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A shadow rate without a lower bound constraint[☆]

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ABSTRACT

We propose a shadow rate without a lower bound constraint that measures the overall stance of monetary policy in any policy environment, prior and during the lower-bound period, as well as in the current "New Normal" environment, where unconventional monetary policies have become more standard. Using daily yield curve data we estimate shadow rates for the US, Sweden, the euro area and the UK, and document that they fall (rise) as monetary policy becomes more expansionary (contractionary), following announcements of policy rate cuts (hikes), forward guidance, and balance sheet expansions (contractions). In addition, we show two applications for our shadow rate. First, we decompose shadow rate responses to monetary policy announcements into conventional and unconventional monetary policy surprises, and assess the pass-through of each type of policy to exchange rates. We find that exchange rates respond more to conventional than to unconventional monetary policy. Lastly, counterfactual experiments in two DSGE models suggest that inflation in the US and in Sweden would have been on average about 0.8 and 0.33 percentage points lower, respectively, had unconventional monetary policy not been used.

1. Introduction

During the financial crisis of 2007–2008 and the following years, a number of central banks reduced their policy rates - the traditional tool of monetary policy - essentially to their lower bounds. In the face of deteriorating economic conditions and deflationary pressures, and with little scope for further policy rate cuts, central banks have relied on a variety of unconventional policies with the main objective of lowering longer-term interest rates, and further ease monetary conditions. Although improving economic conditions and increasing inflation have led some central banks to start reversing these policies, the advent of the Covid-19 crisis has led central banks around the world to expand the monetary easing started in 2007–2008. Lately, as inflation responded and rose sharply, central banks have been combining policy rate increases with unconventional tightening to adjust monetary conditions.

One central issue is that measuring the stance of monetary policy when various policy tools are at hand is challenging. As unconventional policies become widely used, it becomes difficult to attribute this role to one single measure. Moreover, the literature emphasizes that there are various channels through which unconventional policies are transmitted to longer-term interest rates, with effects varying considerably across maturities, meaning that single interest rates are only partially informative[1]

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[1] As emphasized by De Rezende (2017) and Swanson (2021), different monetary policy tools affect different segments of the yield curve, with interest rate policy having stronger effects on short-term rates, forward guidance on mid-term

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A popular approach to the construction of a single monetary policy measure that captures unconventional policy actions is that of shadow rates. Its concept was first introduced by Black (1995), and corresponds to the unobserved short-term interest rate consistent with longer-term rates that would have prevailed had the interest rate lower bound not been binding. The mechanism in Black (1995) shadow rate is that, when the observed short-term rate is at its lower bound and longer-term rates are sufficiently constrained, the shadow rate captures movements in the whole yield curve and decouples from the short-term rate, being commonly interpreted as a measure of the overall stance of monetary policy at the effective lower bound (Krippner, 2012; 2013; 2014; Wu and Xia, 2016; 2020).

In this paper, we estimate a shadow rate that measures the overall stance of monetary policy when the lower bound is not necessarily binding. The particular feature of our specification is that it does not impose any type of lower bound constraint on nominal interest rates. This allows it to measure the interest rate effects of unconventional monetary policy at any point in time, prior and during the lower bound period, as well as in the current "New Normal" policy environment, where unconventional policies have become more standard with major central banks using forward guidance and balance sheet policies in connection with policy rates to offset disturbances to inflation and economic activity when judged necessary. In addition, since there is no need to make assumptions about, or estimate the lower bound value in our specification, our shadow rate is particularly convenient from an estimation point of view, as the literature has emphasized that typical shadow rate estimates seem to be highly sensitive to the assumed numerical value for the lower bound (Bauer and Rudebusch, 2016). All these salient features make our shadow rate an attractive and informative market-based measure of the overall monetary policy stance at any point in time.

In our specification, during a conventional policy period, the shadow rate equals the short-term interest rate, which is commonly assumed to be a good measure of the monetary policy stance in this environment. During an unconventional policy period, the shadow rate is a function of factors extracted directly from the government bond yield curve and its short-rate expectations component, depending on the days on which unconventional policies are announced. On announcement days, the shadow rate responds to yield curve factors, as unconventional monetary policies tend to be transmitted through the short-rate expectations and term premium components that are embedded in yields.[2] On non-announcement days, the shadow-rate is driven by short-rate expectations only, as term premium tends to carry substantial information that is not directly related to monetary policy (Kim and Orphanides, 2007; Wright, 2011), such as investors' degree of risk-aversion, as well as "flight to quality" effects at times of extreme volatility in financial markets, which may all add noise to the monetary policy stance measurement. On the other hand, short-rate expectations tend to adjust to events that affect investors' expectations of future monetary policy on any day, such as macroeconomic news, monetary policy announcements, speeches and so on, and that are naturally connected to the stance of monetary policy.

The computation of the shadow rate involves two steps. First, we use a term structure model to estimate short-rate expectations and yield curve factors, as well as the short-term interest rate that equals the shadow rate in the conventional policy period. Second, we use event study regressions (Kuttner, 2001; Gürkaynak et al., 2005) and inverse prediction (Brown, 1994; Graybill, 1976; Graybill and Iyer, 1994; Osborne, 1991, among others) to obtain the parameter estimates that are needed for the computation of the shadow rate during the unconventional policy period. More specifically, in the second step, we estimate event study regressions of short-rate surprises onto changes in short-rate expectations and yield curve factors around short windows, and use inverse prediction to translate movements in those factors into an unobserved shadow rate that is computed for the unconventional policy period. Importantly, the event study regressions are used as a source of identification of the causal relationship between the short-rate, short-rate expectations and yields (Gürkaynak and Wright, 2013), helping us to pin down consistent and precise estimates for our parameters of interest. In addition, during the unconventional period, we can decompose changes in our shadow rate on announcement days into a conventional monetary policy surprise plus a prediction error, which can be associated with the surprise component of announced unconventional monetary policies, scaled by the associated event-study regression coefficient.

We estimate shadow rates for the US, Sweden, the euro area and the UK. In our main application, we set the day on which unconventional measures were first announced in response to the financial crisis of 2007–2008 as the date marking the beginning of the unconventional period, when the shadow rate may start diverging from the short-term interest rate. We find that our estimates have lied well below policy rates in the four economies, suggesting that the unconventional measures that have been implemented since the financial crisis of 2007–2008 have eased monetary conditions more than otherwise. For instance, the US shadow rates declined by more than 3 percentage points as a result of the monetary easing implemented by the Fed in response to the Covid-19 crisis. Moreover, our estimated shadow rates rise as monetary policy becomes more contractionary, and market participants price this information into the yield curve.

Our estimates also track precisely episodes of policy rate cuts and hikes, forward guidance, and balance sheet expansions and contractions. For instance, the US shadow rate fell by 83.8 basis points on March 18, 2009, when the Fed announced the extension of QE1, as the five- and ten-year bond yields declined by 47.1 and 51.9 basis points. On August 9, 2011, the day of the announcement of explicit calendar-based forward guidance, the US shadow rate fell by 27.6 basis points, and also fell strongly to a number of expansionary announcements during the Covid-19 crisis. In addition, the US shadow rate reacted positively to the tapering of QE3, as well as during the balance sheet contraction period. In Sweden, our shadow rate declined by 26.9 basis points on the day the Riksbank launched its bond purchase program in February 2015. In the UK, the shadow rate declined by 28.4 basis points on the announcement of the post-Brexit stimulus package in August 2016, and by 15.8 and 35.5 basis points following the announcements of Bank Rate cut, further asset purchases and the package of economic measures on March 19, 2020 and March 20, 2020. In the euro area, the shadow rate decreased by 3.6, 1.4, 4.0 and 6.7 basis points on the announcements preceding the extension of ECB' s bond purchase program on December 3, 2015. Sizable effects are also found in other important events.

Besides its use as a market-based monetary policy stance indicator, we show two other applications for our shadow rate. In the first application, we exploit the information contained in shadow rate changes around announcements to better understand the pass-through of conventional and unconventional monetary policies to exchange rates across economies. For this exercise, we use event study regressions with the decomposition of shadow rate

rates, and quantitative easing on long-term rates. The channels through which quantitative easing may be transmitted to interest rates include the portfolio balance channel (Vayanos and Vila, 2021), the reserve-induced portfolio balance channel (Christensen and Krogstrup, 2019), the signaling channel (Bauer and Rudebusch, 2014), the collateral channel (D'Amico and King, 2013) and the liquidity channel.

[2] Forward guidance is typically transmitted through short-rate expectations. Quantitative easing tends to be transmitted through both short-rate expectations and term premia.

changes around announcements into conventional and unconventional policy surprises. Using pooled and single regressions, we find that exchange rates respond more to conventional than to unconventional monetary policy. Our results suggest that a 10 basis points decrease in the conventional surprise measure depreciates the domestic currency by 1.02 percent vis-à-vis the foreign currency. The estimated impact of unconventional policy is lower, about 0.32 percent. The higher impact of conventional policy is confirmed when we estimate event study regressions using announcements by each central bank. These findings are in line with other studies that commonly find that exchange rates respond more to short-term rates, which are more connected to near-term short-rate expectations, than to long-term rates (Glick and Leduc, 2018; Rossi and Inoue, 2019).

In our second application, we measure the macroeconomic effects of unconventional monetary policy. We replace the policy rates in two well-known medium-scale DSGE models, Smets and Wouters (2007) and Riksbank' s Ramses II, by the US and Swedish shadow rates and construct a counterfactual analysis for inflation, unemployment rate and output gap around the unconventional period. We illustrate that in the US, our shadow rate continues to be a useful measure of policy stance during the entire unconventional period, as it accounts for the highly expansionary unconventional measures that continued to be in place during the lift-off periods of 2016–2018 and 2022, and that were enlarged following the Covid crisis of 2020. In summary, results using our shadow rates suggest that the unconventional policies implemented by the Fed since 2008 have raised inflation and the output gap by around 0.8 and 5.5 percentage points on average over 2008–2021, respectively. In addition, the measures implemented by the Riksbank since February 2015 further stimulated the Swedish economy, with CPIF inflation being on average around 0.33 percentage points higher and unemployment rate around 0.58 percentage points lower than otherwise over the period 2015–2021. This type of application is particularly appealing for monetary policy analysis, as DSGE models typically used by central banks can become overly complex when unconventional monetary policy is explicitly modeled. Furthermore, scenarios estimating the effects of further unconventional policies such as bond purchases can be easily constructed.

The remainder of this paper is organized as follows. The next section introduces our shadow rate specification, its estimation method and how it compares to the other existing specifications in the literature. Section three describes the data used in the study. Section four and five describe the main results of the paper, and the sixth section concludes.

2. Shadow rate

In this section, we first describe the term structure model specification that will be used in the study, our shadow-rate specification, and the estimation method based on event-study regressions. Lastly, we describe how our shadow rate specification compares to other existing specifications in the literature.

2.1. Term structure model

Our shadow rate specification requires a model that is able to decompose bond yields into short-rate expectations and term premia. In principle, this could be done by any model designed for this purpose (see Ang and Piazzesi, 2003; Kim and Wright, 2005; Joslin et al., 2011; Joslin et al., 2013; Adrian et al., 2013; Wu and Xia, 2016; Wu and Xia, 2020, among others). In this paper, in order to compare estimates across economies, we use discrete-time Gaussian Dynamic Affine Term Structure Models (DATSMs), which assume that zero-coupon bonds are affine functions of pricing factors. More specifically, the $p \times 1$ vector of pricing factors X_t that drives movements in the whole term structure of interest rates follows a VAR(1) process under the objective probability measure $\mathbb{P}$,

$$X_{t+1} = \mu + \Phi X_t + \Sigma\epsilon_{t+1} \tag{1}$$

where $\epsilon_t \sim iid\, N\left(0, I_p\right)$ and Σ is an $p \times p$ lower triangular matrix. The stochastic discount factor (SDF) that prices all assets under the absence of arbitrage is assumed to be conditionally lognormal

$$M_{t+1} = \exp\left(-r_t - \frac{1}{2}\lambda_t'\lambda_t - \lambda_t'\epsilon_{t+1}\right) \tag{2}$$

where $\lambda_t = \lambda_0 + \lambda_1 X_t$ is a $p \times 1$ vector of risk prices that drive risk premia. We allow the short rate to vary freely, without imposing any constraints or asymmetries in the conditional distributions of short-rate expectations. The short-term interest rate is then affine in the pricing factors, $r_t = \delta_0 + \delta_1' X_t$. Under the risk-neutral measure $\mathbb{Q}$ the vector of pricing factors follows the dynamics,

$$X_{t+1} = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} X_t + \Sigma\epsilon_{t+1} \tag{3}$$

where $\mu^{\mathbb{Q}} = \mu - \Sigma\lambda_0$ and $\Phi^{\mathbb{Q}} = \Phi - \Sigma\lambda_1$.

Under no-arbitrage bond prices are then exponential affine functions of the state variables, $P_t^n = exp\left(A_n + B_n' X_t\right)$, where A_n is a scalar and B_n is an $p \times 1$ vector that satisfy the recursions

$$\begin{aligned} A_{n+1} &= -\delta_0 + A_n + \mu^{\mathbb{Q}\prime} B_n + \tfrac{1}{2} B_n' \Sigma\Sigma' B_n \\ B_{n+1} &= \Phi^{\mathbb{Q}\prime} B_n - \delta_1 \end{aligned} \tag{4}$$

which start from $A_1 = -\delta_0$ and $B_1 = -\delta_1$. Model implied yields are computed as $y_t^n = -n^{-1} log\, P_t^n = -n^{-1}(A_n + B_n' X_t)$.

The functions A_n and B_n that enter the pricing equation above are computed under the risk-neutral measure $\mathbb{Q}$ and not under the objective probability measure $\mathbb{P}$. The difference is determined by the term premium, which is defined as the return difference demanded by investors to invest and hold an n-year bond until maturity instead of rolling over the short-term interest rate,

$$TP_t^n = y_t^n - \frac{1}{n}\sum_{i=0}^{n-1} E_t^{\mathbb{P}}(r_{t+i}) \tag{5}$$

The specification described above is quite general and is suitable for a large number of models in the class of discrete-time Gaussian DATSMs. A key modeling choice is which pricing factors to include in the vector X_t. In this paper, we follow the finance literature and estimate yields-only models, where X_t reflects only information in the yield curve. We use the canonical form of Joslin et al. (2011) (JSZ henceforth), which has as its main distinctive feature the inherent separation between the parameters of the $\mathbb{P}$ and $\mathbb{Q}$ distributions and the use of observable yield portfolios as pricing factors, $X = WY$, where W is a $p \times N$ matrix of portfolio weights and Y is a $N \times T$ matrix of observable yields. Following JSZ, we use the first p principal components of yields as pricing factors (yield factors), which can assume any values from 1 to N, i.e. $p = 1, 2, \ldots, N$. In addition, we assume that bonds are priced without error, i.e. $X = WY = W\hat{Y}$. As noted by JSZ, these features facilitate the estimation of the model with a near-instantaneous convergence to the global optimum of the likelihood function.

2.2. Shadow rate

Similar to the short-rate equation described above, our shadow rate specification is also a function of interest-rate factors. During the conventional monetary policy period, the shadow rate is equal to the short-term interest rate specified above, i.e. r_t. During the unconventional period, the shadow rate is a function of the factors that drive the term structures of yields and average short-rate expectations specified in the model above, depending on the days on which unconventional monetary policies are present, and are announced. More specifically, our specification assumes the following form,

$$\triangle s_t = \begin{cases} \triangle r_t & if \quad t < t_0 \\ \varphi_1 \triangle X_{1t}^{sr} & if \quad t \geq t_0 \ s.t. \ t \neq t^\star \\ \varphi_2 \triangle X_{1t} & if \quad t \geq t_0 \ s.t. \ t = t^\star \end{cases} \tag{6}$$

where r_t is the short-term interest rate, t_0 is the first announcement day of unconventional policy measures, $t^\star$ is a day of an unconventional monetary policy announcement, X_{1t} is an yield factor, and X_{1t}^{sr} is a short-rate expectations factor. These two factors, X_{1t} and X_{1t}^{sr}, are defined as the first principal components of the term structures of yields and average short-rate expectations, respectively. s_t is the shadow rate.[3]

As can be seen from (6), the shadow rate is equal to the short-term interest rate when unconventional policies have not yet been implemented. During the unconventional period, however, the type of factors driving s_t depends on the days on which unconventional policies are announced. On announcement days, we consider that the shadow rate is driven by both the short-rate expectations and the term premium components that are embedded in X_t, since unconventional policies tend to affect both components when $t = t^\star$.[4] On non-announcement days, however, s_t is driven by short-rate expectations only, as the term premium tends to carry substantial information that is not directly related to monetary policy (Kim and Orphanides, 2007; Wright, 2011). One important piece of that information is the degree of investors' risk aversion, which tends to vary with the business cycle (Campbell and Cochrane, 1999; Wachter, 2006) leading term premia to evolve in a countercyclical fashion (Ludvigson and Ng, 2009; Bauer et al., 2014), duration risk (Vayanos and Vila, 2021; Greenwood and Vayanos, 2014), among other information. Additionally, during periods of financial turmoil such as the global financial crisis and the European debt crisis, term premia associated with government bonds of major economies are often compressed by safe-haven demands of investors, who place special value on the safety and liquidity of these assets. All these tend to add noise to the measurement of s_t. On the other hand, X_t^{sr} should adjust to events that affect investors' expectations of future monetary policy intentions in any day, such as domestic and foreign macroeconomic news, monetary policy announcements, speeches and so on, so that it naturally reflects the stance of monetary policy.

The shadow rate in levels is obtained by setting an initial value for s_t, such as the short-rate at $t = 1$, and by iterating Eq. (6) forward until the last sample observation, T. More specifically, we have

$$s_t = r_1 + \sum_{t=2}^{t_0-1} \triangle r_t + \sum_{t=t_0}^{T,\, t\neq t^\star} \varphi_1 \triangle X_{1t}^{sr} + \sum_{t=t_0}^{T,\, t=t^\star} \varphi_2 \triangle X_{1t} \tag{7}$$

Note that s_t may start diverging from r_t from $t = t_0$, which can be set as any day in the sample of data used for the estimation of the term structure model. Hence, the sum $\sum_{t=t_0}^{T} (s_t - r_t)$ indicates how expansionary unconventional monetary policy is compared to conventional monetary policy during the unconventional period, while s_t informs about the level of the stance of monetary policy at time t. To be comparable with other shadow rates available in the literature, in our main application, we set t_0 to be equal to the day on which the central bank first announced unconventional policies after the start of the global financial crisis of 2007–2008.

2.3. Estimation

The parameters of the short-rate equation $r_t = \delta_0 + \delta_1' X_t$ are estimated by maximum likelihood, within the term structure model specified in Section 2.1. The other parameters in (6) are estimated separately. Our approach consists of estimating event study regressions of short-rate surprises onto changes in short-rate expectations and yield curve factors using data observed around conventional monetary policy announcements, and use inverse prediction to translate movements in those factors into an unobserved shadow rate that is computed for the unconventional policy period. Importantly, the event study regressions are used as a source of identification of the causal relationship between the short-rate, short-rate expectations and yields (Gürkaynak and Wright, 2013), helping us to pin down consistent and precise estimates for our parameters of interest.

