}$), as well as risk shocks following (Christiano et al (2014)) ($\sigma_{\omega,t}$) exogenous bankruptcy costs ($b_{liq,t} + b_{safe,t}$) and shocks to the fraction of entrepreneurs surviving period *t* ($\gamma_{e,t}$)

Return on Capital:

$$\widetilde{R_{k,t}} = \pi_t + \frac{r_k^\star}{1 + r_k^\star - \delta} rk_t + \frac{1-\delta}{1 + r_k^\star - \delta} qk_t - qk_{t-1}$$

Spread Equation:

$$E_t\widetilde{R_{k,t+1}} - R_t = \frac{\sigma_c(1 + he^{-\gamma})}{1 - he^{-\gamma}}\left(b_{liq,t} + b_{safe,t}\right) - \zeta_{spb}\left(qk_t + \bar{k}_t\right) + \zeta_{spb} n_t - \sigma_{\omega,t} - \mu_{e,t}$$

With flexible prices the equation is similar as above with flexible-price variables:
$\widetilde{R_{k,t}^f}, R_t^f, qk_t^f, \bar{k}_t^f, n_t^f$.

Net Worth Evolution

$$n_t = \zeta_{nRk}\widetilde{R_{k,t}} - \zeta_{nR}R_{t-1} + \zeta_{nqk}\left(qk_{t-1} + \overline{k_{t-1}}\right) + \zeta_{nn}n_{t-1} - \zeta_{n\sigma_\omega}\sigma_{\omega,t-1} - \zeta_{n\mu_e}\mu_{e,t-1} + \frac{\gamma^\star v^\star}{n^\star} z_t + \gamma_{e,t} + \zeta_{nR}\frac{\sigma_c(1 + he^{-\gamma})}{1 - he^{-\gamma}}\left(b_{liq,t-1} + b_{safe,t-1}\right)$$

In the flexible-price equilibrium variables the fraction of entrepreneurs surviving period (γ_t^e) vanishes as well as the impact of inflation, leading to the following net worth evolution:

$$n_t^f = \zeta_{nRk}\widetilde{R_{k,t}^f} - \zeta_{nR}R_{t-1}^f + \zeta_{nqk}\left(qk_{t-1}^f + \overline{k_{t-1}^f}\right) + \zeta_{nn}n_{t-1}^f - \zeta_{n\sigma_\omega}\sigma_{\omega,t-1} - \zeta_{n\mu_e}\mu_{e,t-1} + \frac{\gamma^\star v^\star}{n^\star} z_t + \zeta_{nR}\frac{\sigma_c(1 + he^{-\gamma})}{1 - he^{-\gamma}}\left(b_{liq,t-1} + b_{safe,t-1}\right)$$

Production and Capital Accumulation

Firms combine labor and capital via a Cobb-Douglas production function. Capital utilization is endogenous and responds to changes in the rental rate of capital. Capital evolves based on past investment and depreciation.

Cobb-Douglas Production:

$$y_t = \Phi\alpha k_t + \Phi(1-\alpha)L_t$$

Capital Utilization:

$$k_t = \overline{k_{t-1}} + z_t - u_t$$

With flexible prices the same as above with flexible-price variables: $k_t^f, \overline{k_t^f}, u_t^f$

Capacity Utilization:

$$u_t = \frac{1-\psi}{\psi} r k_t$$

In the flexible price case the equation has the same form as above with flexible-price variables: u_t^f, rk_t^f.

Law of Motion for Capital:

$$\overline{k_t} = \left(1 - \frac{i^\star}{\overline{k^\star}}\right)\overline{k_{t-1}} + \left(1 - \frac{i^\star}{\overline{k^\star}}\right) z_t + \frac{i^\star}{\overline{k^\star}} i_t - \frac{i^\star S'' e^{2\gamma}\left(1 + \beta e^{(1-\sigma_c)\gamma}\right)}{\overline{k^\star}} \mu_t$$

Flexible Prices}

Same as above with flexible-price variables: $(\overline{k_t^f}, i_t^f)$.

Price and Wage Setting

Price Markup Condition

Sticky Prices and Wages:

$$mc_t = w_t + (1-\alpha)L_t - \alpha k_t$$

Flexible Prices and Wages

$$w_t^f + (1-\alpha)L_t^f = \alpha k_t^f$$

New Keynesian Phillips Curve

$$\pi_t = \iota_p \pi_{t-1} + \beta e^{(1-\sigma_c)\gamma} E_t \pi_{t+1} + \kappa_p mc_t + \lambda_{f,t}$$

where: $\kappa_p = \frac{(1-\zeta_p \beta e^{(1-\sigma_c)\gamma})(1-\zeta_p)}{\zeta_p\left((\Phi-1)\epsilon_p+1\right)} \cdot \frac{1}{1+\iota_p \beta e^{(1-\sigma_c)\gamma}}$

Rental Rate of Capital:

Sticky Prices: $rk_t + k_t = w_t + L_t$

Flexible Prices: $rk_t^f + k_t^f = w_t^f + L_t^f$

Marginal Rate of Substitution, Labor Supply equation:

Sticky Prices: $\mu_{\omega,t} = \nu_l L_t + \frac{1}{1-he^{-\gamma}}(c_t - he^{-\gamma}E_{t-1}c_t) + \frac{he^{-\gamma}}{1-he^{-\gamma}}z_t - w_t$

Flexible Prices: $\mu_{\omega,t}^f = \nu_l L_t^f + \frac{1}{1-he^{-\gamma}}\left(c_t^f - he^{-\gamma}E_{t-1}c_t^f\right) + \frac{he^{-\gamma}}{1-he^{-\gamma}}z_t - w_t^f$

