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

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

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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 when the Fed and ECB provided forward guidance. For the post-Covid period, we find that r* rises much more than in an otherwise standard specification that omits yield-curve observables. By implication, the post-Covid tightening of the monetary policy stance was not nearly 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. Yield-curve information pins down anticipated policy innovations and alters r* estimates and, thus, the monetary policy stance.

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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 (1898/1936), 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^* – here operationalized as the short-term real policy interest rate prevailing in a notional equilibrium in which prices and wages are flexible – to gauge whether their policy stance is stimulative, neutral, or restrictive.[1] 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 (see Laubach and Williams, 2003, Holston, Laubach and Williams, 2017, and Del Negro et al., 2017). The inflation surge during the aftermath of the pandemic in many countries across the globe has sparked a debate about whether r^* has risen materially. Recent papers for the United States and the euro area (see e.g. Baker et al., 2023, IMF, 2023, and Brand, 2024) suggest that r^* has increased to pre-pandemic levels, though uncertainty bands are wide.

In addition to providing post-pandemic estimates of r^* for two major economic regions, our paper also revisits its potential drivers and highlights the important role expectations on future short-term policy rates plays for filtered r^* series. As standard time series models (e.g. Bayesian VAR) cannot account for anticipation effects, our analysis relies on a structural model, namely the state-of-the-art canonical DSGE model developed by Del Negro et al. (2017). In this model framework, short-term policy rate shocks – regardless of whether they are anticipated to occur in the future or hit the economy today as a surprise – do not directly impact r^*. Even so, including data on anticipated future policy rates when estimating the model impact the filtering of other shocks in the economy which impacts r^*. Hence, inclusion of data on actual and expected (overnight index swap, OIS henceforth) policy rates matters for the filtered r^* series, and by re-estimating the model when dropping OIS rates as observables and anticipated policy rate shocks as economic drivers of economic fluctuations, we can examine how r^* in both in the United States and in the euro area is affected.

When we estimate the model, we include data on actual and expected policy (OIS) rates, and allow policy expectations to be driven by anticipated monetary policy shocks. Through impulse response analysis we find that the structural model is able to disentangle safety asset and liquidity channels, which impact r^*, from current and forward guidance shocks that are neutral to the natural rate. We

[1] We follow Del Negro et al. (2017) and define the natural rate as the 5-year ahead short-term real rate in a notional equilibrium with flexible prices and wages in which economic fluctuations are purely driven by efficient shocks. See Section 3.1 for further details.

include a broad set of interest rate series, including policy rates, expected policy rates, long-term yields, and credit spreads.

Our analysis provides four important results. First, related to the preceding discussion, we find that including OIS policy rates 1 to 6 quarters ahead as observables and anticipated policy interest rate (forward guidance information, FGI henceforth) shocks to explain them in the model, lowers the filtered r^* series with more than 1 percentage point in the aftermath of the Global Financial Crisis. Following the Covid pandemic, when policy rates eventually surged, the estimated model with FGI implies that r^* rose sharply, from -0.5 percent to 1.5 percent in the US and from -3.5 to 0.5 percent in the euro area, respectively. The model without FGI implies notably smaller increases in filtered r^* series. Importantly, the estimated models conditional on FGI also imply notably different filtered output gaps (measured as deviation from trend) series. For the US, the filtered output gap in the model with FGI falls close to 4 percent more during the global financial crisis as the fast lift-off implied by expected OIS rates at the time effectively tightened the policy stance. The US output gap also remains persistently weaker in the model with FGI, although Fed communication and OIS rates during the Covid pandemic and its aftermath helped push the filtered output gap temporarily higher than in the model without FGI. For the euro area, we find that the model with FGI matters predominantly following the euro area debt crisis in 2012 when filtered output gap gradually declines to -4 percent, more than 2 percent below the model without FGI.

Second, the large, filtered increases in r^* for the US and EA in our model differ notably from the workhorse r^* model by Holston, Laubach and Williams (2017) (HLW henceforth). The benchmark HLW model suggests that r^* was essentially unchanged in both the US and the euro area during the aftermath of the pandemic. Hence, the HLW model implies that the hikes in nominal policy rates by the Fed and the ECB to curb rising inflation pressures tightened the monetary policy stance – i.e. the gap between nominal policy rates and r^* – notably. Our estimated model, on the other hand, implies that the monetary policy stance was tightening notably less, because the natural rate of interest rose sharply in both economies due to an unexpected sustained increase in r^*.[2] By means of counterfactual simulations with the estimated model, we show that the rise in r^* implies that the policy stance was not tightened nearly as much during the post-Covid rate-hike cycle compared to the standard HLW model (implying a roughly unchanged r^* path). Quantitatively, we find that the less tight policy stance contributed to 4 percent higher output in the US and 2 percent higher output in the euro area from the beginning of 2021 to the end of 2024. It is important to note that our findings should not be interpreted as a single explanation of the post-Covid inflation surge, but they complement other explanatory factors like strong demand (Primiceri and Giannone, 2024), expansionary fiscal policy (Barro and Bianchi, 2026) and misperception of adverse supply side shocks and nonlinear pricing dynamics (Erceg, Linde and Trabandt, 2024).

[2] Since both central banks succeeded to engineer a soft-landing of economic activity, we believe macroeconomic outturns provide some merit to our estimation results.

Third, we show that forward guidance shocks (included in the model to match expectations of future policy rates) can mimic the transmission of convenience yield shocks when policy rates are pinned at the effective lower bound for a prolonged period. By including both expectations of future policy rates and long-term yields as observables, we can distinguish between the two shocks and improve identification of r^* (which we find is primarily driven by convenience yield shocks in the model).

Fourth and finally, using the estimated models for the US and the euro area, we aim to quantify the exorbitant privilege – i.e. more favorable convenience yields in the US relative to convenience yields prevailing in the euro area. We do this in a counterfactual scenario in which we replace the smoothed innovations to the US convenience yield with their euro area counterparts since the inception of the euro in the first quarter 1999. We find that had the United States been exposed to the euro area shocks, r^* and economic activity would have been notably lower, and inflation close to zero following the global financial crisis in 2008. As a result, the unconstrained (shadow) Federal Funds rate would have been notably more negative and the ZLB a more binding constraint.

All told, our results corroborate the evidence of increasing r^* during the post-pandemic period through structural estimation. We argue that providing information about expectations of future policy rates leads to a notably higher estimated r^*. This is not because anticipated monetary policy shocks affect r^* directly in our model – per usual monetary policy shocks do not affect r^*. But conditional on an extensive set of macroeconomic time series, we find that adding the expected path of policy rates at each point in time during estimation leads to a filtered r^* series that rises notably more than when this information is not used to filter r^* series.

The remainder of the paper is organized as follows. Section 2 reviews related literature on neutral rate estimation. Section 3 describes the DSGE model, data used in estimation, and the estimation approach and results. In Section 4 we present our r^* estimates for the U.S. and euro area and discuss how standard surprise and anticipated policy shocks have affected policy rates, inflation and output in both the US and euro area, while Section 5 provides an analysis of how we can disentangle the propagation of monetary policy and convenience yield shocks in estimation and filtering of r^*. Section 6 undertakes two counterfactual exercises, first one on the implications for misreading r^* changes post Covid, and second, an assessment of the macroeconomic effects of the exorbitant privilege of the dollar. Section 7 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 is crucial for explaining low bond yields and term premiums.

For our purposes, however, Del Negro et al. (2017) are the key reference. They show that the decline in r* reflects not only weaker trend growth, but also stronger demand for safe and liquid assets, especially U.S. Treasuries. In their model and the supporting BVAR evidence, the rising convenience yield on Treasuries explains an important part of the long-run fall in the equilibrium real rate.

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) and Brand, Lisack, and Mazelis (2024)). Bayer and Marques (2025) highlight the uncertainty of euro area r^* estimates and call for robust policy conclusions. Fiorentini et al. (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^*. One prominent view, emphasized by Del Negro et al. (2017), is that a rising convenience yield on safe and liquid assets has pushed down the risk-free rate. Closely related, global saving glut hypotheses (Caballero and Farhi (2017); Bernanke and Blanchard (2023)) attribute low r^* to an excess of desired saving worldwide. Rachel and Summers (2019) likewise argue that persistently higher saving, alongside weak investment demand, explains much of the decline in neutral rates.

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.[3]

A complementary mechanism operates through the supply and demand for safe assets: Jiang et al. (2018, 2024) argue that global demand for liquid dollar denominated assets generates a convenience yield, lowering US funding costs and contributing to the dollar's exorbitant privilege. More recent evidence, however, suggests that this mechanism may have weakened or even reversed at longer maturities: rising Treasury supply has compressed convenience yields, driving short-term Treasury convenience yields close to zero and long-term convenience yields into negative territory. Our work is also related to Cheng et al. (2025) documenting an exorbitant privilege loss of the dollar.

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) show that monetary-fiscal gaps can affect r^*. For

[3] 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.

a recent review on the decline and the structural drivers of r^* see the International Monetary Fund's WEO chapter on the topic (2023).

3. The DSGE model

We adopt the medium-scale DSGE model of Del Negro et al. (2017) for the analysis. A DSGE model approach is suitable as it allows us to incorporate forward guidance and convenience yield shocks and thus provide a refined estimate of post-pandemic r^*. Below we provide an overview of the model and some key equations. Appendix I contains a complete detailed description of the full model. The replication package of the results and the model is available online.[4]

3.1. Model Overview

Del Negro et al. (2017)'s 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 Appendix I.

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^*. We model convenience yields as exogenous shock processes without complete micro-foundations. However, large number of modern macro-financial models detail the way of how to build micro-foundations.[5] This mechanism is formalized in a modified Euler equation for per

[4] We use the m1010 version, specification ss20 of the model in the DSGE.jl package. Replication code can be found at: https://github.com/matyasfarkas/RstarsAcrossTheAtlantic

[5] The bond markets with term premium and convenience yield break the full martingale assumption of Bjork (2020). Among others, Diamond and Van Tassel (2026) highlights the constrained risk-bearing capacities of financial (continued…)

capita consumption (c_t) and leisure (L_t) with a spread above the policy rate is influenced by liquidity and safety premia, capturing convenience yields $\left(b_{\text{liq,t}} + b_{\text{safe,t}}\right)$ 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 ($\gamma_{e,t}$):

$$c_t = \bar{h}c_{t-1} - \chi_R(R_t - E_t\pi_{t+1}) - \bar{h}z_t + \chi_c(E_t c_{t+1} + E_t z_{t+1}) + \chi_L(L_t - E_t L_{t+1}) + b_{\text{liq},t} + b_{\text{safe},t}. \quad (1)$$

In equation (1), the composite habit parameter is defined as $\bar{h} \equiv \frac{he^{-\gamma}}{1+he^{-\gamma}}$, and the other parameters as $\chi_R \equiv \frac{1-he^{-\gamma}}{\sigma_c(1+he^{-\gamma})}$, and $\chi_c \equiv \frac{1}{1+he^{-\gamma}}$, and finally $\chi_L \equiv \frac{(\sigma_c-1)\omega_L}{\sigma_c(1+he^{-\gamma})}$. The variable z_t is the sum of transitory and persistent technology shock, σ_c denotes the risk aversion and ω_L is the inverse of Frisch elasticity of labor.

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. *r** is defined as the ex-ante 5 year ahead short-term risk-free real interest rate under flexible prices and wages. This definition is adopted from Del Negro et al. (2017) and implies that the natural rate is defined in a notional equilibrium with flexible prices and wages in which domestic inflation is fully stabilized by the central bank, and there are no price and wage markup shocks. [6]

$$r_t^* = E_t r_{t+20}^f, \quad (2)$$

where $E_t r_{t+20}^f$ is the 20 quarter-ahead predicted risk-free real rate in the flexible price-wage economy. Appendix III shows that r_t^* defined as $E_t r_{t+40}^f$ is similar to that in equation (2).

Convenience yields also enter the capital formation (entrepreneurs' optimization problem) where along with risk shocks (Christiano et al., (2014)) create a wedge between the policy rate and the return on capital ($\tilde{R}_{k,t+1}$)

$$E_t\tilde{R}_{k,t+1} - R_t = -\frac{1}{\chi_R}\left(b_{\text{liq},t} + b_{\text{safe},t}\right) + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + \sigma_{\omega,t} + \mu_{e,t} \quad (3)$$

intermediaries in convenience yield determination, Greenwood et al (2023). Bauer and Rudebusch (2020) microfound deviations from covered interest parity. From a macroeconomic angle, Fisher (2015) shows that the risk premium shock in Smets and Wouters (2007) can be microfounded by household's preference for holding one-period nominally risk-free debt.

[6] However, the equilibrium still features financial frictions and safety and liquidity premium shocks. Appendix I.2 defines the flexible price-wage equilibrium. r_t^* thus differs from the neutral short-term real rate that maintains inflation is at target and closes the output gap when the economy is exposed to a demand-type disturbance (e.g. discount factor shock).

where q_t^k denotes Tobin's q, $\bar{k}_t$ and n_t refer to capital and labor, respectively.

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 the safety and liquidity premiums.

Given this, the mapping from the model variables to some key variables used as observables in the estimation is as follows:

$$\text{OIS Forward Rate}_{t+h|t} = \bar{R} + E_t R_{t+h} \qquad (4)$$

where $\bar{R}$ is the steady state risk free (policy) rate, and $E_t R_{t+h}$ is the expected risk free (policy) rate's deviation from steady state.

Next, we have two equations for the Aaa and Baa spreads:

$$\text{Aaa Spread}_t = \overline{b_{liq}} + \frac{(\lambda_{AAA} - 1)\sigma_c(1 + he^{-\gamma})}{1 - he^{-\gamma}} b_{liq,t} + \\ + \frac{1}{80}\sum_{j=0}^{79} E_t\left[b_{\text{liq},t+1+j}\right] + \lambda_{AAA}\left(E_t\tilde{R}_{k,t+1} - R_t\right) \qquad (5)$$

$$\text{Baa Spread}_t = \overline{b_{liq}} + \overline{b_{safe}} + \frac{1}{80}\sum_{j=0}^{80} E_t\left[\tilde{R}_{k,t+j+1} - R_{t+j}\right] \qquad (6)$$

where $\overline{b_{liq}}$ and $\overline{b_{safe}}$ denote the values of liquidity and safety spread in the deterministic steady state.

We define the convenience yield from Equation (3) as:

$$CY_t = -\frac{1}{\chi_R}\left(b_{\text{liq},t} + b_{\text{safe},t}\right) \qquad (7)$$

The definition in equation (7) means that the convenience yield when inserted in the Consumption Euler equation (1) appears additively with the short-term policy rate and is scaled to be an interest rate equivalent. Thus, as outlined in Fisher (2015), an increase in demand for liquid and safe assets, i.e. rising CY_t driven by lower $b_{\text{liq},t}$ and/or $b_{\text{safe},t}$, will put downward pressure on the economy, and if the central bank wants to offset this downward pressure, it needs to lower its short-term policy rate path commensurately. A lower policy rate path, via the expectations hypothesis, generates downward pressure on long-term government bonds yields (i.e. their prices increase) and r^* falls as well.[7] So if country A has a higher convenience yield than country B, this means that there is more demand for liquid and safe assets in A than B, this

[7] Del Negro et al. (2017) shows that r^* is inversely related to CY_t in the flex price-wage equilibrium of the model.

ceteris paribus, puts downward on government borrowing costs of country A and lowers its r^* relative to country B.

Finally, the short-term policy rate (R_t as deviation from steady state) is governed by a standard policy rule, amended by anticipated policy shocks, where y_t and y_t^f denote output in the sticky price and in the flexible price economy, respectively:

$$R_t = \rho R_{t-1} + (1-\rho)\psi_1(\pi_t - \pi_t^\star) + (1-\rho)\psi_2\left(y_t - y_t^f\right) + \psi_3\left(\Delta y_t - \Delta y_t^f\right) + r_{m,t}, \quad (8)$$

$$r_{m,t} = \rho_{r_m} r_{m,t-1} + \varepsilon_{r_{m,t}} + \varepsilon_{r_{m,t+h|t}}.$$

In equation (8), the short-term policy rate shock $r_{m,t}$ has two elements; one standard contemporaneous shock ($\varepsilon_{r_{m,t}}$) that is a surprise each period and an anticipated shock component ($\varepsilon_{r_{m,t+h|t}}$) for h=1, ..., T that is modelled as in Laser and Svensson (2011).

3.2. Data and Estimation

The sample for the United States is 1960Q1–2025Q4 and for the euro area 1970Q2–2024Q3. For the euro area we use the Area Wide Model database until 1994Q4, and data from Eurostat from thereon. Exact sources and definitions of the observables used are provided in Appendix II, along with figures that plot the time series.

Following Del Negro et al. (2017), standard macroeconomic observables are augmented with data on an extensive set of financial spreads and yields, as well as long-term inflation expectations. The set of observables include Baa and Aaa spreads (starting from 1997Q4 and 2025Q4, respectively), 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.[8] Baa spreads for the euro area are obtained from ICE Bofa euro area high yield option-adjusted spreads.

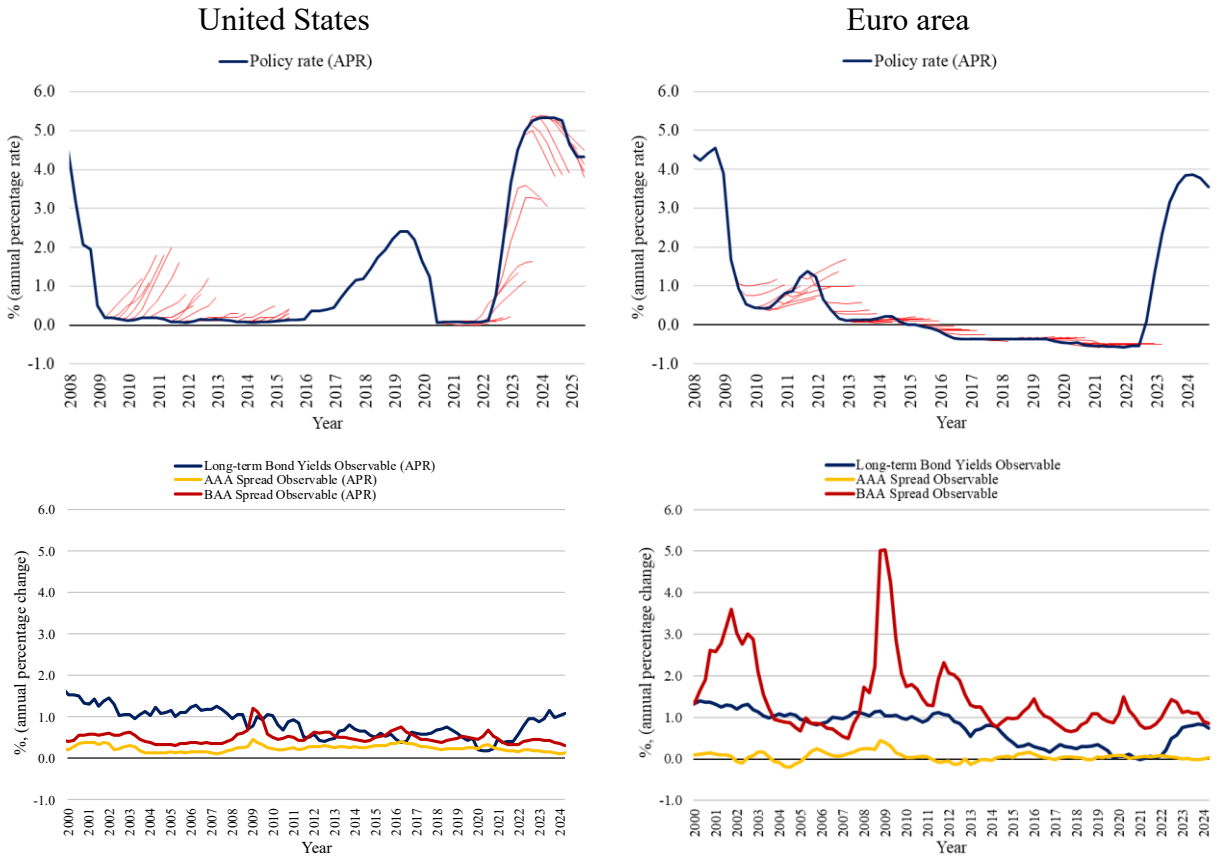
To capture policy expectations, we include yield-curve information. The anticipated policy component was modelled as an observable during times during periods in which forward guidance is operative: at the effective lower bound and under the post-Covid policy frameworks (including AIT in the US). Outside these periods, the yield curve is left to be determined by the model.

Two key features of the dataset differ from HLW and is worth discussing in somewhat more detail. First, as noted earlier we augmented the DSGE observables with the term-structure of policy expectations from the OIS curve. The first row in Figure 1 plots the policy rate paths for US and the euro area, along with OIS data for the periods when the ZLB was binding in the US and ECB

[8] For the euro area we used our own seasonal adjustment instead of Eurostat seasonally and working day adjusted series. The euro area utilization-adjusted TFP growth series is the one by Comin et al. (2025). For the details see Appendix II.

perceived that they were close to an ELB. We use OIS data to measure policy expectations up to 6 quarters ahead.

Figure 1: Actual and Expected Policy Rates, Long-term Yields, and Financial Spreads.