More specifically, we estimate event study regressions as in Kuttner (2001); Gürkaynak et al. (2005) and other related studies,

$$\triangle X_{1t^\diamond}^{sr} = \beta \triangle r_{t^\diamond}^{u} + \xi_{t^\diamond} \tag{8}$$

$$\triangle X_{1t^\diamond} = \alpha \triangle r_{t^\diamond}^{u} + \epsilon_{t^\diamond} \tag{9}$$

where $\triangle r_{t^\diamond}^{u}$ is the unexpected change in the short-rate, or short-rate surprise, observed in a day of conventional monetary policy announcement, $t^\diamond$. Regressions (8) and (9) are estimated over a pre-lower bound sample when $t < t_0$, as β and α should identify the link between the short-rate, short-rate expectations and yields that are embedded in r_t^u, X_{1t}^{sr} and X_{1t} when conventional monetary policy was the main instrument of monetary policy, and the relationship between these variables clearly existed.[5]

We then translate movements in X_{1t}^{sr} and X_{1t} into estimates for the shadow rate change during the unconventional policy period through inverse prediction, or statistical calibration, which involves the use of an observed response variable to predict the corresponding unknown explanatory variable.[6] More specifically, from (6), (8) and (9) we have that,

$$\widehat{\triangle s_t} = \begin{cases} \triangle r_t & if \quad t < t_0 \\ \frac{1}{\beta} \triangle X_{1t}^{sr} & if \quad t \geq t_0 \ s.t. \ t \neq t^\star \\ \frac{1}{\alpha} \triangle X_{1t} & if \quad t \geq t_0 \ s.t. \ t = t^\star \end{cases} \tag{10}$$

where $\frac{1}{\beta}$ and $\frac{1}{\alpha}$ are used as estimates for φ_1 and φ_2, and where $\frac{1}{\beta} \triangle X_{1t}^{sr} = \widehat{\triangle r_t^u} = \triangle r_t^u + \frac{1}{\beta}\widehat{\xi}_t$ when $t \neq t^\star$, and $\frac{1}{\alpha} \triangle X_{1t} = \widehat{\triangle r_t^u} = \triangle r_t^u + \frac{1}{\alpha}\widehat{\epsilon}_t$ when $t = t^\star$. Therefore, notice from the relations above that, on a non-unconventional monetary policy announcement day, the estimated shadow rate change equals (i) the conventional monetary policy surprise observed on that day, which is commonly zero, and (ii) a prediction error, which can be associated with any news that affect short-rate expectations on that particular day, scaled by $\frac{1}{\beta}$. On an unconventional monetary policy announcement day, the estimated shadow rate change equals (i) the conventional monetary policy surprise observed on that day, and (ii) a prediction

[3] X_1 is the first row vector of the matrix $X = WY$ defined in section "2.1 Term structure model" above. X_1^{sr} can be obtained in the following way. Following the term structure model above, we can define the matrix of term structures of average short-rate expectations, Y^{sr}. Y^{sr} is an affine function of the yield factors X, meaning that X^{sr} can be directly obtained from X itself. We do that by rotating X. More specifically, we define a $p \times p$ orthogonal rotation matrix U^{sr} such that $W^{sr} = U^{sr}W$, and then obtain X^{sr} through $X^{sr} = W^{sr}Y^{sr}$. We use the rotation matrix U^{sr} such that X^{sr} equals the first p principal components of the $N \times T$ matrix Y^{sr}. We can then use the first row vectors of X and X^{sr} as factors for s_t in (6), such that φ_1 and φ_2 are scalars. In this way, X_1 and X_1^{sr} become the first principal components of the term structures of yields and average short-rate expectations, respectively.

[4] This may happen through at least two channels: the portfolio balance channel and the signaling channel.

[5] We abstract from the constants in (8) and (9), as their values in monetary policy surprise regressions are typically very small and statistically non-significant.

[6] For more details on regression inversion and statistical calibration please see Graybill (1976); Osborne (1991); Graybill and Iyer (1994), Brown, 1994, among others.

error, which can be associated with the surprise component of the unconventional monetary policies announced on that particular day, scaled by $\frac{1}{\alpha}$. Importantly, the scaling parameters $\frac{1}{\beta}$ and $\frac{1}{\alpha}$ are the ones that translate yield curve information into an unobserved short-rate equivalent measure, the shadow rate. The estimated shadow rate in levels, $\widehat{s_t}$, is obtained by accumulating $\widehat{\triangle s_t}$ over the whole sample as in (7).

As noted above, we use the respective first principal components of the term structures of yields and short-rate expectations as factors in (6) and (7), abstracting from the information contained in other higher dimensional factors. There are two reasons for that, which are connected and part of our overall method. First, the first principal component (level factor) typically explains over 95 percent of the cross-sectional variation in the term structures of yields and average short-rate expectations, capturing almost all the movements in the data. Second, the event study methodology, which requires the dimension of X_{1t} and X_{1t}^{sr} to be one, works as a powerful way of identifying the true causal relationship between the short-rate, short-rate expectations and yields, and of obtaining precise and consistent estimates for our parameters of interest (Gürkaynak and Wright, 2013). In conjunction, these two features of our approach allows our shadow rate to capture the observed daily movements in the yield curve with high precision, as we show in Sections 4.1 and 4.2.

2.4. Alternative shadow rate specifications

Based on the work by Black (1995), a number of recent studies have proposed alternative formulations for the shadow rate, which respect a constant or time-varying lower bound constraint for interest rates (Krippner, 2012; 2013; 2014; Wu and Xia, 2016; 2020; Bauer and Rudebusch, 2016; Lemke and Vladu, 2016; Kortela, 2016). These formulations posit the existence of a shadow interest rate that is linear in Gaussian factors, with the short-term interest rate being the maximum of the shadow rate, s_t, and the lower bound, $\underline{r}$ $(\underline{r_t})$. More specifically, one may have,

$$r_t = \max(\underline{r},\ s_t) \quad or \quad r_t = \max(\underline{r_t},\ s_t) \qquad s_t = \delta_0 + \delta_1' X_t \tag{11}$$

Note that when the short-rate is close enough to the lower bound and long-term yields are sufficiently constrained, the shadow rate tends to diverge from the short-rate, being commonly interpreted as a better measure of the stance of monetary policy at the lower bound than the short-rate itself (Krippner, 2012; 2013; 2014; Wu and Xia, 2016; 2020).

Another type of shadow rate is the one proposed by Lombardi and Zhu (2018). Their shadow rate is obtained by estimating a dynamic factor model that allows for missing observations and that treats the short-term interest rate as a missing variable in the model during the zero-lower bound period in the US. For estimating their shadow rate Lombardi and Zhu (2018) use a range of indicators in the model, including several interest rates, monetary aggregates and central bank balance sheet variables.

Our shadow rate specification described in (6) and (7) shares one key similarity with those based on Black (1995) and proposed by Lombardi and Zhu (2018). The fact that they are all intended to inform about the overall stance of monetary policy. There are, however, differences between them. The first difference is that while our shadow rate and the one proposed by Wu and Xia (2016) and Krippner (2014) are driven by yield curve information only, Lombardi and Zhu (2018) shadow rate is estimated from on a number of indicators such as interest rates, monetary aggregates and balance sheet variables. The main motivation for not including such large information set is the idea embedded in the majority of macro-finance term structure models where any factor in addition to yield factors are completely spanned by the yield curve information within the model (Duffee, 2013). In fact, Bauer and Rudebusch (2016) perform a number of tests for the "spanning" condition and provide strong support for it in the data.

The key difference, however, comes from the fact that, differently from Wu and Xia (2016); Krippner (2014) and Lombardi and Zhu (2018), specification (6) and (7) does not impose a lower bound constraint on nominal interest rates, and hence does not necessarily equal the short-rate when the lower-bound is not binding. We consider this to be particularly appealing as (6) and (7) is able to measure the overall stance of monetary policy at any point in time, i.e. $t \geq t_0$, and not only when the lower-bound is a binding constraint for interest rates. Because of this feature, Eqs. (6) and (7) is able to capture the interest rate effects of unconventional policies that are present when the central bank exits the lower bound. This is particularly relevant in the current "New Normal" policy environment, where unconventional policies have become more standard with major central banks using forward guidance and balance sheet policies in connection with policy rates to offset disturbances to inflation and economic activity when judged necessary.[7] Another related difference is that, there is no need to specify or to estimate the value of the interest rate lower bound in our formulation, which is particularly convenient as (11) tends to be sensitive to the value assigned to $\underline{r}$ (see Bauer and Rudebusch, 2016). It is also worth mentioning that specification (6) and (7) can be used in conjunction with any term structure model.

Considering all these aspects, our specification (6) and (7) is very flexible, as it is able to: (i) estimate a measure of the overall stance of monetary policy at any point in time, including when the lower bound is a non-binding constraint for interest rates, (ii) accommodate any type of lower bound constraint found in the data, and (iii) be used in conjunction with any term structure model.

3. Data and term structure model estimation

3.1. Zero-coupon government bond yield data

We estimate shadow rates for four economies, i.e. the US, Sweden, the euro area and the UK. For the US, we use the daily zero-coupon government bond yields provided by Gürkaynak et al. (2007). These are constructed using a smooth discount function based on the Svensson (1994) parameterization and are provided by the Federal Reserve Board.[8] In addition, nine maturities are used for estimation - one, three and six-months, and one, two, three, five, seven and ten-years - together with a sample that ranges from January 2, 1987 to May 13, 2022. This sample is consistent with other studies in the literature (Wright, 2011; Bauer et al., 2012; Adrian et al., 2013), and coincides with the Great Moderation period and a shift in the conduction of monetary policy by the Fed after the presidency of Paul Volcker (Clarida et al., 2000; Galí et al., 2003; Kim and Nelson, 2006, among others).[9]

Swedish zero-coupon government bond yields are also constructed using the Svensson (1994) parameterization. The term structure model is estimated using yields for nine maturities - one, three and six-months, and one, two, three, five, seven and ten-years - and a sample that ranges from January 2, 1996 to May 13, 2022, which is consistent with the introduction of the inflation targeting regime by the Riksbank in 1995.

[7] We discuss this in more detail in Section 4.2.

[8] The Svensson (1994) yield curve parameterization assumes the following functional form, $y_t^n = \beta_{0,t} + \beta_{1,t}\left(\frac{1-e^{-\lambda_{1,t}n}}{\lambda_{1,t}n}\right) + \beta_{2,t}\left(\frac{1-e^{-\lambda_{1,t}n}}{\lambda_{1,t}n} - e^{-\lambda_{1,t}n}\right) + \beta_{3,t}\left(\frac{1-e^{-\lambda_{2,t}n}}{\lambda_{2,t}\tau} - e^{-\lambda_{2,t}n}\right)$.

[9] The model is estimated using end-of-month data and parameter estimates are used to fit the daily data.

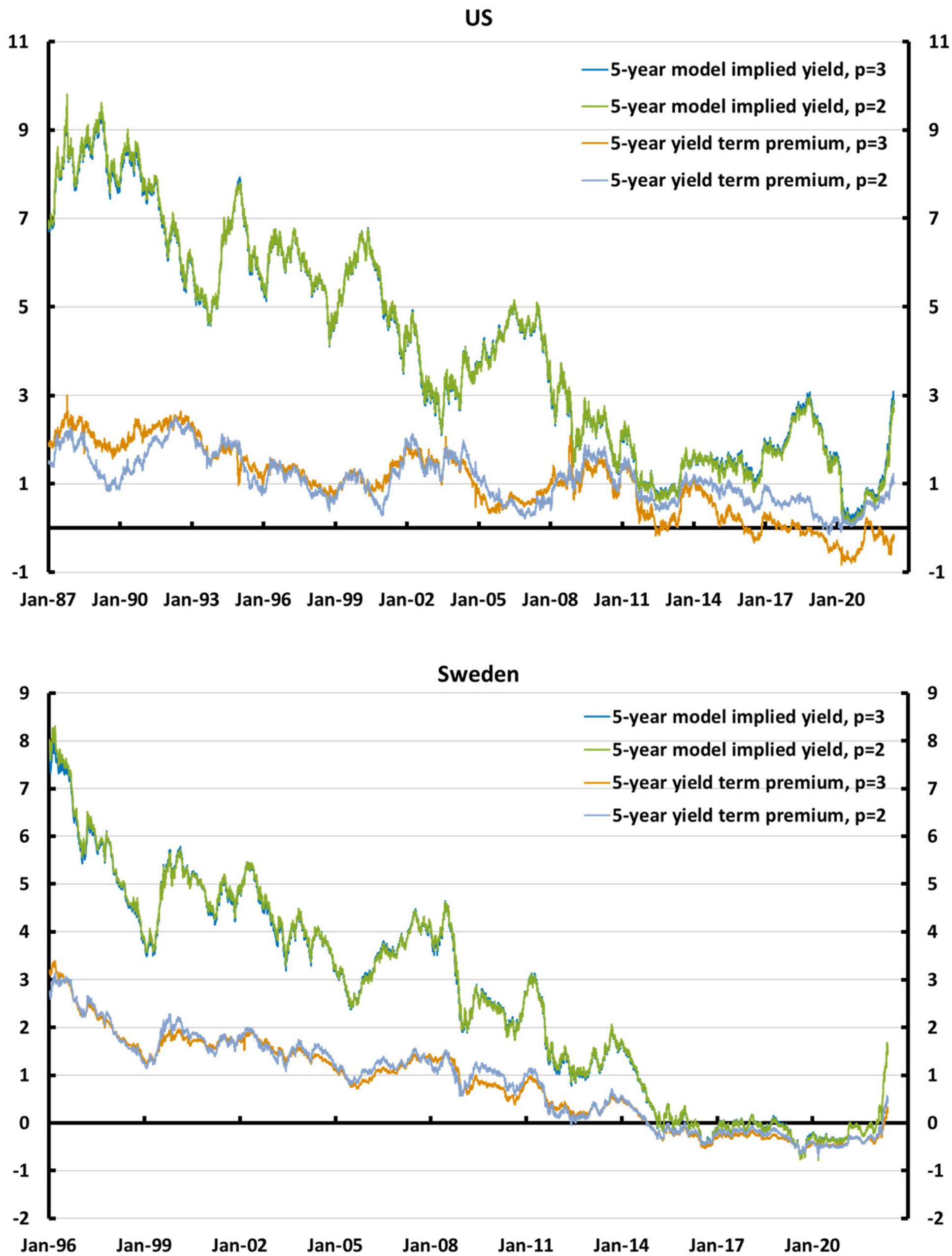


Fig. 1. Decomposition of five-year government bond yield for the US and Sweden. *Notes:* This figure shows the decompositions of the five-year zero-coupon government bond yield into short-rate expectations and term premium for the US and Sweden. The Swedish sample ranges from January 2, 1996 to May 13, 2022. The US sample ranges from January 2, 1987 to May 13, 2022. The decompositions are obtained using the Joslin et al. (2011) model with two ($p = 2$) and three ($p = 3$) pricing factors.

For the euro area, we estimate the model using zero-coupon overnight index swap (OIS) rates based on Eonia. As reliable longer-maturity zero-coupon OIS rates are only available from August 2005, we follow Lemke and Vladu (2016) and extend the dataset backwards by merging the OIS data with spread-adjusted zero-coupon rates based on Euribor swaps.[10] Our dataset then consists of zero-coupon OIS rates for maturities of one, three and six-months (one, two, three, five, seven and ten-years) from January 4, 1999 (August 15, 2005) to May 13, 2022, and spread-adjusted Euribor zero-coupon swap rates for maturities of one, two, three, five, seven and ten-years from January 4, 1999 to August 12, 2005. As discussed by the ECB (2014), these swap interest rates have been considered as adequate proxies for risk-free rates in the euro area, in particular after the onset of the global financial crisis in 2007.

For the UK, we use the zero-coupon yields provided by the Bank of England for maturities of six-months, one, two, three, five, seven and ten-years, in addition to the Bank Rate. We use a sample comprising the period from October 1, 1992 to May 13, 2022, which is motivated by the adoption of the inflation targeting framework in the UK (see Malik and Meldrum (2016).

The term structure models are estimated using two and three pricing factors, $p = 2, 3$ (Krippner, 2012; 2014; Wu and Xia, 2016; Bauer and Rudebusch, 2016). The decompositions of the five-year

[10] Since swap contracts are traded at par, zero-coupon swap rates are constructed by bootstraping the original data. For merging the two datasets we follow Lemke and Vladu (2016) and first compute the average spreads between OIS and Euribor zero-coupon swap rates over the period from July 2005 to June 2007. We then subtract these average spreads from the Euribor zero-coupon swap rates from January 1999 to June 2005. We use these rates to replace the non-existent OIS zero-coupon interest rates over this period.

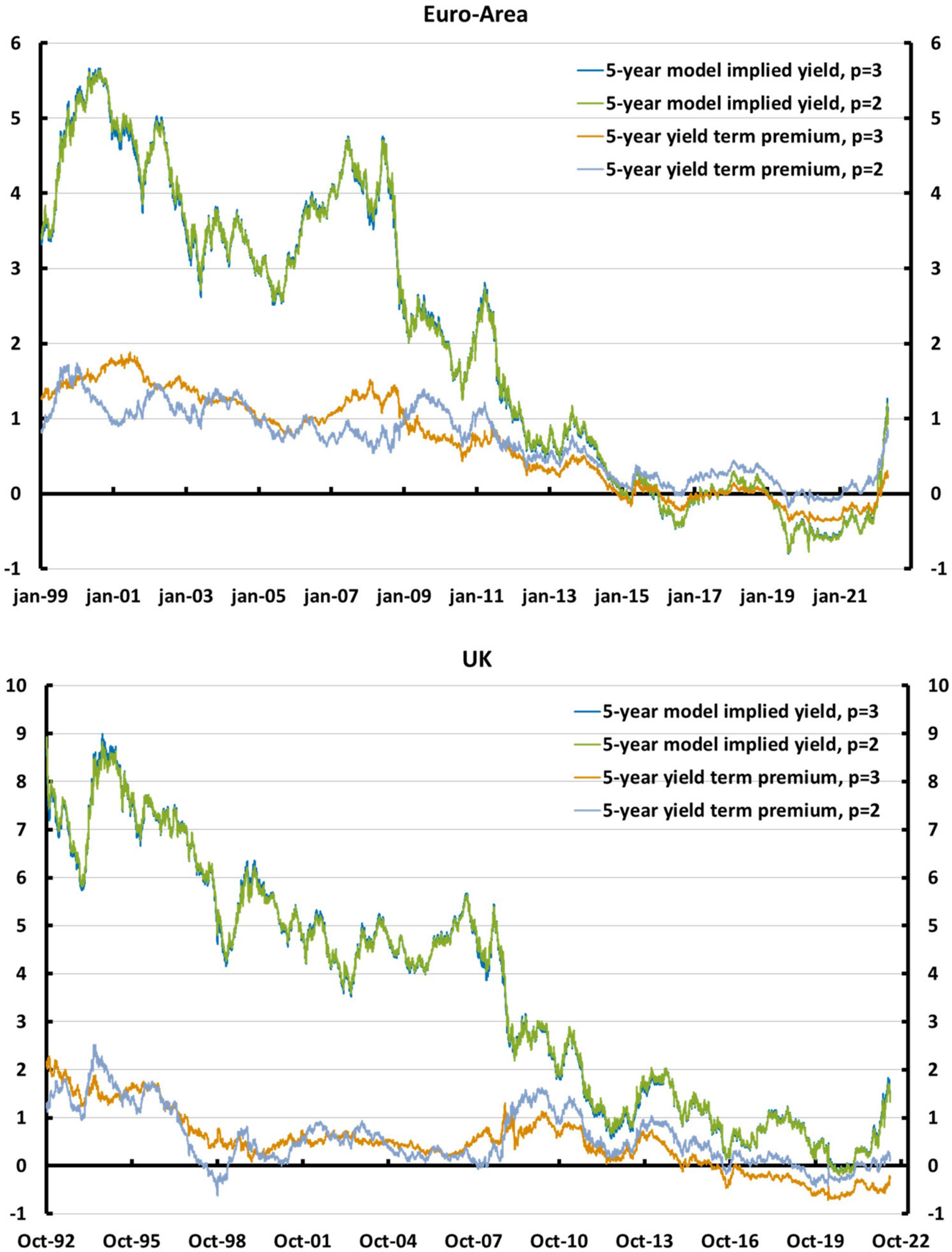


Fig. 2. Decomposition of five-year government bond yield for the euro area and the UK. *Notes:* This figure shows the decompositions of the five-year zero-coupon government bond yield into short-rate expectations and term premium for the euro area and the UK. The euro area sample ranges from January 19, 1999 to May 13, 2022. The UK sample ranges from October 1, 1992 to May 13, 2022. The decompositions are obtained using the Joslin et al. (2011) model with two $(p = 2)$ and three $(p = 3)$ pricing factors.

yields for the four economies are shown in Figs. 1 and 2. As can be seen, term premia for all economies have reached low and even negative levels in recent periods (see also Wright, 2011). Possible explanations for such phenomenon include: (i) the declining inflation environment and prospects for future inflation in major economies observed since the mid-1990s, which has led bondholders to be willing to accept less or even negative compensation for bearing inflation risk; (ii) the state of the business cycle and the prospects of positive growth since the financial crisis, which leads to a lower degree of risk aversion; (iii) the effective lower bound, which imposes a constraint on policy rate expectations, and consequently has helped to lower uncertainty about future policy rates in several economies; (iv) the bond purchases in the US, Sweden, the euro area and the UK, which have helped to compress long-term term premia; and lastly (v) the facts that government bonds typically work as a hedge against different types of risk that may hurt returns on riskier assets, and that they are especially demanded by certain institutional investors due to liquidity, safety and regulatory reasons, which together may induce investors to be willing to accept low or even negative compensation for holding them.