Wage Phillips Curve

$$w_t = \frac{1}{1+\beta e^{(1-\sigma_c)\gamma}}w_{t-1} + \frac{\beta e^{(1-\sigma_c)\gamma}}{1+\beta e^{(1-\sigma_c)\gamma}}E_t w_{t+1} \quad + \kappa_w\mu_{\omega,t} + \pi_t + \iota_w\pi_{t-1} + \beta e^{(1-\sigma_c)\gamma}E_t\pi_{t+1}$$
$$+ \frac{1}{1+\beta e^{(1-\sigma_c)\gamma}}z_t \quad - \beta e^{(1-\sigma_c)\gamma}E_t z_{t+1} - \beta e^{(1-\sigma_c)\gamma}E_t\pi_{t+1} + \lambda_{w,t}$$

Where $\kappa_w = \frac{(1-\zeta_w\beta e^{(1-\sigma_c)\gamma})(1-\zeta_w)}{\zeta_w((\lambda_w-1)\epsilon_w+1)} \cdot \frac{1}{1+\beta e^{(1-\sigma_c)\gamma}}$

Resource Constraint

$$y_t = \frac{c^\star}{y^\star}c_t + \frac{i^\star}{y^\star}i_t + \frac{g^\star}{y^\star}g_t + \frac{r_k^\star k^\star}{y^\star}u_t$$

Monetary Policy Rule

$$R_t = \rho R_{t-1} + (1-\rho)\psi_1(\pi_t - \pi_t^\star) + (1-\rho)\psi_2\left(y_t - y_t^f\right) + \psi_3\left(y_t - y_t^f\right) + r_{m,t}$$

Exogenous Shocks

Technology Shocks

Neutral Technology (Stationary and Trend Components):

$$z_t = z_t^p + \frac{\rho_z - 1}{1-\alpha}z_t^{trans} + \frac{1}{1-\alpha}\varepsilon_t^z$$

$$z_t^{trans} = \rho_z z_{t-1}^{trans} + \varepsilon_t^z$$

$$z_t^p = \rho_z^p z_{t-1}^p + \varepsilon_t^{z^p}$$

Government Spending Shock

$$g_t = \rho_g g_{t-1} + \eta_{gz}\varepsilon_t^z + \varepsilon_t^g$$

Liquidity Shocks (Transitory and Permanent)

Transitory Component:

$$b_{\text{liq,trans,t}} = \rho_{b_{\text{liq,trans}}} b_{\text{liq,trans,t-1}} + \varepsilon_t^{b^{\text{liq,trans}}}$$

Permanent Component:

$$b_{\text{liq,p,t}} = \rho_{b_{\text{liq,p}}} b_{\text{liq,p,t-1}} + \varepsilon_t^{b_{\text{liq,p}}}$$

Total Liquidity Shock:

$$b_{\text{liq,t}} = b_{liq,trans,t} + b_{\text{liq,p,t}}$$

Safety Shocks (Transitory and Permanent)

Transitory Component:

$$b_{\text{safe,trans,t}} = \rho_{b_{\text{safe,trmas}}} b_{\text{safe,trans,t-1}} + \varepsilon_t^{b_{\text{safe,trans}}}$$

Permanent Component:

$$b_{\text{safe,p,t}} = \rho_{b_{\text{safe,p}}} b_{\text{safe,p,t-1}} + \varepsilon_t^{b_{\text{safe,p}}}$$

Total Safety Shock:

$$b_{safe,t} = b_{safe,trans,t} + b_{safe,p,t}$$

Investment-Specific Technology

$$\mu_t = \rho_\mu \mu_{t-1} + \varepsilon_t^\mu$$

Price and Wage Markup Shocks

Price Markup Shock:

$$\lambda_{f,t} = \rho_{\lambda_f}\lambda_{f,t-1} - \eta_{\lambda_f}\lambda_{f,t-1} + \varepsilon_t^{\lambda_f}\lambda_{f,t-1} = \varepsilon_t^{\lambda_f}$$

Wage Markup Shock:

$$\lambda_{w,t} = \rho_{\lambda^w}\lambda_{w,t-1} - \eta_{\lambda^w}\lambda_{w,t-1} + \varepsilon_t^{\lambda_w}\lambda_{w,t-1} = \varepsilon_t^{\lambda_w}$$

Monetary Policy Shock

$$r_t^m = \rho_{r^m} r_{t-1}^m + \varepsilon_t^{r^m}$$

Anticipated Monetary Policy Shocks

One-Step-Ahead Anticipation:

$$r_{t+1}^m = r_{t+1|t}^m$$

$$r_\{t+1|t = \varepsilon_t^{r_{t+1}^m\ m}$$

Recursive Rule for *i*-Step-Ahead Anticipated Shocks ($i = 2, \ldots, 6$)

$$r_{t+i|t=r_{t+i|t-1}}^m$$

With $r_{t+i|t=\varepsilon_t^{r^m,i^m}}$

Financial Friction Shocks

Entrepreneur Capital Shock (Standard Deviation):

$$\sigma_t^\omega = \rho_{\sigma^\omega} \sigma_{t-1}^\omega + \varepsilon_t^{\sigma^\omega}$$

Bankruptcy Cost Shock:

$$\mu_t^e = \rho_{\mu^e} \mu_{t-1}^e + \varepsilon_t^{\mu^e}$$

Entrepreneurial Survival Probability:

$$\gamma_t = \rho_\gamma \gamma_{t-1} + \varepsilon_t^\gamma$$

Long-Term Inflation Expectation Shock

$$\pi_t^\star = \rho_{\pi^\star} \pi_{t-1}^\star + \varepsilon_t^{\pi^\star}$$

Measurement Equations

$$\pi_t^{PCE} = \pi_t^* + \pi_t + \varepsilon_t^{PCE}$$

$$R_t^{FF} = R^* + R_t$$

$$R_t^{10y} = R^* + \frac{1}{40} \sum_{j=0}^{39} E_t\left[R_{t+j}\right] + \varepsilon_t^{10y}$$

$$\text{Aaa Spread}_t = c_t^{y,l} + \frac{1}{80}\sum_{j=0}^{79} E_t\left[c_{t+j}^{y,l}\right] + \varepsilon_t^{Aaa}$$

$$\text{Baa Spread}_t = c_t^{y,l} + c_t^{y,s} + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + \frac{1}{80}\sum_{j=0}^{79} E_t\left[R_{t+j+1}^k - R_{t+j}\right] + \varepsilon_t^{Baa}$$