Notes: The upper panel shows the policy rate observable with real time yield curve data. The lower panel shows the long-term government bond yields and the matching maturity Aaa and Baa spread observables. Expected policy rates are shown for the periods when the Effective Lower Bound (ELB) was binding or when new monetary framework was AIT (Average Inflation Targeting for the US) introduced.
Sources: IMF staff calculations, Fred database, Haver Analytics.

Second, we include information on a set of long-term yields that allows us to identify and filter out various financial yield shocks. These observables are plotted in the second row in Figure 1. Using equation (4) the long-term yield observation equation (specified in Appendix I) and the expected policy rate identify the term premium. Then we can filter the whole path forward of the expected risk-free policy rate. Finally, equations (5) and (6) and observations on Aaa and Baa spreads allow us to estimate the convenience yield shocks (the liquidity and the safety premium shocks) together with the average spreads. Third, long term inflation expectations from the survey of professional forecasters (SPF) are used as an observable variable to help in estimating the time-varying inflation target $\pi_t^\star$ in the monetary reaction function equation (8), which then helps pin down r_t^* in equation (2).

Following Smets and Wouters (2003, 2007), Bayesian techniques are adopted to estimate the parameters for the US and euro area. Bayesian inference starts out from a prior distribution that describes the available information prior to observing the data used in the estimation. The observed data is subsequently used to update the prior, via Bayes' theorem, to the posterior distribution of the model's parameters which can be summarized in the usual measures of location (e.g. mode or mean) and spread (e.g. standard deviation and probability intervals).

In the estimation, we adopt the priors from Del Negro et al. (2017): For the US we estimate autocorrelation coefficient for the persistent components of the convenience yield shocks, instead of calibrating them to 0.99.[9] For the euro area we change the parameters governing steady-state to ensure the model fits the euro area sample averages. In particular, we lower trend growth to match the lower average per capita growth rate in the euro area. Moreover, we increase the prior mean for the capacity utilization costs (ψ) and tighten the prior variance on the inverse Frisch elasticity of labor disutility (υ_l) and the investment adjustment cost prior (S'') to match priors from Smets Wouters (2003). To reflect widely documented structural differences we adapt priors governing nominal rigidities, indexation and monetary policy rule from Smets Wouters (2003) and the NAWM (Christoffel et al. 2008). The estimation results – which features in very flat price- and wage Phillips curves as in Del Negro, Giannoni and Schorfheide (2015) but otherwise very similar posterior as in other estimated DSGE models – are presented in Appendix III. As in any estimated DSGE model, identification of parameters, and as a result implied *r** estimates, can be weak and prior driven (Canova and Sala, 2009). Appendix III reports the prior and posterior distributions of the estimated parameters and shock standard deviations, and consistent with the evidence in Adolfson et al. (2019), it provides evidence that data was informative and pinned down the dynamics of the model.

4. Estimated r* Series and Drivers

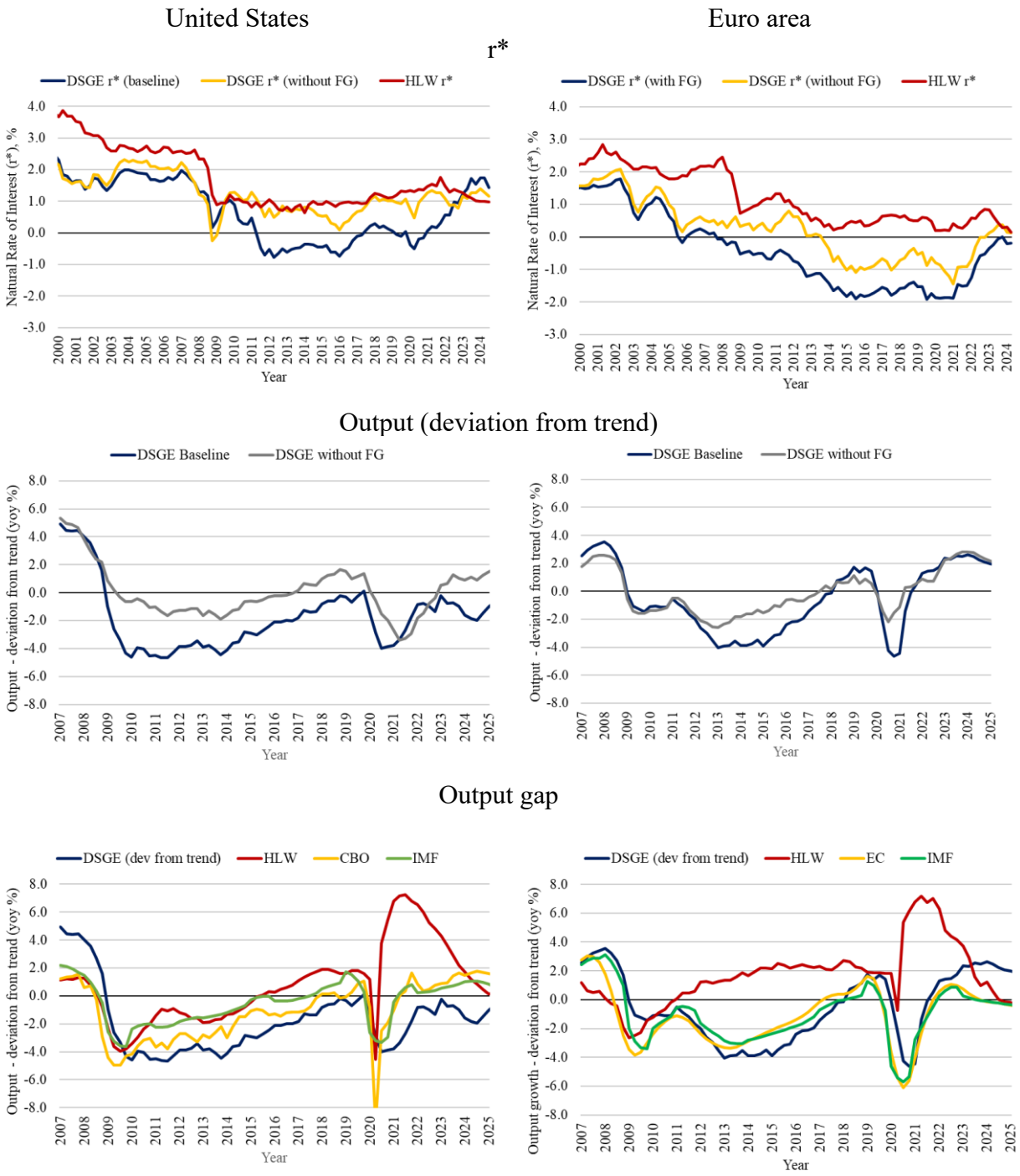
In this section, we first report filtered *r** estimates for both the US and the euro area and then discuss the role of policy expectations and other shocks driving *r** and economic fluctuations in the model.

4.1. Estimates of r* Across the Atlantic

Having estimated the model, we use it to present the model implied *r** estimates and output gaps for the US and the Euro area. Following HLW, we use the Kalman filter to calculate *r** as the one-sided filtered estimate according to equation (2). The results are presented in Figure 2, with results pertaining to the US (euro area) reported in the left (right) column.

[9] Our estimated autocorrelations are 0.985 and 0.983 for the persistent component of liquidity and safety shocks in the US and 0.985 and 0.979 in the euro area. Furthermore, for the euro area the transient safety shocks are more persistent than in the US (autocorrelation 0.853). To enable a better separation of transient and persistent convenience yield shocks in the euro area, we increase the prior mean and loosen the prior tightness for the standard errors for both the persistent components.

Figure 2: Model Estimates of *r and Output Gaps.**



Notes: Baseline DSGE model include OIS rates as observables and both contemporaneous and anticipated monetary policy shocks while the DSGE (without FG) excludes this information. HLW is the Holston, Laubach and Williams (2023) results, see Appendix IV. *Source:* IMF staff calculations.

The first row in Figure 2 show *r** results in the baseline model which incorporates OIS rates (see first row in Figure 1) as observables and include both contemporaneous and anticipated monetary

policy shocks $h = 1, \ldots, 6$ to account for fluctuations in $r_{m,t}$ and ultimately in the policy rate R_t. But the yellow line in the upper panels depict results for variant of the model without the expected policy rates as observables and without the anticipated policy shocks. Finally, the red lines report the one-sided filtered r_t^* with the workhorse HLW model.

For both economies, our baseline DSGE model suggests a significant fall in natural rates during the GFC and a subsequent return to the pre-GFC level during and after the pandemic. However, there are some important nuances between the US and the EA. In the US, r^* fell sharply during the GFC, then rebounded somewhat, before falling persistently below its pre-GFC level during the euro area debt crisis and its aftermath. For the euro area, our model estimates that the decline in r^* started already following the inception of the euro and crossed into negative territory persistently following the GFC and subsequent euro area debt crisis that started in 2010. Post-Covid, the r^* series is back very close to its pre-GFC level in the US and the euro area.

Comparing the filter r^* series in the baseline model to the one without OIS rates and anticipated policy shocks (denoted DSGE without FG), we see that a wedge for the filtered r^* series emerges after 2008. The alternative models imply notably smaller decline in r^* than the baseline model. Hence, when policy expectations are not explicitly accounted for, the estimated post-pandemic increase in r^* is materially smaller in the estimation with anticipated policy shocks. Furthermore, our r^* in the baseline DSGE model is notably different from the workhorse HLW model, which implies an essentially flat filtered r^* series following the GFC in the US and only a slight decline in the euro area. Although not shown in depicted in Figure 2, the Lubik and Matthes (2015) r^* remained close to the HLW r^* series from the GFC until after the pandemic (2009-2022), but has during 2023-2024 risen with one 1 percentage point and is even slightly above r^* in the DSGE model at the end of the sample period.

This result is best understood as a reallocation of explanatory weight between two persistent forces that both fit the positive inflation–interest 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^*.

The second row in Figure 2 highlights the role of policy expectations by depicting the smoothed output gap series (output as deviation from its stochastic trend) in the model with and without policy expectations. Given an actual real rate, the alternative models imply smoothed output series which are notably lower in the baseline model compared to the alternative model without OIS rates and anticipated policy shocks. In the US, a major difference in the output gaps develops early on the GFC and persists to the end of the sample period. In the euro area, a notable difference emerges

following the euro area debt crisis and during the Covid pandemic, but differences are closed by the end of the sample period. The difference between the two lines is the impact of policy expectations. As the forward guidance shocks have no impact on r^* but on the 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. The second row in Figure 2 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. We will discuss this in greater detail in Section 4.2.

The third row in Figure 2 compares the filtered output gap with our baseline DSGE model with the one implied in the HLW model and leading policy institutions; the US congressional budget office (CBO, for US only), the European Commission (EC, for euro area only), and the IMF. From the figure we can see that our model tracks the output gaps by the policy institutions notably closer that the HLW model, especially following the Covid pandemic.

Table 1: Drivers of Filtered r_t^* in the Baseline (with FGI) DSGE Model.

	United States		**Euro area**	
	1990Q1-2019Q4	2020Q1-2025Q4	1999Q1-2019Q4	2020Q1-2024Q4
r^* Change	-2.53%	1.93%	-3.20%	1.67%
CY Innovations	-0.68%	1.47%	-2.51%	1.78%
Other	-1.85%	0.46%	-0.70%	-0.11%

Notes: Changes in filtered r^* series in the baseline DSGE model is based on the posterior mode. "CY Innovations" denotes pertains to innovations to the 4 convenience yield shocks. "Other" pertain to all other innovations.
Source: IMF staff calculations.

The surge in filtered r_t^* following the Covid pandemic begs the question of its drivers pre- and post-Covid. In splitting the sample this way, we follow Del Negro et al. (2026).

The fall in US r^* pre-Covid is in line with the estimate (-3.11 percent) reported by Del Negro, Elbarmi and Pham (2026) in their VAR model with convenience yields, with similar driving forces (split into convenience yield and other factors). In the VAR, the convenience yield is identified as the common trend between Aaa and Baa spreads, similar to the model we employ. In contrast we estimate a significantly larger increase in r^* (close to 2 percent) following the pandemic than Del Negro et al. (2026) who reports about a 1 percent increase. The larger increase in our filtered r^* estimate is entirely driven by convenience yield innovations that we attribute to the reversal of anticipated policy shocks. In the US, technology shocks are a dominant source of r^* movements before the pandemic. Technology shock may also capture non-modelled demographic factors, but even so, their role has diminished after the Covid episode. For the euro area, we also find a sizeable, yet smaller increase in r^* following the pandemic driven by convenience yield factors. As the estimated model implies that r^* fell more in the euro area compared to the US prior to the pandemic, it hence remains at a lower level than in the US. Before the pandemic, in the euro area other factors mostly took the form of investment specific technology shocks. Appendix IV

provides a complete historical decomposition of r^* into various drivers in the DSGE model and offers a comparison with the drivers in the benchmark HLW model.

4.2. Impact of Current and Anticipated Monetary Policy Shocks

Panel A of Figure 3 shows that filtered raw shock across the Atlantic. Here we plot the contemporaneous shocks $\varepsilon_{r_{m,t}}$ and the anticipated shocks $\varepsilon_{r_{m,t+h|t}}$ for h = 1,…,6. These shocks measure the deviations from the policy rule either because of surprises or because of anticipation effects. The figure depicts a narrative of the nature of monetary policy surprise. If their cumulative effect (surprise and anticipated shocks) is positive, monetary policy is defined as restrictive, perhaps driven by the ELB or market expectations of a tight policy stance from the central bank. If the sum is negative, we call it an expansionary monetary policy.

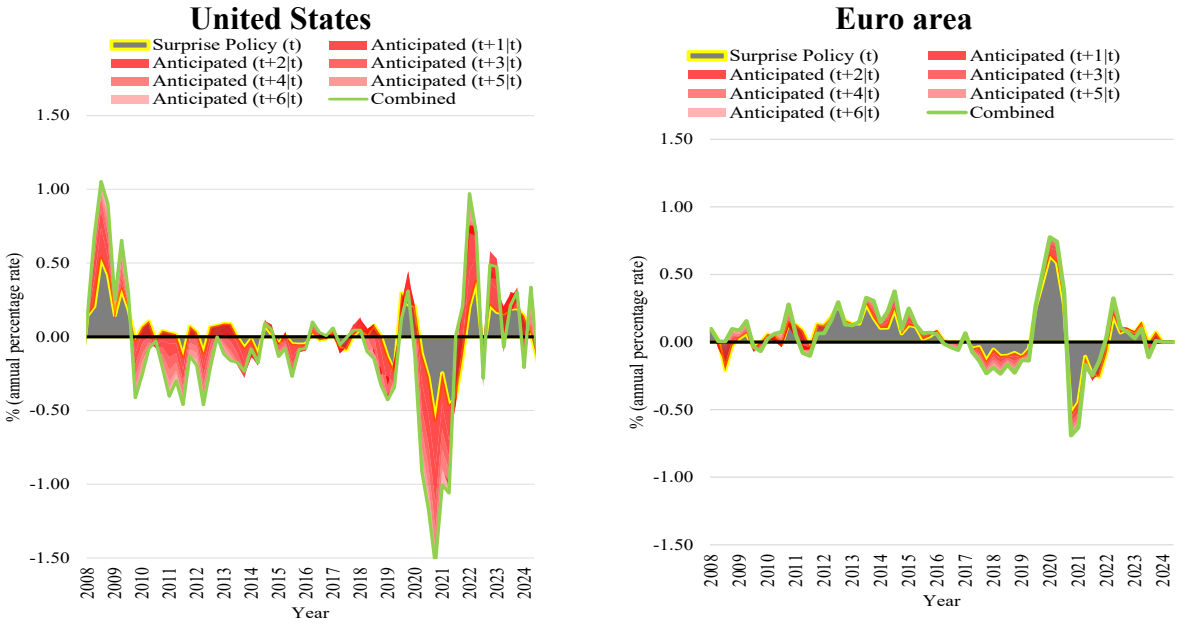
Panel B of Figure 3 on the other hand, demonstrates the historical importance of these shocks on policy rates. It shows the overall effect of all policy shocks' impact from the past using our model. The two figures differ in timing: while Panel A shows the innovations, Panel B maps these innovations into the policy rate and plots the cumulative direct and indirect contributions of current and anticipated monetary policy surprises on the policy rate.

One can observe that in especially the US, the years after the GFC was accompanied by positive, tightening contemporaneous monetary policy shocks. This most likely reflects that markets first expected a normal, V-type recession and US OIS rates depicted in upper left panel of Figure 1 suggests fast policy lift-off from the ZLB. This is reflected in the steep yield curves until 2011 in the second row in Figure 1. During the Covid pandemic, on the other hand, both the surprise and anticipated policy innovations suggest a notably more expansionary policy stance by the Fed and priced in market expectations than normal. For the euro area, we see that the innovations to policy were mostly predominantly positive during the post-GFC period until 2018 when they became more expansionary. Then they tightened up during Covid pandemic before becoming expansionary during the recovery from the pandemic. Not until 2023 the innovations became restrictive again.

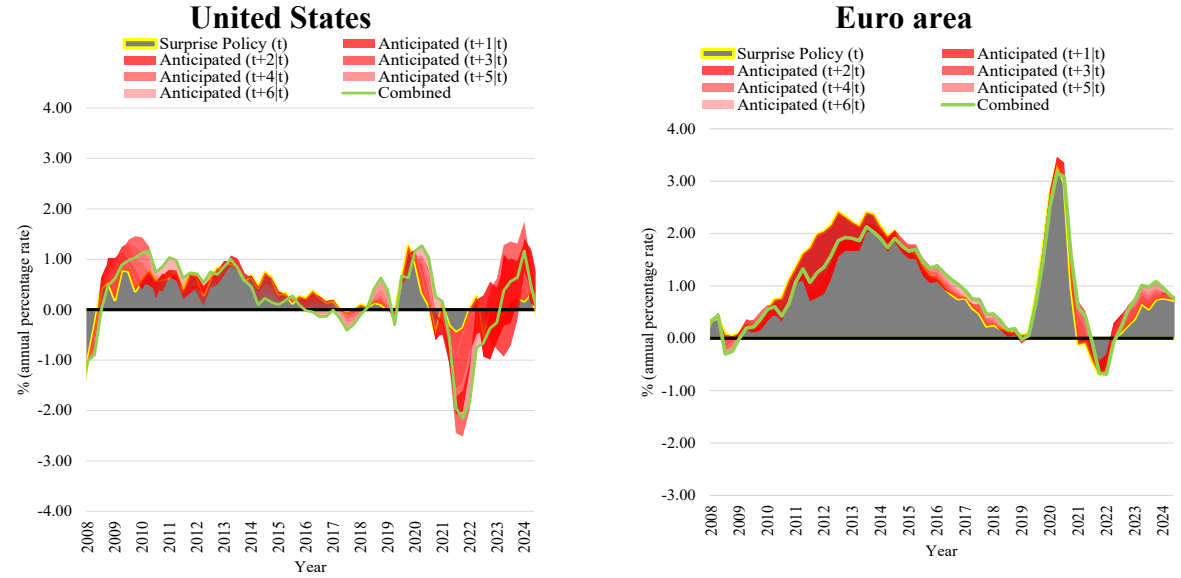
In the US during the GFC, anticipated policies pointed toward tightening. This could capture the public perception of inflationary effects of QE at the time. Afterwards, forward guidance, lower for longer announcements, gained a dominant role and for almost ten years they were effectively offsetting the constrained nature of monetary policy shocks at the ZLB. During the temporary period of *"taper tantrum"* and the lift-off from the ZLB had a slight output and inflationary effect. During the Covid-19 pandemic, both surprise and anticipated policies became expansionary. The introduction of a new monetary framework, average inflation targeting (AIT) together with sizeable fiscal expansion led to a modest change in corporate spreads (safety premia), unlike in other recessions. Afterwards, the withdrawal of accommodative policy created a positive co-movement between policy rates, inflation, and r_t^*. The rise in r_t^* worked against monetary tightening and in part contributed to the rise in inflation. We argue that this latter channel is captured in our model.

Figure 3: Estimated Policy Innovations and Contribution to Policy Rates.