We test whether the decompositions shown in Figs. 1 and 2 are adequate for capturing the dynamics of term premia. For that we use the LPY(ii) test of Dai and Singleton (2002). The LPY(ii) test considers a risk adjusted version of Campbell and Shiller (1991) regressions, i.e. $y_{t+1}^{n-1} - y_t^n - E_t\left(rx_{t+1}^n\right)/(n-1) = \alpha^n + \phi^n\left(y_t^n - r_t\right)/(n-1) + \xi_t^n$, where $rx_{t+1}^n = log\left(P_{t+1}^{n-1}/P_t^n\right) - r_t$. If the models generate adequate term premia decompositions, we should

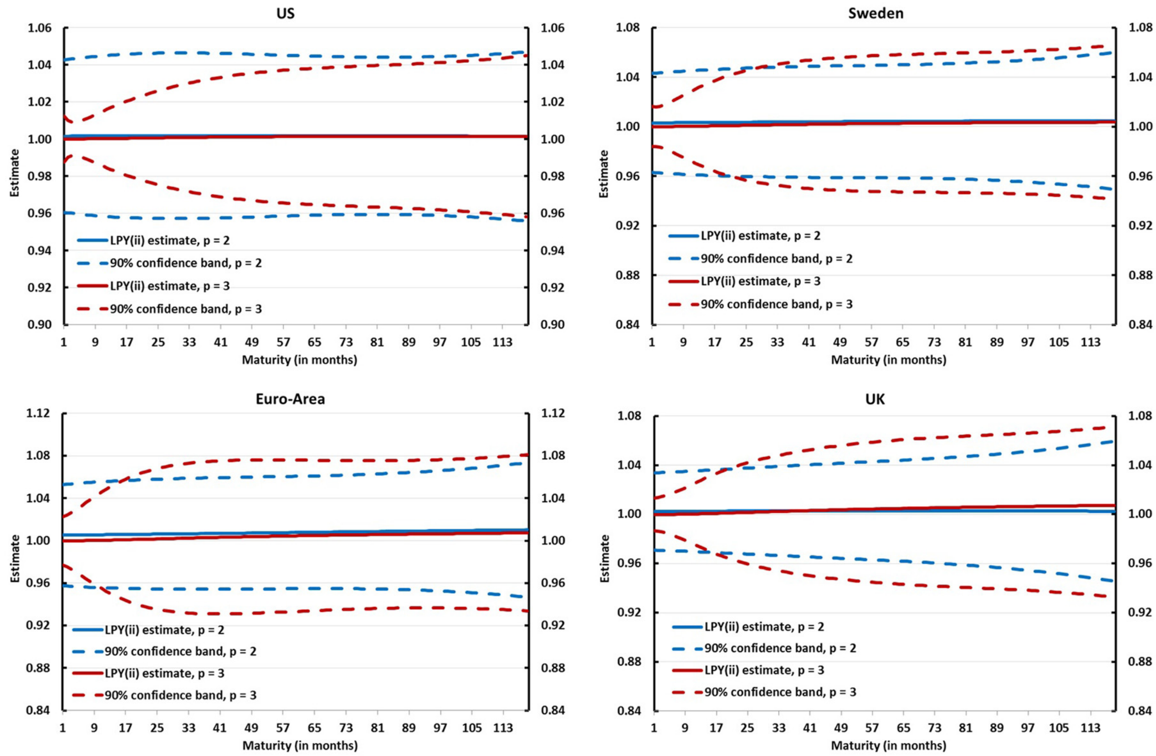


Fig. 3. LPY(ii) test of model adequacy. *Notes:* This figure shows results of the LPY(ii) test of model adequacy. The LPY(ii) test estimate is the coefficient ϕ^n of the regression $y_{t+1}^{n-1} - y_t^n - E_t\left(rx_{t+1}^n\right)/(n-1) = \alpha^n + \phi^n(y_t^n - r_t)/(n-1) + \xi_t^n$, where $rx_{t+1}^n = log\left(P_{t+1}^{n-1}/P_t^n\right) - r_t$. The model is able to adequaly capture the dynamics of term premia when $\widehat{\phi^n} = 1$. Decompositions are obtained using the Joslin et al. (2011) model with two $(p = 2)$ and three $(p = 3)$ pricing factors. Dashed lines are 90% confidence bands.

recover estimates $\widehat{\phi^n} = 1$. Fig. 3 shows results of the LPY(ii) tests for the four economies. As can be seen, the test generates coefficient estimates $\widehat{\phi^n}$ that are statistically indistinguishable from one.

3.2. Short-rate surprises

As noted in Section 2.3, in order to estimate the shadow rates for the four economies, we need to specify measures of short-rate surprises. For the US, we follow Kuttner (2001) and Gürkaynak et al. (2005), and construct short-rate surprises using interest rate changes for the front contract of the one-month federal funds future. These are measured using a window of ten minutes before and twenty minutes after each monetary policy announcement. In addition, these changes are scaled to account for the timing of FOMC meetings within the month in which the contract is valid.

Short-rate surprises for Sweden are measured using changes in the one-month STINA (Stockholm Tomorrow Next Interbank Average) interest rate. STINA is an overnight index swap contract that has the T/N STIBOR (Tomorrow Next Stockholm Interbank Offered Rate) interest rate as the underlying rate. Since the STIBOR contract is commonly traded in the interbank market with an interest rate spread of ten basis points above the repo rate, the STINA interest rate becomes a natural candidate for measuring conventional monetary policy surprises. We use a window of fifteen minutes before and two hours and forty five minutes after each monetary policy announcement, in addition to adjustment terms that take into account the timing of the implementation of the repo rate within the month of the contract.

Short-rate surprises for the euro area are measured using interest rates for the front contract of the three-month Euribor future, which is considered to be a reliable predictor for policy rates in the euro area Bernoth and Von Hagen (2004). In this paper, we follow Bredin et al. (2009) and Haitsma et al. (2016) and use daily interest rates changes.

For the UK we use one-day interest rate changes for the front contract of the three-month short-sterling future, as a long-history of overnight swap or Bank Rate future rates are not available (see Miranda-Agrippino, 2017). These contracts settle based on the three-month interbank (GBP) Libor rate rather than on overnight rates, but are much more liquid and available for a much longer history. Furthermore, as suggested by Joyce et al. (2008), their forecasting performance is only slightly inferior to the performance of overnight swap rates.[11]

3.3. Monetary policy announcements

For computing the US shadow rate, we use the key monetary policy announcements made by the Fed since September 15, 2008, when Lehman Brothers filled for bankruptcy and the Fed loosened lending restrictions to banks. These are listed in Tables 1 and 2, and include announcements that involved balance sheet expansions, forward guidance, tapering, balance sheet contractions and repurchase agreement operations. We also include the more recent announcements of rises and cuts in the fed funds target rate, as these may provide some guidance on future interest rate and balance sheet policies, as well as the announcements of all policies following the Covid-19 crises.

For estimating the Swedish shadow rate we use all the monetary policy announcements made by the Riksbank since its bond purchase program was launched in February 2015. As can be seen from Tables 3 and 4, in addition to its conventional monetary policy tool, the repo rate, the Riksbank has been using

[11] The appendix show details on how the short-rate surprise measures for the four economies are computed. The window sizes differ due to availability of data.

Table 1
Monetary policy announcements by the Fed. *Notes:* This table describes the key monetary policy announcements by the Fed since the launch of its unconventional monetary policy measures.

Date	Announcement description
Sep 15, 2008	Fed loosens lending restrictions to banks. Lehman Brothers files for bankruptcy
No. 25, 2008	QE1 announcement: Fed to purchase up to $500 billion in MBS and $100 billion in GSE debt
Dec 1, 2008	Announcement indicating potential purchases of Treasury securities
Dec 16, 2008	Fed sets the range of 0% to 0.25% for the federal funds rate, and mentions that it could purchase long-term Treasury securities
Mar 18, 2009	QE1 extension. Fed to purchase $300 billion in Treasuries, additional $750 billion in MBS and $100 billion in agency debt
Aug 10, 2010	Fed to continue rolling over its holdings of Treasury securities as they mature
Aug 27, 2010	Bernanke foreshadows QE2 at Jackson Hole
Sep 21, 2010	Fed to continue rolling over its holdings of Treasury securities as they mature and is prepared to provide additional stimulus
Oct 15, 2010	Bernanke indicates that monetary easing will continue
No. 3, 2010	Announcement of QE2. Purchase of $600 billion in longer dated treasuries, at $75 billion per month
Dec 14, 2010	Fed to retain the fed funds target rate near 0 percent “for an extended period”
Aug 9, 2011	Fed announces first explicit calendar forward guidance (mid-2013)
Sep 21, 2011	Announcement of the “Operation-Twist”
Jan 25, 2012	Extension of calendar-based forward guidance to late-2014
Aug 31, 2012	Bernanke announces intention for further action at Jackson Hole
Sep 13, 2012	Extension of calendar-based forward guidance to mid-2015. Announcement of QE3. $40 billion per month in MBS
Dec 12, 2012	QE3 extension. Fed to purchase additional $45 billion per month of Treasury securities
May 22, 2013	Bernanke foreshadows the potential tapering of QE3
Dec 18, 2013	Fed announces first tapering of QE3 and reduces purchases by $10 billion per month
Jan 29, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Mar 19, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Apr 30, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Jun 18, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Jul 30, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Sep 17, 2014	Fed announces tapering of QE3 and reduces purchases by $10 billion per month
Oct 29, 2014	Fed announces last tapering of QE3 and reduces purchases by $15 billion per month
Oct 28, 2015	Fed leaves fed funds target rate unchanged and hints at possible hike in December 2015
Dec 16, 2015	Fed increases the fed funds target rate to the range of 0.25% - 0.5%
Dec 14, 2016	Fed increases the fed funds target rate to the range of 0.5% - 0.75%
Mar 15, 2017	Fed increases the fed funds target rate to the range of 0.75% - 1.0%
Apr 5, 2017	Minutes indicating that balance sheet contraction may start in late 2017
May 3, 2017	Fed keeps the fed funds target rate in the range 0.75% - 1.0%
Jun 14, 2017	Fed increases the fed funds target rate to the range of 1.0% - 1.25% and reveals plans to contract its balance sheet
Jul 26, 2017	Fed keeps the fed funds target rate in the range of 1.0% to 1.25%
Sep 20, 2017	Fed keeps the fed funds target rate in the range of 1.0% - 1.25% and announces balance sheet contraction
Dec 13, 2017	Fed increases the fed funds target rate to the range of 1.25% - 1.5% and the pace of balance sheet contraction
Mar 21, 2018	Fed increases the fed funds target rate to the range of 1.5% - 1.75% and the pace of balance sheet contraction

at least three additional unconventional policy instruments: asset purchases, communication, and forward guidance, which has been provided mainly through its published repo rate path.[12] In addition, we include the announcements of policies aimed at providing liquidity to banks and companies during the Covid-19 crisis, the Riksbank's extended asset purchase program to purchase government, municipal and mortgage bonds, and commercial paper, as well as the announcements of recent repo rate increases.

The ECB has provided unconventional stimulus through a number of measures (see Table 5). These involved liquidity provisions to improve the functioning of the interbank market and intermediation, and asset purchases that were designed to lower the borrowing costs of banks, firms and governments in the euro area (CBPP1, CBPP2, CBPP3, LTROs, OMT, SMP), and to provide further monetary easing in a lower bound environment (EAPP). In addition, we include the announcements that involved a reduction in the pace of the ECB asset purchase program, starting from late 2016, and its reinvestment policy, and the various measures to fight the Covid-19 crisis (additional LTROs, PEPP, TLTRO, PELTRO, among others).

A large part of the unconventional measures in the UK has been provided through the purchase of assets such as government and corporate bonds. For estimating shadow rates for the UK we then use all the monetary policy announcements that involved asset purchases. In addition, we include the announcement by the British Government when it launched a bank support package of £500 billion in October 2008, with £200 billion made available through Bank of England's Special Liquidity Scheme. We also include the announcement of the result in the Brexit referendum, which may have led market participants to price in additional monetary accommodation by the Bank of England, and that in fact happened in August 2016. We also include the more recent announcements of Bank Rate increases, those in which the Bank of England provided some guidance on the reduction of its stock of purchased assets, and all the announcements of the expansionary policies following Covid-19 such as Bank Rate cuts, further asset purchases, TSFME, CcyB, CCFF, CTRF, W&M, among others (see Table 6).

4. Shadow rate estimates

4.1. Shadow rate estimates

In this section, we describe the estimated shadow rates for the four economies. Table 7 provides the parameter estimates for regressions (8) and (9), estimated over the pre-lower bound samples, when the relationship between the short-rate, short-rate expectations and yields clearly existed. As can be seen, both $\triangle X^{sr}_{1t}$ and $\triangle X_{1t}$ respond significantly to short-rate surprises for all economies, with R^2 values ranging from 0.20 to 0.74. These determine the link between the short-rate, and the term structures of yields and short-rate expectations.

4.1.1. United States

The estimated shadow rates using the two and three-factor models for the US are shown in Fig. 4. As can be seen, the two

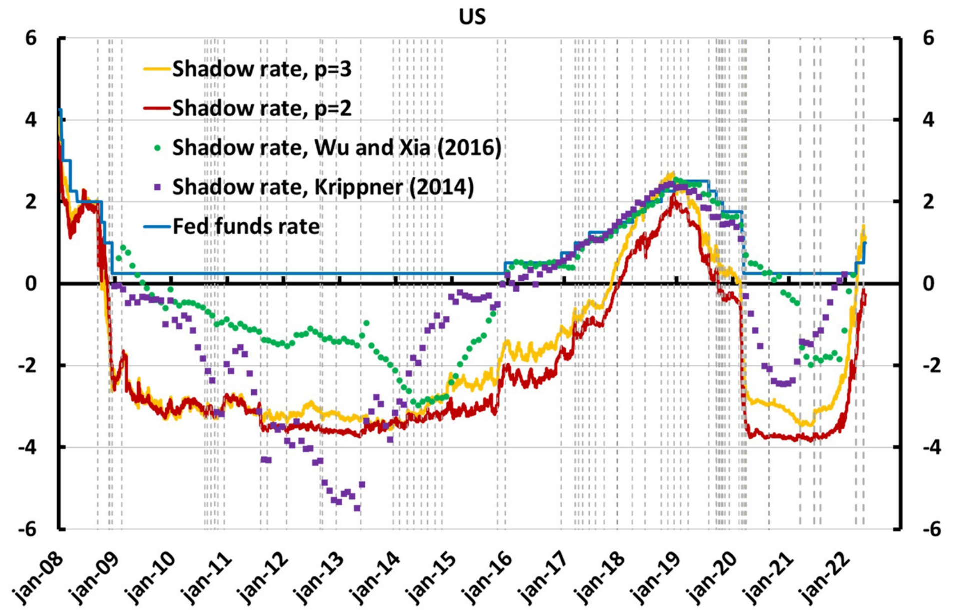
[12] Norges Bank and the Reserve Bank of New Zealand are among the other central banks that use policy rate paths to manage policy rate expectations.

Table 2
Monetary policy announcements by the Fed, continued. *Notes:* This table describes the key monetary policy announcements by the Fed since the launch of its unconventional monetary policy measures.

Date	Announcement description
Jun 13, 2018	Fed increases the fed funds target rate to the range of 1.75%–2.0% and the pace of balance sheet contraction
Sep 26, 2018	Fed increases the fed funds target rate to the range of 2.0%–2.25% and the pace of balance sheet contraction
No. 8, 2018	Fed resumes discussion on long-run monetary policy implementation frameworks
Dec 19, 2018	Fed increases the fed funds target rate to the range of 2.25%–2.5% and discusses levels of excess reserves and balance sheet composition in the long-run
Jan 30, 2019	Fed issues statement on monetary policy implementation and balance sheet normalization
Mar 20, 2019	Fed issues its principles and plans for balance sheet normalization
Jul 31, 2019	Fed lowers the fed funds target rate to the range of 2.0%–2.25%, and to conduct repurchase agreement (repo) operations
Sep 18, 2019	Fed lowers the fed funds target rate to the range of 1.75%–2.0%
Sep 20, 2019	Fed to conduct overnight and term repurchase agreement (repo) operations of at least $75 and $30 billion each
Oct 4, 2019	Fed to conduct overnight and term repurchase agreement (repo) operations of at least $75 and $35 billion each
Oct 11, 2019	Fed to purchase $60 billion of Treasury bills per month
Oct 23, 2019	Fed to conduct overnight and term repurchase agreement (repo) operations of at least $120 and $45 billion each
Oct 30, 2019	Fed lowers the fed funds target rate to the range of 1.5% - 1.75%
No. 14, 2019	Fed announces it will conduct longer-term repurchase agreement (repo) operations
Dec 12, 2019	Fed to conduct overnight and (longer-)term repurchase agreement (repo) operations of at least $150 and ($50) $75 billion each
Feb 13, 2020	Fed to conduct overnight and term repurchase agreement (repo) operations of at least $100 and $25 billion each
Mar 3, 2020	Fed lowers the fed funds target rate to the range of 1%–1.25%
Mar 9, 2020	Fed to conduct overnight and term repurchase agreement (repo) operations of at least $150 and $45 billion each
Mar 11, 2020	Fed to conduct overnight and (longer-)term repurchase agreement (repo) operations of at least $175 and ($50) $45 billion each
Mar 12, 2020	Fed to conduct one- and three-month repurchase agreement (repo) operations of at least $500 billion each and to purchase $60 billion of Treasury securities per month across maturities
Mar 15, 2020	Fed lowers the fed funds target rate to the range of 0%–0.25%, and announces the purchase of $500 billion in Treasuries and $200 billion in MBS, expanded repurchase agreement operations, foreign dollar swap lines, a credit facility for commercial banks, and reserve requirement ratio of 0%
Mar 16, 2020	Fed to conduct additional overnight repurchase agreement (repo) operations amounting to $500 billion
Mar 17, 2020	Fed to conduct additional overnight repurchase agreement (repo) operations, and lauches Commercial Paper Funding Facility (CPFF) and Primary Dealer Credit Facility (PDCF)
Mar 18, 2020	Fed announces Money Market Mutual Fund Liquidity Facility (MMLF)
Mar 19, 2020	Fed announces US dollar swap lines with 9 other central banks
Mar 23, 2020	Fed announces open-ended purchase of Treasuries and MBS, introduces Primary and Secondary Market Corporate Credit Facility, Term Asset-Backed Securities Loan Facility (TALF), and expands MMLF and CPFF
Mar 31, 2020	Fed announces a temporary repurchase agreement facility for international monetary authorities (FIMA Repo Facility)
Apr 9, 2020	Fed expands PMCCF, SMCCF as well as TALF
Aug 27, 2020	Fed updates its statement on longer-run goals and monetary policy strategy
Dec 16, 2020	Fed to increase its SOMA holdings of Treasury securities by $80 billion and MBS by $40 billion
Mar 17, 2021	Fed to conduct overnight reverse repo at a rate of 0% and with a per-counterparty limit of $80 billion per day
Jun 16, 2021	Fed to conduct overnight reverse repos at a rate of 0.05% and with a per-counterparty limit of $80 billion per day
Jul 28, 2021	Fed to conduct overnight repos at a minimum rate of 0.25% and with an aggregate operation limit of $500 billion
Mar 16, 2022	Fed raises the fed funds target rate to the range of 0.25%–0.5%, to conduct overnight repos at a minimum rate of 0.5%, to conduct overnight reverse repos at a rate of 0.3% and with a per-counterparty limit of $160 billion per day
May 4, 2022	Fed raises the fed funds target rate to the range of 0.75%–1.0%

Table 3
Monetary policy announcements by the Riksbank. *Notes:* This table describes the key monetary policy announcements by the Riksbank since the launch of its unconventional monetary policy measures.