Estimation and Priors

The model is estimated using Bayesian methods on a sample of 1960Q1-2023Q4 with standard priors as in \citet{DelNegro2017}. We summarize the priors in Table~tab:priors. The observables are

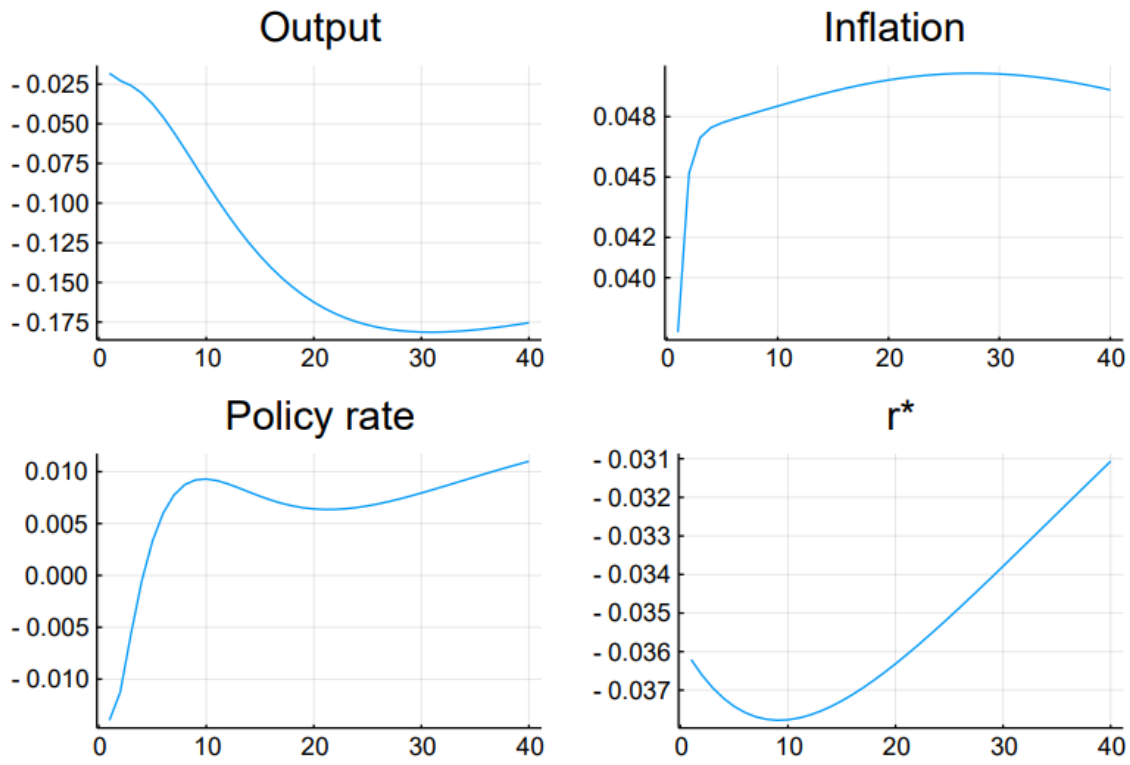
Selected impulse responses

Productivity shocks

A permanent fall in TFP, as shown on fig:IRF_pTFP, reduces output persistently and pushes up inflation (prices adjust sluggishly); the policy rate initially falls but subsequently overshoots zero, and the natural rate exhibits a U-shaped pattern: it falls sharply and then gradually returns to its pre-shock level. This pattern arises because a decline in productivity temporarily lowers the real return on capital but eventually investment adjusts and the natural rate recovers. Overall, natural rate declines and thus these shocks could only partially account for the surge in inflation, policy rates and *r** at the same time.

Figure III.1 Impulse response of a productivity shock in the US model with forward guidance

(percentage difference from steady state)