Panel A: Policy Rate Innovations



Panel B: Contribution to Nominal Policy Rates

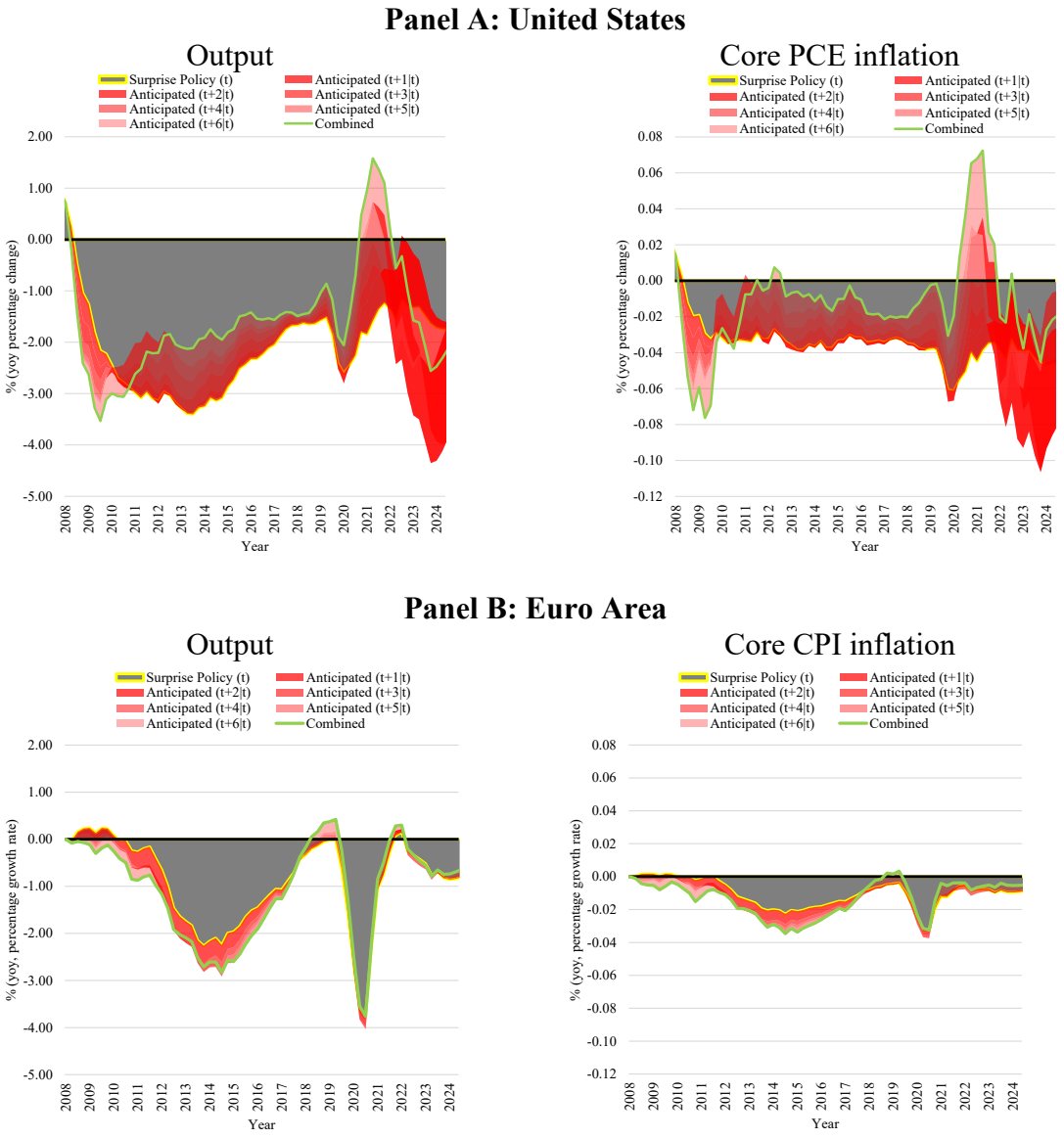


Notes: Panel A shows surprise $\varepsilon_{r_{m,t}}$ (contemporaneous) and anticipated innovations $\varepsilon_{r_{m,t+h|t}}$ at horizons $h = 1,2,\ldots 6$, whereas Panel B shows the contributions to observed policy rates by those innovations.
Sources: IMF staff calculations.

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_t^* was lower than in the US. Despite a temporary rise in 2011-12 markets did not expect this 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"* announcement. Anticipated policy remained accommodative until 2015. In 2016 reinvigorated large scale asset purchases implied shortage of safe assets and lowered r_t^* to negative territory, and hence policy stayed accommodative even at the ELB.

Figure 4: Contributions of Monetary Policy Shocks on core Inflation and Output.



Notes: The chart shows the policy impact of the observed variable decomposition of US PCE core inflation (yoy) and euro area core HICP inflation (yoy) and output (deviation from trend). See Appendix II for data sources.
Sources: IMF staff calculations.

During the Covid-19 Pandemic, 2020-2021, both surprise and anticipated policy became constrained; leading to a stronger tightening than in the US, together with supply disruptions, Russia's invasion of Ukraine, geopolitical tensions, energy price increases.

Following the pandemic, surprise policy tightened and rate guidance reversed. This masks the surge in r_t^* and led to a rise in inflation. Ultimately as anticipated policy withdrawal was realized and liquidity injection was withdrawn, the policy rate turned first neutral and then restrictive.

Figure 4 reports the impact the surprise and anticipated monetary policies in Figure 3 had on output and inflation and output during this period. In both regions, we see surprise shocks lowered economic activity notably prior to the pandemic. In our estimated model, those shocks capture the direct effects of the ELB, and they contributed to sustained lower economic activity in the US with 2 percent. Anticipated policy shocks contributed to an additional 1 percent output decline prior to 2017. In the euro area, we find that the shocks contributed to a similar sized, yet less persistent contraction in economic activity that peaked during 2014. The tight policy stance also nudged inflation further below the central bank's target, and somewhat more so in the US compared to the euro area. But as the estimated linearized model implies very low slopes of the pricing and wage Phillips curves, the near-term impact on inflation is quantitatively very modest.

The policy stance and the influence of current and anticipated shocks were reversed during the pandemic, and their combined contribution raised US output during the pandemic with 1 percent. For the euro area, we find a substantial adverse spike of tight monetary conditions on output with almost 4 percent. This is driven by an estimated policy rule for the ECB that reacts strongly to output growth, and when output growth fell in the EA during the pandemic and did not bounce back as vigorously as in the US, the model filters out righter monetary conditions as a contributing factor in the euro area.

Finally, during the post-Covid inflation surge, we find that the gradually tightened policy stance contributed to lower economic activity in the US notably (building up around -4 percent as can be seen in Panel A), whereas tighter monetary conditions also implied a negative – yet notably less adverse – impact on economic activity (gradually shaving of -1 percent in output) in the euro area as can be seen in Panel B. As before the Covid pandemic, the discretionary policy actions post-pandemic are only associated with minor impact on inflation in both the US and the euro area. But our linear framework with linear Phillips curves and maintained assumption of constant policy rules means that our model likely underestimates the effects of the sustained policy actions on inflation during this period, see Hodge et al. (2025) and Laséen, Söderström and Lindé (2022).

5. Transmission of Monetary Policy and Convenience Yield Innovations

In this section we study the propagation of contemporaneous and anticipated monetary policy shocks and compare them to those of the most important convenience yield shock. We do this to solidify that we can disentangle these shocks when we estimate the model.

To do this, we impose a lower policy rate with -1 percentage points (annualized rate) for six consecutive quarters $t = 1,\ldots,6$. This duration is intended to match the number of periods we include forward (OIS) rates as observables when estimating the model. Next, we assume that the lower policy rate path is driven by the following alternative constellations of innovations:

> **Experiment 1**: A sequence of negative surprise monetary policy innovations $\varepsilon_{r_{m,t}}$ that hits the economy as a surprise in each quarter $t = 1,\ldots,6$.
> **Experiment 2**: A sequence of anticipated monetary policy shocks, understood by all agents in period $t = 1$ that hits the economy in quarters $t = 2,\ldots,7$.
> **Experiment 3**: An arbitrarily sized negative surprise monetary policy innovation in $t = 1$ followed by a sequence of anticipated policy innovations in quarters $t = 2,\ldots,7$.
> **Experiment 4**: A sequence of transient and permanent liquidity premium shocks in quarters $t = 1,\ldots,6$.[10]

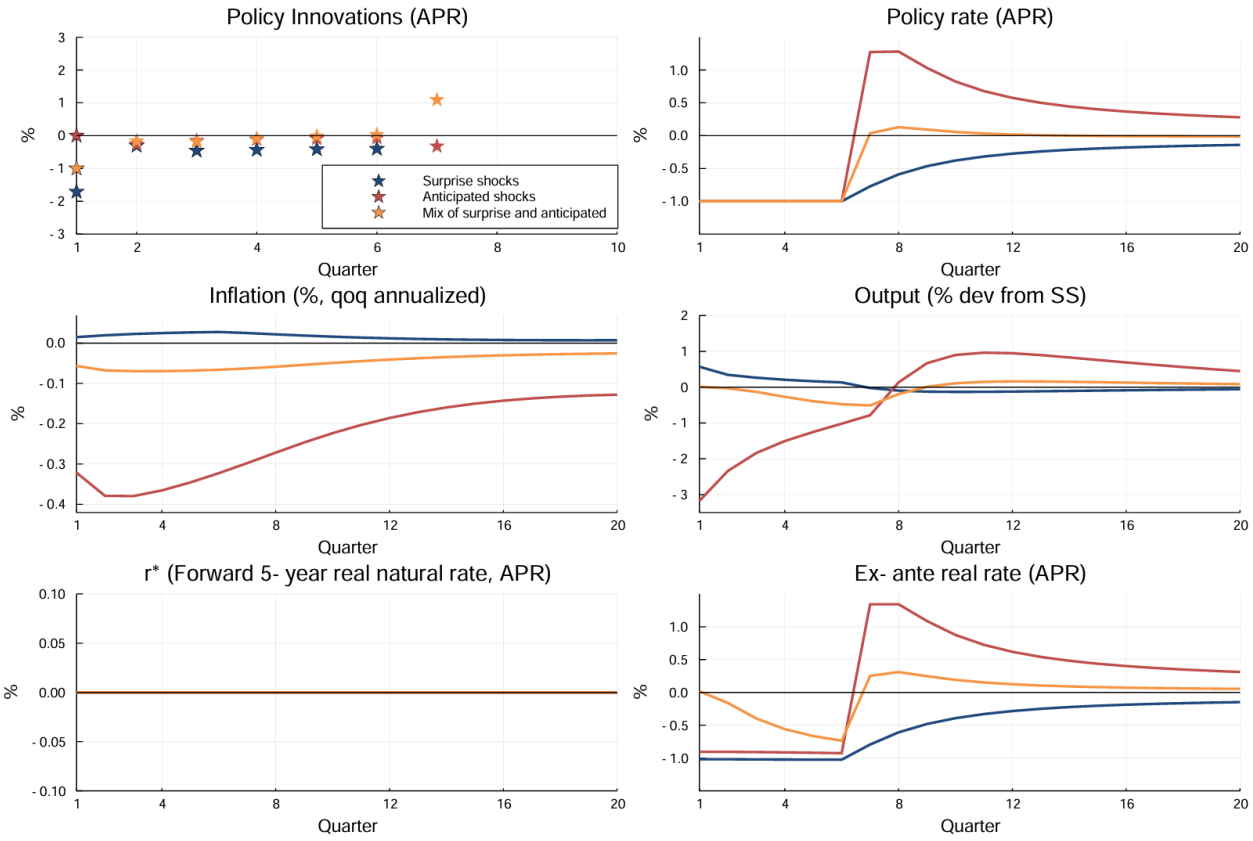
The results of Experiments 1-3 are shown in Figure 5, in blue, red and orange, whereas Experiment 4 is shown in Figure 6. We see from the blue line on Figure 5, showing Experiment 1, that a sequence of surprise monetary policy shocks that lower the policy rate to -1 percent for 6 quarters stimulates output and inflation in line with conventional wisdom on the transmission of monetary policy.

However, as shown in several papers (see e.g. Laseen and Svensson, 2011, Carlstrom, Fuerst and Paustian, 2015, and Holden, 2023), it is possible that a sequence of anticipated policy innovations that imposes the same policy rate path can switch sign, so that a negative policy rate path must be imposed by a sequence of positive anticipated monetary policy innovations that lowers output and inflation notably. This can happen in the model when as in Experiment 2 shown by red lines in Figure 5, the anticipated innovations $t+h|t$ are announced for periods $h = 1,\ldots,6$ and hence do not coincide in time with the policy rate path they impose. In this case, we obtain a sequence of positive policy rate innovations – which themselves put upward pressure on the policy rate – that drives down output and inflation but in addition also the policy rate due the systematic part of the policy rule (recalling that the actual policy rate is the sum of the systematic arguments and the current and anticipated shocks in the rule in eq. 6). Finally, experiment 3, the orange line on Figure 5, shows the third combination with a mixture of an initial negative monetary policy surprise like the

[10] An exercise with permanent safety shocks would result in very similar outcomes, transitory liquidity and safety shocks, on the other hand have generally smaller impact on r*.

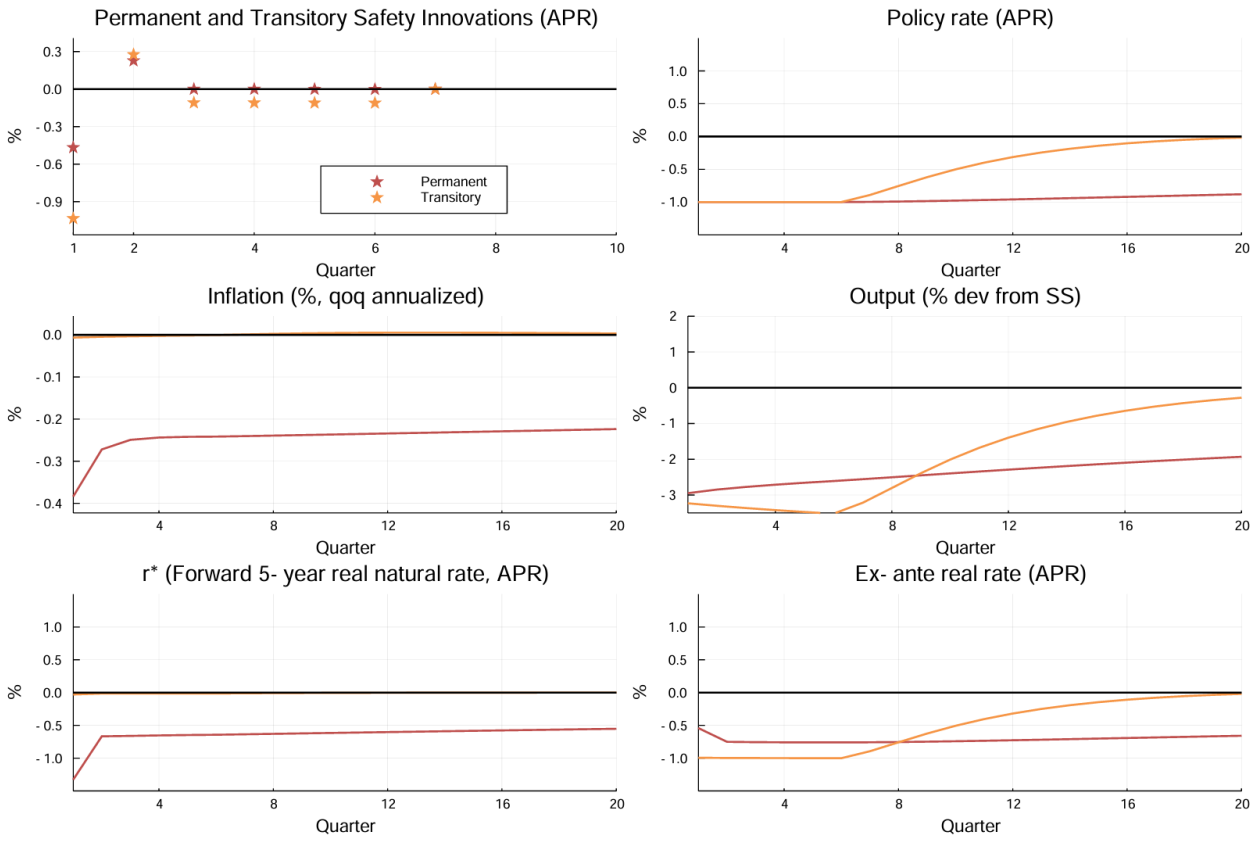
one in experiment 1, shown in blue, followed by a sequence of anticipated innovations. In this case, we see that output is first unchanged before falling.

Figure 5: Interest Rate Peg with Contemporaneous and Anticipated Monetary Shocks.



Notes: The figure shows a policy rate peg implemented with a combination of contemporaneous policy innovations and anticipated policy innovations. The blue line implements the peg with sequence of negative surprise monetary policy innovations (Experiment 1). The red line implements the peg with a sequence of anticipated monetary policy innovations in periods $t+h$, h=1,2,...,6 announced in period t=1 (Experiment 2). Finally, the orange combines the two and implements the policy rate peg conditional on an initial negative surprise monetary policy innovation in t=1 followed by a sequence of anticipated policy innovations $t+h$, h=1,2,...,6 announced in period 1 (Experiment 3). Inflation is defined as annualized percentage quarterly rate, policy rate, r^* and ex-ante real rate are defined as annual percentages. All variables are reported as deviations from their respective steady states.
Source: IMF staff calculations.

Figure 6: Interest Rate Peg with Convenience Yield Shocks.



Notes: The figure assumes that a sequence of unanticipated transient and persistent (near-permanent) innovations to the liquidity premium shock $b_{liq,t} = b^t_{liq,t} + b^p_{liq,t}$ in eq. (1) implements a peg of the nominal policy rate at -1% for the first 6 periods. The effects of transient and persistent innovations to safety convenience yield shock $b_{safe,t}$ yields near identical effects.
Source: IMF staff calculations.

Importantly, all these combinations of current and anticipated monetary policy shocks leave r_t^* unaffected, whereas Figure 6 shows that a sequence of innovations that induces the same short-term interest rate path for 6 quarters by lowering the (near-) permanent component $b^p_{liq,t}$ of the liquidity premium $b_{liq,t}$, leads to a substantial persistent decline in r_t^* as can be seen in the lower left panel. On the other hand, a sequence of innovations to the transient liquidity premium $b^t_{liq,t}$ sized to lower the short-term policy rate with -1 percent for 6 quarters only has negligible impact on r_t^*. As the systematic component of the monetary policy rule in equation (6) only reacts to inflation and output, and hence does not lean directly against any movements in r_t^* when unconstrained by the ELB, the permanent shock to the convenience yield shock we study will lower output and inflation notably in order for the policy rate to fall with -1 percent. And when we assume that the conditional path for the policy rate is driven by the (near-) permanent shock to the convenience yield, the effects on output persist for quite some time which causes inflation to fall

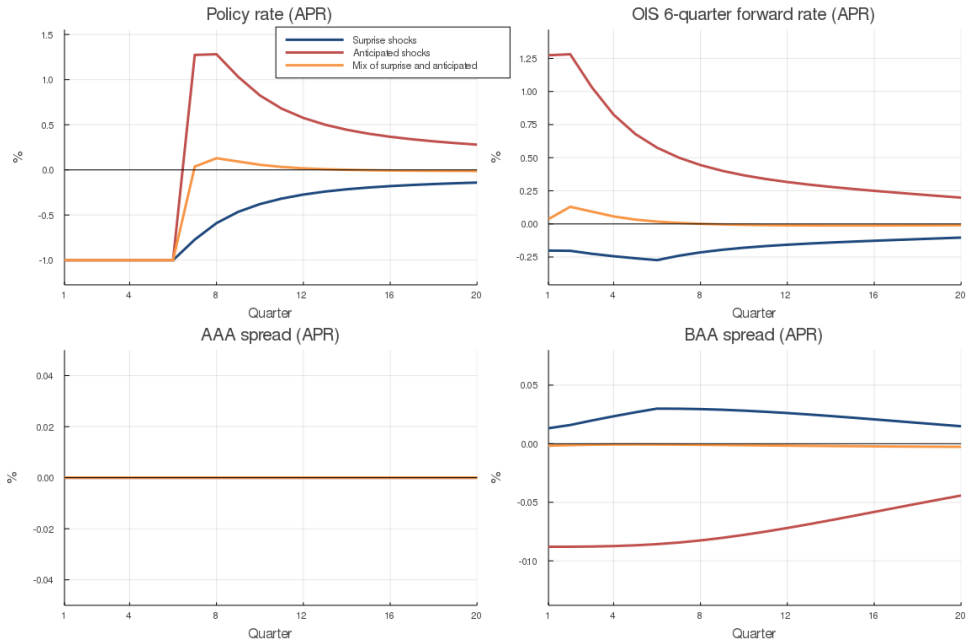
notably as can be seen in the middle-left panel in Figure 6. When the transient shock to the liquidity premium drives the decline in the nominal policy rate, the output decline is notably less persistent and inflation – which is driven by the future path of output – thus barely falls. Because of the notably more transient impact on output and inflation, the nominal policy rate returns notably faster to its pre-shock value and the ex-ante short-term risk-less real interest rate 20 quarters ahead barely moves (and thus r_t^* as can be seen from equation 8) as shown in the lower left panel when the lower policy rate is driven by temporary liquidity premium shock. The near-permanent liquidity premium shock drives a notably larger decline in r_t^* by persistently lower output and inflation and thus the 20 quarter ahead short-term risk-free real interest rate.

Although the transmission of transient and near-permanent innovations to the safety premium $b_{safe,t}$ shock and the liquidity premium shock $b_{liq,t}$ propagates identically in the model, we can disentangle their role using spread information from risky and less risky (corporate and government) bonds. Specifically, as seen from equations (5)-(6), $b_{liq,t}$ shock will affect the Aaa spread, whereas both $b_{liq,t}$ and $b_{safe,t}$ will affect the Baa spread. We illustrate the identification of the different shocks through interest rate observables in Figure 7. As before, we implement an interest rate peg on the policy rate, either with contemporaneous and anticipated monetary innovations, in Panel A, or with transitory and permanent convenience yield, $b_{liq,t}$ innovations, in Panel B. Panel A shows that the Aaa spread does not respond to contemporaneous and anticipated monetary policy shocks, as it is determined by the liquidity premium, furthermore monetary policy shocks have a small effect on the Baa spread, through the expected excess return on capital. Panel B shows that convenience yield shocks impact both spreads almost the same way. Therefore, policy rate shock is associated with movements in the policy and OIS rates, while convenience yield shocks are pinned down by strong co-movement of the spreads in the data.