Date	Announcement description
Feb 12, 2015	Riksbank cuts repo rate to −0.10%, buys government bonds for SEK 10 billion and is prepared to do more at short notice
Mar 18, 2015	Riksbank cuts repo rate to −0.25% and buys government bonds for SEK 30 billion
Apr 29, 2015	Riksbank buys government bonds for SEK 40–50 billion and lowers the repo-rate path significantly
Jul 2, 2015	Repo rate cut to −0.35% and purchases of government bonds extended by SEK 45 billion
Sep 3, 2015	Repo rate unchanged at −0.35%
Oct 28, 2015	Riksbank purchases government bonds for a further SEK 65 billion and keeps the repo rate at −0.35% for a longer time
Dec 15, 2015	Repo rate unchanged at –0.35% and the Riksbank is still highly prepared to act
Feb 11, 2016	Repo rate cut to −0.50%
Apr 21, 2016	Riksbank to purchase government bonds for a further SEK 45 billion and repo rate held unchanged at -0.50%
Jul 6, 2016	Repo rate unchanged at -0.50%, future rate increases postponed
Sep 7, 2016	Repo rate unchanged at −0.50%
Oct 27, 2016	Low repo rate for longer, Executive Board ready to extend government bond purchases in December
Dec 21, 2016	Further purchases of government bonds for SEK 30 billion, repo rate unchanged at -0.50%
Feb 15, 2017	Repo rate unchanged at −0.50%
Apr 27, 2017	Government bond purchases extended by SEK 15 billion, repo rate unchanged at -0.50%, rate increases postponed
Jul 4, 2017	Repo rate unchanged at −0.50% and bond purchases according to plan
Sep 7, 2017	Repo rate unchanged at −0.50% and bond purchases according to plan
Oct 26, 2017	Repo rate unchanged at −0.50%
Dec 20, 2017	Repo rate unchanged at −0.50%, and bond reinvestments starting in January 2018
Feb 14, 2018	Repo rate unchanged at −0.50%
Apr 26, 2018	Repo rate unchanged at −0.50%, increase not expected until towards end of year
Jul 3, 2018	Repo rate unchanged at −0.50%
Sep 6, 2018	Repo rate unchanged at −0.50%, but expected to raise by 0.25% either in December or February
Oct 24, 2018	Repo rate unchanged at −0.50%, but will be raised by 0.25% either in December or February
Dec 20, 2018	Repo rate raised to −0.25%. Next repo rate rise is likely to occur during the second half of 2019



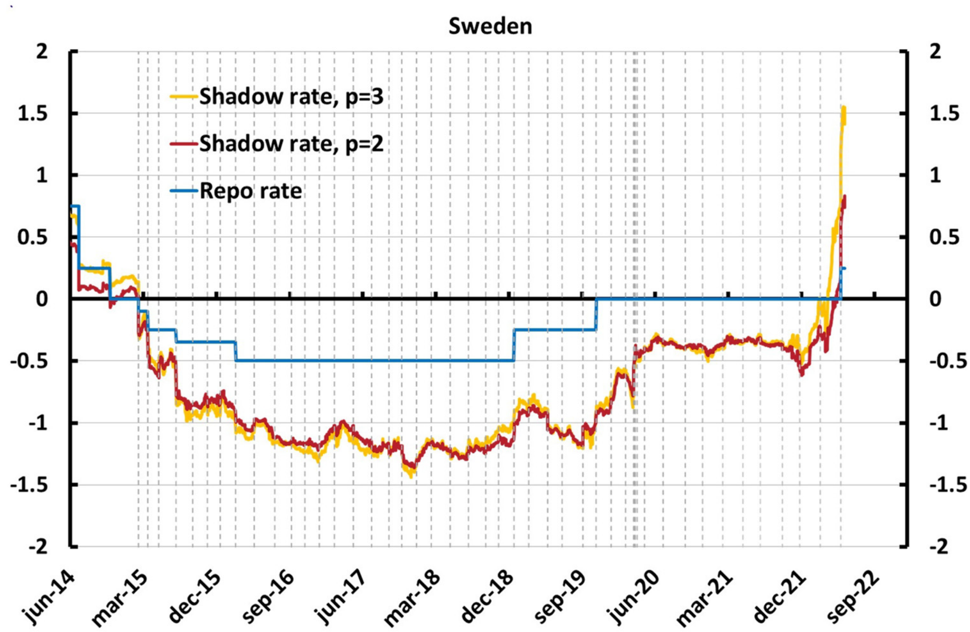


Fig. 4. Shadow rate estimates for the US and Sweden. *Notes:* This figure shows shadow rate estimates for the US and Sweden. Dashed vertical lines indicate the unconventional monetary policy announcements described in Tables 1, 2 and 3.

estimates lie below the federal funds target rate for most of the unconventional period, suggesting that the unconventional measures implemented by the Fed eased monetary conditions in the US. Shadow rates fall as market participants price in new information about the expansionary policies implemented by the Fed, such as QE1, QE2, QE3, forward guidance, the last interest rate cuts, and the unprecedented policies to ease monetary and financial conditions during Covid-19. They also rise as market participants expect monetary policy to become more contractionary, as around the announcements of tapering, interest rate hikes and balance sheet contractions.

Tables 8 and 9 show how the shadow rates responded to the unconventional policy announcements that are listed in Tables 1 and 2. These responses better identify how the stance of monetary policy has changed with these policies. As can be seen, the US shadow rates responded strongly to the first five announcements related to QE1 and the bankruptcy of Lehman Brothers. Since short-rate surprises were small - except on December 16, 2008 - these movements can be almost fully attributed to unconventional policy. The US shadow rates responded more mildly to the subsequent announcements of QE2 and QE3.

Other important events with significant responses of Treasury yields are Ben Bernanke's speech at the Jackson Hole conference on August 27, 2010 and the two forward-guidance announcements made on December 14, 2010 and August 9, 2011. As can be seen from Table 8, the shadow rates increased following Bernanke's speech and the first forward-guidance announcement, but dropped by 27.6 basis points after the Fed announced that it would keep the fed funds target rate at zero until mid-2013. As shown in Fig. 4, shadow rates remained low and stable after that event, suggesting

Table 4
Monetary policy announcements by the Riksbank, continued. *Notes:* This table describes the key monetary policy announcements by the Riksbank since the launch of its unconventional monetary policy measures.

Date	Announcement description
Feb 13, 2019	Repo rate unchaged at −0.25%. Next repo rate rise is likely to occur during the second half of 2019
Apr 25, 2019	Repo rate unchaged at −0.25%. Next repo rate rise is likely to occur at the end of 2019, or early 2020
Jul 3, 2019	Repo rate unchaged at −0.25%. Next repo rate rise is likely to occur at the end of 2019, or early 2020
Sep 5, 2019	Repo rate unchaged at −0.25%. Next repo rate rise is likely to occur at the end of 2019, or early 2020
Oct 24, 2019	Repo rate unchaged at −0.25% and expected to be raised to 0% in December
Dec 19, 2019	Repo rate raised to 0% and expected to remain at 0% in the coming years
Feb 12, 2020	Repo rate unchanged at 0% and expected to remain at 0% in the coming years
Mar 13, 2020	Riksbank to lend up to SEK 500 billion to safeguard credit supply
Mar 16, 2020	Riksbank to offer increased loans to banks on favourable terms. During 2020, it also intends to buy government, municipal and mortgage bonds for up to an additional SEK 300 billion
Mar 19, 2020	Riksbank will enable loans in US dollars to ensure its continued supply for Swedish companies. Limit rules for mortgage bonds to be used as colateral are removed in order to facilitate lending to banks. Riksbank also intends to buy commercial paper within its SEK 300 billion asset purchase program
Mar 20, 2020	In addition, to government, municipal and covered bonds, Riksbank to purchase also securities issued by non-financial corporations within its SEK 300 billion asset purchase program
Mar 26, 2020	Riksbank to also purchase commercial paper within its SEK 300 billion asset purchase program
Apr 22, 2020	Riksbank to purchase bonds issued by Swedish municipalities and regions, by Kommuninvest i Sverige AB by a nominal amount of SEK 15 billion
Jul 1, 2020	Riksbank to extend its asset purchases from SEK 300 billion to SEK 500 billion
Sep 22, 2020	Riksbank to keep stimulus in the form of low interest rates and large amount of liquidity for the foreseeable future. It is also prepared to do more to provide support to the economy and inflation, including cutting the repo rate if necessary
No. 26, 2020	Riksbank to extend asset purchases to up to SEK 700 billion up to December 31, 2021 Programme now also includes treasury bills, and sovereign and municipal green bonds.
Feb 10, 2021	Riksbank keeps repo rate at zero and purchases of assets within its SEK 700 billion package
Apr 27, 2021	Riksbank keeps repo rate at zero and purchases of assets within its SEK 700 billion package
Jul 1, 2021	Riksbank keeps repo rate at zero and purchases of assets within its SEK 700 billion package to sustain inflation at 2%
Sep 21, 2021	Riksbank keeps repo rate at zero and plans to keep its security holdings more or less unchanged during 2022
No. 25, 2021	Repo rate to be raised later in 2024 and plans to keep its security holdings roughly unchanged during 2022
Feb 10, 2022	Repo rate to be raised later in 2024 and plans to keep its security holdings roughly unchanged during 2022
Apr 28, 2022	Repo rate raised to 0.25% and expected to be below 2% in three years time. Pace of asset purchases is reduced

that the Fed was successful in lowering uncertainty about future interest rate policy, keeping policy rate expectations low and stable for some time.

The stance of monetary policy in the US started changing after May 22, 2013, when Bernanke announced the potential tapering of QE3, which led long-term yields to rise during the "taper tantrum" episode in mid-2013. After that date, it is possible to identify a number of contractionary announcements by the Fed: (i) QE3 tapering, (ii) interest rate hikes, and (iii) the announcements involving balance sheet contractions starting from mid-2017, which mostly led the shadow rates to rise. Interestingly, the US shadow rates rose substantially faster from the date when the Fed started contracting its balance sheet in September 20, 2017. Right after the last interest rate hike on December 19, 2018 the shadow rates started dropping again, with market participants already pricing in future monetary easing by the Fed, which in fact came with the interest rate cuts announced on July 31, 2019 and September 18, 2019, followed by a series of repurchase agreement operations. Unprecedented monetary and financial easing has also been provided in response to the Covid-19 crisis, with shadow rates reacting strongly to various announcements as, for instance, the open-ended purchase of Treasuries and MBS announced on March 23, 2020. More recently, as inflation has risen sharply, the Fed has announced monetary tightening through increases in the fed funds rate and balance sheet contractions, with the shadow rate responding accordingly.

It is also interesting to compare our estimates with alternative estimates available in the literature, such as the ones by Wu and Xia (2016) and Krippner (2014). Both alternative estimates suggest sizable monetary stimulus when the lower bound is binding, in the period 2009–2015, but equal the fed funds rate otherwise. Our shadow rates respond strongly in the first four expansionary announcements made by the Fed, suggesting that QE was particularly expansionary at its start. They are also able to track quite well the contraction of the US monetary policy stance during the tapering of QE3, increasing during that period, and on most announcements. The (Wu and Xia, 2016) shadow rate shows a sharp decline during this period, whereas (Krippner, 2014) estimates also start rising as soon as Bernanke announced the potential tapering of QE3 on May 22. Another distinctive feature of our estimates is that they do not equal the short-rate when the Fed started hiking its policy rate in late 2015, being able to capture the interest rate effects of the balance sheet contractions and further policy rate increases that were announced later on. In addition, they suggest that the policies implemented in response to the Covid-19 crisis were extremely expansionary. These are better captured by our estimates than those provided by Krippner (2014) and Wu and Xia (2016), which have remained fairly close to the fed funds rate, in particular during the lift-off period of 2016–2018. As the alternative estimates respect the lower bound constraint and necessarily equal the observed short-rate as soon as the lower bound is not binding, they are somewhat unable to capture the interest rate effects of unconventional policies that have continued to be used during the whole unconventional period starting from 2007 to 2008, especially when the Fed exited the lower bound.

4.1.2. Sweden

The shadow rate estimates for Sweden are shown in Fig. 4. As can be seen from the two estimated shadow rates, the unconventional policies by the Riksbank have provided additional monetary stimulus compared to the repo rate since February 2015. We can also study the expansionary interest rate effects of the unconventional policies in Sweden by looking at how the shadow rates respond to monetary policy announcements. In order to do so, we focus here on the responses to announcements that involved bond purchases only, with numbers being provided by Tables 10 and 11.

The announcement of February 12, 2015 marks the start of the bond purchase program in Sweden. The repo rate was lowered to −0.10 percent on that day, informing market participants that the Riksbank could set negative interest rates and make conventional

Table 5
Monetary policy announcements by the ECB. *Notes:* This table describes the key monetary policy announcements made by the ECB since the launch of its unconventional monetary policy measures.

Date	Announcement description
May 7, 2009	ECP lowers policy rates, announces its first Covered Bond Purchase Program (CBPP1) and LTRO with 1-year maturity
May 10, 2010	Securities Markets Program (SMP)
Oct 6, 2011	Second Covered Bond Purchase Program (CBPP2)
Dec 8, 2011	ECB announces LTROs with 3-years maturity
Sep 6, 2012	Outright Monetary Transactions (OMT) program
Jun 5, 2014	ECP lowers policy rates and announces its Asset-Backed Securities Purchase Program (ABSPP)
Sep 4, 2014	ECP lowers policy rates and announces its third Covered Bond Purchase Program (CBPP3)
Dec 4, 2014	ECB does not announce its Expanded Asset Purchase Program (EAPP) and frustrates market participants
Jan 2, 2015	Draghi hints that ECB is in technical preparations to adjust the size, speed and composition of its stimulus program
Jan 22, 2015	EAPP is announced. ECB to buy € 60 billion per month until September 2016
Sep 3, 2015	Draghi hints at further purchases if necessary
Oct 22, 2015	Draghi hints at further measures to be announced in December 2015
Dec 3, 2015	ECB lowers its deposit facility rate and extends EAPP to March 2017
Jan 21, 2016	ECB signals more easing to come as early as March 2016
Feb 18, 2016	ECB minutes indicate further actions to be announced in March 2016
Mar 10, 2016	ECP lowers policy rates and expands EAPP to € 80 billion per month, which is expected to last until March 2017
Apr 21, 2016	Corporate Sector Purchase Program (CSPP)
Sep 8, 2016	ECB surprises by not announcing EAPP extension
Oct 20, 2016	ECB hints at EAPP extension to be announced in December 2016
Dec 8, 2016	EAPP extended to December 2017, but purchases reduced to € 60 billion per month
Jun 27, 2017	Draghi's speech in Sintra reveals that ECB is considering scaling back its EAPP
Sep 7, 2017	ECB leaves rates on hold and paves its way to tapering its stimulus program
Oct 26, 2017	Purchases under EAPP extended to September 2018, but reduced to € 30 billion per month from January 2018 Reinvestments of principal payments from maturing securities to happen for an extended period of time after September 2018
Jun 14, 2018	Purchases under EAPP to end in December 2018, but reduced to € 15 billion per month from October 2018
Sep 13, 2018	ECB confirms that asset purchases under EAPP will decline to € 15 billion per month until December 2018
Oct 25, 2018	Purchases under EAPP to end in December 2018 provided that incoming data confirm the expected medium term outlook
Dec 13, 2018	ECB to keep key interest rates at their present levels at least through the summer of 2019. Purchases under EAPP will end in December 2018. Reinvestments to continue for an extended period of time past the date when key interest rates are increased
Mar 7, 2019	ECB announces its TLTRO-III program to start in September 2019 and end in March 2021, with a maturity of 2-years
Jun 18, 2019	Draghi's speech in Sintra reveals that additional stimulus is needed if outlook does not improve
Jul 25, 2019	ECB keeps policy on hold, but signals additional future stimulus
Sep 12, 2019	ECB announces -10 bps cut to its deposit rate, € 20 billion per month (EAPP), tiering system, and lower rates under TLTRO III
Mar 2, 2020	Lagarde states that ECB is closely monitoring developments related to Covid-19 and is ready to act
Mar 12, 2020	ECB announces additional LTROs for banks, more favorable LTROIII terms in upcoming operations, additional € 120 billion asset purchases until the year end, temporary capital, and operational relief to banks
Mar 18, 2020	ECB announces € 750 billion Pandemic Emergency Purchase Programme (PEPP)
Apr 30, 2020	Conditions on the TLTROIII are further eased, and new series of non-targeted PELTROs are announced PEPP to continue to be conducted in a flexible manner over time, across asset classes and among jurisdictions
Jun 4, 2020	PEPP increased by € 600 billion to € 1350 billion, with net purchases to happen at least until the end of June 2021. Maturing principal payment of securities purchased will be reinvested until at least the end of 2022
Dec 10, 2020	Easing package: (i) PEPP increased to € 1850 billion, and extended until the end of March 2022. (ii) Reinvestments extended until the end of 2023. (iii) TLTROIII conditions further eased. (iv) Duration of collateral easing measures extended. (v) Four additional PELTROs announced. (vi) EUREP, temporary swap and repo lines with non-euro area central banks extended until March 2022
Dec 16, 2021	Net purchases under APP at € 40 and € 30 billion per month in early 2022 and € 20 billion from October 2022 No scheduled end date for reinvestments under APP. Reinvestments under PEPP to continue at least until the end of 2024
Mar 10, 2022	Russian invasion of Ukraine. Net purchases under APP at € 40, € 30 and € 20 billion per month in April, May and June 2022 Eurosystem repo facility for central banks (EUREP) until 15 January 2023

monetary policy more expansionary. We see a fairly large response of shadow rates, which declined by 26.9 basis points. This is only partially explained by the interest rate cut. The repo rate surprise measure is −5.9 basis points, with the rest being largely attributed to the bond purchase announcement, as market newsletters collected before the decision suggest that the announcement of SEK 10 billion was a full surprise.[13] However, we believe that an additional effect came from the Riksbank setting a negative repo rate for the first time in history. Our interpretation is that breaking the zero lower bound worked as an additional tool of unconventional monetary policy, with repo rate expectations becoming particularly unconstrained after that date.

Other important expansionary announcements were made on March 18, 2015, July 2, 2015, October 28, 2015 and April 27, 2017, when market participants were surprised by repo rate cuts and/or bond purchases. The first two announcements had strong impacts on yields, leading the shadow rates to decline by 22.8 and 21.2 basis points. The other two announcements affected mostly the long-end of the Swedish yield curve, with shadow rates declining by 7 and 8 basis points, respectively. Notice also that the declines in shadow rates were larger than the surprises in the repo rate, suggesting that bond purchases and forward guidance were successful in lowering the stance of monetary policy in Sweden.