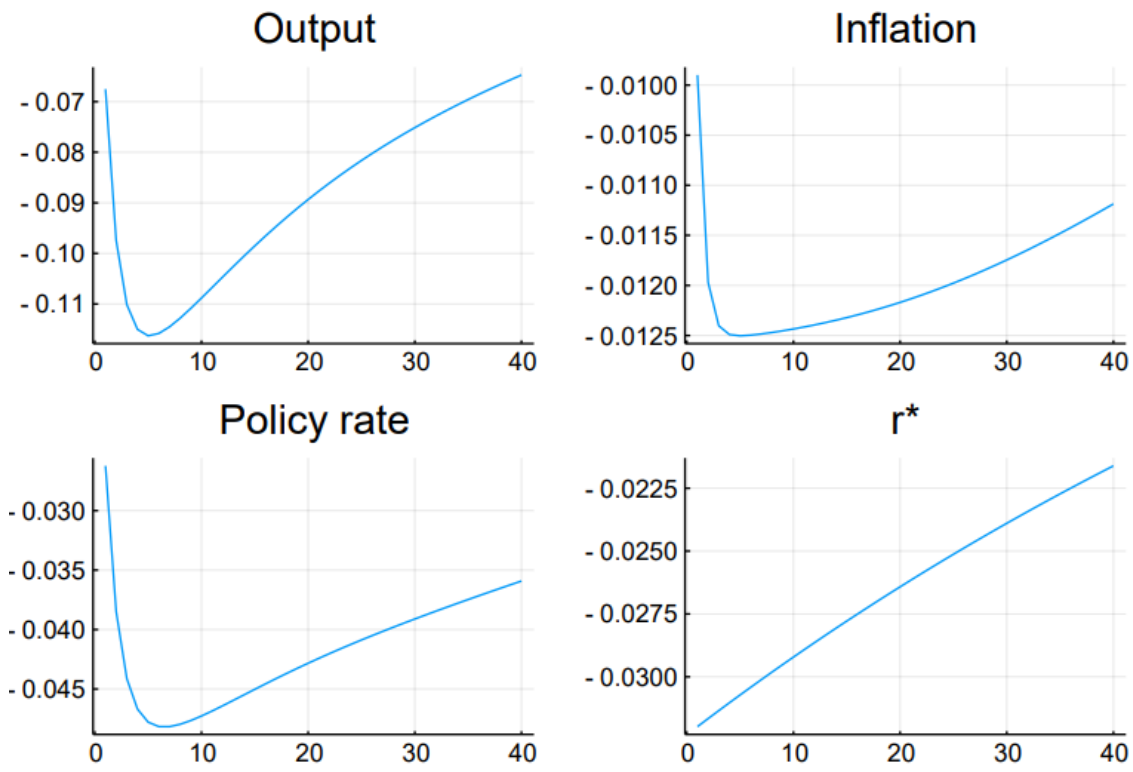
Source: IMF Staff calculations

Convenience yield shocks

Figure III.2 presents impulse responses of output, inflation, the policy rate and the natural rate to a one-standard-deviation liquidity shock (plots of safety shocks look similar) for the estimated model of the US (similar results apply for the euro area model). The shock raises the convenience yield on Treasuries, lowering the real return on households' bond holdings. Output and inflation fall on impact and remain below baseline for several quarters. The policy rate drops sharply as the central bank responds to weaker activity, but the natural rate also declines, reflecting the lower safe return. Over time both rates recover, and the natural rate rises as the effect of the convenience yield dissipates. Importantly, because the negative shock is estimated to be persistent, it creates a positive correlation between the path of the natural rate, inflation and the policy rate.

Figure III.2 Impulse response of a safety shock in the US model with forward guidance

(percentage difference from steady state)



Source: IMF Staff calculations

APPENDIX IV. Estimation Results

Table IV. 1. US parameter estimates

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
$F(\bar{\omega})$	-	0.030	0.000	0.030	0.030	0.030
$I\{\alpha^{model}\}$	-	0.000	0.000	-0.000	-0.000	0.000
$\bar{L}$	N	-45.000	5.000	-47.630	-49.879	-45.446
S''	N	4.000	1.500	2.170	1.430	2.863
Υ	-	1.000	0.000	1.000	1.000	1.000
g_*	-	0.180	0.000	0.180	0.180	0.180
h	B	0.700	0.100	0.590	0.532	0.645
$ln(b_{liq})$	-	0.117	0.000	0.117	0.117	0.117
$ln(b_{safe})$	-	0.065	0.000	0.065	0.065	0.065
C_{me}	-	1.000	0.000	1.000	1.000	1.000
ψ	B	0.500	0.150	0.613	0.471	0.756
SP_*	G	1.000	0.100	1.040	0.879	1.206
γ_{gdpdef}	N	1.000	2.000	1.038	0.958	1.113
Φ_p	-	1.000	0.000	1.000	1.000	1.000
α	N	0.300	0.050	0.175	0.151	0.199
$100(\beta^{-1}-1)$	G	0.250	0.100	0.307	0.183	0.432
100γ	N	0.400	0.100	0.420	0.341	0.508
γ_{gdi}	-	1.000	0.000	1.000	1.000	1.000
γ_*	-	0.990	0.000	0.990	0.990	0.990
δ	-	0.025	0.000	0.025	0.025	0.025
δ_{gdi}	-	0.000	0.000	0.000	0.000	0.000
δ_{gdpdef}	N	0.000	2.000	-0.000	-0.047	0.045
ζ_p	B	0.500	0.100	0.952	0.941	0.963
$\zeta_{sp,b}$	B	0.050	0.005	0.047	0.040	0.055
ζ_w	B	0.500	0.100	0.965	0.957	0.973

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
η_{gz}	B	0.500	0.200	0.434	0.131	0.719
η_{λ_f}	B	0.500	0.200	0.652	0.471	0.831
η_{λ_w}	B	0.500	0.200	0.424	0.241	0.614
ι_p	B	0.500	0.150	0.223	0.091	0.351
ι_w	B	0.500	0.150	0.790	0.680	0.896
λ_{AAA}	-	0.000	0.000	0.000	0.000	0.000
λ_w	-	1.500	0.000	1.500	1.500	1.500
ν_l	N	2.000	0.750	2.492	1.719	3.228
π_*	-	0.500	0.000	0.500	0.500	0.500
ρ_R	B	0.750	0.100	0.845	0.801	0.891
ρ_{AAA}	B	0.500	0.100	0.619	0.480	0.762
ρ_{BBB}	B	0.500	0.100	0.900	0.850	0.948
$\rho_{b^p,liq}$	-	0.990	0.000	0.990	0.990	0.990
$\rho_{\tilde{b},liq}$	B	0.500	0.200	0.514	0.235	0.754

$\rho_{b^p,safe}$	-	0.990	0.000	0.990	0.990	0.990
$\rho_{\tilde{b},safe}$	B	0.500	0.200	0.748	0.620	0.875
ρ_{pce}	B	0.500	0.200	0.249	0.045	0.438
ρ_g	B	0.500	0.200	0.989	0.980	0.997
ρ_{gdi}	N	0.000	0.200	0.946	0.910	0.984
ρ_{gdp}	N	0.000	0.200	0.074	-0.136	0.284
ρ_{gdpdef}	B	0.500	0.200	0.510	0.383	0.640
ϱ_{gdp}	N	0.000	0.400	-0.144	-0.786	0.453
ρ_{10y}	B	0.500	0.200	0.961	0.937	0.987
ρ_{r^m}	B	0.500	0.200	0.236	0.143	0.327
ρ_{tfp}	B	0.500	0.200	0.181	0.075	0.283
ρ_z	B	0.500	0.200	0.940	0.907	0.973
ρ_{z^p}	-	0.990	0.000	0.990	0.990	0.990
ρ_γ	-	0.750	0.000	0.750	0.750	0.750