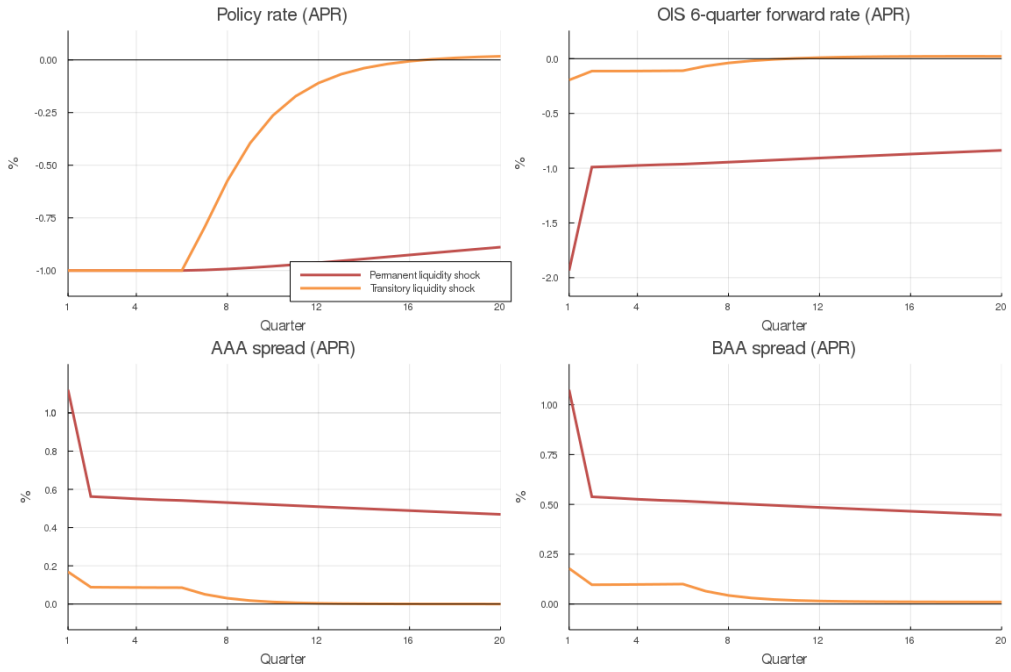
All told, we conclude that including the short-term policy rate, OIS rates, along with Aaa and Baa spreads and a set of macro-observables allows us to filter out the role and transmission of surprise and future policy shocks, and the shocks that determine the convenience yield when estimating the model with Bayesian likelihood methods. The estimated model provides a large role for the near-permanent shocks behind the fall in the euro area convenience yield (and movements in r_t^*) since the adoption of the common currency in the euro area, whereas in the US we find a larger role a transient shocks to the convenience yield which has moved r_t^* less 1999-2024 in the US compared to the euro area.

Figure 7: Impact of Interest Rate Peg on Interest Rates and Spreads

Panel A: Interest Rate Peg with Contemporaneous and Anticipated Monetary Shocks



Panel B: Interest Rate Peg with Convenience Yield Shocks



Notes: Panel A shows a policy rate peg implemented with a combination of contemporaneous policy innovations and anticipated policy innovations. Panel B assumes the policy rate peg is a result of of a sequence of unanticipated convenience yield innovations. See notes of Figure 5 and 6 for further information.
Source: IMF staff calculations.

6. Counterfactual Analysis

After showing that convenience yield shocks and monetary policy shocks can be disentangled in the estimation and filtering of r_t^*, we now use the model to do two counterfactual scenarios. Our first counterfactual exercise seeks to answer how economic activity would have unfolded during the post-Covid pandemic if r_t^* had not risen during this period. Second, we use the estimated model to analyze how the US economy had unfolded if it had been exposed to the same convenience yield innovations as in the euro area since the inception of the euro in 1999. This seeks to answer the hypothetical question: how would the US economy have been affected this period if the US dollar did not enjoy the exorbitant privilege?

6.1. What if r* had not Risen During the Post-Pandemic Period?

This exercise tries to demonstrate how the movement in the natural rate of interest may have played a role in the post-pandemic inflation episode. Panel A in Figure 8 shows that r_t^* on our DSGE model has varied significantly relative to the HLW r_t^* series, and risen significantly relative to its pre-Covid level in both the US and the Euro area, taking uncertainty around the point estimate into consideration.

Even so, Panel B shows that this sharp increase came as a surprise in real time; the red lines with the predicted $r_{t+h\}t}^*$ for $h = 1,\ldots T$ show that at each point in time r_t^* was predicted to remain around its current level according to our baseline estimated DSGE model. This means that we can model the macroeconomic implications of the r_t^* surge during this period as sequence of surprise shocks to the stance of monetary policy, i.e. shocks $\varepsilon_{r_{m,t}}$ in the monetary policy rule (7). We will next do this in an alternative scenario in which we assume that the actual stance of monetary policy became gradually looser during the post-Covid period as r_t^* rose.

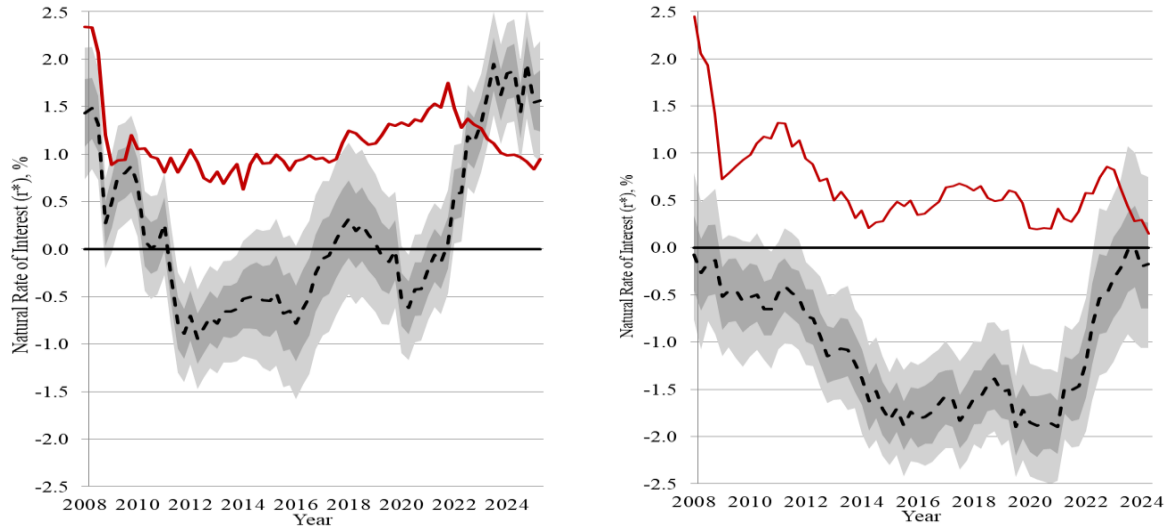
Specifically, to gauge the quantitative importance of this channel on the macroeconomy, we will consider a counterfactual scenario in which the change in the natural rate follows the evolution of the filtered r_t^* in the HLW model instead of the filtered r_t^* series in the baseline DSGE model, starting from its pre-Pandemic, 2020Q1 level for both the US and the euro area. That is, we calculate how r_t^* have unfolded according to the HLW and our DSGE model since 2020Q4 and feed our model with this difference in r_t^* for t = 2021Q1, 2021Q2,… For the US, the counterfactual runs until end-2024, and for the euro area it ends mid-2024 (2024Q2).

The first row in Figure 9 shows how r_t^* in the HLW and DSGE models have unfolded since 2020Q1. The paths depicted in the figure are the same as those depicted in Panel A in Figure 9, provided that both series in Figure 9 are rescaled to 0 in 2020Q4 in both the US and the euro area. We see that the HLW model implies that r_t^* rose somewhat initially and then fell back (or even below in the US) to its pre-Covid value. The DSGE model, on the other hand, implies that r_t^* rose by close to 2 percentage points (annualized rate) in the US and around 1.5 percentage points (annualized rate) in the euro area. This implies that the counterfactual simulation in the US will

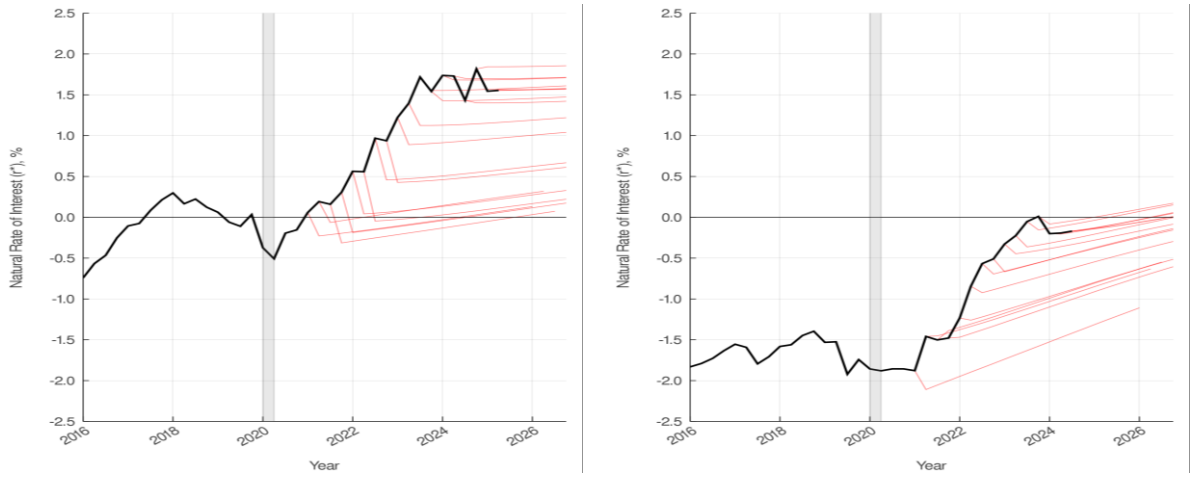
feature a monetary policy stance that eventually became close to 2.5 percentage points tighter in real terms (i.e. difference between the DSGE and HLW r_t^* series), whereas the euro area policy stance becomes a little over 1.5 tighter in real terms.

Figure 8: Uncertainty Bands, and Projected Post-Pandemic US and EA r* Estimates.

Panel A: r_t^* with uncertainty bands in DSGE model and in HLW (red solid) model



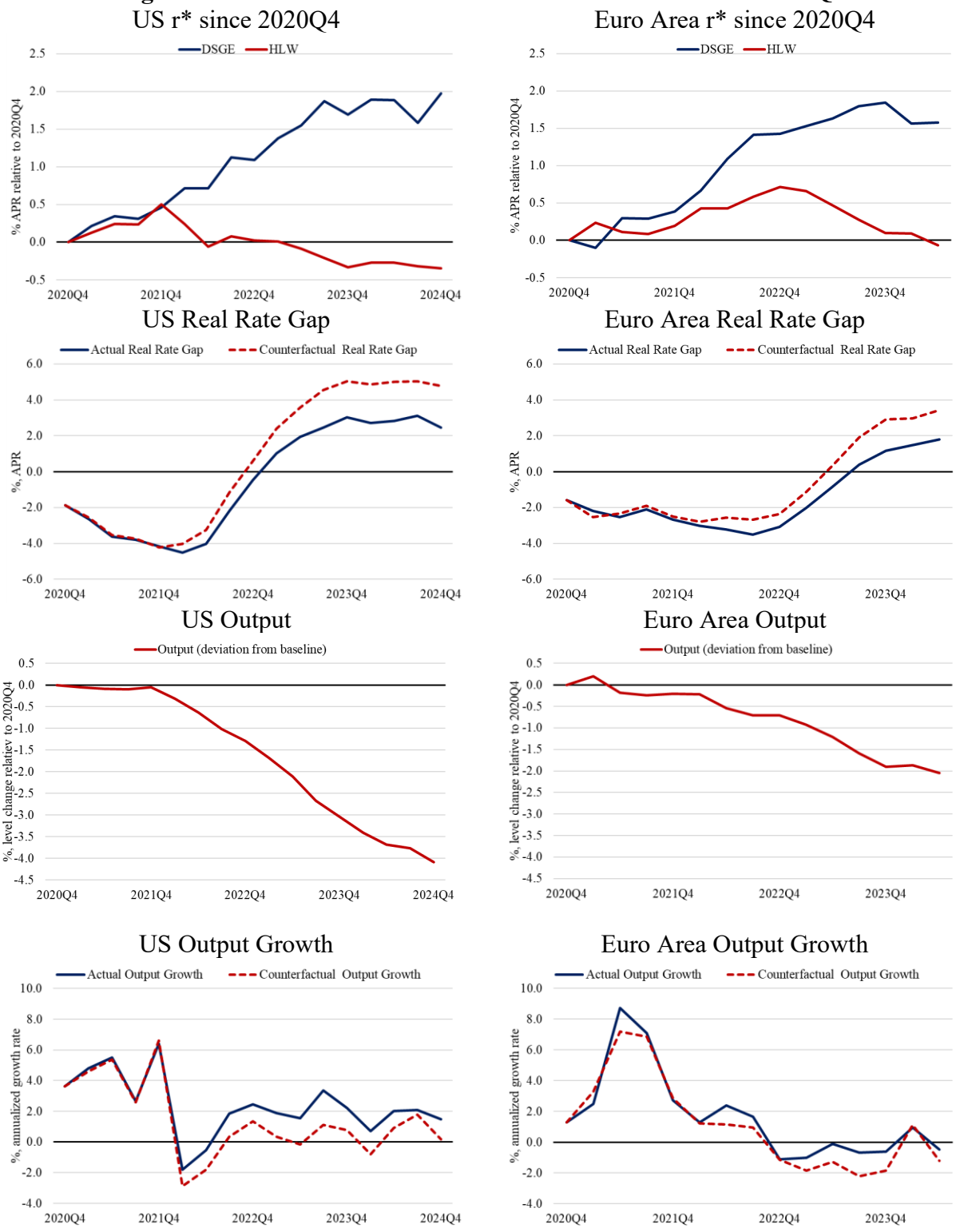
Panel B: Actual (black) and predicted (thin red dotted) r_t^*



Notes: Panel A shows the US and euro area posterior mean *r** estimates from the baseline DSGE with anticipated policy in black dashed line and associated posterior CI of 68 and 90 percentiles as grey shaded area. HLW model estimates are in red. Panel B show US and euro area actual and predicted *r** estimates in the baseline DSGE model with anticipated policy in black and the pseudo real time out of sample predicted *r** forecasts.
Sources: Haver Analytics; IMF staff calculations.

The second row of Figure 9 displays the realized short-term real rate gap (solid blue line), and the counterfactual path with a tighter real rate path (red dashed lines) based on the evolved difference in the filtered *r** series in the HLW and SGE models in the first row.

Figure 9: Counterfactual Simulation Under HLW r* Since 2020Q4.



Notes: Counterfactual scenario of the US DSGE model had *r** not increased following Covid-19, starting 2020Q4. DSGE and HLW *r** series are relative to their values in 2020Q4, i.e. -0.34 and -1.86 annualized percentage points (see Figure 2 for smoothed *r** series in the HLW model and the DSGE model with OIS rates and FG shocks).
Source: IMF staff calculations.

As noted previously, our estimated model features flat price and wage Phillips curves for both the US and the euro area. Thus, the alternative policy has a muted impact on inflation. However, recent research has shown that the slope of the Phillips curve may be state contingent, so it's conceivable that the transmission to inflation may be notably higher than implied by our estimated model.

When the counterfactual with a tighter r^* series is imposed on the economies with surprise monetary policy shocks, output falls gradually over time in both the US and the euro area as can be seen in the third row in Figure 9. In the euro area, output even initially expands a little since the HLW model implies a higher r^* series than the DSGE model. Over time, the gradually tighter monetary policy conditions – especially in the US – in the counterfactual lowers output with about 4 percent in the US and about 2 percent in the euro area. We do not show counterfactual for the nominal short-term policy rate, but since inflation moves little due to our maintained assumption of a constant sensitivity of inflation to economic activity, the alternative r^* path can be approximately translated into an equivalent path for the nominal short-term policy rate. Hence, we can compare the results for output in Figure 9 with the impulse for output in Experiment 1 in Figure 5 (blue line), suitably rescaled to capture the size and persistence of the policy deviation.

The last row in Figure 9 shows the implications for quarterly output growth (expressed at an annual rate). In the counterfactual, we see that the tighter monetary policy stance would have pushed euro area to sustained negative growth rate close to -2 percent, and in the US the tighter policy stance would have resulted in zero growth from 2022 and onwards. With NBER's two consecutive quarters of GDP decline rule-of-thumb for classifying recessions, it is certainly possibly that NBER would have classified the US economy as moving into a recession in 2022, and with a similar criterion the euro area in the counterfactual would have moved into a recession in 2023. All told, the results in Figure 9 are an important reminder that policy strategies that abstract from the level of r^* are not immune to their changes. As a result, uncertainty or misperception regarding the evolution of r^* can translate into a different degree of effective accommodation than intended.[11]

6.2. Measuring the Exorbitant Privilege of the US Dollar

In this final counterfactual exercise, we examine how US macroeconomic outcomes would have differed if all shocks to the convenience yield associated with dollar-denominated assets had instead resembled those prevailing in the euro area since the inception of the common currency in 1999. The exercise can be interpreted as an attempt to quantify the macroeconomic implications of the United States benefiting from an *"exorbitant privilege"* on US government securities compared to that in the euro area during this period. Panel A in Figure 10 depicts the filtered convenience yield denoted as CY_t, in the US and the euro area, defined as

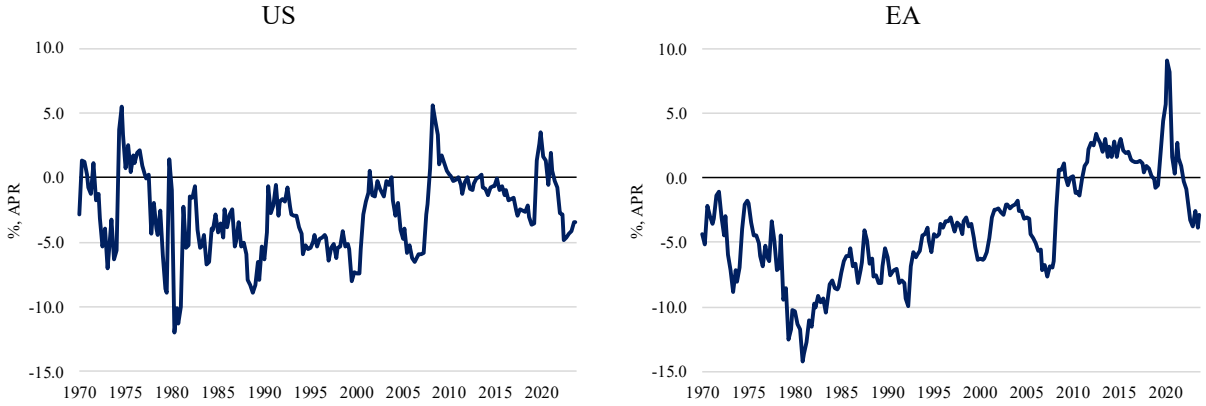
[11] Levin, Wieland, and Williams (1998) and Orphanides and Wieland (2013), highlights the robustness of first-difference policy rules in environments where the level of the neutral rate is difficult to pin down.

$$\mathrm{CY}_t = -\frac{1}{\chi_R}(\overline{b_{liq}} + \overline{b_{safe}} + b^t_{liq,t} + b^t_{safe,t} + b^p_{liq,t} + b^p_{safe,t}). \quad (9)$$

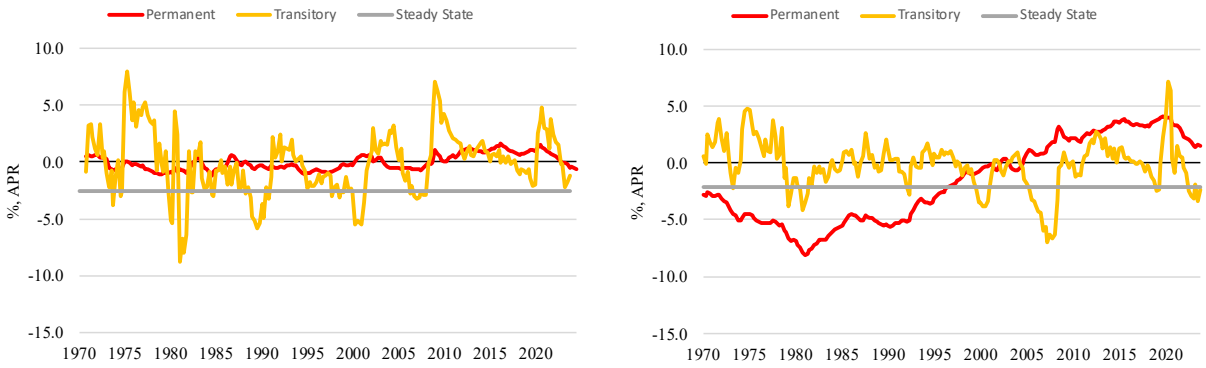
This convenience yield measure is transformed into the interest rate domain, the unscaled part $(\overline{b_{liq}} + \overline{b_{safe}} + b^t_{liq,t} + b^t_{safe,t} + b^p_{liq,t} + b^p_{safe,t}.)$ is a measure in the utility domain reflecting the preferences of investors for safety and liquidity. Equation (9) details the components in Equation (7); the steady state, transient and permanent (highly persistent) components of the shocks. When filtered in the model, we see from Panel A in that there appears to be an upward trend in the convenience yield over time in the euro area, whereas CY_t appears stationary in the United States.