Contractionary announcements can be seen on April 29, 2015, April 21, 2016, December 20, 2018 and April 28, 2022, with positive responses of shadow rates. This can be mainly attributed to market participants being surprised by the Riksbank not cutting the repo rate ($\triangle r_t^u = 7.3$ basis points on April 29, 2015), by announcing increments in bond purchases that were smaller than expected, and by raising the repo rate. The announcement made on September 5, 2019, when the Riksbank reasserted that it would raise its policy rate within the next six months was also largely contractionary,

[13] Information about QE expectations is collected from market newsletters before every monetary policy announcement. Market participants providing such information include Nordea, Handelsbanken, SEB, Swedbank, Citibank, Danske Bank, JP Morgan, Nykredit, RBS and Goldman Sachs. We construct a measure of QE surprise by subtracting the average of QE expectations from the announced amount of bond purchases.

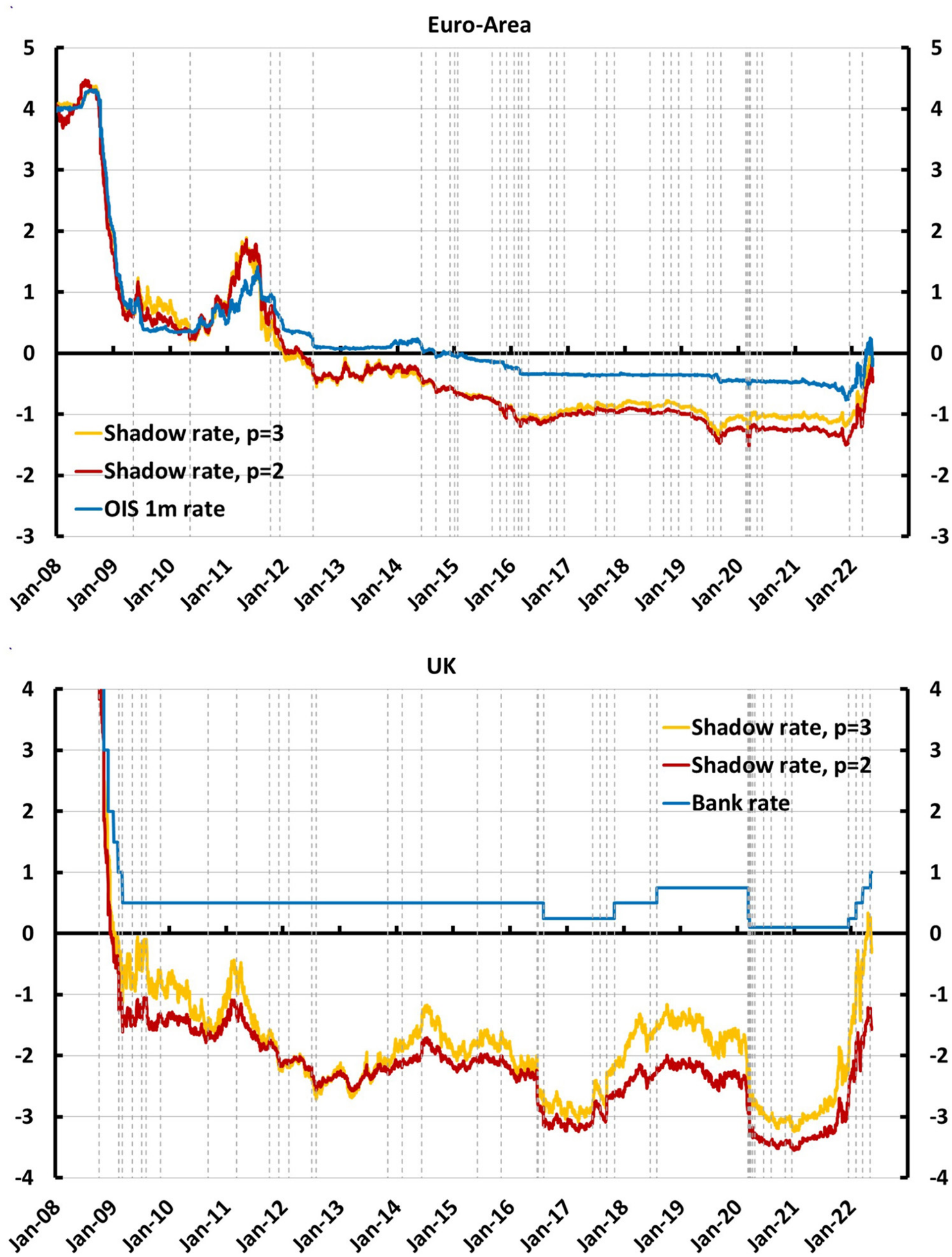


Fig. 5. Shadow rate estimates for the euro area and the UK. *Notes:* This figure shows shadow rate estimates for the euro area and the UK. Dashed vertical lines indicate the unconventional monetary policy announcements described in Tables 4 and 5.

with shadow rates raising by 14.9 basis points. Swedish shadow rates also show positive responses in the start of the Covid-19 crisis, but this seems to be linked to the overall stress in the Swedish and international markets.

Interestingly, we can also use the shadow rate estimates to provide an estimate of the interest rate effect of an unanticipated bond purchase announcement of SEK 10 billion in terms of the repo rate. We use five announcements in which we can clearly identify the effects of bond purchases: March 18, 2015, July 2, 2015, October 28, 2015, April 21, 2016 and April 27, 2017. We calculate the shadow rate responses minus the repo rate surprises provided in Table 10, $\triangle s_{t^\star} - \triangle r^u_{t^\star}$, and scale them in terms of a suprise of SEK 10 billion in purchases obtained from market newsletters and also provided in Table 9. We find: −2.7, −2.8, −3.7, −2.2 and −4.8 basis points, which give an average response of −3.3 basis points in repo rate terms, that is, an unanticipated bond purchase announcement of SEK 10 billion is equivalent to lowering the repo rate by 3.3 basis points.

4.1.3. Euro area

The ECB has been using a number of unconventional measures, and we set the date on which the ECB launched its first covered bond purchase program, May 7, 2009, as the date marking the unconventional period. This date is also quite close to the day on which the deposit facility rate was lowered to 0.25 percent, April 8, 2009. The estimated shadow rates for the euro area are shown in Fig. 5. As can be seen, there is a clear downward trend in the estimates, which is only interrupted by the interest rate hikes from late 2010 to late 2011, and by the mild increase in the period from the end of 2016 to the end of 2018, when the pace of ECB's Expanded Asset Purchase Program (EAPP) was reduced. The estimated shadow rates lie well below the one-month OIS interest

Table 6
Monetary policy announcements by the Bank of England. *Notes:* This table describes the key monetary policy announcements made by the Bank of England since the launch of its unconventional monetary policy measures.

Date	Announcement description
Oct 8, 2008	Bank support package of £500 billion. £200 billion is made available through Bank of England's Special Liquidity Scheme
Feb 11, 2009	Press conference and Inflation Report indicate that asset purchases were likely
Mar 5, 2009	Bank of England cuts Bank Rate to 0.5% and announces asset purchases of £75 billion within the next three months
May 7, 2009	Bank of England to buy additional £50 billion in assets. Total of £125 billion to be completed within the next three months
Jul 9, 2009	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £125 billion
Aug 6, 2009	Bank of England to purchase additional £50 billion in assets within the next three months
No. 5, 2009	Bank of England to purchase additional £25 billion in assets within the next three months
Sep 9, 2010	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £200 billion
Mar 10, 2011	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £200 billion
Oct 6, 2011	Bank of England to purchase additional £75 billion in assets
Dec 8, 2011	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £275 billion
Feb 9, 2012	Bank of England to purchase additional £50 billion in assets
Jul 5, 2012	Bank of England to purchase additional £50 billion in assets
Aug 2, 2012	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £375 billion
No. 7, 2013	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £375 billion
Feb 6, 2014	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £375 billion
Jun 13, 2014	Carney states that "Bank Rate may be increased sooner than expected by markets"
Jun 4, 2015	Bank of England keeps Bank Rate at 0.5% and maintains the stock of purchased assets at £375 billion
No. 5, 2015	Bank of England intends not to reduce the stock of purchased assets until Bank Rate is around 2%
Jun 24, 2016	Result of Brexit referendum is announced followed by the resignation of Prime Minister David Cameron
Jun 30, 2016	Carney states that "some monetary easing will likely be required over the summer"
Aug 4, 2016	Bank of England cuts Bank Rate to 0.25%, introduces Term Funding Scheme (TFS), and announces it will purchase up to £10 billion of corporate bonds and an additional of £60 billion of government bonds
Jun 15, 2017	Bank of England keeps Bank Rate at 0.25%, but three MPC members call for an increase to 0.5%
Aug 3, 2017	Bank of England keeps Bank Rate at 0.25%
Sep 14, 2017	Bank of England keeps Bank Rate at 0.25%, but hints at rate rise in the coming months
No. 2, 2017	Bank of England raises Bank Rate to 0.5%
Jun 21, 2018	Bank of England intends not to reduce the stock of purchased assets until Bank Rate is around 1.5%
Aug 2, 2018	Bank of England raises Bank Rate to 0.75%
Mar 11, 2020	Bank of England cuts Bank Rate to 0.25%, announces further term funding scheme (TFSME), and reduces CCyB to 0% Chancellor announces UK Budget, with £30 billion in stimulus consisting of "largest sustained fiscal boost for 30 years"
Mar 17, 2020	Chancellor announces measures to support economy, including Covid Corporate Financing Facility (CCFF) for commercial paper purchases. Total direct fiscal stimulus of £50 billion in 2020–2021
Mar 19, 2020	Bank of England cuts Bank rate to 0.1%, and to purchase additional £200 billion in government and corporate bonds
Mar 20, 2020	Chancellor announces "unprecedented" package of economic measures, including wage support for employees
Mar 24, 2020	Bank of England launches Contingent Term Repo Facility (CTRF)
Mar 30, 2020	Bank of England extends Contingent Term Repo Facility (CTRF)
Apr 9, 2020	HM Treasury and Bank of England announce temporary extension to Ways and Means (W&M) facility
Apr 24, 2020	Bank of England extends Contingent Term Repo Facility (CTRF)
Jun 18, 2020	Bank of England to purchase additional £100 billion in government bonds
Aug 6, 2020	Bank of England discusses its toolkit and the effectiveness of negative policy rates
No. 5, 2020	Bank of England to increase the target stock of UK government bonds by an additional of £150 billion
Dec 17, 2020	Bank of England to commence the previously announced programme of £150 billion of UK government bonds
Dec 16, 2021	Bank of England raises Bank rate to 0.25%, and to maintain the total stock of assets at £895 billion
Feb 3, 2022	Bank of England raises Bank rate to 0.5%, and to complete the sale of its stock of corporate bonds towards the end of 2023
Mar 17, 2022	Bank of England raises Bank rate to 0.75%
May 5, 2022	Bank of England raises Bank rate to 1.00%

rate for the majority of the time, suggesting that the various unconventional measures implemented by the ECB eased monetary conditions in the euro area.

In Table 12, we see the shadow rate responses to a series of unconventional announcements by the ECB. They moved by not much following most announcements. Clear exceptions are found on October 6, 2011 when the shadow rates increased by 17.2 basis points, an event that can be largely attributed to the surprise in the short-rate that strongly affected the shorter-end of the yield curve. The first extension of the Expanded Asset Purchase Program (EAPP) announced in December 2015 also led the European shadow rates to increase by 21.6 basis points, as the announcement surprised market participants, who expected a larger expansion of the program.

The stance of monetary policy in the euro area started to revert to a contractionary phase around the end of 2016, when market participants started pricing in a reduction in the pace of EAPP purchases. As the ECB announced the tapering of its asset purchases under EAPP, and gave hints about its reinvestment strategy, the euro area shadow rates increased continuously, as can be seen from Fig. 4. However, they fell again as market participants started pricing in further monetary easing by the ECB during 2019, which came with a series of expansionary measures such as the announcements of TLTRO III, deposit rate cut and additional bond purchases under EAPP. Durind the Covid-19 crisis, European shadow rates declined following Lagarde' s speech on March 2, 2020 and the announcement of further measures on April 30, 2020, but show positive reactions on March 12, 2020 and March 18, 2020, although these moves seem more linked to the overall stress in the European and international markets seen on those days.

4.1.4. United Kingdom

The shadow rates for the UK are shown in Fig. 5. As for other economies, the UK shadow rates show a downward trend, as a result of the highly expansionary measures provided by the Bank of England since 2008, reaching the values of −1.53 (two-factor model) and −0.25 (three-factor model) percent on May 13, 2022.

We can also learn about the behavior of the UK shadow rates by measuring their reactions to the monetary policy announcements made by the Bank of England during its unconventional period. As can be seen from Tables 13 and 14, there were seven announce-

Table 7
Regression results. *Notes:* This table shows estimation results for the regressions $\triangle X_{t^\circ} = \alpha \triangle r^u_{t^\circ} + \epsilon_{t^\circ}$ and $\triangle X^{sr}_{t^\circ} = \beta \triangle r^u_{t^\circ} + \varepsilon_{t^\circ}$, where $\triangle X_{t^\circ}$ and $\triangle X^{sr}_{t^\circ}$ are the changes in the first principal components of the yield curve and its short-rate expectations component. $\triangle r^u_{t^\circ}$ is the unexpected change in the short-rate, or short-rate surprise. The regressions are estimated for the US, Sweden, the euro area and the UK, with data observed on days of conventional monetary policy announcements only. The estimation samples are: February 08, 1990 to October 29, 2008, with a total of 175 observations (US); February 07, 2003 to December 16, 2014, with a total of 76 observations (Sweden); November 08, 2001 to July 3, 2008, with a total of 81 observations (euro area); January 11, 2001 to Ferbuary 5, 2009, with a total of 99 observations (UK). Huber–White heteroskedasticity consistent standard errors are provided in parenthesis.

	α	R2	β $(p=2)$	R2	β $(p=3)$	R2
US	1.018*** (0.270)	0.20	1.282*** (0.276)	0.31	1.241*** (0.232)	0.31
Sweden	1.354*** (0.286)	0.67	1.945*** (0.192)	0.79	1.549*** (0.104)	0.74
Euro area	1.665*** (0.346)	0.32	1.829*** (0.287)	0.55	1.988*** (0.482)	0.36
UK	1.282*** (0.374)	0.35	1.525*** (0.570)	0.29	1.182*** (0.185)	0.46

ments that can be considered strongly expansionary - October 8, 2008, February 11, 2009, March 5, 2009, June 24, 2016, August 4, 2016, March 19, 2020 and March 20, 2020 - and four that can be considered strongly contractionary - July 9, 2009, June 13, 2014, June 15, 2017, September 14, 2017 and February 3, 2022.

On February 11, 2009 the Bank of England suggested that it could buy assets in the near-future. This led the UK shadow rates to fall sharply, by 46.5 basis points. After that, on March 5, 2009, the Bank of England announced its first round of QE together with a cut of 0.5 percent in Bank Rate. According to our estimates, the Bank Rate cut was largely expected by market participants, meaning that the decline of 36.7 basis points in the UK shadow rates can be largely attributed to the QE announcement. Interestingly, the result of the Brexit referendum on June 24, 2016 and the following speech by Carney on June 30, 2016 also caused the UK shadow rates to decline strongly, 43.8 and 10.4 basis points respectively, as market participants priced in future monetary easing, which materialized a few months later with the post-Brexit stimulus package. Still, the announcement of the post-Brexit stimulus package on August 4, 2016 was largely expansionary, with shadow rates declining by 28.6 basis points on that particular day. As the cut of 0.25 percent in Bank Rate was largely expected, the decline in UK shadow rates can be almost fully attributed to the announcement of the various other measures. The announcements of March 10, 2011, June 30, 2016 and August 3, 2017, together with other QE announcements, were also expansionary, with UK shadow rates declining by 11.6, 10.4 and 11.7 basis points, respectively.

The most important contractionary announcements happened on July 9, 2009, June 13, 2014, June 15, 2017, September 14, 2017 and February 3, 2022. On the first date, UK shadow rates increased by 20.3, when market participants were surprised when the Bank of England did not announce additional monetary easing. On June 13, 2014 the shadow rates increased by 17.6 basis points, after Mark Carney stated that Bank Rate would be increased sooner than expected by market participants. The next two announcements are characterized by the Bank of England signaling that Bank Rate could be increased soon, which led market participants to quickly

Table 8
Shadow rate responses to monetary policy announcements by the Fed. *Notes:* This table shows shadow rate responses to the key unconventional monetary policy announcements made by the Fed, and that are described in Tables 1 and 2. It also shows the responses of government bond yields as well as the values for the short-rate surprise measure. Interest rate provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r^u_{t^\circ}$)	2-year yield	5-year yield	10-year yield	Shadow rate ($p=2, 3$)
Sep 15, 2008	0.0	−6.3	−45.0	−36.8	−23.8	−113.1
No. 25, 2008	0.0	−1.0	−14.3	−22.5	−21.4	−38.3
Dec 1, 2008	0.0	−1.0	−11.9	−21.4	−21.5	−33.9
Dec 16, 2008	−75.0	−16.0	−10.7	−16.3	−17.5	−32.6
Mar 18, 2009	0.0	0.0	−26.4	−47.1	−51.9	−83.8
Aug 10, 2010	0.0	0.4	−2.7	−7.1	−6.9	−8.6
Aug 27, 2010	0.0	0.0	5.4	12.3	16.6	19.3
Sep 21, 2010	0.0	0.0	−3.7	−9.6	−10.7	−11.5
Oct 15, 2010	0.0	0.0	−1.2	2.6	8.6	4.7
No. 3, 2010	0.0	0.8	−1.5	−4.0	4.1	−2.1
Dec 14, 2010	0.0	0.0	4.9	16.8	20.2	22.5
Aug 9, 2011	0.0	−0.7	−8.6	−19.1	−20.5	−27.6
Sep 21, 2011	0.0	0.8	6.5	1.8	−8.4	0.4
Jan 25, 2012	0.0	−0.5	−3.8	−9.4	−8.0	−8.9
Aug 31, 2012	0.0	0.0	−3.7	−6.4	−7.0	−10.6
Sep 13, 2012	0.0	0.9	−0.9	−3.7	−2.9	−4.6
Dec 12, 2012	0.0	0.4	0.0	2.3	5.7	3.4
May 22, 2013	0.0	0.0	1.3	6.8	9.6	6.5
Dec 18, 2013	0.0	0.0	−1.5	2.6	4.6	6.6
Jan 29, 2014	0.0	0.0	−2.0	−5.9	−7.7	−8.6
Mar 19, 2014	0.0	0.0	10.6	18.4	9.8	24.6
Apr 30, 2014	0.0	0.0	−2.4	−4.8	−3.5	−7.9
Jun 18, 2014	0.0	0.0	−1.3	−4.9	−4.7	−5.2
Jul 30, 2014	0.0	−0.5	2.7	7.5	10.2	18.5
Sep 17, 2014	0.0	0.0	3.2	3.6	2.0	8.1
Oct 29, 2014	0.0	0.5	6.7	8.8	3.0	11.4
Oct 28, 2015	0.0	−0.5	8.5	9.2	5.3	13.2
Dec 16, 2015	25.0	2.2	4.3	5.0	2.9	4.8
Dec 14, 2016	25.0	0.0	9.9	10.1	5.4	15.6
Mar 15, 2017	25.0	0.5	−6.3	−10.6	−9.5	−17.5
Apr 5, 2017	0.0	0.0	−1.7	−3.2	−1.9	0.5
May 3, 2017	0.0	0.0	3.9	4.9	3.8	10.9
Jun 14, 2017	25.0	0.9	−1.5	−4.5	−6.5	−7.0
Jul 26, 2017	0.0	0.0	−4.3	−6.2	−4.1	−8.6
Sep 20, 2017	0.0	0.0	4.9	5.0	3.7	5.8
Dec 13, 2017	25.0	0.5	−4.6	−5.7	−4.2	−7.8
Mar 21, 2018	25.0	0.9	−2.0	−0.5	1.2	−0.9