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
ρ_{λ_f}	B	0.500	0.200	0.804	0.706	0.905
ρ_{λ_w}	B	0.500	0.200	0.325	0.086	0.557
ρ_μ	B	0.500	0.200	0.256	0.021	0.487
ρ_{μ_e}	-	0.750	0.000	0.750	0.750	0.750
ρ_{π_*}	-	0.990	0.000	0.990	0.990	0.990
ρ_{σ_ω}	B	0.750	0.150	0.980	0.963	0.998
σ_{AAA}	IG	0.100	2.000	0.025	0.021	0.028
σ_{BBB}	IG	0.100	2.000	0.053	0.047	0.059
$\sigma_{b^p,liq}$	IG	0.013	100.000	0.013	0.012	0.015
$\sigma_{\tilde{b},liq}$	IG	0.100	2.000	0.102	0.053	0.147
$\sigma_{b^p,safe}$	IG	0.013	100.000	0.011	0.010	0.013
$\sigma_{\tilde{b},safe}$	IG	0.100	2.000	0.117	0.078	0.157
σ_c	N	1.500	0.370	0.876	0.752	1.001
σ_{pce}	IG	0.100	2.000	0.099	0.080	0.117
σ_g	IG	0.100	2.000	2.248	2.048	2.442
σ_{gdi}	IG	0.100	2.000	0.305	0.267	0.343
σ_{gdp}	IG	0.100	2.000	0.250	0.209	0.290
σ_{gdpdef}	IG	0.100	2.000	0.164	0.146	0.182
σ_{10y}	IG	0.750	2.000	0.121	0.110	0.132
σ_{r^m}	IG	0.100	2.000	0.225	0.202	0.248
$\sigma_{1,r}$	IG	0.200	4.000	0.093	0.072	0.112
$\sigma_{2,r}$	IG	0.200	4.000	0.086	0.068	0.104
$\sigma_{3,r}$	IG	0.200	4.000	0.088	0.068	0.106
$\sigma_{4,r}$	IG	0.200	4.000	0.085	0.066	0.104
$\sigma_{5,r}$	IG	0.200	4.000	0.086	0.068	0.104
$\sigma_{6,r}$	IG	0.200	4.000	0.091	0.069	0.111
σ_{tfp}	IG	0.100	2.000	0.752	0.681	0.821
σ_z	IG	0.100	2.000	0.536	0.487	0.585

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
σ_{z^p}	IG	0.100	2.000	0.058	0.045	0.070
σ_γ	-	0.000	0.000	-0.000	-0.000	0.000
σ_{λ_f}	IG	0.100	2.000	0.077	0.060	0.094
σ_{λ_w}	IG	0.100	2.000	0.421	0.376	0.467
σ_μ	IG	0.100	2.000	0.468	0.345	0.592
σ_{μ_e}	-	0.000	0.000	0.000	-0.000	0.000
σ_{π_*}	IG	0.030	6.000	0.055	0.039	0.072
σ_{σ_ω}	IG	0.050	4.000	0.090	0.061	0.118
ψ_1	N	1.500	0.250	1.840	1.531	2.151
ψ_2	N	0.120	0.050	0.252	0.201	0.302
ψ_3	N	0.120	0.050	0.315	0.262	0.366
ϵ_p	-	10.000	0.000	10.000	10.000	10.000

Table IV. 2. Euro area parameter estimates

Parameter	Type	Prior Mean	Prior SD	Posterior Mean	Posterior 90.0% Lower Band	Posterior 90.0% Upper Band
$F(\bar{\omega})$	-	0.030	0.000	0.030	0.030	0.030
$l\{\alpha^{model}\}$	-	0.000	0.000	0.000	0.000	0.000
$\bar{L}$	N	0.910	1.000	-46.352	-52.688	-40.245
S''	N	4.000	1.500	4.963	4.771	5.148
Υ	-	1.000	0.000	1.000	1.000	1.000
g_*	-	0.180	0.000	0.180	0.180	0.180
h	B	0.700	0.100	0.494	0.471	0.512
$ln(b_{liq})$	-	0.117	0.000	0.117	0.117	0.117
$ln(b_{safe})$	-	0.065	0.000	0.065	0.065	0.065
C_{me}	-	1.000	0.000	1.000	1.000	1.000
ψ	B	0.500	0.150	0.895	0.860	0.930
SP_*	G	1.000	0.100	1.588	1.490	1.686
γ_{gdpdef}	N	1.000	2.000	3.746	3.086	4.397
Φ_p	-	1.000	0.000	1.000	1.000	1.000
α	N	0.300	0.050	0.046	0.039	0.053
$100(\beta^{-1}-1)$	G	0.250	0.100	0.295	0.177	0.402
100γ	N	0.182	0.100	0.238	0.198	0.279
γ_{gdi}	-	1.000	0.000	1.000	1.000	1.000
γ_*	-	0.990	0.000	0.990	0.990	0.990
δ	-	0.025	0.000	0.025	0.025	0.025
δ_{gdi}	-	0.000	0.000	0.000	0.000	0.000
δ_{gdpdef}	N	0.000	2.000	0.167	0.051	0.284
ζ_p	B	0.500	0.100	0.995	0.994	0.995
$\zeta_{sp,b}$	B	0.050	0.005	0.029	0.026	0.031
ζ_w	B	0.500	0.100	0.458	0.427	0.482
η_{gz}	B	0.500	0.200	0.541	0.244	0.858
η_{λ_f}	B	0.500	0.200	0.938	0.924	0.950
η_{λ_w}	B	0.500	0.200	0.573	0.427	0.670
ι_p	B	0.500	0.150	0.291	0.196	0.384
ι_w	B	0.500	0.150	0.534	0.350	0.696
λ_{AAA}	-	0.000	0.000	-0.000	-0.000	-0.000
λ_w	-	1.500	0.000	1.500	1.500	1.500
ν_l	N	2.000	0.750	0.039	0.000	0.082
π_*	-	0.500	0.000	0.500	0.500	0.500