Figure 10: US and EA Convenience Yield Estimates.

Panel A: Filtered Convenience Yields



Panel B: Drivers of Convenience Yields



Notes: Panel A show US and euro area convenience yield estimates at the posterior model of the DSGE models with forward-guidance shocks, whereas Panel B decomposes the overall smoothed series CY_t in eq. (8) into the fluctuations driven by the highly persistent $-\frac{1}{\chi_R}(b^p_{liq,t} + b^p_{safe,t})$, transient $-\frac{1}{\chi_R}(b^t_{liq,t} + b^t_{safe,t})$, and steady state $-\frac{1}{\chi_R}(\overline{b_{liq}} + \overline{b_{safe}})$.
Sources: Haver Analytics; IMF staff calculations.

We also see that the euro area has experienced larger movements in CY_t post-1999 than the US, but that its currently filtered to be close to -4 percent in both economies. Following the GFC, the filtered US and euro area CY_t series show that the demand for safe and liquid assets surged in both economies, and while the US could recover, the euro area entered the fiscal debt crisis with an larger sustained upward pressure on its convenience yield. Ceteris paribus, this puts upward

pressure on long-term government yields and downward pressure on r^* in the euro area relative to the US. Even so, there are also other factors that affect long-term nominal yields, which explains why actual nominal long-term bond yields in in the US and the euro were similar following the GFC as can be seen in the lower panels in Figure 1. CY_t rose sharply again during the initial phase of the Covid pandemic, especially in the euro area. In post-pandemic period, CY_t normalized in both economies and the difference between them dissipated.

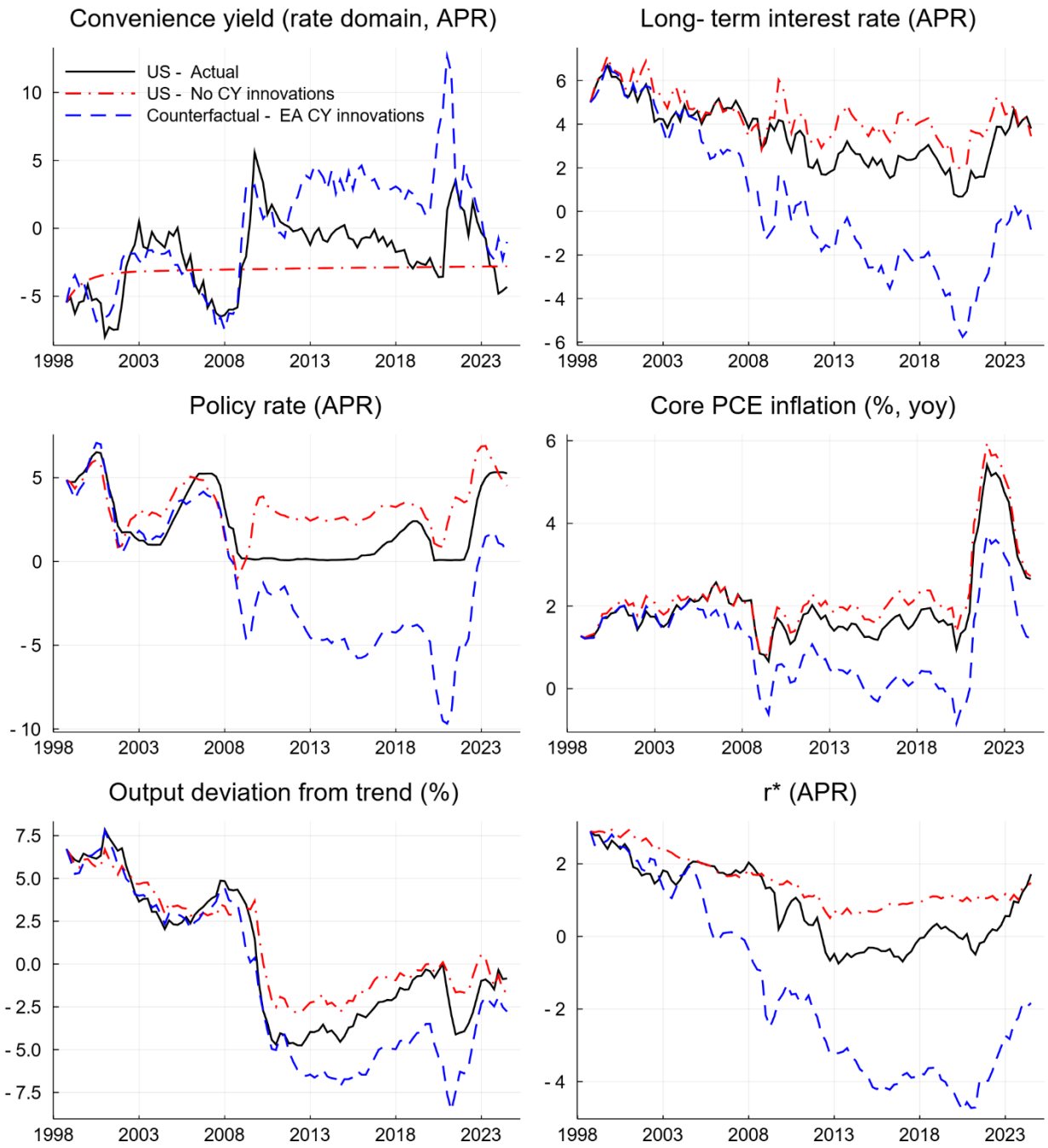
Panel B in Figure 10 decomposes the total convenience yield into its steady state $-\frac{1}{\chi_R}(\overline{b_{liq}} + \overline{b_{safe}})$, highly persistent $-\frac{1}{\chi_R}(b^p_{liq,t} + b^p_{safe,t})$ and transient $-\frac{1}{\chi_R}(b^t_{liq,t} + b^t_{safe,t})$ components. The steady state premium in the US is -2.6 percentage points and -2.1 percentage points in the euro area. Panel B also shows that the smoothed permanent component accounts for a minor share of the fluctuations in the US convenience yield, whereas the permanent component drives the secular decline in the euro area convenience yield. As the (near-) permanent convenience yields are associated with notably larger fluctuations in r^* and inflation compared to transient drivers of CY_t (for reasons discussed in connection with the analysis in Figure 6), it matters for macroeconomic outcomes if permanent or temporary shocks drives fluctuations in CY_t.

With this in mind, we move on to the counterfactual scenario for the US economy, in which the permanent safety and liquidity innovations are removed from the first quarter in 1999 until the end of the sample period, and US investors are instead assumed to require innovations to transient and permanent liquidity and safety shocks in equation (9) filtered in the euro area variant of the model. Since Panel A shows that $CY^{US}_{1998Q4} \approx CY^{EA}_{1998Q4}$ and that the estimated AR(1) shock processes for (near-) permanent (highly persistent) and temporary safety and liquidity have similar persistence parameters, this implies that the counterfactual scenario will essentially replace the filtered CY_t series in the US (left chart in Panel A) with the EA series (right chart in Panel A) in the counterfactual scenario.[12]

The results are reported in Figure 11. In this figure, the solid black line shows actual outturns, whereas the red dashed-dotted line shows a counterfactual without any new innovations to the US safety and liquidity premiums 1999Q1 and onwards, in which case CY_t in the upper left panel eventually converges to its steady state value -2.58 percentage points reported in Figure 10 (Panel A) as the dynamic path of $-\frac{1}{\chi_R}(b^t_{liq,t} + b^t_{safe,t} + b^p_{liq,t} + b^p_{safe,t})$ converges towards nil. Finally, the blue dashed line shows the counterfactual when the US innovations 1999Q1 and onwards for the four convenience yield shocks are replaced with the euro area innovations.

[12] Specifically, we assume that the permanent and temporary innovations to the convenience yield shocks ($b_{liq,t}$ and $b_{safe,t}$) in the US are replaced by the filtered innovations in the euro area variant of the model. Because safety and liquidity premia in the model are driven exclusively by transitory and permanent liquidity and safety innovations, only these innovations and shock paths are adjusted; all other structural relationships are left unchanged in the US.

Figure 11: Counterfactual with EA Convenience Yield Innovations in the United States.



Notes: Counterfactual scenario simulated by the US DSGE model. The red dotted line drops all convenience yield innovations from 1999Q1 and onwards. The blue dashed line shows a counterfactual implements the smoothed convenience yield innovations of the EA model in the US model at respective posterior mode in the two models. Convenience yields are shown in the interest rate (spread) domain
Source: IMF staff calculations.

The post-GFC increase in convenience yields, both in the US and euro area, resulted in a decline in r^*. The top left panel of Figure 11 shows that even in the US, increasing convenience yields

following the GFC pushed r^* down, as the black line is above the red-dashed line (without any convenience yield innovations after 1998Q4). With euro area convenience yield innovations, the US CY_t would have risen notably more persistently in 2010 and onwards and r^* would have fallen notably more as shown in the bottom right panel in Figure 11. At the ELB a decline in r^* makes the policy stance more contractionary. Hence, had the US faced the euro-area pattern of convenience-yield shocks post-GFC, it would have entered a deeper liquidity trap and experienced a notably larger output contraction relative to baseline.

According to Figure 11, the resulting deviations of this counterfactual from actual outturn would have been modest for most variables until the global financial crisis (GFC). But from the GFC and onwards, the counterfactual reproduces features associated with the euro area sovereign debt crisis, and US output would have been substantially lower and inflationary pressures would have remained well below the Federal Reserve's inflation target. In turn, both r^* and the Federal Funds rate would have been notably lower. Furthermore, as this exercise does not impose an ELB on the federal funds rate (i.e. ZLB in the case of the Federal Reserve), the ELB would have become an even more binding constraint on the policy rate in the counterfactual. Thus, the scenario likely underestimates the adverse impact of these shocks. All told, our model implies that less favorable convenience yield shocks – and thus a diminishing exorbitant privilege for the United States – could be a source of severe macroeconomic headwinds in the US economy moving forward.

7. Conclusion

Up until the Covid-19 pandemic, estimates of the natural rate of interest, r^*, across advanced economies were declining. However, the inflation following the pandemic has initiated a debate whether r^* is was on the rise.

In this paper, we provide post-pandemic estimates of r^* and revisit its potential drivers in a DSGE model by Del Negro et al. (2017). This model allows us to estimate the convenience yield, the premium investors assign to safe and liquid assets, which was found to be a crucial driver of the natural real rate.

When we estimate the model, we include data on the yield curve to capture policy expectations. This allows us to disentangle convenience yields from anticipated policy. We show that the former impact r^*, while changes in anticipated policy are neutral to the natural rate.

We have four main contributions to literature:

First, we show that accounting for policy expectations alters r^* estimates. During the inflation following the Covid pandemic our estimated r^* rose sharply, from -0.5 percent to 1.5 percent in the US and from -3.5 to 0.5 percent in the euro area. This is in stark contrast to the estimates without policy expectations, where r^* is estimated to rise to a smaller extent or not at all.

Second, we argue that the forward guidance puzzle can conceal the changes in r^*. When policy rates are at the ELB, a combination of current and anticipated policy innovations may result in similar transmission as convenience yield changes. By including both expectations of future policy rates and long-term yields as observables, we distinguish between the two and improve the identification of r^*.

Third, our results point to a new reading of the post-Pandemic period. In both the United States and the euro area, the sharp rise in nominal policy rates was accompanied by a sizeable increase in the estimated natural rate. This implies that the increase in real policy restraint was smaller than one would infer from models in which r^* remained broadly unchanged. In a counterfactual exercise with unchanged r^* during the post-pandemic period, monetary policy stance would have been tighter and output substantially weaker, most likely classified as recessions in both the US and the EA. Our findings help explain how the soft landing across the Atlantic was achieved.

Fourth and finally, in a counterfactual exercise we attempt to assess the exorbitant privilege of the US dollar and found that US economic developments from the GFC and onwards would have been notably weaker if it had been exposed to the same movements in the convenience yield that the euro area has experienced during this period. Our estimates refer to each economy's own risk-free natural rate. The framework includes term-premium and convenience-yield wedges, but it does not model currency risk premium, sovereign default risk, or open-economy safe-asset spillovers. Extending the model in that direction would be useful, especially for jurisdictions that are not safe-asset issuers.

Future research may also shed light on the role of fiscal policy, balance-sheet policy and monetary-fiscal interaction in the determination of convenience yields through supply and demand for safe assets. We leave these issues for future work and stress that empirical estimates of r^* depend on how the econometrician accounts for policy expectations. If that information is omitted, r^* may be mismeasured.

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APPENDIX I. 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.

The appendix proceeds as follows. Tables I.1-I.3 define the variables, observables, and parameters that appear in the equilibrium and measurement equations below. Section I.1 gives the sticky-price system used for estimation. Section I.2 gives the flexible-price system used to define the output gap and the natural rate of interest. Section I.3 reports the exogenous shock processes. Section I.4 gives the measurement equations.

Unless otherwise stated, variables are log deviations from the non-stochastic steady state. Flexible-price variables are denoted by the superscript f or, equivalently, the suffix f in the DSGE.jl implementation. The notation follows the model code as closely as possible, while using standard paper notation in the equations.

Table I.1. Variables

Symbol	*Definition*
y_t, y_t^f	Output in the sticky-price economy and in the flexible-price benchmark.
c_t, c_t^f	Consumption in the sticky-price economy and in the flexible-price benchmark.
i_t, i_t^f	Investment in the sticky-price economy and in the flexible-price benchmark.
$q_t^k, q_t^{k,f}$	Real value of installed capital, or Tobin's q.
k_t, k_t^f	Effective capital services rented to firms.
$\bar{k}_t, \bar{k}_t^f$	Installed capital owned by households.
u_t, u_t^f	Capital utilization.
$r_t^k, r_t^{k,f}$	Rental rate of capital.
R_t^k	Gross return on capital in the sticky-price economy.
$R_t^{k,f}$	Gross return on capital in the flexible-price economy.
n_t, n_t^f	Entrepreneurial net worth.
mc_t	Real marginal cost.
π_t	Gross inflation, expressed in deviations from the steady-state inflation rate.
w_t, w_t^f	Real wage in the sticky-price economy and in the flexible-price benchmark.
L_t, L_t^f	Hours worked or labor input.
R_t	Nominal short-term policy rate.
r_t^f	Short-term risk-free real rate in the flexible-price economy; used to construct r*.
r_t^{star}	Five-year-ahead average short-term risk-free real rate in the flexible-price economy.
b_t^{liq}	Liquidity convenience-yield factor; a higher value raises the convenience value of liquid safe assets.
b_t^{safe}	Safety convenience-yield factor; a higher value raises the convenience value of safe assets.

Notes: All variables are expressed as log deviations from the non-stochastic steady state unless otherwise indicated. A subscript t denotes the current quarter; E_t denotes the model-consistent conditional expectation. Flexible-price variables carry either the superscript f or the suffix *"f"*.

Table I.2. Shocks

Symbol	*Definition*
g_t	Government-spending shock.
μ_t	Marginal efficiency of investment, or investment-specific technology shock.
z_t	Stationary component of neutral technology.
z_t^p	Permanent component of neutral technology.
$\lambda_{f,t}$	Price-markup shock.
$\lambda_{w,t}$	Wage-markup shock.
r_t^m	Contemporaneous monetary-policy shock in the policy rule.
$r_{t+h\|t}^m$	Anticipated monetary-policy shock announced at t and realized h quarters ahead.
$\sigma_{\omega,t}$	Entrepreneurial risk, or spread, shock.
$\mu_{e,t}$	Exogenous bankruptcy-cost shock.
γ_t	Shock to the fraction of entrepreneurs that survive into the next period.
π_t^*	Time-varying inflation target.
$\tilde{b}_t^{liq}, b_t^{p,liq}$	Transitory and persistent components of the liquidity convenience-yield process.
$\tilde{b}_t^{safe}, b_t^{p,safe}$	Transitory and persistent components of the safety convenience-yield process.

Table I.3. Observables

Symbol	*Definition*
obs_{gdp}	Quarterly real GDP growth per capita.
obs_{gdi}	Quarterly real GDI growth per capita.
obs_{hours}	Log hours per capita.
obs_{wages}	Quarterly real wage growth.
obs_{gdpdef}	GDP-deflator inflation.
$obs_{corepce}$	Core PCE inflation.
obs_R	Nominal short-term policy-rate.
obs_c	Consumption growth per capita.
obs_i	Investment growth per capita.
obs_{BBB}	Baa/BBB corporate spread over Treasury yield.
obs_{AAA}	Aaa/AAA corporate spread over Treasury yield.
$obs_{\pi LR}$	Long-run inflation expectations.
obs_{10y}	Long-term government bond yield.
obs_{tfp}	Measured TFP.
$obs_{R,h}$	OIS-implied expected policy rate h quarters ahead, h = 1, ..., H.

Table I.3. Parameters

Symbol	*Definition*
α	Capital share in intermediate-goods production.
β	Household discount factor.
δ	Capital depreciation rate.
Φ	Fixed cost in production.
S''	Second derivative of the investment-adjustment-cost function.
h	External habit-persistence parameter.
ψ	Capital-utilization cost parameter.
ν_l	Curvature of the labor term in household utility.
σ_c	Coefficient of relative risk aversion for consumption.
ζ_p	Calvo price-stickiness parameter.
ι_p	Price-indexation parameter.
ζ_w	Calvo wage-stickiness parameter.
ι_w	Wage-indexation parameter.
λ_w	Steady-state wage markup.
ρ_R	Interest-rate smoothing in the policy rule.
ψ_1, ψ_2, ψ_3	Policy-rule coefficients on inflation, the output gap, and output-gap growth.
ρ_x	Autoregressive coefficient of exogenous process x.
σ_x	Innovation standard deviation of exogenous process x.
η_{gz}	Correlation between government-spending and technology shocks.
$\eta_{\lambda f}, \eta_{\lambda w}$	Moving-average coefficients in the price- and wage-markup shock processes.

Table I.4. Steady-state parameters

Symbol	*Definition*
$\pi star$	Steady-state inflation rate.
$F(\omega)$	Steady-state probability of entrepreneur default.
$SPstar$	Steady-state spread.
b_{liq}, b_{safe}	Steady-state liquidity and safety convenience yields.
λ_{AAA}	Weight on the expected excess return component in the Aaa spread measurement equation.
$\zeta_{sp,b}$	Elasticity of the expected excess return on capital with respect to leverage.
$\gamma star$	Steady-state survival probability of entrepreneurs.
γ	Steady-state growth rate of technology.
$gstar$	Steady-state government-spending share, defined as one minus the steady-state private-spending share.
L	Mean level of hours.
$zstar$	Steady-state balanced-growth term.
$rstar$	Steady-state real natural rate.
$Rtar_s^n$	Steady-state nominal policy rate.
$rtar_s^k$	Steady-state short-term return on capital.
$ytar_s, ctar_s, itar_s$	Steady-state output, consumption, and investment.
$ktar_s, ktar_s$	Steady-state effective and installed capital.
$ntar_s, vtar_s$	Steady-state entrepreneurial net worth and entrepreneurial value.

I.1 Sticky-price equilibrium

Households

For compactness, define

$$\chi_c \equiv \frac{1}{1+he^{-\gamma}}, \qquad \bar{h} \equiv \frac{he^{-\gamma}}{1+he^{-\gamma}}, \qquad \chi_R \equiv \frac{1-he^{-\gamma}}{\sigma_c(1+he^{-\gamma})},$$

and

$$\chi_L \equiv \frac{(\sigma_c-1)\omega_L}{\sigma_c(1+he^{-\gamma})}, \qquad \chi_b \equiv \frac{\sigma_c(1+he^{-\gamma})}{1-he^{-\gamma}}.$$

The consumption Euler equation is

$$c_t = \bar{h}c_{t-1} - \chi_R(R_t - E_t\pi_{t+1}) - \bar{h}z_t + \chi_c(E_tc_{t+1} + E_tz_{t+1}) + \chi_L(L_t - E_tL_{t+1}) + b_{\text{liq},t} + b_{\text{safe},t}.$$

Higher expected real policy rates lower current consumption. Higher liquidity and safety convenience yields enter with the opposite sign from the safe real return.