Table 9
Shadow rate responses to monetary policy announcements by the Fed, continued. *Notes:* This table shows shadow rate responses to the key unconventional monetary policy announcements made by the Fed, and that are described in Tables 1 and 2. It also shows the responses of government bond yields as well as the values for the short-rate surprise measure. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r_t^u$)	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
Jun 13, 2018	25.0	−0.4	4.2	3.2	2.1	14.0
Sep 26, 2018	25.0	0.0	−1.4	−3.0	−3.4	−4.2
No. 8, 2018	0.0	0.3	2.2	2.6	1.6	4.9
Dec 19, 2018	25.0	3.6	−1.3	−3.5	−5.8	−5.5
Jan 30, 2019	0.0	0.0	−4.9	−5.1	−0.5	−6.3
Mar 20, 2019	0.0	1.5	−6.0	−7.9	−6.1	−11.8
Jul 31, 2019	−25.0	0.0	4.1	0.0	−3.7	4.3
Sep 18, 2019	−25.0	0.6	3.4	2.1	−0.5	1.8
Sep 20, 2019	0.0	−3.3	−4.7	−4.9	−4.8	−7.4
Oct 4, 2019	0.0	−1.2	0.9	−0.5	−2.5	−5.0
Oct 11, 2019	0.0	−1.6	8.3	10.7	9.2	17.0
Oct 23, 2019	0.0	0.0	−0.9	−1.2	−0.9	−2.1
Oct 30, 2019	−25.0	−5.7	−3.3	−5.0	−5.8	−9.8
No. 14, 2019	0.0	−0.5	−4.1	−6.0	−5.2	−9.6
Dec 12, 2019	0.0	−0.5	5.0	9.3	11.1	15.2
Feb 13, 2020	0.0	0.5	0.0	−1.0	−1.6	−1.9
Mar 3, 2020	−50.0	−29.7	−12.4	−10.8	−7.4	−42.4
Mar 9, 2020	0.0	−17.5	−10.1	−10.4	−17.5	−20.7
Mar 11, 2020	0.0	−14.5	0.1	4.8	−0.4	12.2
Mar 12, 2020	0.0	−5.1	−0.6	1.3	9.9	−6.1
Mar 16, 2020	−100.0	−13.0	−11.4	−21.4	−22.8	−22.6
Mar 17, 2020	0.0	3.8	8.7	19.8	33.1	11.3
Mar 18, 2020	0.0	5.5	7.2	16.9	16.2	1.2
Mar 19, 2020	0.0	0.7	−11.0	−10.1	−5.1	−21.9
Mar 23, 2020	0.0	−4.6	−9.3	−17.6	−20.4	−22.7
Mar 31, 2020	0.0	0.0	−0.3	−1.9	1.5	3.7
Apr 9, 2020	0.0	−0.4	−2.1	−5.7	−4.6	−4.1
Aug 28, 2020	0.0	−5.2	0.4	2.0	5.5	2.6
Mar 17, 2021	0.0	0.0	−2.0	−3.1	1.3	−0.9
Jun 16, 2021	25.0	2.0	4.6	9.0	6.6	16.3
Jul 28, 2021	0.0	−0.1	0.5	0.9	0.7	3.6
Mar 16, 2022	0.0	−1.5	9.7	7.3	4.2	13.6
May 4, 2022	50.0	−3.5	−9.9	−8.1	−2.9	−21.5

Table 10
Shadow rate responses to monetary policy announcements by the Riksbank. *Notes:* This table shows shadow rate responses to unconventional monetary policy announcements made by the Riksbank, and that are described in Tables 3 and 4. It also shows the responses of government bond yields as well as the values for the short-rate and the QE surprise measures. QE surprises are measured in SEK billions (bn) and are obtained from market newsletters by subtracting the expected amount from the announced amount of purchases. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r_t^u$)	QE surprise	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
Feb 12, 2015	−10.0	−5.9	10 bn	−12.0	−15.6	−11.1	−26.9
Mar 18, 2015	−15.0	−14.5	30 bn	−10.4	−11.8	−14.8	−22.8
Apr 29, 2015	0.0	7.3	10–20 bn	5.5	6.7	6.9	11.2
Jul 2, 2015	−10.0	−8.5	45 bn	−11.2	−13.1	−8.9	−21.2
Sep 3, 2015	0.0	5.3	0 bn	2.6	−2.2	−3.6	−0.5
Oct 28, 2015	0.0	4.5	30 bn	−2.2	−7.5	−8.2	−7.0
Dec 15, 2015	0.0	−0.4	0 bn	3.1	6.4	8.4	7.9
Feb 11, 2016	−15.0	−7.9	0 bn	−4.1	−4.0	−4.1	−7.6
Apr 21, 2016	0.0	1.0	-15 bn	−0.3	3.8	8.3	4.5
Jul 6, 2016	0.0	1.2	0 bn	0.4	1.5	−0.1	−0.5
Sep 7, 2016	0.0	0.0	0 bn	0.3	1.7	0.7	1.2
Oct 27, 2016	0.0	0.2	0 bn	−2.6	0.8	6.0	0.7
Dec 21, 2016	0.0	0.0	0 bn	3.3	−0.7	−2.3	0.4
Feb 15, 2017	0.0	0.0	0 bn	−2.5	−2.0	−1.8	−1.7
Apr 27, 2017	0.0	−0.6	15 bn	−3.4	−6.7	−7.3	−8.0
Jul 4, 2017	0.0	1.0	0 bn	−4.1	−4.3	−3.6	−5.9
Sep 7, 2017	0.0	0.0	0 bn	−2.6	−4.4	−3.6	−5.4
Oct 26, 2017	0.0	−0.8	0 bn	−3.2	−3.7	−3.8	−5.2
Dec 20, 2017	0.0	0.0	0 bn	1.2	2.6	1.8	2.7
Feb 14, 2018	0.0	−1.3	0 bn	1.3	2.0	1.8	2.3
Apr 26, 2018	0.0	1.1	0 bn	−2.8	−4.9	−3.9	−5.5
Jul 3, 2018	0.0	0.9	0 bn	2.9	3.3	2.0	4.3
Sep 6, 2018	0.0	−2.1	0 bn	3.4	0.4	−0.4	1.5
Oct 24, 2018	0.0	−3.1	0 bn	−1.5	−2.2	−1.3	−1.1
Dec 20, 2018	15.0	0.8	0 bn	4.8	0.7	−0.5	7.2

Table 11
Shadow rate responses to monetary policy announcements by the Riksbank, continued. *Notes:* This table shows shadow rate responses to unconventional monetary policy announcements made by the Riksbank, and that are described in Tables 3 and 4. It also shows the responses of government bond yields as well as the values for the short-rate and the QE surprise measures. QE surprises are measured in SEK billions (bn) and are obtained from market newsletters by subtracting the expected amount from the announced amount of purchases. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r_{t^*}^u$)	QE surprise	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
Feb 13, 2019	0.0	0.0	0 bn	2.8	3.2	2.3	4.0
Apr 25, 2019	0.0	0.0	0 bn	−7.0	−7.8	−8.3	−11.4
Jul 3, 2019	0.0	0.6	0 bn	1.6	0.1	−2.1	0.3
Sep 5, 2019	0.0	2.1	0 bn	9.5	10.7	9.9	14.9
Oct 24, 2019	0.0	−0.5	0 bn	5.9	2.0	−0.1	4.8
Dec 19, 2019	25.0	3.1	0 bn	1.1	3.6	3.8	3.7
Feb 12, 2020	0.0	1.2	0 bn	−0.9	−0.2	0.3	−0.8
Mar 13, 2020	0.0	0.3	0 bn	7.8	14.5	19.1	17.8
Mar 16, 2020	0.0	−0.1	300 bn	2.0	8.4	13.5	10.0
Mar 19, 2020	0.0	−4.7	0 bn	3.3	6.4	8.0	8.9
Mar 20, 2020	0.0	4.5	0 bn	1.0	−3.8	−7.1	−4.9
Mar 26, 2020	0.0	−5.7	0 bn	−1.3	−2.3	−1.2	−2.2
Apr 22, 2020	0.0	1.5	0 bn	1.3	2.6	2.4	3.1
Jul 1, 2020	0.0	1.9	0 bn	−1.0	−2.1	−2.3	−2.3
Sep 22, 2020	0.0	1.5	0 bn	−0.1	2.0	2.1	2.0
No. 26, 2020	0.0	1.5	200 bn	0.7	−0.5	−1.0	−0.6
Feb 10, 2021	0.0	3.6	0 bn	−0.5	−0.3	−0.4	−0.4
Apr 27, 2021	0.0	1.5	0 bn	0.3	0.3	0.7	0.7
Jul 1, 2021	0.0	−2.8	0 bn	−1.3	−1.9	−0.3	−3.1
Sep 21, 2021	0.0	0.7	0 bn	−1.8	−3.7	−3.7	−4.0
No. 25, 2021	0.0	0.6	0 bn	−3.1	−3.3	−2.4	−4.0
Feb 10, 2022	0.0	−3.6	0 bn	−6.3	−2.8	−2.7	−6.0
Apr 28, 2022	25.0	12.5	0 bn	11.8	15.9	15.1	40.4

Table 12
Shadow rate responses to monetary policy announcements by the ECB. *Notes:* This table shows shadow rate responses to key unconventional monetary policy announcements made by the ECB, and that are described in Table 4. It also shows the responses of government bond yields as well as the values for the short-rate surprise measure. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate (MRO)	Short-rate surprise ($\triangle r_{t^*}^u$)	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
May 7, 2009	−25.0	−5.0	−1.0	10.2	16.0	8.3
May 10, 2010	0.0	−15.5	5.0	8.5	13.2	8.2
Oct 6, 2011	0.0	10.5	20.4	7.7	5.6	17.2
Dec 8, 2011	0.0	10.5	−5.9	2.6	−7.9	−4.8
Sep 6, 2012	0.0	1.0	3.3	2.9	7.6	6.0
Jun 5, 2014	−10.0	−2.0	0.5	−4.2	−3.1	−3.9
Sep 4, 2014	−10.0	−4.0	−6.3	−4.6	1.0	−8.4
Dec 4, 2014	0.0	0.5	1.5	1.1	2.4	0.4
Jan 2, 2015	0.0	−1.0	−1.2	−2.2	−6.0	−3.6
Jan 22, 2015	0.0	0.0	−0.8	−1.9	−1.3	−1.4
Sep 3, 2015	0.0	0.0	−0.9	−3.7	−5.5	−4.0
Oct 22, 2015	0.0	−3.5	−4.3	−5.2	−4.9	−6.7
Dec 3, 2015	0.0	7.5	12.7	18.1	16.6	21.6
Jan 21, 2016	0.0	−2.5	−3.2	−5.1	−3.2	−5.7
Feb 18, 2016	0.0	−1.0	−2.1	−2.9	−5.8	−4.6
Mar 10, 2016	−5.0	1.5	6.5	5.3	3.7	7.8
Apr 21, 2016	0.0	0.0	1.0	3.9	6.3	3.9
Sep 8, 2016	0.0	1.0	2.5	4.0	6.9	5.2
Oct 20, 2016	0.0	−0.5	0.7	0.1	−1.6	0.0
Dec 8, 2016	0.0	−0.5	−2.4	−0.5	2.1	−1.1
Jun 27, 2017	0.0	0.5	3.4	8.5	9.5	8.0
Sep 7, 2017	0.0	−0.5	−4.3	−2.4	−2.1	−2.7
Oct 26, 2017	0.0	−0.5	−1.8	−4.1	−5.0	−3.6
Jun 14, 2018	0.0	0.0	−3.4	−4.8	−4.5	−5.2
Sep 13, 2018	0.0	0.0	0.2	1.1	1.1	0.8
Oct 25, 2018	0.0	0.0	0.3	0.9	0.6	0.7
Dec 13, 2018	0.0	0.0	−0.7	−1.9	−1.3	−1.1
Mar 7, 2019	0.0	0.0	−2.5	−4.5	−5.8	−4.8
Jun 18, 2019	0.0	−4.0	−5.8	−6.9	−6.7	−8.5
Jul 25, 2019	0.0	2.0	0.2	−1.1	−1.1	0.3
Sep 12, 2019	0.0	4.5	8.5	9.0	7.0	13.1
Mar 2, 2020	0.0	−4.0	−4.7	−3.9	−2.4	−6.9
Mar 12, 2020	0.0	7.5	7.0	6.7	3.7	12.0
Mar 18, 2020	0.0	1.0	5.3	11.7	16.0	13.2
Apr 30, 2020	0.0	−1.0	−3.3	−5.3	−7.1	−6.7
Jun 4, 2020	0.0	0.0	1.1	1.3	2.8	1.8
Dec 10, 2020	0.0	0.0	0.5	−0.2	−0.8	0.3
Dec 16, 2021	0.0	1.3	1.3	1.8	4.7	−0.2
Mar 10, 2022	0.0	−1.4	12.2	10.1	7.0	14.9

Table 13
Shadow rate responses to monetary policy announcements by the BoE. *Notes:* This table shows shadow rate responses to the key monetary policy announcements made by the Bank of England, and that are described in Table 6. It also shows the responses of government bond yields as well as the values for the short-rate surprise measure. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r_{t}^{u}$)	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
Oct 8, 2008	0.0	1.0	−6.0	5.9	5.1	−22.9
Feb 11, 2009	0.0	−7.0	−29.8	−25.2	−20.4	−46.5
Mar 5, 2009	−50.0	5.0	−2.0	−18.0	−31.7	−36.7
May 7, 2009	0.0	−4.0	1.3	4.6	5.7	5.9
Jul 9, 2009	0.0	2.0	8.9	14.6	17.1	20.3
Aug 6, 2009	0.0	−6.0	−3.4	−11.1	−7.3	−10.0
No. 5, 2009	0.0	2.0	0.6	4.5	6.9	5.2
Sep 9, 2010	0.0	−1.0	3.1	4.7	6.7	7.3
Mar 10, 2011	0.0	−3.0	−5.8	−8.1	−8.2	−11.6
Oct 6, 2011	0.0	0.0	4.1	3.2	4.5	6.5
Dec 8, 2011	0.0	0.0	−1.8	−8.4	−10.2	−9.6
Feb 9, 2012	0.0	1.0	0.9	−1.4	5.4	1.3
Jul 5, 2012	0.0	−2.0	−7.2	−9.5	−6.0	−11.9
Aug 2, 2012	0.0	4.0	−4.0	−6.9	−7.9	−8.9
No. 7, 2013	0.0	−1.0	−5.1	−5.8	−3.9	−7.7
Feb 6, 2014	0.0	0.0	2.5	4.7	5.9	5.6
Jun 13, 2014	0.0	3.0	12.6	8.5	2.8	17.6
Jun 4, 2015	0.0	1.0	−3.6	−5.7	−6.0	−7.6
No. 5, 2015	0.0	−1.0	−3.5	−3.4	−2.2	−5.2
Jun 24, 2016	0.0	−10.0	−23.8	−29.5	−26.4	−43.8
Jun 30, 2016	0.0	−6.0	−5.5	−5.2	−3.7	−10.4
Aug 4, 2016	−25.0	−2.0	−8.3	−15.8	−16.8	−28.6
Jun 15, 2017	0.0	0.5	8.1	11.0	10.2	17.0
Aug 3, 2017	0.0	−2.0	−4.9	−6.8	−8.2	−11.7
Sep 14, 2017	0.0	−0.5	8.2	8.8	7.1	15.7
No. 2, 2017	25.0	−1.5	−8.9	−10.4	−8.4	−8.6

Table 14
Shadow rate responses to monetary policy announcements by the BoE, continued. *Notes:* This table shows shadow rate responses to the key monetary policy announcements made by the Bank of England, and that are described in Table 6. It also shows the responses of government bond yields as well as the values for the short-rate surprise measure. Interest rate changes are provided in basis points.

Monetary policy announcement	Policy rate	Short-rate surprise ($\triangle r_{t}^{u}$)	2-year yield	5-year yield	10-year yield	Shadow rate ($p = 2, 3$)
Jun 21, 2018	0.0	4.5	1.3	0.2	−1.7	0.8
Aug 2, 2018	25.0	0.5	−0.4	−0.5	−0.9	6.5
Mar 11, 2020	−25.0	−15.5	−0.3	3.7	6.8	−12.9
Mar 17, 2020	0.0	2.0	0.1	4.9	7.1	3.7
Mar 19, 2020	−15.0	−8.5	−10.0	−3.1	2.2	−15.8
Mar 20, 2020	0.0	−0.5	−13.1	−25.3	−30.5	−35.5
Mar 24, 2020	0.0	0.0	5.4	4.4	5.0	9.5
Mar 30, 2020	0.0	0.0	−0.5	−2.3	−3.0	−2.8
Apr 9, 2020	0.0	−10.0	−6.6	−6.3	−7.1	−12.3
Apr 24, 2020	0.0	−3.0	0.4	0.4	−0.2	0.3
Jun 18, 2020	0.0	0.0	1.9	2.6	4.5	4.8
Aug 6, 2020	0.0	0.5	1.4	0.7	−2.6	0.7
No. 5, 2020	0.0	1.0	2.3	2.6	3.0	4.7
Dec 17, 2020	0.0	−0.5	0.9	0.4	−0.8	0.0
Dec 16, 2021	15.0	5.7	2.9	3.0	2.4	7.6
Feb 3, 2022	25.0	17.9	12.8	12.4	12.3	31.8
Mar 17, 2022	25.0	−14.6	−10.8	−8.5	−5.5	−10.4
May 5, 2022	25.0	−10.0	−11.7	−7.7	−1.5	−9.1

price in this information, leading shadow rates to increase by 17 and 15.7 basis points, respectively. After that, shadow rates continued rising as monetary policy started being normalized in the UK. However, the advent of the Covid-19 crisis led the UK shadow rate to drop strongly again following the large expansionary measures implemented by the Bank of England and the UK government. For instance, following the announcements of Bank Rate cut, further asset purchases and the package of economic measures announced by the Chancellor, the UK shadow rates fell by 15.8 and 35.5 basis points on March 19, 2020 and March 20, 2020. On February 3, 2022, when the Bank of England announced the rise of Bank Rate and the sale of its stock of corporate bonds the shadow rates raised by 31.8 basis points.