Parameter	Type	Prior Mean	Prior SD	Posterior Mean	Posterior 90.0% Lower Band	Posterior 90.0% Upper Band
ρ_R	B	0.750	0.100	0.968	0.959	0.976
ρ_{AAA}	-	0.000	0.000	-0.000	-0.000	-0.000
ρ_{BBB}	-	0.000	0.000	-0.000	-0.000	-0.000
$\rho_{b^p,liq}$	-	0.990	0.000	0.990	0.990	0.990
$\rho_{\tilde{b},liq}$	B	0.500	0.200	0.828	0.774	0.880
$\rho_{b^p,safe}$	-	0.990	0.000	0.990	0.990	0.990
$\rho_{\tilde{b},safe}$	B	0.500	0.200	0.126	0.037	0.206
ρ_{pce}	B	0.500	0.200	0.805	0.757	0.855
ρ_g	B	0.500	0.200	0.987	0.982	0.992
ρ_{gdi}	N	0.000	0.200	0.384	0.167	0.598
ρ_{gdp}	N	0.000	0.200	0.707	0.558	0.835
ρ_{gdpdef}	B	0.500	0.200	0.368	0.272	0.460
ϱ_{gdp}	N	0.000	0.400	0.834	0.631	0.999
ρ_{10y}	B	0.500	0.200	0.963	0.956	0.970
ρ_{r^m}	B	0.500	0.200	0.127	0.080	0.166
ρ_{tfp}	B	0.500	0.200	0.644	0.319	0.876
ρ_z	B	0.500	0.200	0.543	0.230	0.881
ρ_{z^p}	B	0.500	0.200	0.754	0.598	0.911
ρ_γ	-	0.750	0.000	0.750	0.750	0.750
ρ_{λ_f}	B	0.500	0.200	0.959	0.950	0.968
ρ_{λ_w}	B	0.500	0.200	0.967	0.962	0.974
ρ_μ	B	0.500	0.200	0.998	0.997	0.999
ρ_{μ_e}	-	0.750	0.000	0.750	0.750	0.750
ρ_{π_*}	-	0.990	0.000	0.990	0.990	0.990
ρ_{σ_ω}	B	0.750	0.150	0.995	0.991	1.000
σ_{AAA}	IG	0.100	2.000	0.039	0.039	0.040
σ_{BBB}	-	0.000	0.000	0.000	0.000	0.000
$\sigma_{b^p,liq}$	IG	0.030	6.000	0.043	0.041	0.046
$\sigma_{\tilde{b},liq}$	IG	0.100	2.000	0.124	0.101	0.146
$\sigma_{b^p,safe}$	IG	0.030	6.000	0.082	0.077	0.087
$\sigma_{\tilde{b},safe}$	IG	0.100	2.000	0.021	0.021	0.022
σ_c	N	1.500	0.370	0.635	0.620	0.654
σ_{pce}	IG	0.100	2.000	0.162	0.158	0.167
σ_g	IG	0.100	2.000	2.459	2.265	2.656
σ_{gdi}	IG	0.100	2.000	0.614	0.540	0.695
σ_{gdp}	IG	0.100	2.000	0.406	0.382	0.427
σ_{gdpdef}	IG	0.100	2.000	0.301	0.291	0.309
σ_{10y}	IG	0.750	2.000	0.125	0.123	0.127

Parameter	Type	Prior Mean	Prior SD	Posterior Mean	Posterior 90.0% Lower Band	Posterior 90.0% Upper Band
σ_{r^m}	IG	0.100	2.000	0.367	0.320	0.414
$\sigma_{1,r}$	IG	0.200	4.000	0.332	0.309	0.362
$\sigma_{2,r}$	IG	0.200	4.000	0.086	0.081	0.091
$\sigma_{3,r}$	IG	0.200	4.000	0.065	0.063	0.067
$\sigma_{4,r}$	IG	0.200	4.000	0.059	0.058	0.060
$\sigma_{5,r}$	IG	0.200	4.000	0.059	0.058	0.060
$\sigma_{6,r}$	IG	0.200	4.000	0.066	0.064	0.068
σ_{tfp}	IG	0.100	2.000	0.113	0.075	0.155
σ_z	IG	0.100	2.000	0.089	0.058	0.119
σ_{z^p}	IG	0.100	2.000	0.126	0.065	0.189
σ_γ	-	0.000	0.000	0.000	0.000	0.000
σ_{λ_f}	IG	0.100	2.000	0.036	0.031	0.042
σ_{λ_w}	IG	0.100	2.000	0.164	0.142	0.183
σ_μ	IG	0.100	2.000	2.943	2.595	3.296
σ_{μ_e}	-	0.000	0.000	-0.000	-0.000	-0.000
σ_{π_*}	IG	0.030	6.000	0.031	0.025	0.034
σ_{σ_ω}	IG	0.050	4.000	0.280	0.262	0.296
ψ_1	N	1.500	0.250	1.600	1.498	1.724
ψ_2	N	0.120	0.050	0.156	0.120	0.192
ψ_3	N	0.120	0.050	0.198	0.159	0.234
ϵ_p	-	10.000	0.000	10.000	10.000	10.000
ϵ_w	-	10.000	0.000	10.000	10.000	10.000

APPENDIX V. Data

V.1. Observable variables: United States

The table below summarizes the twenty U.S. observables used in estimating the DSGE model. The raw series codes refer to Federal Reserve Economic Data (FRED) or the Board of Governors' macroeconomic database (':series_FRED') or to the Board's Data Library (':series_DLX') for the long-run expectations series and TFP. Population is measured by the FRED mnemonic CE16OV, which counts civilians aged 16 and over. The functions percapita, nominal_to_real and oneqtrpctchange are implemented in DSGE.jl and perform per-capita scaling, conversion from nominal to real terms using the relevant deflator and one-quarter approximate percent changes, respectively. All growth variables are expressed in quarterly percent; interest rates and spreads are converted from annual rates to quarterly by dividing by 4 using annualtoquarter. Each series is defined and mapped to the model according to Del Negro et al. (2017), Appendix B.1.