Investment

Define

$$\chi_i \equiv \frac{1}{1+\beta e^{(1-\sigma_c)\gamma}}, \qquad \varphi_i \equiv \frac{\beta e^{(1-\sigma_c)\gamma}}{1+\beta e^{(1-\sigma_c)\gamma}},$$

and

$$\chi_q \equiv \frac{1}{S''e^{2\gamma}(1+\beta e^{(1-\sigma_c)\gamma})}.$$

Investment satisfies

$$i_t = \chi_i i_{t-1} + \varphi_i(E_ti_{t+1} + E_tz_{t+1}) + \chi_q q_t^k - \chi_i z_t + \mu_t.$$

Financial frictions

The return on capital is

$$\tilde{R}_{k,t} = \pi_t + \frac{r_k^\star}{1+r_k^\star-\delta} rk_t + \frac{1-\delta}{1+r_k^\star-\delta} q_t^k - q_{t-1}^k.$$

The spread equation is

$$E_t\tilde{R}_{k,t+1} - R_t = -\chi_b\left(b_{\text{liq},t} + b_{\text{safe},t}\right) + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + \sigma_{\omega,t} + \mu_{e,t}.$$

Net worth evolves according to

$$\begin{aligned} n_t = \quad & \gamma_{e,t} - \frac{\gamma^\star v^\star}{n^\star} z_t + \zeta_{nRk}\tilde{R}_{k,t} - (\zeta_{nRk} - \zeta_{nR})\pi_t \\ & - \frac{\zeta_{n\sigma_\omega}}{\zeta_{sp,\sigma_\omega}}\sigma_{\omega,t-1} - \frac{\zeta_{n\mu_e}}{\zeta_{sp,\mu_e}}\mu_{e,t-1} + \zeta_{nqk}\left(q_{t-1}^k + \bar{k}_{t-1}\right) + \zeta_{nn}n_{t-1} \\ & - \zeta_{nR}R_{t-1} + \zeta_{nR}\chi_b\left(b_{\text{liq},t-1} + b_{\text{safe},t-1}\right). \end{aligned}$$

Production and capital accumulation

Output is produced with capital and labor:

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

Effective capital is

$$k_t = \bar{k}_{t-1} - z_t + u_t.$$

Capital utilization satisfies

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

Installed capital evolves according to

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

Price and wage setting

Real marginal cost is

$$mc_t = w_t + \alpha L_t - \alpha k_t.$$

Inflation follows the New Keynesian Phillips curve

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

where

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

The rental rate of capital satisfies

$$rk_t + k_t = w_t + L_t.$$

The marginal rate of substitution wedge is

$$\mu_{\omega,t} = w_t - \nu_l L_t - \frac{1}{1 - he^{-\gamma}} c_t + \frac{he^{-\gamma}}{1 - he^{-\gamma}} c_{t-1} - \frac{he^{-\gamma}}{1 - he^{-\gamma}} z_t.$$

Define

$$\chi_w \equiv \frac{1}{1 + \beta e^{(1-\sigma_c)\gamma}}, \qquad \varphi_w \equiv \frac{\beta e^{(1-\sigma_c)\gamma}}{1 + \beta e^{(1-\sigma_c)\gamma}},$$

$$\xi_w \equiv \frac{\iota_w}{1 + \beta e^{(1-\sigma_c)\gamma}}, \qquad \chi_{\pi,w} \equiv \frac{1 + \iota_w \beta e^{(1-\sigma_c)\gamma}}{1 + \beta e^{(1-\sigma_c)\gamma}},$$

and

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

The real wage equation is

$$\begin{aligned} w_t = \quad & \chi_w w_{t-1} + \xi_w \pi_{t-1} - \kappa_w \mu_{\omega,t} - \chi_{\pi,w} \pi_t - \chi_w z_t \\ & + \varphi_w (E_t w_{t+1} + E_t z_{t+1} + E_t \pi_{t+1}) + \lambda_{w,t}. \end{aligned}$$

The resource constraint is

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

Monetary policy rule

The nominal policy rate follows

$$\begin{aligned} R_t = \quad & \rho R_{t-1} + (1 - \rho)\psi_1(\pi_t - \pi_t^\star) + \left((1 - \rho)\psi_2 + \psi_3\right)\left(y_t - y_t^f\right) \\ & - \psi_3\left(y_{t-1} - y_{t-1}^f\right) + r_{m,t}. \end{aligned}$$

I.2 Flexible-price equilibrium

The flexible-price system uses the same preferences, technologies, financial frictions, and exogenous shocks as the sticky-price system, but removes nominal price and wage rigidities. It defines the natural-rate benchmark.

Households

The flexible-price Euler equation is

$$c_t^f = \bar{h}c_{t-1}^f - \chi_R r_t^f - \bar{h}z_t + \chi_c\left(E_t c_{t+1}^f + E_t z_{t+1}\right) + \chi_L\left(L_t^f - E_t L_{t+1}^f\right) + b_{\text{liq},t} + b_{\text{safe},t}.$$

Investment

Flexible-price investment satisfies

$$i_t^f = \chi_i i_{t-1}^f + \varphi_i\left(E_t i_{t+1}^f + E_t z_{t+1}\right) + \chi_q q_t^{k,f} - \chi_i z_t + \mu_t.$$

Financial frictions

The flexible-price return on capital is

$$\tilde{R}_{k,t}^f = \frac{r_k^\star}{1 + r_k^\star - \delta} r k_t^f + \frac{1-\delta}{1 + r_k^\star - \delta} q_t^{k,f} - q_{t-1}^{k,f}.$$

The flexible-price spread equation is

$$E_t \tilde{R}_{k,t+1}^f - r_t^f = -\chi_b\left(b_{\text{liq},t} + b_{\text{safe},t}\right) + \zeta_{sp,b}\left(q_t^{k,f} + \bar{k}_t^f - n_t^f\right) + \sigma_{\omega,t} + \mu_{e,t}.$$

Flexible-price net worth evolves as

$$\begin{aligned} n_t^f = \quad & -\frac{\gamma^\star v^\star}{n^\star} z_t + \zeta_{nRk}\tilde{R}_{k,t}^f - \frac{\zeta_{n\sigma_\omega}}{\zeta_{sp,\sigma_\omega}}\sigma_{\omega,t-1} - \frac{\zeta_{n\mu_e}}{\zeta_{sp,\mu_e}}\mu_{e,t-1} \\ & + \zeta_{nqk}\left(q_{t-1}^{k,f} + \bar{k}_{t-1}^f\right) + \zeta_{nn} n_{t-1}^f - \zeta_{nR} r_{t-1}^f + \zeta_{nR}\chi_b\left(b_{\text{liq},t-1} + b_{\text{safe},t-1}\right). \end{aligned}$$

Production and capital accumulation

Flexible-price output is

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

Effective capital is

$$k_t^f = \bar{k}_{t-1}^f - z_t + u_t^f.$$

Capital utilization satisfies

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

Installed capital evolves according to

$$\bar{k}_t^f = \left(1 - \frac{i^\star}{\bar{k}^\star}\right)\bar{k}_{t-1}^f - \left(1 - \frac{i^\star}{\bar{k}^\star}\right)z_t + \frac{i^\star}{\bar{k}^\star}i_t^f + \frac{i^\star S'' e^{2\gamma}\left(1 + \beta e^{(1-\sigma_c)\gamma}\right)}{\bar{k}^\star}\mu_t.$$

Flexible price and wage conditions

The flexible-price markup condition is

$$w_t^f + \alpha L_t^f = \alpha k_t^f.$$

The flexible-price rental-rate condition is

$$rk_t^f + k_t^f = w_t^f + L_t^f.$$

The flexible-price intra-temporal condition is

$$w_t^f = \nu_l L_t^f + \frac{1}{1 - he^{-\gamma}}c_t^f + \frac{he^{-\gamma}}{1 - he^{-\gamma}}z_t - \frac{he^{-\gamma}}{1 - he^{-\gamma}}c_{t-1}^f.$$

There is no separate flexible-price wage-markup wedge state in the implementation.

The flexible-price resource constraint is

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

Finally, $r_t^{\star,}$ is defined as the five-year forward real natural rate:

$$r_t^\star = E_t r_{t+20}^f.$$

I.3 Exogenous shocks and auxiliary states

Technology shocks

Let (z_t) denote the stationary neutral-technology component. The technology term entering the equilibrium conditions is

$$z_t = z_t^p + \frac{\rho_z - 1}{1 - \alpha}\tilde{z}_{t-1} + \frac{1}{1 - \alpha}\varepsilon_t^z,$$

with

$$\tilde{z}_t = \rho_z \tilde{z}_{t-1} + \varepsilon_t^z,$$

and permanent technology follows

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

Expected technology growth is implemented as

$$E_t z_{t+1} = \frac{\rho_z - 1}{1 - \alpha} \tilde{z}_t + \rho_z^p z_t^p.$$

Government spending follows

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

Liquidity and safety shocks

Liquidity has transitory and persistent components:

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

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

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

Safety has the same structure:

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

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

$$b_{\text{safe},t} = b_{\text{safe},t}^t + b_{\text{safe},t}^p.$$

Other structural shocks

Investment-specific technology follows

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

The price markup shock follows

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

with the auxiliary state

$$\lambda_{f,1,t} = \varepsilon_t^{\lambda_f}.$$

The wage markup shock follows

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

with

$$\lambda_{w,1,t} = \varepsilon_t^{\lambda_w}.$$

Financial-friction shocks follow the entrepreneur-risk shock, and the bankruptcy shock processes

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

$$\mu_{e,t} = \rho_{\mu_e}\mu_{e,t-1} + \varepsilon_t^{\mu_e},$$

as well as entrepreneur-survival shock

$$\gamma_{e,t} = \rho_\gamma\gamma_{e,t-1} + \varepsilon_t^{\gamma}.$$

The inflation target follows

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

Monetary-policy shocks

The contemporaneous monetary-policy shock evolves as

$$r_{m,t} = \rho_{r_m} r_{m,t-1} + \varepsilon_{r_{m,t}} + \varepsilon_{r_{m,t+h|t}}.$$

$\varepsilon_{r_{m,t+h|t}}$ is the anticipated policy shock announced in *t* that becomes effective in period (*t*+*h*).

I.4 Measurement equations

The measurement system maps model states into observables as

$$y_t^{obs} = Zs_t + D + u_t.$$

Real GDP growth is

$$\Delta y_t^{obs} = 100\left(e^{z^\star} - 1\right) + y_t - y_{t-1} + z_t.$$

Real GDI growth is

$$\Delta gdi_t^{obs} = 100\left(e^{z^\star} - 1\right) + \delta_{gdi} + \gamma_{gdi}(y_t - y_{t-1} + z_t).$$

Hours are measured as

$$Hours_t^{obs} = L^{mean} + L_t.$$

Real wage growth is

$$\Delta w_t^{obs} = 100\left(e^{z^\star} - 1\right) + w_t - w_{t-1} + z_t.$$

GDP-deflator inflation is

$$\pi_t^{GDPdef,obs} = 100(\pi^\star - 1) + \delta_{gdpdef} + \Gamma_{gdpdef}\pi_t$$

Core PCE inflation is

$$\pi_t^{core,obs} = 100(\pi^\star - 1) + \pi_t.$$

The nominal policy-rate observable is

$$R_t^{obs} = \bar{R} + R_t,$$

with

$$\bar{R} \equiv R_n^\star.$$

Consumption growth is

$$\Delta c_t^{obs} = 100\left(e^{z^\star} - 1\right) + c_t - c_{t-1} + z_t.$$

Investment growth is

$$\Delta i_t^{obs} = 100\left(e^{z^\star} - 1\right) + i_t - i_{t-1} + z_t.$$

Let

$$\mathcal{A}_{80}x_t \equiv \frac{1}{80}\sum_{j=0}^{79} E_t\, x_{t+j},$$

and

$$\mathcal{A}_{40}x_t \equiv \frac{1}{40}\sum_{j=0}^{39} E_t\, x_{t+j}.$$

The BBB or Baa spread observable is

$$BBB_t^{obs} = \overline{b_{liq}} + \mathcal{A}_{80}\left(E_t\tilde{R}_{k,t+1} - R_t\right).$$

The Aaa spread observable is

$$\begin{aligned} AAA_t^{obs} = \quad & \overline{b_{liq}} + \overline{b_{safe}} \\ & + \mathcal{A}_{80}\left[-(1-\lambda_{AAA})\chi_b b_{\mathrm{liq},t} + \lambda_{AAA}\left(E_t\tilde{R}_{k,t+1} - R_t\right)\right]. \end{aligned}$$

with the steady states defined as:

$$\overline{b_{liq}} \equiv 100\log\left(spr \cdot lnb_{\text{safe}} \cdot lnb_{\text{liq}}\right),$$

$$\overline{b_{liq}} + \overline{b_{safe}} \equiv 100\log\left(lnb_{\text{liq}}\right) + 100\lambda_{AAA}\log(spr \cdot lnb_{\text{safe}}).$$

Long-run inflation expectations are

$$\pi_t^{10y,obs} = 100(\pi^\star - 1) + \mathcal{A}_{40}\pi_t.$$

The long-term government bond yield is

$$R_t^{10y,obs} = \bar{R} + \mathcal{A}_{40}R_t + lr_t + \varepsilon_t^{10y}.$$

Measured TFP is

$$TFP_t^{obs} = [(1-\alpha)I_{\text{endo}\alpha} + 1(1 - I_{\text{endo}\alpha})]z_t + tfp_t + \frac{\alpha}{(1-\alpha)(1-I_{\text{endo}\alpha}) + I_{\text{endo}\alpha}}(u_t - u_{t-1}).$$

For anticipated policy-rate observables at horizons (h=1,,H), the measurement equation is

$$R_{t,h}^{obs} = \bar{R} + E_t R_{t+h}.$$

These expected policy-rate observables do not enter as separate measurement-error equations in the baseline implementation. Their variation is disciplined by the anticipated monetary-policy shock states.

APPENDIX II. Data

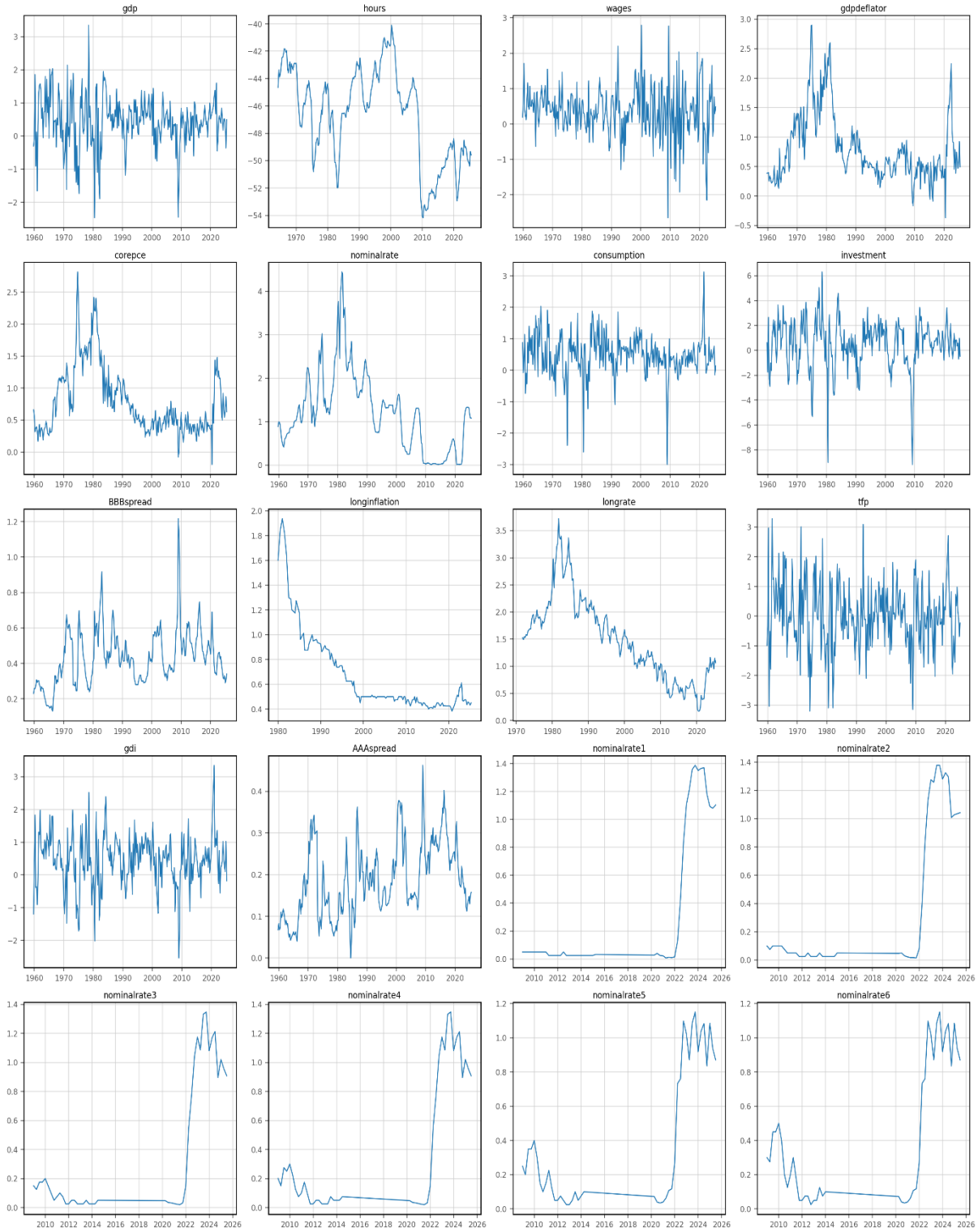
II.1. Observable variables: United States

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 annual to quarter. Each series is defined and mapped to the model according to Del Negro et al. (2017), Appendix B.1.

Table II.1: Sources and definitions of US observable variables.

Observable	Source series	Transformation/Unit	Formula
Real GDP growth (`obs_gdp`)	FRED: `GDP` (nominal), FRED: `GDPDEF` (GDP deflator), FRED: `CE16OV` (population)	Construct real GDP per capita as GDP/GDPDEF divided by population; take the one-quarter log-difference and express as a percentage	$\text{obs_gdp}_t = 100 \times \left[\log\left(\frac{\text{GDP}_t}{\text{GDPDEF}_t \cdot \text{Pop}_t}\right) - \log\left(\frac{\text{GDP}_{t-1}}{\text{GDPDEF}_{t-1} \cdot \text{Pop}_{t-1}}\right)\right]$
Log hours per capita (`obs_hours`)	FRED: `AWHNONAG` (average weekly hours, private sector), FRED: `CE16OV` (population)	Total weekly hours are given by $\text{AWHNONAG}_t \times \text{CE16OV}_t$; divide by population to obtain hours per person; multiply by 3 (weeks per quarter) and take $100 \times \log(\cdot/100)$	$\text{obs_hours}_t = 100 \times \log\left(3\,\frac{\text{AWHNONAG}_t \times \text{CE16OV}_t}{100\,\text{Pop}_t}\right)$
Real wage growth (`obs_wages`)	FRED: `COMPNFB` (nominal compensation per hour), FRED: `GDPDEF`	Convert nominal compensation per hour to real terms dividing by the GDP deflator; compute the one-quarter percent change	$\text{obs_wages}_t = 100 \times \left(\frac{\text{COMPNFB}_t/\text{GDPDEF}_t}{\text{COMPNFB}_{t-1}/\text{GDPDEF}_{t-1}} - 1\right)$
GDP deflator inflation (`obs_gdpdeflator`)	FRED: `GDPDEF` (GDP deflator index)	One-quarter percent change of the GDP deflator	$\text{obs_gdpdeflator}_t = 100 \times \left(\frac{\text{GDPDEF}_t}{\text{GDPDEF}_{t-1}} - 1\right)$
Core PCE inflation (`obs_corepce`)	FRED: `PCEPILFE` (core PCE price index)	One-quarter percent change of the core PCE index	$\text{obs_corepce}_t = 100 \times \left(\frac{\text{PCEPILFE}_t}{\text{PCEPILFE}_{t-1}} - 1\right)$
Nominal short-term rate (`obs_nominalrate`)	FRED: `DFF` (effective federal funds rate, annual rate)	Annual rate converted to quarterly rate via division by 4	$\text{obs_nominalrate}_t = \frac{\text{DFF}_t}{4}$
Real consumption growth (`obs_consumption`)	FRED: `PCE` (nominal consumption), FRED: `GDPDEF`, FRED: `CE16OV`	Compute real consumption per capita by deflating nominal consumption with the GDP deflator and dividing by population; then take the one-quarter percent change	$\text{obs_consumption}_t = 100 \times \left(\frac{\text{PCE}_t/(\text{GDPDEF}_t \cdot \text{Pop}_t)}{\text{PCE}_{t-1}/(\text{GDPDEF}_{t-1} \cdot \text{Pop}_{t-1})} - 1\right)$
Real investment growth (`obs_investment`)	FRED: `FPI` (nominal private fixed investment), FRED: `GDPDEF`, FRED: `CE16OV`	Compute real private fixed investment per capita by deflating by the GDP deflator and dividing by population; take the one-quarter percent change	$\text{obs_investment}_t = 100 \times \left(\frac{\text{FPI}_t/(\text{GDPDEF}_t \cdot \text{Pop}_t)}{\text{FPI}_{t-1}/(\text{GDPDEF}_{t-1} \cdot \text{Pop}_{t-1})} - 1\right)$
BBB spread (`obs_BBBspread`)	FRED: `BAA` (Moody's Baa corporate bond yield), FRED: `GS20` (20-year Treasury yield), FRED: `GS10`, `GS30` (10- and 30-year Treasury yields)	Construct the 20-year Treasury yield by splicing the GS20 series with the average of GS10 and GS30 between 1987Q1 and 1993Q3; compute the difference between the Baa yield and the 20-year yield and divide by 4 to express the spread at a quarterly rate	$\text{obs_BBBspread}_t = \frac{\text{BAA}_t - \text{Treasury20}_t}{4}$
Long-term inflation expectations (`obs_longinflation`)	DLX: `ASACX10` (Survey of Professional Forecasters 10-year CPI inflation expectations)	Subtract 0.5 percentage points from the annual expectation and divide by 4 to express at quarterly frequency	$\text{obs_longinflation}_t = \frac{\text{ASACX10}_t - 0.5}{4}$
Long-term interest rate (`obs_longrate`)	DLX: `FYCCZA` (10-year zero-coupon Treasury yield, annual rate)	Annual yield converted to quarterly rate by dividing by 4	$\text{obs_longrate}_t = \frac{\text{FYCCZA}_t}{4}$
Total factor productivity (`obs_tfp`)	DLX: `TFPKQ` (Fernald unadjusted TFP), DLX: `TFPJQ` (Fernald capital share series)	Demean TFP over the presample and estimation periods, then divide by $4(1-\alpha)$ where $\alpha = \text{TFPJQ}_t$ is the estimated capital share; this yields the quarterly percentage deviation of TFP	$\text{obs_tfp}_t = \frac{\text{TFPKQ}_t - \overline{\text{TFPKQ}}}{4\,(1 - \text{TFPJQ}_t)}$
Real GDI growth (`obs_gdi`)	FRED: `GDI` (nominal gross domestic income), FRED: `GDPDEF`, FRED: `CE16OV`	Construct real GDI per capita by deflating nominal GDI with the GDP deflator and dividing by population; take the one-quarter percent change	$\text{obs_gdi}_t = 100 \times \left(\frac{\text{GDI}_t/(\text{GDPDEF}_t \cdot \text{Pop}_t)}{\text{GDI}_{t-1}/(\text{GDPDEF}_{t-1} \cdot \text{Pop}_{t-1})} - 1\right)$
AAA spread (`obs_AAAspread`)	FRED: `AAA` (Moody's AAA corporate bond yield), FRED: `GS20`, `LTGOVTBD` (20-year or long-term Treasury yield)	Splice the 20-year Treasury yield as for the Baa spread; compute the difference between the AAA yield and the 20-year Treasury yield and divide by 4	$\text{obs_AAAspread}_t = \frac{\text{AAA}_t - \text{Treasury20}_t}{4}$
Anticipated policy shocks (obs_nominalrate_i for i=1, . . . , 6)	OIS term structure derived from eurodollar futures (`ant1_OIS`, . . . , `ant6_OIS`)	Each series records the market expectation of the federal funds rate i quarters ahead. They are already annualised; dividing by 4 converts to quarterly rates	$\text{obs_nominalrate}_i(t) = \frac{\text{ant}_i(t)}{4} \quad (i = 1, \ldots, 6)$

Figure II.1: Evolution of observable variables in the United States.