4.2. Robustness checks

Following our estimation, we conduct a number of robustness checks using the US data, which is the most studied case in the literature. First, we discuss the sensitivity of estimates with respect to the sample used for estimating our underlying term structure model. The argument in favor of this check is that affine term structure models typically do a worse job than shadow rate models a la (Black, 1995) in estimating the term structures of short-rate expectations and term premia when the lower bound is binding. To do that, we verify how our shadow rate estimates change when the parameters of the term structure model are estimated using the pre-lower-bound sample only (until June 30, 2008) with

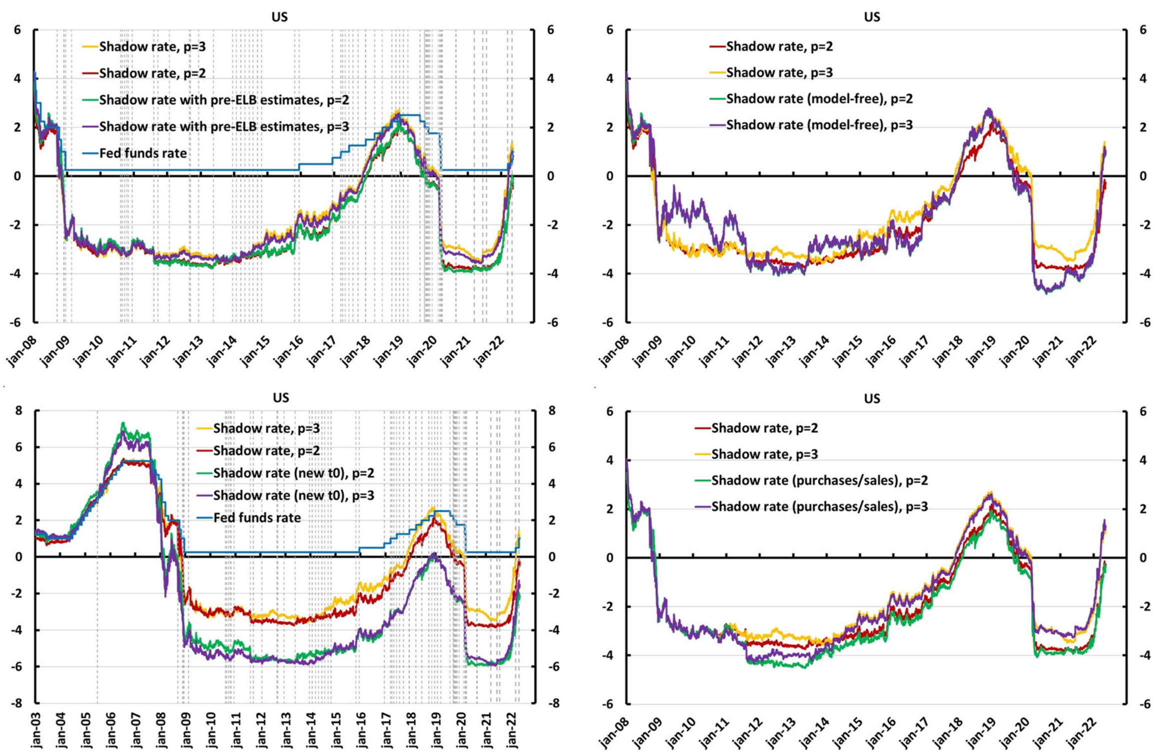


Fig. 6. Robustness checks. *Notes:* This figure shows the result of a number of robustness checks using the US shadow rates. The top-left chart provides estimates when the parameters of the underlying term structure model are estimated using (i) the full data sample, and (ii) the pre-lower-bound data sample only. The top-right chart provides estimates with and without an underlying term structure model for decomposing yields into the term structures of short-rate expectations and term premia. The bottom chart provides estimates when t_0 is set as June 30, 2005, that is, prior to the financial crisis of 2007–2008 and the more intensive use of unconventional monetary policies.

the yield curve decomposition and shadow rates being estimated for the whole sample. Results are shown in the top-left chart of Fig. 6. As can be seen, estimates barely change. Estimates with the three-factor model are essentially on top of each other.

Our second robustness check is to conduct a model-free shadow rate estimation, where $\triangle X_{1t}$ is used at all times in (6) and (7) and there is no switch between $\triangle X_{1t}$ and $\triangle X_{1t}^{sr}$. The main reason for such check is that the choice of unconventional monetary policy announcement dates may drive the shadow rate estimates, as they determine when to use $\triangle X_{1t}$ versus $\triangle X_{1t}^{sr}$. As can be seen from the top-right chart in Fig. 6, although the levels are somewhat similar to the model-dependent estimates, model-free estimates show a higher degree of variation. This is due to the inclusion of term premia at all times in the estimates. As explained in Section 2.2 above, term premia may contain information that is not necessarily related to monetary policy, such as investors' risk aversion, which tend to vary according to a number of factors, adding noise to the measurement of s_t and increasing its variation.

In our third check we provide shadow rate estimates for a different t_0, prior to the financial crisis of 2007–2008 and the more intense use of unconventional monetary policies by the Fed. For such exercise, we set t_0 to be equal to June 30, 2005, when forward guidance was the only unconventional measure used by the Fed (Gürkaynak et al., 2005). As can be seen in the bottom-left chart of Fig. 6, the estimates with a new t_0 start decoupling from the short-rate already from mid-2005, when short-rate expectations are rising with the fed funds rate, forward guidance, and all the other relevant information available in the economy that affect investors' short-rate expectations. With the onset of the financial crisis, these expectations dropped dramatically, leading to a large fall in shadow rates.

There are several reasons why we are able to draw a shadow rate that can decouple from the short-rate from a different t_0 such as June 30, 2005. The first is by construction. As Eqs. (6) and (7) inform, the information contained in $\triangle X_t^{sr}$ start kicking into the shadow rate from t_0, affecting s_t from that point in time. This is an innovation compared to other specifications that require the short-rate to be at the effective lower bound to be able to draw a shadow rate. The other reasons why we allow for that are grounded in the literature. From a theoretical perspective, the argument relies on the New Keynesian frameworks of Clarida et al. (1999) and Woodford (2003), which consider that the output gap at any point in time depends on the entire expected future path of short-rates ($\triangle X_{1t}^{sr}$ in our case), not on the short-term rate itself only. From a more practical perspective, starting prior to the lower bound period, central banks have relied on different forms of communication to provide forward guidance to market participants and affect longer-term interest rates through short-rate expectations. For instance, Gürkaynak et al. (2005) find that monetary policy statements contain relevant information about future short-term rates and estimate a short-rate "path" factor connected to market participants' expectations that is shown to affect a number of asset prices. Swanson (2021) extends their framework and confirms the existence of a "forward guidance" factor since the early 1990's.

Lastly, we verify whether the actual purchases/sales of bonds in the market (not only monetary policy announcements) affect interest rates through term premia and, therefore, our shadow rate estimates. As discussed by D'Amico and King (2013), the reason could be that the particular bonds purchased/sold and the exact amounts of such purchases/sales could be unknown in advance to market participants, and yields could be impacted when they actually occurred. In addition, changes in market liquidity and in other factors such as investors risk and maturity preferences could happen in response to purchases/sales, causing yields to move. We verify these by including the dates of actual purchases/sales of bonds in our shadow rate specification and by re-estimating them.[14] We included a total of 287 dates, with results shown in the bottom-right chart of Fig. 6. As can be seen, results are not strong enough to change our estimates in a very significant way. Our estimates for the two and three factor shadow rates drop in levels by only 28 and 19 basis points on average from September 15, 2008 to May 13, 2022, respectively. One possible reason for this result is that, as discussed by D'Amico and King (2013), actual purchases/sales of bonds affect yields mostly locally, i.e. on the maturity buckets in which purchases/sales actually occur. As our shadow rate is driven by first principal components, which are essentially a weighted average of yields across maturities, it is very likely that the local effects are averaged out in the computation process, becoming not strong enough to change our estimates in a significant way. Another potential explanation is that actual purchases/sales may contain substantial signaling effects, which are already incorporated in the shadow rates through $\triangle X_{1t}^{sr}$ on all dates.

4.3. Monetary policy in the "new normal": Discussion

To the extent that the natural rate of interest has remained persistently low and that central bank balance sheets have grown in size and composition, policy makers and academics have recognized that unconventional policies have become more standard, i.e. they are likely to be used on a regular basis to offset disturbances to inflation and economic activity, with central bank balance sheets becoming part of the standard monetary policy toolkit, also to ensure an efficient and effective implementation of monetary policy in an ample reserves regime. Since our shadow rate does not impose any type of lower bound constraint on nominal interest rates, it becomes useful for measuring the stance of monetary policy in the "New Normal" environment.

The Fed has continued to rely on its balance sheet to deliver its policy objectives. After a series of announcements aimed at contracting its balance sheet throughout 2017, 2018 and 2022, the Fed has been communicating the transition to a regime of ample supply of reserves as its balance sheet contraction process ends. In the meantime, the Fed has conducted a series of operations financed through the creation of reserves, such as repurchase agreements, purchases of short-term Treasury bills, and various other measures aimed at easing monetary and financial conditions during the Covid-19 crisis. Throughout this process the Fed's balance sheet has grown in size and composition. By May 2022, its assets had reached nearly USD 8.5 trillion, with more than USD 5.7 trillion in US Treasury securities. More recently, the Fed has communicated its intention to maintain securities holdings in amounts needed to implement monetary policy efficiently and effectively in an ample reserves regime.[15]

Other central banks have also continued to use their balance sheets to achieve their policy objectives. In June 2018, the Bank of England stated it would meet banks' demand for central bank reserves in full at Bank Rate during any future unwind of its Asset Purchase Facility. In response to the Covid-19 crisis and resulting recession, the Bank announced extensions to its asset purchase program, with its balance sheet surpassing GBP 1.05 trillion by May 2022. More recently, the Bank has announced reductions to its stock of bonds as the Bank Rate is raised. In December 2017, the Riksbank communicated its intentions to reduce the level of its government bond holdings, but was uncertain about its exact size in the long-run at that point.[16] More recently, in response to the Covid-19 crisis and the forseed recession, the Riksbank has extended its asset purchase program to SEK 700 billion in assets. In a speech on June 10, 2020 its governor Stefan Ingves stated that "Central bank balance sheets are increasingly inportant for monetary policy". The ECB started communicating reductions in the pace of asset purchases around the end of 2016, followed by some guidance on how long its asset holdings were expected to last. From mid-2019, facing a slowdown of the euro area economy, the ECB announced further asset purchases under EAPP, and more recently, under PEPP, in additional to a number of other expansionary measures through the creation of central bank reserves. By December 2021, ECB's balance sheet had passed EUR 8.5 trillion in assets, with more than EUR 7 trillion used for monetary policy purposes.

Given this scenario and the indication that unconventional policies, including those connected to the balance sheet, will continue to be used on a regular basis by central banks, our shadow rate becomes an important variable for continuously measuring changes in the stance of monetary policy implied by central banks' balance sheet contractions and expansions during the whole unconventional period.

5. Applications

This section presents two additional applications for the shadow rate. In the first application, we exploit the information about the stance of monetary policy contained in the shadow rate responses around announcements to try to better understand the pass-through of conventional and unconventional monetary policies to exchange rates across economies. In the second application, we measure the macroeconomic effects of unconventional monetary policy in the US and Sweden using two medium-scale DSGE models, Smets and Wouters (2007) and Riksbank' s Ramses II. In the experiment, we replace the US and Swedish policy rates by the shadow rates shown in Fig. 4 and run a counterfactual experiment to evaluate the effects of unconventional monetary policy on inflation, unemployment and output gap.

5.1. Monetary policy stance surprises and exchange rates

In this section, we exploit the information contained in the shadow rates on announcement days and measure the pass-through of monetary policy to exchange rates. For the analysis we use event study regressions. More specifically, we regress exchange rate changes around announcements on measures of monetary policy surprises, and assess their responses.

To measure surprises, we use a decomposition of shadow rate changes into conventional and unconventional policy surprises. More specifically, we subtract the short-rate surprise measure, $\triangle r_{t^\star}^u$, from shadow rate changes and obtain a measure of unconventional monetary policy surprise, $\triangle ump_{t^\star}^u = \triangle s_{t^\star} - \triangle r_{t^\star}^u$, which includes information about monetary policy that affects the whole term structure of interest rates, and that is unrelated to $\triangle r_{t^\star}^u$.[17] This decomposition, which is shown in Figs. 7 and 8, can be used to

[14] We include the dates provided by the New York Fed in its Schedule of Treasury Operations. These dates can be obtained from https://www.newyorkfed.org/markets/tot_operation_schedule.html#tabs-2, https://www.newyorkfed.org/markets/omo_transaction_data, and https://www.newyorkfed.org/markets/domestic-market-operations/monetary-policy-implementation/treasury-securities/treasury-securities-operational-details.

[15] See https://www.federalreserve.gov/releases/h41/20201231/.

[16] See https://www.riksbank.se/globalassets/media/rapporter/ppr/fordjupningar/engelska/2017/the-riksbanks-strategy-for-a-gradual-normalisation-of-monetary-policy-article-in-monetary-policy-report-december-2017.

[17] As noted in Section 2.3, from regression (9), shadow rate changes on unconventional announcement days can be decomposed into two terms: (i) the conventional monetary policy surprise observed on that day, and (ii) a prediction error, which can be associated with the surprise component of the unconventional monetary policies announced on that particular day, scaled by $\frac{1}{\alpha}$.

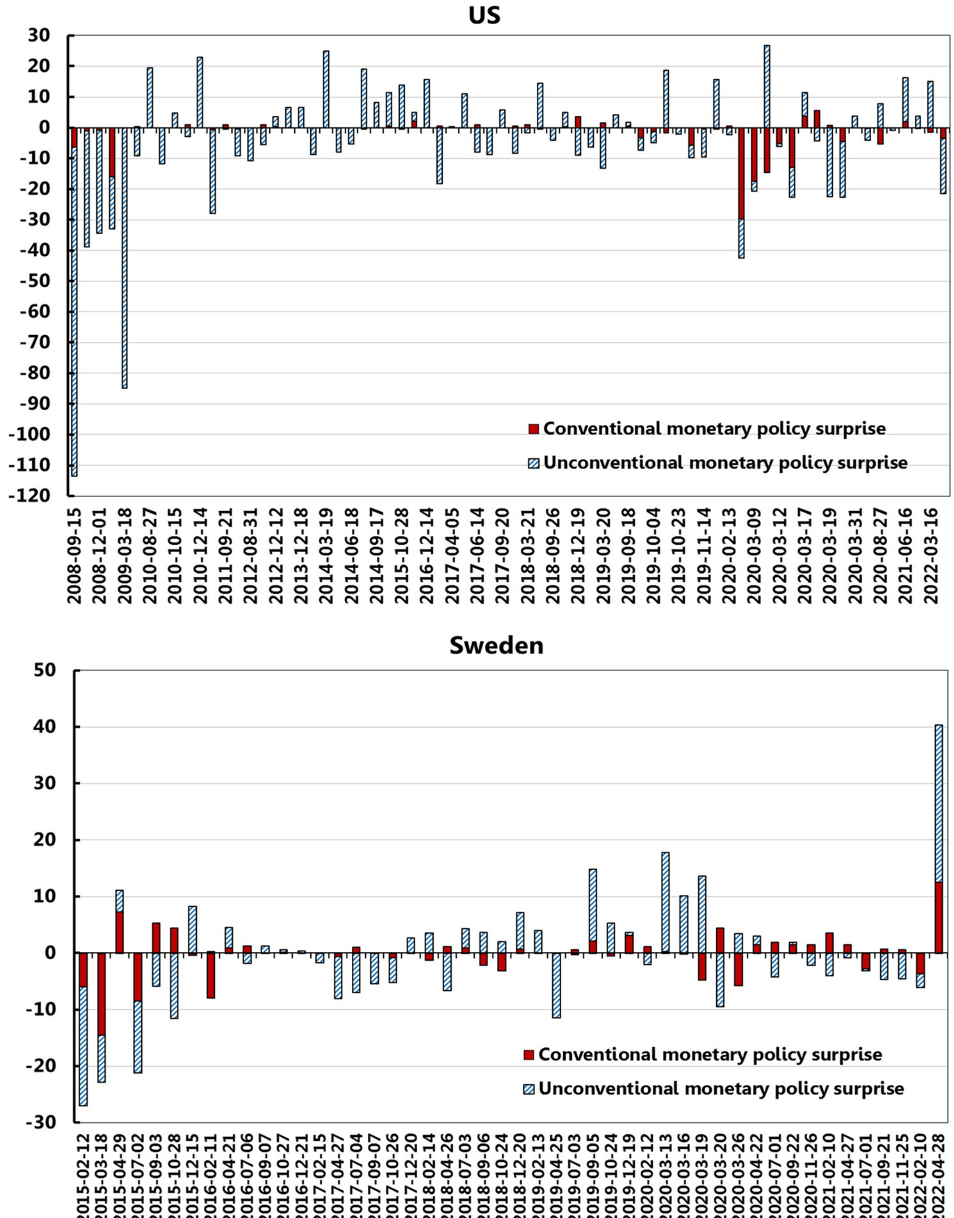


Fig. 7. Decomposition of shadow rate changes around announcements for the US and Sweden. *Notes:* This figure shows the measures of conventional and unconventional monetary policy surprises for the US and Sweden. The measure of unconventional monetary policy surprise is defined as the difference between shadow rate changes and short-rate surprises, computed on unconventional announcement days, i.e. $\triangle ump^u_{t^\star} = \triangle s_{t^\star} - \triangle r^u_{t^\star}$. Values are provided in basis points.

assess the pass-through of each type of monetary policy, i.e. conventional and unconventional, to exchange rates, with effects being directly comparable, as the two variables are short-rate equivalent. Therefore, we estimate event study regressions as the following,

$$\triangle e_{t^\star} = \eta + \gamma \triangle r^u_{t^\star,d} + \vartheta \triangle ump^u_{t^\star,d} + \omega \triangle s_{t^\star,f} + \epsilon_{t^\star} \quad (12)$$

where $\triangle e_{t^\star}$ is the percentage change in the nominal exchange rate between the domestic currency and the foreign currency, and $\triangle r^u_{t^\star,d}$ and $\triangle ump^u_{t^\star,d}$ are the measures of conventional and unconventional surprises for the domestic economy. In addition, we add the foreign shadow rate change, $\triangle s_{t^\star,f}$, in order to control for changes in foreign interest rates that may also affect $\triangle e_{t^\star}$. We expect coefficients on $\triangle r^u_{t^\star,d}$ and $\triangle ump^u_{t^\star,d}$ to be negative, that is, expansionary monetary policy announcements lead to a depreciation of the domestic currency vis-à-vis the foreign currency.

5.1.1. Results

We measure the percentage change in exchange rates using intraday data, with a window of 30 min before and 30 min after each announcement. On announcements by the ECB we use a window from 11:30 to 14:00 (GMT 0), which includes both the monetary policy decision and the press conference. Results are provided by Table 15. As can be seen, we find negative and highly statistically significant coefficient estimates for both surprise measures across the four economies, suggesting that exchange rates have responded to both conventional and unconventional measures. However, our results suggest that conventional monetary policy has been more effective, with coefficient estimates ranging from −0.087 to −0.195, compared to −0.019 to −0.103 for the unconventional policy measure. These results are confirmed by pooled event study regressions, where we put together the percentage changes of the twelve exchange rates available, and run one single OLS regression using

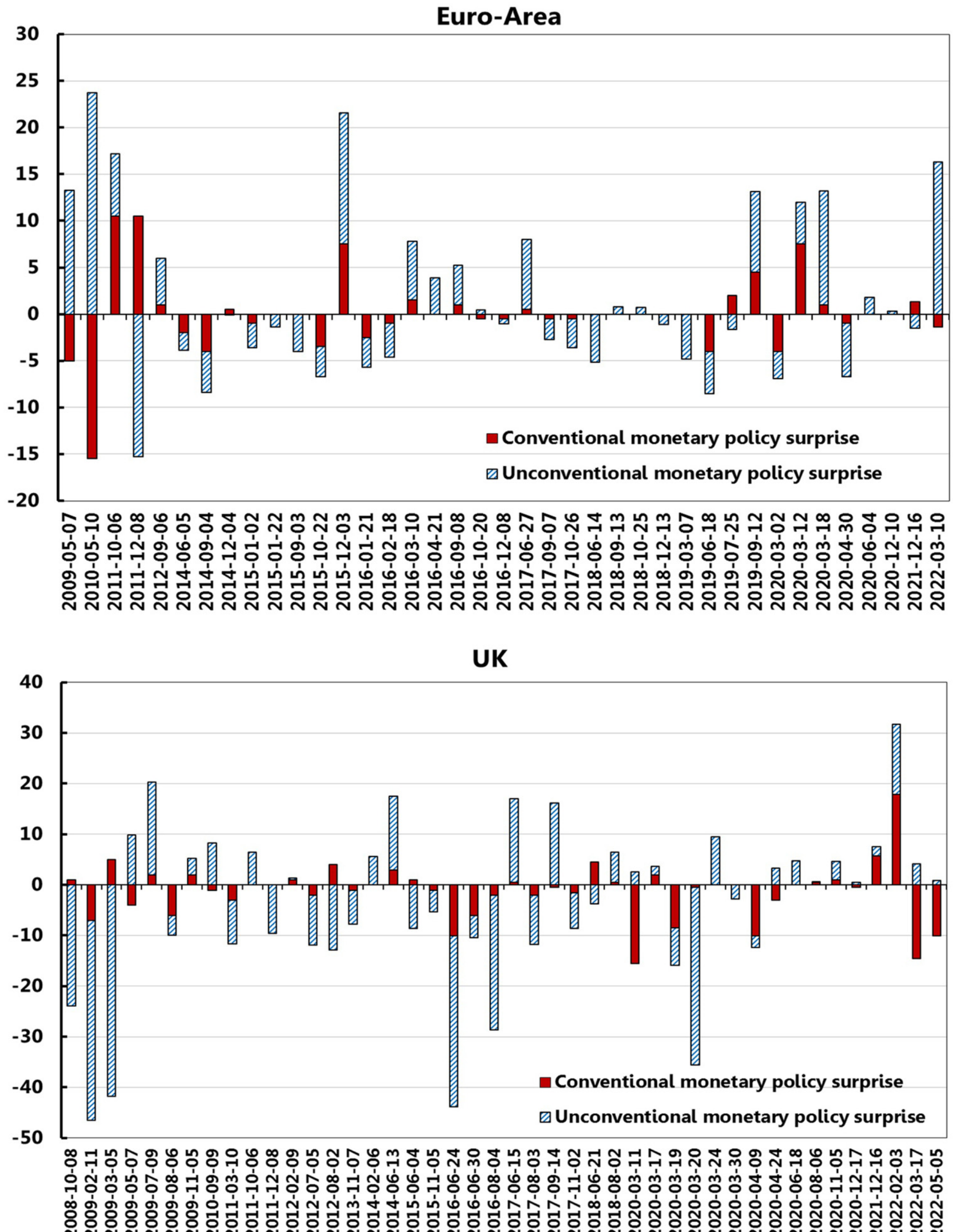


Fig. 8. Decomposition of shadow rate changes around announcements for the euro area and the UK. *Notes:* This figure shows the measures of conventional and unconventional monetary policy surprises for the euro area and the UK. The measure of unconventional monetary policy surprise is defined as the difference between shadow rate changes and short-rate surprises, computed on unconventional announcement days, i.e. $\triangle ump^u_{t^*} = \triangle s_{t^*} - \triangle r^u_{t^*}$. Values are provided in basis points.

all the announcements listed in Tables 1–5.[18] On average, a 10 basis point drop in the conventional surprise measure depreciates the domestic currencies by 1.02 percent vis-à-vis foreign currencies. The estimated impact of unconventional monetary policy is lower, about 0.32 percent for a decrease of 10 basis points in the unconventional measure. These results are in line with other studies that commonly find that exchange rates respond more to short-term rates, which are more connected to near-term short-rate expectations, than to long-term rates (Glick and Leduc, 2018; Rossi and Inoue, 2019).