Table V. 1. US observable variables



V.2. Observable variables: Euro area

The same twenty variables as for the United States appear, defined with the prefix "EA" in the data files. They include measures of real activity (output, hours, wages, consumption, investment, GDI and TFP), price indices (GDP deflator, core inflation and long-run inflation), monetary policy instruments (policy rate, long bond yield and expected rates at horizons 1–6 quarters) and credit spreads (BBB and AAA). All series are quarterly and expressed in percent. The table below describes the construction of the euro-area observables. Because the euro area does not publish identical series to FRED, the codes below refer to the Eurostat/ECB data mnemonics. The per-capita variables are formed using the seasonally adjusted population of individuals older than 15 years (N025PP2T@EUDATA). Nominal aggregates are deflated by the appropriate price deflators before computing quarter-to-quarter growth. Each series is defined and mapped to the model according to Del Negro et al. (2017), Appendix B.1.

Table V. 2. Euro area observable variables

Observable	Source series	Transformation/Unit	Formula
Real GDP growth (obs_gdp)	EUDATA: **JGDGDPT** (nominal GDP), EUDATA: **JGDGDPF** (GDP deflator), EUDATA: **BGDPF2Y** (population aged ≥15)	Compute real GDP per capita by dividing nominal GDP by the GDP deflator and population; then take the one-quarter percent change	$obs_gdp_t = 100 \times \left(\frac{JGDGDPT_t / (JGDGDPF_t \cdot Pop_t)}{JGDGDPT_{t-1} / (JGDGDPF_{t-1} \cdot Pop_{t-1})} - 1 \right)$
Log hours per capita (obs_hours)	Essential: hours worked per employee (**QGDHRS**), Essential: employment (**QGDLEE**), EUDATA: **BGDPF2Y** (population)	Total hours per quarter are approximated by **QGDHRS** × **QGDLEE**; divide by population to get hours per capita; multiply by 3 (months per quarter) and take $200 \times \log(\cdot/100)$ as in the U.S. definition	$obs_hours_t = 100 \times \log\left(3 \frac{QGDHRS_t \times QGDLEE_t}{100 Pop_t} \right)$
Real wage growth (obs_wages)	EUDATA: **LGDCBEH** (nominal compensation per employee), EUDATA: **JGDGDPF** (GDP deflator)	Convert compensation per employee to real terms by dividing by the GDP deflator; compute the one-quarter percent change	$obs_wages_t = 100 \times \left(\frac{LGDCBEH_t / JGDGDPF_t}{LGDCBEH_{t-1} / JGDGDPF_{t-1}} - 1 \right)$
GDP deflator inflation (obs_gdpdeflator)	EUDATA: **JGDGDPF** (GDP deflator)	One-quarter percent change of the GDP deflator	$obs_gdpdeflator_t = 100 \times \left(\frac{JGDGDPF_t}{JGDGDPF_{t-1}} - 1 \right)$
Core HICP inflation (obs_corepce)	Essential: HICP excluding energy and unprocessed food (**QXEHPH**)	Compute the one-quarter percent change in the core HICP index	$obs_corepce_t = 100 \times \left(\frac{QXEHPH_t}{QXEHPH_{t-1}} - 1 \right)$
Nominal short-term rate (obs_nominalrate)	EUDATA: **IRSMO** (three-month money market rate, annualized)	Divide the annualized short-term rate by 4 to convert to a quarterly rate	$obs_nominalrate_t = \frac{IRSMO_t}{4}$
Real consumption growth (obs_consumption)	EUDATA: **JGDPCN** (nominal consumption), Essential: consumption deflator (**QXEHCE**), EUDATA: **BGDPF2Y**	Compute real consumption per capita by deflating nominal consumption with its price deflator and dividing by population; compute the one-quarter percent change	$obs_consumption_t = 100 \times \left(\frac{JGDPCN_t / (QXEHCE_t \cdot Pop_t)}{JGDPCN_{t-1} / (QXEHCE_{t-1} \cdot Pop_{t-1})} - 1 \right)$
Real investment growth (obs_investment)	EUDATA: **JGDIFN** (nominal investment), Essential: investment deflator (**QXEGFE**), EUDATA: **BGDPF2Y**	Compute real investment per capita by deflating nominal investment with its price deflator and dividing by population; then compute the one-quarter percent change	$obs_investment_t = 100 \times \left(\frac{JGDIFN_t / (QXEGFE_t \cdot Pop_t)}{JGDIFN_{t-1} / (QXEGFE_{t-1} \cdot Pop_{t-1})} - 1 \right)$
BBB spread (obs_BBBspread)	ICE BofA option-adjusted spread for euro-area BBB corporates (**Quarterly DAS**) from the "Option Adjusted rate" sheet, EUDATA: **IRGBE10** (10-year government bond yield)	Compute the difference between the BBB corporate yield and the 10-year government bond yield; divide by 4 to convert from annual to quarterly	$obs_BBBspread_t = \frac{OASc - IRGBEY10_t}{4}$
Long-term inflation expectations (obs_longinflation)	EUDATA: **VEZHMP** (SPF 10-year HICP inflation expectations)	Subtract 0.5 percentage points and divide by 4 to express the annual expectation at quarterly frequency	$obs_longinflation_t = \frac{VEZHMP_t - 0.5}{4}$
Long-term rate (obs_longrate)	EUDATA: **IRGBE10** (10-year government bond yield, annualized)	Divide the 10-year yield by 4 to convert to a quarterly rate	$obs_longrate_t = \frac{IRGBEY10_t}{4}$
Total factor productivity (obs_tfp)	Banco de España "Euro-prod" dataset: unadjusted TFP and capital share (**Dat_Productivity_BdEspma**)	Demean the unadjusted TFP series over the estimation sample and divide by $4(1-\alpha_t)$, where α_t is the estimated capital share for the euro area, to obtain the quarterly TFP deviation	$obs_tfp_t = \frac{TFP_t - \overline{TFP}}{4(1-\alpha_t)}$
Real GDI growth (obs_gdi)	Essential: nominal national disposable income plus consumption of fixed capital ("NDI" and "Consumption of fixed capital" columns in the spreadsheet), Essential: **JGDGDPF**, EUDATA: **BGDPF2Y**	Construct nominal GDI by summing national disposable income and consumption of fixed capital; deflate by the GDP deflator and divide by population; compute the one-quarter percent change	$obs_gdi_t = 100 \times \left(\frac{NDI_t + CFC_t}{JGDGDPF_t \cdot Pop_t} \Big/ \frac{NDI_{t-1} + CFC_{t-1}}{JGDGDPF_{t-1} \cdot Pop_{t-1}} - 1 \right)$
AAA spread (obs_AAAspread)	IHS Markit iBoxx EUR Corporates AAA 10+ yield (**IHSMARKBOXXEUR**), EUDATA: **IRGBE10** (10-year government bond yield)	Compute the difference between the AAA corporate bond yield and the 10-year government bond yield; divide by 4 to convert from annualized yields to quarterly	$obs_AAAspread_t = \frac{AAArate_t - IRGBEY10_t}{4}$
Anticipated policy shocks (obs_nominalrate_lag for $i=1,\ldots,8$)	EUDATA: **IRGBE2**, **IRGBE3**, **IRGBE4**, **IRGBE5**, **IRGBE6**, **IRGBE7**, **IRGBE8**, **IRGBE9**, **IRGBE10**, etc. (2-, 3-, 4-, 5- and 10-year government bond yields)	Each series represents the average expected short-term interest rate over the corresponding maturity. Divide each annual yield by 4 to obtain the quarterly anticipated rate	$obs_nominalrate_t(i) = \frac{IRGBEY(i)_t}{4}, \; i \in \{2,3,4,5,10\}$