II.2. Observable variables: Euro area

As in the U.S. case, the dataset includes 20 quarterly observables that capture real activity, prices, interest rates, expected short rates at horizons of 1–6 quarters, and credit spreads. Compared with the earlier euro-area dataset, we made two important measurement changes. First, nominal investment is now seasonally adjusted before it is deflated and scaled per capita, using sa(D025IFN@EUDATA).[13]Second, the anticipated policy-rate observables are built from monthly OIS data: which we interpolated by the 3-month, 6-month, 1-year, and 2-year OIS rates to maturities of 3, 6, 9, 12, 15, and 18 months, and then took quarterly averages. In addition, to limit Covid-related measurement distortions, we exclude the real observables obs_gdp, obs_hours, obs_wages, obs_consumption, obs_investment, obs_gdi, and obs_tfp from the estimation likelihood in 2020Q1–2020Q3, this is equivalent to setting the measurement error to infinity during these quarters.

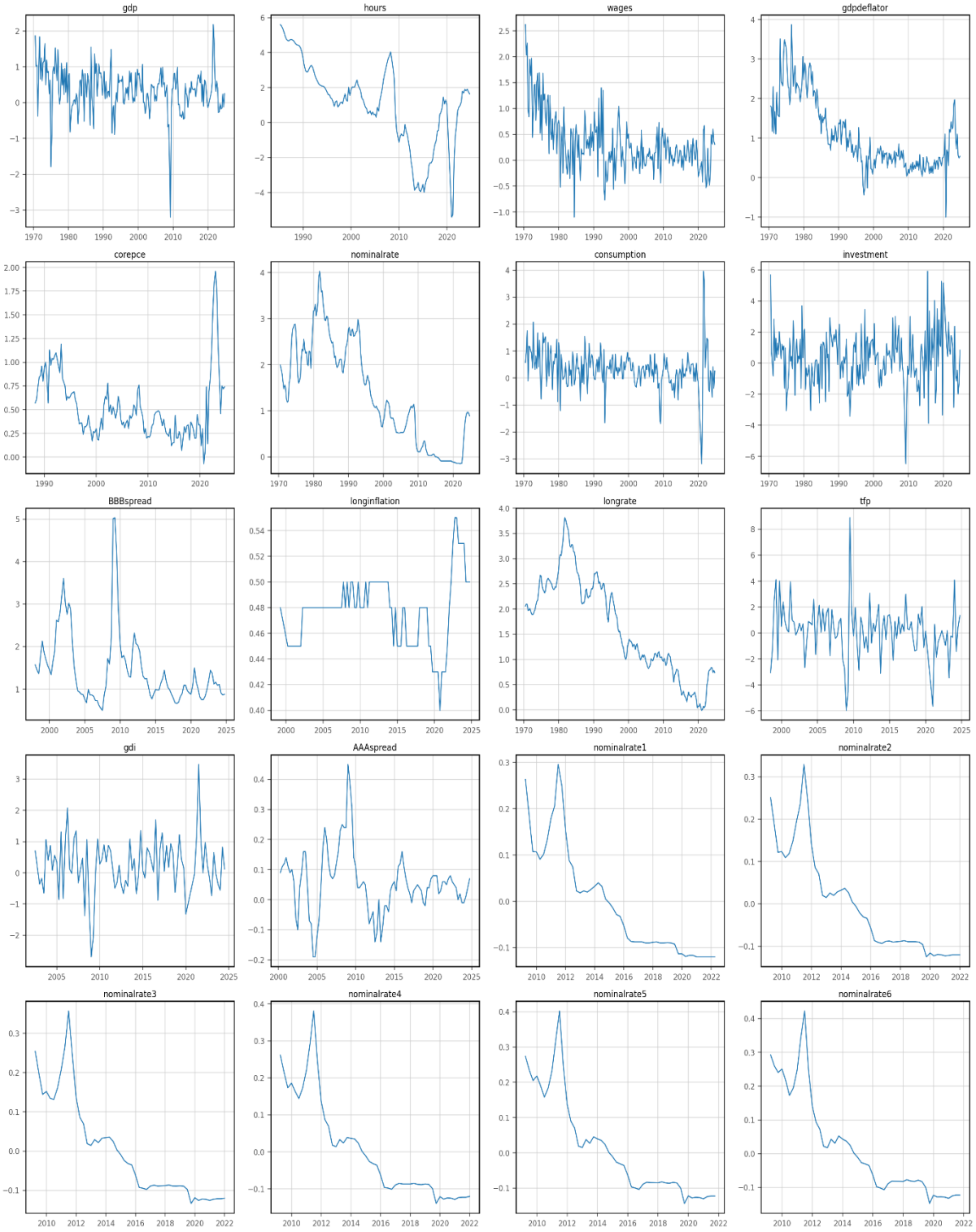
The table below summarizes how the euro-area observables are constructed. Source mnemonics refer to the Eurostat/ECB codes used in the construction workbook. Per-capita variables use the seasonally adjusted population aged 15 and over, sa(N025PP2T@EUDATA).

[13] The reason is that the seasonally and working day adjusted data from Eurostat had large irregular components caused by large spikes in intellectual property rights investment. In euro area national accounts, these spikes are offset by approximately same spikes in imports of goods and services. Hence, it is washed away in GDP but remained in the investment series. As our estimation does not use foreign trade related national accounts this would show up as large spikes in the GDP measurement errors. To avoid this, we used our own seasonal adjustment (X12) which has associated these spikes as seasonal, and thus did not distort the investment series.

Table II.2: Sources and definitions of Euro area observable variables

Observable	Source series	Transformation/Unit	Formula
Real GDP growth (obs_gdp)	EUDATA: J025GDPT, EUDATA: J025GDPP, EUDATA: sa(N025PP2T)	Real GDP per capita is nominal GDP divided by the GDP deflator and seasonally adjusted population; take the one-quarter percent change	$\text{obs_gdp}_t = 100\left(\frac{\text{J025GDPT}_t/(\text{J025GDPP}_t\,\text{Pop}_t^{SA})}{\text{J025GDPT}_{t-1}/(\text{J025GDPP}_{t-1}\,\text{Pop}_{t-1}^{SA})} - 1\right)$
Log hours per capita (obs_hours)	EUDATA: sa(Q023HEX), EUDATA: Q023LEN × 1000, EUDATA: sa(N025PP2T)	Multiply seasonally adjusted hours per employee by employment, divide by seasonally adjusted population, multiply by 3, and take $100\log(\cdot/100)$	$\text{obs_hours}_t = 100\log\left(3\,\frac{\text{Q023HEX}_t^{SA}\text{Emp}_t}{100\,\text{Pop}_t^{SA}}\right)$
Real wage growth (obs_wages)	EUDATA: L025CESI, EUDATA: J025GDPP	Deflate compensation per employee by the GDP deflator and compute the one-quarter percent change	$\text{obs_wages}_t = 100\left(\frac{\text{L025CESI}_t/\text{J025GDPP}_t}{\text{L025CESI}_{t-1}/\text{J025GDPP}_{t-1}} - 1\right)$
GDP deflator inflation (obs_gdpdeflator)	EUDATA: J025GDPP	One-quarter percent change	$\text{obs_gdpdeflator}_t = 100\left(\frac{\text{J025GDPP}_t}{\text{J025GDPP}_{t-1}} - 1\right)$
Core HICP inflation (obs_corepce)	EUDATA: Q023STN	One-quarter percent change	$\text{obs_corepce}_t = 100\left(\frac{\text{Q023STN}_t}{\text{Q023STN}_{t-1}} - 1\right)$
Nominal short-term rate (obs_nominalrate)	EUDATA: I023M1	Annualised 3-month money-market rate divided by 4	$\text{obs_nominalrate}_t = \frac{\text{I023M1}_t}{4}$
Real consumption growth (obs_consumption)	EUDATA: J025PCN, EUDATA: Q023PCD, EUDATA: sa(N025PP2T)	Deflate nominal consumption, divide by seasonally adjusted population, and compute the one-quarter percent change	$\text{obs_consumption}_t = 100\left(\frac{\text{J025PCN}_t/(\text{Q023PCD}_t\,\text{Pop}_t^{SA})}{\text{J025PCN}_{t-1}/(\text{Q023PCD}_{t-1}\,\text{Pop}_{t-1}^{SA})} - 1\right)$
Real investment growth (obs_investment)	EUDATA: sa(D025IFN), EUDATA: Q023ITD, EUDATA: sa(N025PP2T)	Seasonally adjusted nominal investment is deflated by the investment deflator and divided by seasonally adjusted population; take the one-quarter percent change	$\text{obs_investment}_t = 100\left(\frac{\text{I}_t^{SA}/(\text{Q023ITD}_t\,\text{Pop}_t^{SA})}{\text{I}_{t-1}^{SA}/(\text{Q023ITD}_{t-1}\,\text{Pop}_{t-1}^{SA})} - 1\right)$, $\text{I}_t^{SA} \equiv \text{sa(D025IFN)}_t$
BBB spread (obs_BBBspread)	ICE BofA euro-area BBB OAS, quarterly series	Use the quarterly OAS directly and divide by 4	$\text{obs_BBBspread}_t = \frac{\text{OAS}_t}{4}$
Long-term inflation expectations (obs_longinflation)	EUDATA: V025IMPL	Subtract 0.5 percentage points and divide by 4	$\text{obs_longinflation}_t = \frac{\text{V025IMPL}_t - 0.5}{4}$
Long-term rate (obs_longrate)	EUDATA: I023BY10	Annualised 10-year government bond yield divided by 4	$\text{obs_longrate}_t = \frac{\text{I023BY10}_t}{4}$
Total factor productivity (obs_tfp)	Banco de España Europrod dataset	Demean TFP over the estimation sample and divide by $4(1-\alpha_t)$	$\text{obs_tfp}_t = \frac{\text{TFP}_t - \overline{\text{TFP}}}{4(1-\alpha_t)}$
Real GDI growth (obs_gdi)	EUDATA: sa(D025NDIN), EUDATA: sa(D025K1N), EUDATA: J025GDPP, sa(N025PP2T)	Nominal GDI is seasonally adjusted disposable income plus seasonally adjusted consumption of fixed capital, deflated by the GDP deflator and divided by seasonally adjusted population; take the one-quarter percent change	$\text{obs_gdi}_t = 100\left(\frac{\text{NDI}_t^{SA} + \text{CFC}_t^{SA}}{\text{J025GDPP}_t\,\text{Pop}_t^{SA}} \Big/ \frac{\text{NDI}_{t-1}^{SA} + \text{CFC}_{t-1}^{SA}}{\text{J025GDPP}_{t-1}\,\text{Pop}_{t-1}^{SA}} - 1\right)$
AAA spread (obs_AAAspread)	AAA_SPREAD from the AAA_bond_data sheet	Use the preconstructed quarterly AAA spread directly	$\text{obs_AAAspread}_t = \text{AAAspread}_t$
Anticipated policy shocks (obs_nominalrate_i, $i = 1,\ldots,6$)	Monthly OIS: OIS3m, OIS6m, OIS1y, OIS2y	Interpolate monthly OIS to 3, 6, 9, 12, 15, and 18 months; average within quarter and divide by 4	$\text{obs_nominalrate}_i(t) = \frac{\overline{\text{OIS}}_{i,t}}{4}$, $i = 1,\ldots,6$

Figure II.2: Evolution of observable variables in the Euro area.



APPENDIX III. Estimation Results

The model is estimated using Bayesian methods on a sample of 1960Q1-2023Q4 with most priors adopted from Del Negro (2017). Before estimating the model for the euro area, we adjusted some priors to take into account a priori differences between the US and euro area economies. We provide the prior and posterior distributions for the US and the euro area in Tables III.1 and III.2, respectively.

Table III.1.a: Prior and posterior for the United States.

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
			Steady State			
100γ	N	0.400	0.100	0.441	0.407	0.476
α	N	0.300	0.050	0.171	0.164	0.178
$100(\beta^{-1}-1)$	G	0.250	0.100	0.309	0.251	0.364
σ_c	N	1.500	0.370	0.842	0.731	0.944
h	B	0.700	0.100	0.668	0.629	0.702
ν_l	N	2.000	0.750	3.136	2.300	3.943
δ	-	0.025	0.000	0.025	0.025	0.025
Φ_p	-	1.000	0.000	1.000	1.000	1.000
S''	N	4.000	1.500	2.862	1.985	3.604
ψ	B	0.500	0.150	0.645	0.533	0.749
δ_{gdpdef}	N	0.000	2.000	-0.010	-0.010	-0.010
$\bar{L}$	N	-45.000	5.000	-46.342	-48.065	-44.528
λ_w	-	1.500	0.000	1.500	1.500	1.500
π_*	-	0.500	0.000	0.500	0.500	0.500
g_*	-	0.180	0.000	0.180	0.180	0.180
			Nominal Rigidities			
ζ_p	B	0.500	0.100	0.962	0.954	0.971
ζ_w	B	0.500	0.100	0.958	0.953	0.963
ι_p	B	0.500	0.150	0.409	0.336	0.480
ι_w	B	0.500	0.150	0.640	0.582	0.697
ϵ_p	-	10.000	0.000	10.000	10.000	10.000
ϵ_w	-	10.000	0.000	10.000	10.000	10.000
			Policy			
ψ_1	N	1.500	0.250	1.726	1.496	2.007
ψ_2	N	0.120	0.050	0.216	0.201	0.230
ψ_3	N	0.120	0.050	0.271	0.250	0.293
ρ_R	B	0.750	0.100	0.894	0.878	0.907
ρ_{r^m}	B	0.500	0.200	0.126	0.087	0.168
			Financial Frictions			
$F(\bar{\omega})$	-	0.030	0.000	0.030	0.030	0.030
SP_*	G	1.000	0.100	0.895	0.719	1.072
$\zeta_{sp,b}$	B	0.050	0.005	0.043	0.041	0.044
γ_*	-	0.990	0.000	0.990	0.990	0.990
$ln(b_{safe})$	-	0.065	0.000	0.065	0.065	0.065
$ln(b_{liq})$	-	0.117	0.000	0.117	0.117	0.118
λ_{AAA}	-	0.000	0.000	-0.000	-0.000	0.000

Table III.1:b Prior and posterior for the United States.(continued)

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
ρ_g	B	0.500	0.200	0.987	0.980	0.995
ρ_μ	B	0.500	0.200	0.790	0.705	0.889
ρ_{z^p}	-	0.990	0.000	0.990	0.990	0.990
ρ_z	B	0.500	0.200	0.950	0.946	0.954
$\rho^p_{b,liq}$	B	0.990	0.030	0.985	0.983	0.987
$\rho^{til}_{b,liq}$	B	0.500	0.200	0.460	0.357	0.572
$\rho^p_{b,safe}$	B	0.990	0.030	0.983	0.981	0.984
$\rho^{til}_{b,safe}$	B	0.500	0.200	0.699	0.650	0.749
ρ_{σ_ω}	B	0.750	0.150	0.986	0.979	0.992
ρ_{π_*}	-	0.990	0.000	0.990	0.990	0.990
ρ_{λ_f}	B	0.500	0.200	0.876	0.861	0.892
ρ_{λ_w}	B	0.500	0.200	0.317	0.280	0.354
η_{λ_f}	B	0.500	0.200	0.809	0.809	0.809
η_{λ_w}	B	0.500	0.200	0.396	0.396	0.396
η_{gz}	B	0.500	0.200	0.812	0.812	0.812
σ_g	IG	0.100	2.000	2.303	2.150	2.461
σ_μ	IG	0.100	2.000	0.315	0.275	0.346
σ_{z^p}	IG	0.100	2.000	0.088	0.076	0.101
σ_z	IG	0.100	2.000	0.541	0.522	0.554
$\sigma_{b^p,liq}$	IG	0.013	100.000	0.013	0.013	0.013
$\sigma_{\tilde{b},liq}$	IG	0.100	2.000	0.101	0.070	0.130
$\sigma_{b^p,safe}$	IG	0.013	100.000	0.012	0.012	0.012
$\sigma_{\tilde{b},safe}$	IG	0.100	2.000	0.125	0.107	0.145
σ_{σ_ω}	IG	0.050	4.000	0.076	0.060	0.090
σ_{π_*}	IG	0.030	6.000	0.068	0.061	0.077
σ_{λ_f}	IG	0.100	2.000	0.078	0.076	0.080
σ_{λ_w}	IG	0.100	2.000	0.426	0.410	0.444
σ_{r^m}	IG	0.100	2.000	0.219	0.211	0.226
$\sigma_{1,r}$	IG	0.200	4.000	0.097	0.097	0.097
$\sigma_{2,r}$	IG	0.200	4.000	0.123	0.123	0.123
$\sigma_{3,r}$	IG	0.200	4.000	0.098	0.098	0.098
$\sigma_{4,r}$	IG	0.200	4.000	0.107	0.107	0.107
$\sigma_{5,r}$	IG	0.200	4.000	0.112	0.112	0.112
$\sigma_{6,r}$	IG	0.200	4.000	0.074	0.074	0.074
δ_{gdpdef}	N	0.000	2.000	-0.010	-0.010	-0.010
γ_{gdpdef}	N	1.000	2.000	1.056	1.056	1.056
ρ_{gdp}	N	0.000	0.200	0.196	0.052	0.354
ρ_{gdi}	N	0.000	0.200	0.921	0.883	0.964
ϱ_{gdp}	N	0.000	0.400	-0.270	-0.844	0.249
ρ_{gdpdef}	B	0.500	0.200	0.449	0.388	0.504

Table III.1.c: Prior and posterior for the United States (continued)

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
ρ_{pce}	B	0.500	0.200	0.164	0.030	0.307
ρ_{AAA}	B	0.500	0.100	0.638	0.536	0.737
ρ_{BBB}	B	0.500	0.100	0.889	0.842	0.938
ρ_{10y}	B	0.500	0.200	0.937	0.910	0.953
ρ_{tfp}	B	0.500	0.200	0.167	0.103	0.226
σ_{gdp}	IG	0.100	2.000	0.256	0.232	0.282
σ_{gdi}	IG	0.100	2.000	0.307	0.307	0.307
σ_{gdpdef}	IG	0.100	2.000	0.175	0.172	0.178
σ_{pce}	IG	0.100	2.000	0.115	0.111	0.120
σ_{AAA}	IG	0.100	2.000	0.022	0.022	0.022
σ_{BBB}	IG	0.100	2.000	0.051	0.051	0.051
σ_{10y}	IG	0.750	2.000	0.137	0.134	0.140
σ_{tfp}	IG	0.100	2.000	0.701	0.679	0.723

Notes: Parameters without prior distribution are calibrated. N stands for Normal, G for Gamma, B for Beta and IG for inverse-Gamma distribution.
Source: IMF staff calculations.

Table III.2.a: Prior and posterior in the Euro area.