Figure V. 1. Evolution of observable variable in the United States

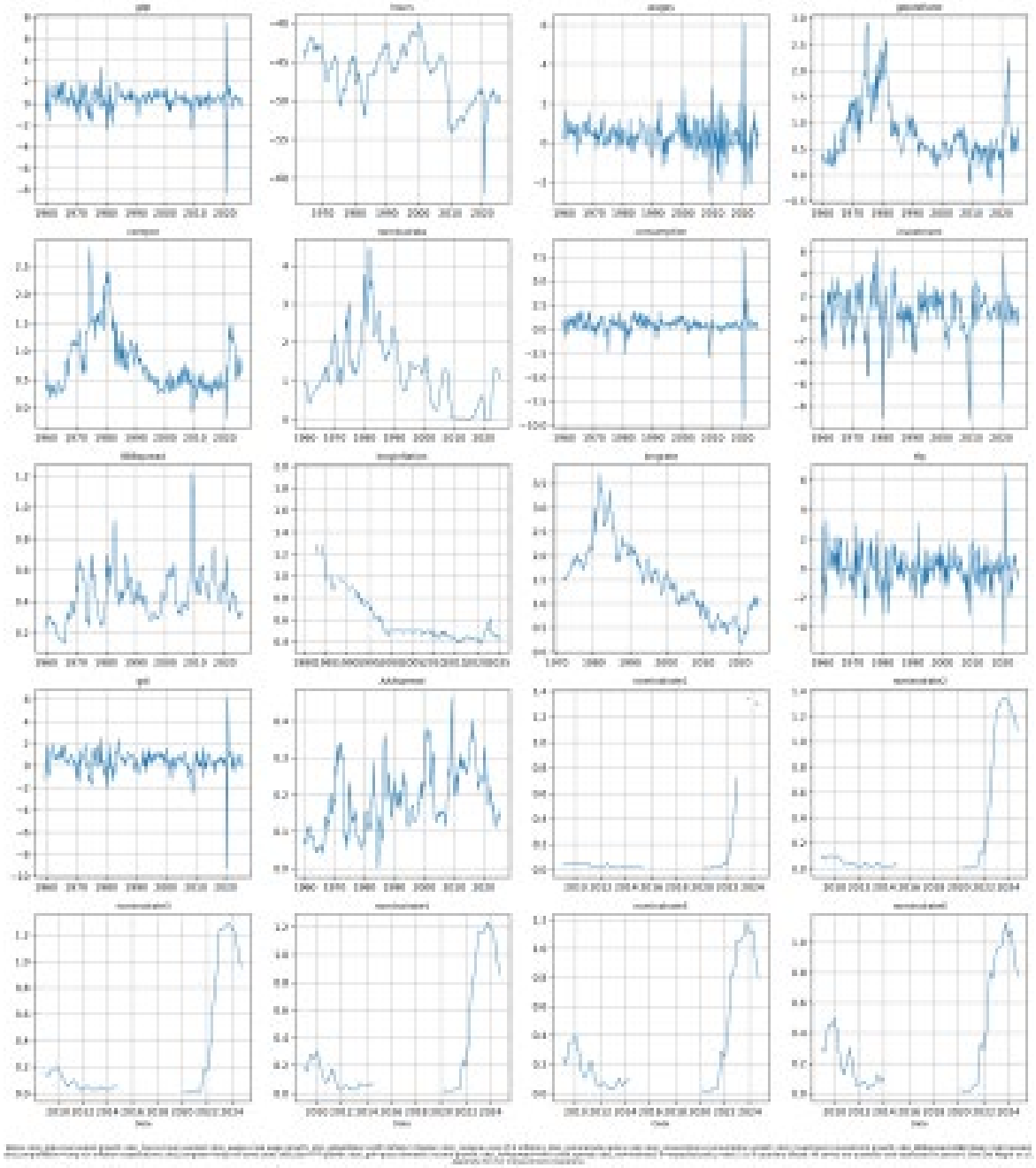


Figure V. 2. Evolution of observable variables in the euro area