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
			Steady State			
100γ	-	0.340	0.000	0.340	0.340	0.340
α	N	0.300	0.050	0.058	0.051	0.065
$100(\beta^{-1}-1)$	G	0.250	0.100	0.179	0.092	0.267
σ_c	N	1.500	0.370	0.831	0.764	0.922
h	B	0.700	0.050	0.562	0.540	0.579
ν_l	N	2.000	0.500	2.517	2.318	2.679
δ	-	0.025	0.000	0.025	0.025	0.025
Φ_p	-	1.000	0.000	1.000	1.000	1.000
S''	N	4.000	0.500	4.680	4.525	4.835
ψ	B	0.800	0.100	0.864	0.797	0.943
δ_{gdpdef}	N	0.000	2.000	-0.008	-0.008	-0.008
$\bar{L}$	N	0.000	2.000	0.231	-2.494	2.824
λ_w	-	1.500	0.000	1.500	1.500	1.500
π_*	-	0.475	0.000	0.475	0.475	0.475
g_*	-	0.215	0.000	0.215	0.215	0.215
			Nominal Rigidities			
ζ_p	B	0.750	0.050	0.985	0.984	0.986
ζ_w	B	0.750	0.050	0.856	0.846	0.866
ι_p	B	0.500	0.150	0.265	0.162	0.369
ι_w	B	0.600	0.150	0.345	0.179	0.481
ϵ_p	-	10.000	0.000	10.000	10.000	10.000
ϵ_w	-	10.000	0.000	10.000	10.000	10.000
			Policy			
ψ_1	N	1.700	0.100	1.646	1.490	1.773
ψ_2	N	0.125	0.050	0.285	0.267	0.304
ψ_3	N	0.063	0.050	0.179	0.142	0.219
ρ_R	B	0.750	0.050	0.829	0.795	0.861
ρ_{r^m}	B	0.100	0.100	0.470	0.401	0.539
			Financial Frictions			
$F(\bar{\omega})$	-	0.030	0.000	0.030	0.030	0.030
SP_*	G	1.000	0.100	1.545	1.442	1.654
$\zeta_{sp,b}$	B	0.050	0.005	0.028	0.025	0.031
γ_*	-	0.990	0.000	0.990	0.990	0.990
$ln(b_{safe})$	-	0.065	0.000	0.065	0.065	0.065
$ln(b_{liq})$	-	0.118	0.000	0.118	0.118	0.118
λ_{AAA}	-	0.000	0.000	-0.000	-0.000	0.000

Table III.2.b: Prior and posterior in the Euro area. (continued)

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
ρ_g	B	0.500	0.200	0.963	0.927	0.998
ρ_μ	B	0.500	0.200	0.999	0.999	0.999
ρ_{z^p}	B	0.500	0.200	0.523	0.305	0.732
ρ_z	B	0.500	0.200	0.666	0.444	0.900
$\rho^p_{b,liq}$	B	0.990	0.030	0.985	0.985	0.986
$\rho_{\tilde{b},liq}$	B	0.500	0.200	0.409	0.158	0.656
$\rho^p_{b,safe}$	B	0.990	0.030	0.979	0.977	0.981
$\rho_{\tilde{b},safe}$	B	0.500	0.200	0.853	0.824	0.881
ρ_{σ_ω}	B	0.750	0.150	1.000	1.000	1.000
ρ_{π_*}	-	0.990	0.000	0.990	0.990	0.990
ρ_{λ_f}	B	0.500	0.200	0.799	0.775	0.824
ρ_{λ_w}	B	0.500	0.200	0.613	0.409	0.762
η_{λ_f}	B	0.500	0.200	0.701	0.701	0.701
η_{λ_w}	B	0.500	0.200	0.865	0.865	0.865
η_{gz}	B	0.500	0.200	0.554	0.554	0.554
σ_g	IG	0.100	2.000	1.806	1.646	1.969
σ_μ	IG	0.100	2.000	2.897	2.648	3.149
σ_{z^p}	IG	0.100	2.000	0.327	0.236	0.431
σ_z	IG	0.100	2.000	0.210	0.069	0.323
$\sigma_{b^p,liq}$	IG	0.030	6.000	0.025	0.024	0.027
$\sigma_{\tilde{b},liq}$	IG	0.100	2.000	0.073	0.065	0.079
$\sigma_{b^p,safe}$	IG	0.030	6.000	0.025	0.023	0.027
$\sigma_{\tilde{b},safe}$	IG	0.100	2.000	0.090	0.078	0.103
σ_{σ_ω}	IG	0.050	4.000	0.208	0.200	0.216
σ_{π_*}	IG	0.030	6.000	0.046	0.041	0.050
σ_{λ_f}	IG	0.100	2.000	0.055	0.053	0.057
σ_{λ_w}	IG	0.100	2.000	0.224	0.217	0.236
σ_{r^m}	IG	0.100	2.000	0.149	0.139	0.158
$\sigma_{1,r}$	IG	0.200	4.000	0.069	0.069	0.069
$\sigma_{2,r}$	IG	0.200	4.000	0.056	0.056	0.056
$\sigma_{3,r}$	IG	0.200	4.000	0.055	0.055	0.055
$\sigma_{4,r}$	IG	0.200	4.000	0.054	0.054	0.054
$\sigma_{5,r}$	IG	0.200	4.000	0.054	0.054	0.054
$\sigma_{6,r}$	IG	0.200	4.000	0.055	0.055	0.055
δ_{gdpdef}	N	0.000	2.000	-0.008	-0.008	-0.008
γ_{gdpdef}	N	1.000	2.000	2.668	2.668	2.668
ρ_{gdp}	N	0.000	0.200	0.161	-0.039	0.381
ρ_{gdi}	N	0.000	0.200	0.522	0.417	0.624
ϱ_{gdp}	N	0.000	0.400	-0.282	-0.710	0.121
ρ_{gdpdef}	B	0.500	0.200	0.140	0.096	0.192

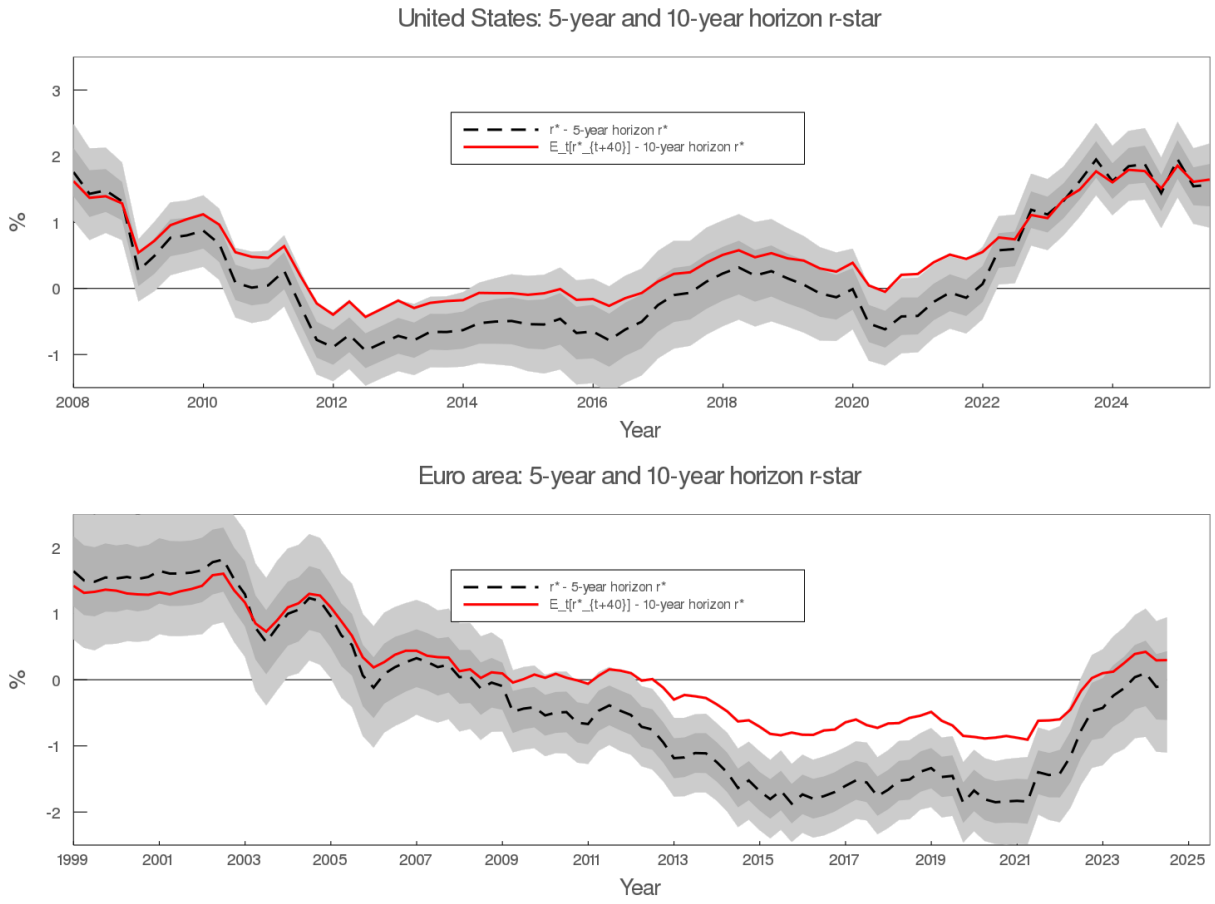
Table III.2.c: Prior and posterior in the Euro area. (continued)

		Prior		Posterior		
Parameter	Type	Mean	SD	Mean	90.0% Lower Band	90.0% Upper Band
ρ_{pce}	B	0.500	0.200	0.795	0.750	0.830
ρ_{AAA}	-	0.000	0.000	0.000	-0.000	0.000
ρ_{BBB}	-	0.000	0.000	-0.000	-0.000	0.000
ρ_{10y}	B	0.500	0.200	0.968	0.964	0.972
ρ_{tfp}	B	0.500	0.200	0.060	0.022	0.092
σ_{gdp}	IG	0.100	2.000	0.159	0.159	0.159
σ_{gdi}	IG	0.100	2.000	0.504	0.504	0.504
σ_{gdpdef}	IG	0.100	2.000	0.213	0.213	0.213
σ_{pce}	IG	0.100	2.000	0.136	0.136	0.136
σ_{AAA}	IG	0.100	2.000	0.036	0.036	0.036
σ_{BBB}	-	0.000	0.000	0.000	0.000	0.000
σ_{10y}	IG	0.750	2.000	0.110	0.109	0.111
σ_{tfp}	IG	0.100	2.000	2.006	1.740	2.299

Notes: Parameters without prior distribution are calibrated. N stands for Normal, G for Gamma, B for Beta and IG for inverse-Gamma distribution.
Source: IMF staff calculations.

Finally, to assess whether our conclusions depend on the horizon at which the natural rate is measured, Figure III.1 compares estimates of the forward natural real interest rates, expected in 5 and 10 years respectively. Del Negro et al. (2017) highlight that different, horizon-specific measures of r^* can capture distinct aspects of underlying equilibrium forces and note that the 5–10 year horizon is most comparable to the HLW measure. We find that the two measures move very similarly over time, with only modest differences around the pre- and post-GFC period, while the post-pandemic increase in r^* is nearly identical across horizons, suggesting that our main conclusions are robust to the choice of horizon.

Figure III.1: Alternative US and Euro Area Natural Rate of Interest (r^*) Measures: 5-year horizon and 10-year horizon forward natural real interest rates

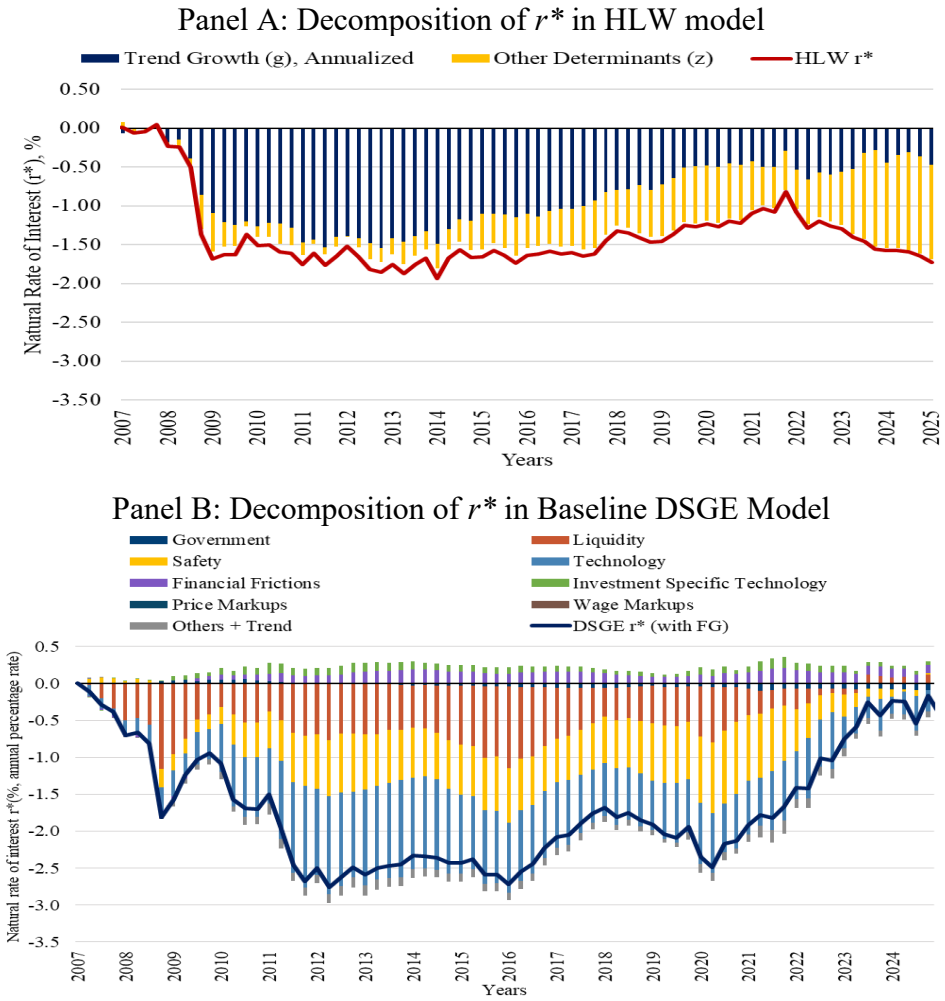


Notes: The figure compares the US and euro area r^* estimates, that is the forward natural real interest rate $E_t[r^f_{t+h}]$ for h=20 (5-year horizon) and h=40 (10 year horizon) between 1999 and 2025.
Sources: IMF staff calculations.

APPENDIX IV. Drivers of r^* During the GFC and Covid Pandemic

Figure IV.1 compares two decompositions of the post-GFC movement in US r^*. Panel A reports the Holston-Laubach-Williams (HLW) decomposition into trend growth, g_t, and the residual, other determinants component, z_t. Panel B reports the corresponding historical decomposition from our baseline DSGE model with forward-guidance shocks.

Figure IV.1: US Natural Rate of Interest (r*) Decompositions: HLW model vs. Baseline DSGE model



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, IMF staff calculations.

The HLW decomposition gives a simple reading of the US r^* evolution. US r^* fell sharply after the GFC and remained low through the 2010s. The initial decline is mainly associated with weaker potential growth. As potential growth recovered from its post-GFC trough, the residual component z_t became the main drag. In other words, the HLW model attributes the later part of the low r^*

episode less to weak growth and more to other persistent forces and other factors not separately identified in the model. Shorter-run, cyclical movements in r^* are also mostly absorbed by z_t.

The DSGE decomposition is sharper because it assigns these movements to structural shocks. In the US, the post-GFC decline in r^* is mainly explained by permanent liquidity shocks. Safety shocks and adverse technology shocks also contributed, but their role is smaller and only picks up after 2010. The anticipated quick recovery after the GFC briefly signaled an increase in r^*, mostly due to reversal of the permanent liquidity component, while the drag from safety and technology shocks started to dominate gradually. This lines up with the HLW's natural rate decomposition: the DSGE liquidity and safety shocks are the closest structural counterpart to HLW's z_t, while the persistent shocks to technology maps more closely into the HLW trend growth component.

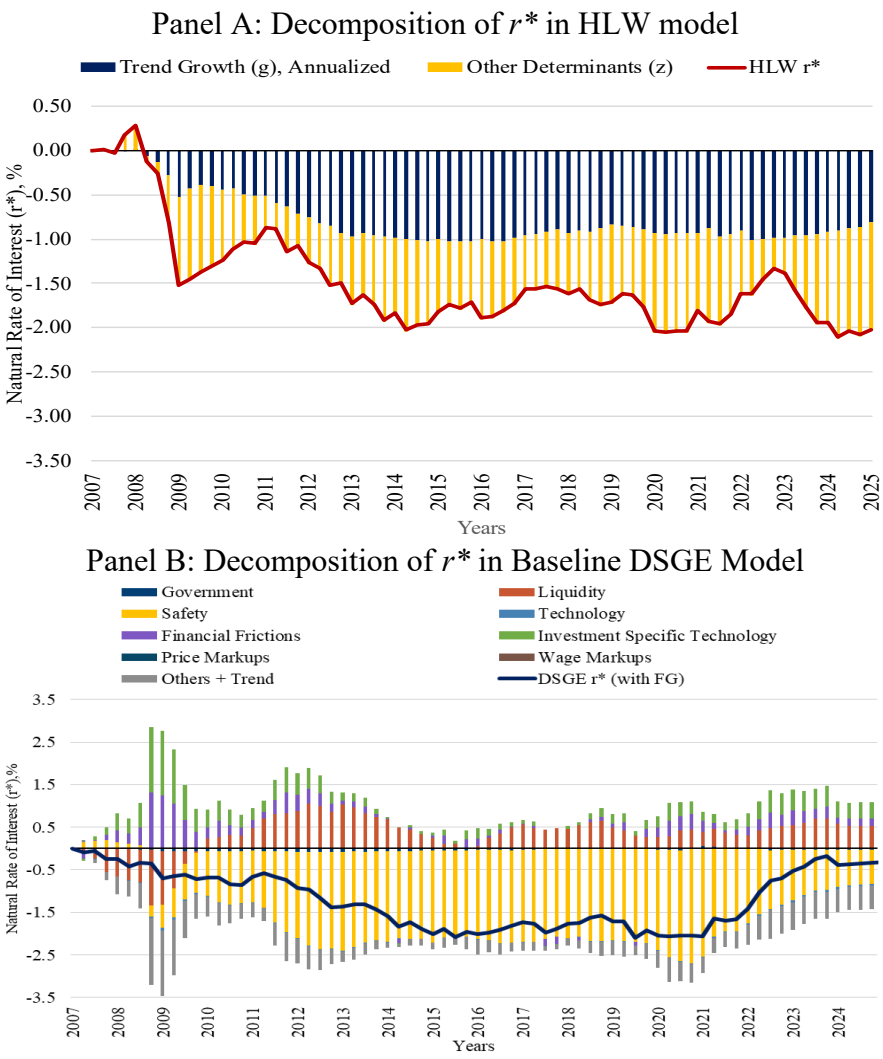
The post-Covid increase in US r^* is clear in the DSGE decomposition. As Del Negro et al. (2026) we find that the increase is mostly driven by permanent convenience yield shocks, both safety and liquidity. The interpretation is therefore different from a standard growth story. In the model, the post-Covid rise in r^* reflects a reversal of the forces that had compressed safe real rates after the GFC, that is the convenience value of safe and liquid assets falls relative to the return on real capital, and the natural rate rises.

Figure IV.2 repeats the same comparison for the euro area. The euro area HLW decomposition looks different from the US one. Euro area r^* also declined after the GFC and stayed low, but the growth component plays a larger and more persistent role. Potential growth falls in two steps: first after the GFC, and then again after the euro area sovereign debt crisis. Unlike in the US, it does not recover meaningfully. As a result, weak potential growth remains a persistent drag on euro area r^*. The residual, other determinants component (z_t) still accounts for most of the higher-frequency movements. While the main secular decline is attributed to weaker trend growth.

Our DSGE decomposition for the euro area is less clean than for the US, but it points in the same broad direction. Safety and convenience yield shocks contribute to the post-GFC and sovereign-debt-crisis decline in r^*. At the same time, the liquidity-premium contribution turns positive over the most part of the sample, which makes the decomposition less one-sided than in the US. The post-Covid increase in euro area r^* is again predominantly convenience-yield driven, but here investment specific technology shocks, compared to permanent TFP shocks are increasing. Overall the mapping to the HLW components is less transparent, because the euro area combines a persistent growth drag with large movements in financial premia and crisis-related shocks.

The cross-country comparison reveals that while the HLW sees similar patterns in the drivers of r^*, the DSGE gives a different picture. In both economies, HLW shows a large post-GFC fall in r^* and a long period of low neutral rates. In both economies, z_t explains most of the higher-frequency, cyclical variation. But the secular drivers differ. In the United States, weak potential growth matters early on, then fades as z_t becomes the dominant force. In the euro area, weak potential growth is more persistent and remains a drag on r^* even after the sovereign debt crisis.

Figure IV.2: Euro Area Natural Rate of Interest (r*) Decompositions: HLW model vs. Baseline DSGE model



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, IMF staff calculations.

The DSGE model helps interpret HLW's residual. For the US, the association is relatively clear: HLW's z_t behaves like the DSGE convenience-yield block, especially permanent liquidity shocks. Technology shocks line up more naturally with the HLW growth component. For the euro area, a similar mapping cannot be established. In the euro area convenience-yield shocks matter for the decline, and convenience-yield shocks explain much of the post-Covid increase, but the persistent weakness in potential growth remains outside of the decomposition in the DSGE, calling for revisiting the growth trend specification.



PUBLICATIONS

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