[18] We also estimated panel regressions with fixed and random effects. Coefficient estimates are very similar to those using pooled OLS.

5.1.2. Understanding UMP surprises

As our measure of unconventional monetary policy surprises, $\triangle ump^u_{t^*}$, are estimated from the prediction errors of regression (9), scaled by $\frac{1}{\alpha}$, they include information about unconventional monetary policy that affects the whole term structure of interest rates, and that is unrelated to $\triangle r^u_{t^*}$. Therefore, it makes sense to shed more light on the nature of these prediction errors to understand what information about monetary policy they really carry. To do so, we focus on US data and increase the sample of US unconventional monetary policy surprises by including 49 additional unconventional monetary policy days, starting from January 19, 2003. We then split the sample into two sub-samples, one pre-QE, from January 19, 2003 to August 5, 2008, and one during QE, from September 15, 2008 to May 4, 2022, and analyze how the unconventional surprises correlate with changes in different segments of the term

Table 15
Exchange rate effects of conventional and unconventional monetary policy surprises. *Notes:* This table shows the exchange rate effects of conventional and unconventional monetary policy announcements for each individual currency. Percentage changes in exchange rates are regressed onto the decomposition of shadow rate changes into conventional $\left(\triangle r^u_{t\star,d}\right)$ and unconventional $\left(\triangle ump^u_{t\star,d}\right)$ monetary policy surprises, as well as onto shadow rate changes for the foreign economy $(\triangle s_{t\star,f})$. Regressions are estimated using data observed on days of unconventional monetary policy announcements by each central bank, which are listed in Tables 1–5. Huber–White heteroskedasticity-consistent standard errors are provided in parenthesis.

	Federal Reserve			Riksbank		
	USD/SEK	USD/EUR	USD/GBP	SEK/USD	SEK/EUR	SEK/GBP
const.	0.061 (0.101)	0.043 (0.082)	0.156 (0.126)	−0.042 (0.054)	−0.030 (0.050)	−0.090** (0.057)
$\triangle r^u_{t\star,d}$	−0.125*** (0.035)	−0.094*** (0.020)	−0.091*** (0.026)	−0.103*** (0.014)	−0.097*** (0.014)	−0.102*** (0.017)
$\triangle ump^u_{t\star,d}$	−0.042*** (0.006)	−0.029*** (0.007)	−0.019*** (0.005)	−0.037*** (0.009)	−0.036*** (0.008)	−0.046*** (0.012)
$\triangle s_{t\star,f}$	0.027 (0.020)	0.040 (0.030)	0.029 (0.018)	0.007 (0.008)	0.017 (0.022)	0.015 (0.011)
$\overline{R2}$	0.69	0.64	0.30	0.77	0.77	0.72
	ECB			Bank of England		
	EUR/USD	EUR/SEK	EUR/GBP	GBP/USD	GBP/SEK	GBP/EUR
const.	0.170 (0.140)	0.117 (0.087)	0.189 (0.116)	0.146 (0.094)	0.036 (0.120)	0.072 (0.085)
$\triangle r^u_{t\star,d}$	−0.141*** (0.040)	−0.087*** (0.019)	−0.121*** (0.031)	−0.189*** (0.063)	−0.195*** (0.065)	−0.118** (0.044)
$\triangle ump^u_{t\star,d}$	−0.103*** (0.027)	−0.064*** (0.024)	−0.069*** (0.022)	−0.038*** (0.008)	−0.054*** (0.012)	−0.052*** (0.009)
$\triangle s_{t\star,f}$	0.002 (0.022)	0.020 (0.032)	0.017 (0.026)	−0.008 (0.012)	−0.004 (0.022)	0.043** (0.020)
$\overline{R2}$	0.55	0.39	0.58	0.64	0.65	0.67

Table 16
Understanding UMP surprises. *Notes:* This table shows results for regressions of unconventional monetary policy surprises ($\triangle ump^u_{t\star}$) onto changes in forward premium (6-months to 3-years and 5-years to 10-years) as well as risk-neutral forward rates (6-months to 3-years and 5-years to 10-years). Regressions are estimated using data observed on days of unconventional monetary policy announcements by the Fed, using two samples of data: (i) January 19, 2003 to August 5, 2008 (49 observations), and (ii) September 15, 2008 to May 4, 2022 (70 observations). Huber-White heteroskedasticity-consistent standard errors are provided in parenthesis.

Dependent variable: $\triangle ump^u_{t\star}$, Sample: January 19, 2003 to August 5, 2008					
const.	0.013 (0.035)	0.015 (0.034)	*const.*	−0.014 (0.016)	−0.016 (0.013)
$\triangle fw\ premium^{6m,3y}_{t\star}$	0.384 (1.547)		$\triangle fw\ risk\ neutral^{6m,3y}_{t\star}$	2.522*** (0.271)	
$\triangle fw\ premium^{5y,10y}_{t\star}$		−1.271 (0.840)	$\triangle fw\ risk\ neutral^{5y,10y}_{t\star}$		7.946*** (0.740)
$\overline{R2}$	0.00	0.04	$\overline{R2}$	0.86	0.90
Dependent variable: $\triangle ump^u_{t\star}$, Sample: September 15, 2008 to May 4, 2022					
const.	−0.035 (0.021)	−0.038 (0.022)	*const.*	−0.014 (0.012)	−0.011 (0.010)
$\triangle fw\ premium^{6m,3y}_{t\star}$	2.551*** (0.366)		$\triangle fw\ risk\ neutral^{6m,3y}_{t\star}$	2.551*** (0.227)	
$\triangle fw\ premium^{5y,10y}_{t\star}$		1.354*** (0.247)	$\triangle fw\ risk\ neutral^{5y,10y}_{t\star}$		5.243*** (0.626)
$\overline{R2}$	0.42	0.36	$\overline{R2}$	0.79	0.85

structures of short-rate expectations and premia, i.e. six-months to three-years forward rates, and five- to ten-years forward rates.[19] As prior to QE the Fed has used forward guidance as the only instrument of unconventional monetary policy, our unconventional surprise measure should correlate with the term structure of short-rate expectations in that period, while in the QE period, when the Fed has used both forward guidance and asset purchases as instruments of unconventional monetary policy, there should be a strong correlation with both short-rate expectations and forward premia.

Results are provided by Table 16. As can be seen, we find a strong and significant relationship between unconventional surprises and forward premia during the QE period, but no relationship during the pre-QE period, while a strong and significant relationship is found between unconventional surprises and short-rate expectations in both the pre-QE and QE periods. These results confirm that term premium became relevant for the transmission of unconventional monetary policy to interest rates (through the portfolio balance channel, at least) when asset purchases became an active instrument of monetary policy, while short-rate expectations have been relevant for the transmission of unconventional policy through forward guidance in both the pre-QE and QE periods, and through the signaling channel in the QE period. Hence, we conclude that our unconventional monetary policy surprise measure carries information about “forward guidance” in the pre-QE period, and about “forward guidance + asset purchases” in the QE period. These findings are similar to Swanson (2021), who finds relevance for “forward guidance” surprises prior to QE and for “forward guidance” and “asset purchase” surprises during the QE period. While we condense information about forward guidance and asset purchases surprises into one single surprise measure, $\triangle ump^u_{t\star}$, Swanson (2021) disentangles that information into the two surprise measures. In addition, our unconventional surprise measure is short-rate equivalent, while Swanson (2021) surprises are scaled according to movements in 1-year (forward guidance surprise) and 10-year interest rates (asset purchase surprise).

[19] We use pre-QE announcement dates provided by Swanson (2021) at https://www.socsci.uci.edu/~swanson2/researchpublished.html.

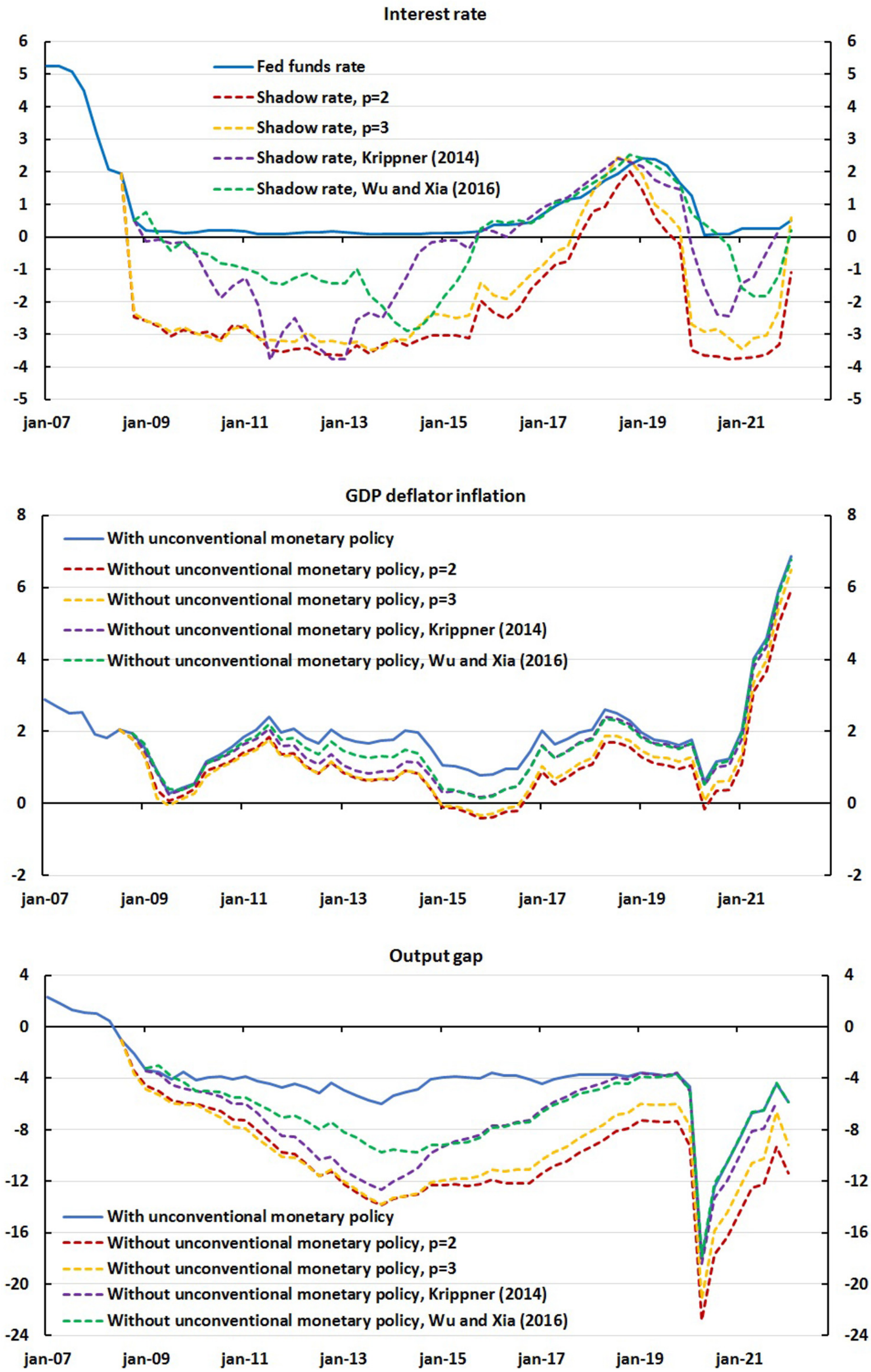


Fig. 9. The macroeconomic effects of unconventional monetary policy in the US. *Notes:* This figure shows the counterfactuals for GDP deflator inflation and output gap in the US, as well as the shadow rates that are used in the counterfactuals: (i) the proposed shadow rate obtained with the two- and three-factor models, (ii) Wu and Xia (2016) shadow rate, and (iii) Krippner (2014) shadow rate. The IRFs are obtained from Smets and Wouters (2007) model, but with increased Calvo parameters on prices and wages by 0.15, following De Groot et al. (2021). Values are provided in percentage points.

5.2. The macroeconomic effects of unconventional monetary policy

As a second application we measure the macroeconomic effects of unconventional monetary policies and show how the shadow rates can be useful for measuring the policy stance in an otherwise standard DSGE model. To do so, we construct counterfactuals for the unconventional period in the US and in Sweden to measure what inflation, output gap and unemployment would have been without these policies. For the US we use the (Smets and Wouters, 2007) model and for Sweden the Riksbank' s DSGE model Ramses II. Both are medium-scale DSGE models with enough shocks to make effects quantitatively realistic. In practice,

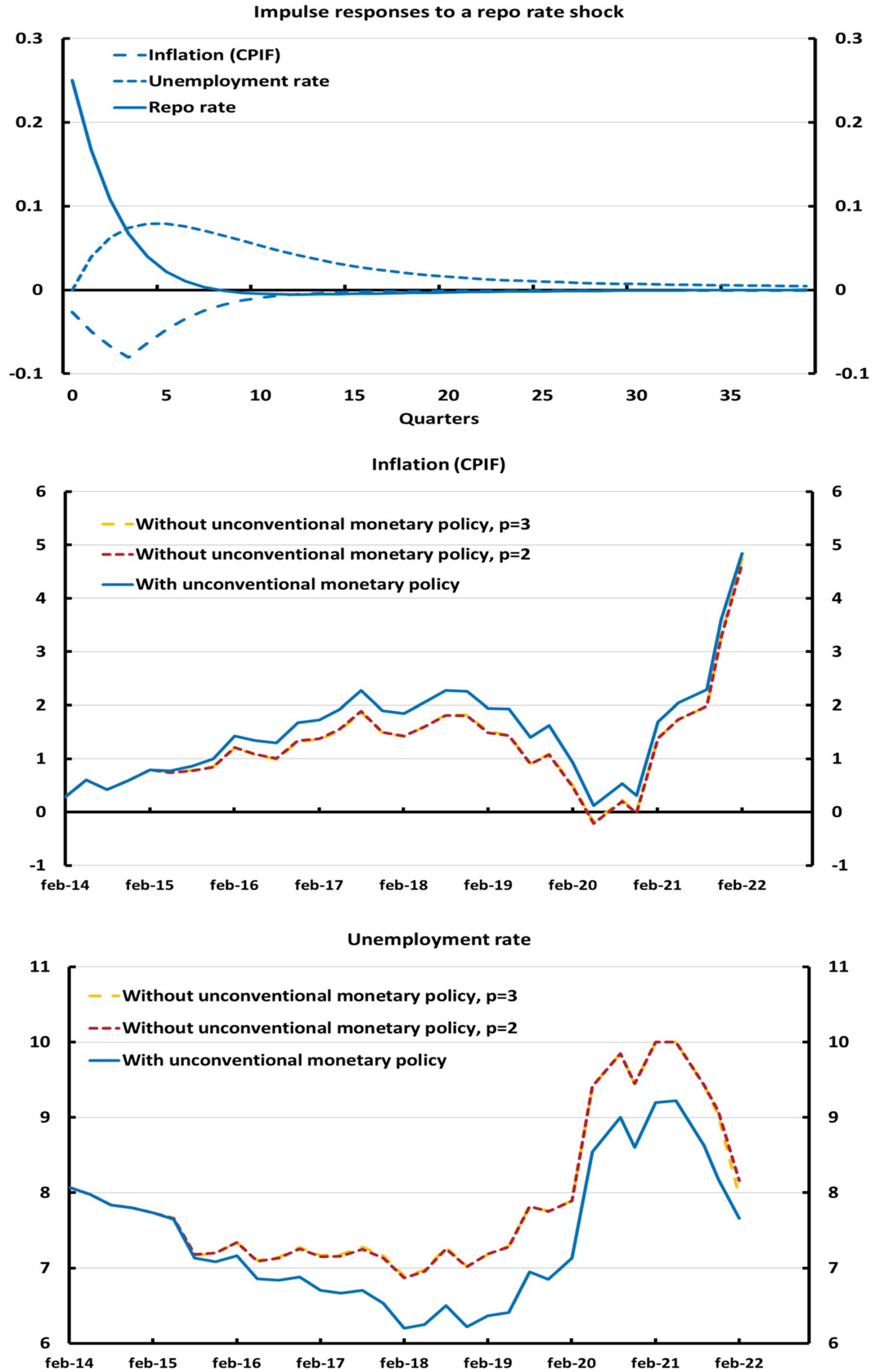


Fig. 10. The macroeconomic effects of unconventional monetary policy in Sweden. *Notes:* This figure shows the counterfactuals for inflation (CPIF) and the unemployment rate in Sweden, as well as the impulse response functions (IRFs) to a 25 basis points shock in the repo rate, which are used to construct the counterfactuals. The IRFs are obtained from Ramses II, estimated with data from the first quarter of 1995 to the fourth quarter of 2014. Values are provided in percentage points.

negative monetary policy shocks are fitted to the difference between the policy rates and the shadow rates shown in Fig. 4. The gist of the exercise is that there were other shocks with negative effects on inflation and resource utilization hitting the economy, and the appropriate response to those would be to lower the policy rate to the shadow rate. In case the Fed and the Riksbank had not done that, monetary policy would have been tighter, which would have led to lower inflation, larger output gap, and higher unemployment in the US and Sweden. For the analysis, we use the estimated impulse responses from Smets and Wouters (2007) and

Ramses II.[20] However, as the Smets and Wouters (2007) model is estimated using data from 1966 to 2004, it exhibits a relatively steep Phillips curve compared to what we observe currently. To ensure that the impulse responses to a monetary policy shock are more current we modify the Calvo parameters in the model following De Groot et al. (2021) so that impulse responses, in particular for inflation, are more in line with those from the FRB/US model.[21]

5.2.1. Results

Results for the US are shown in Fig. 9. As can be seen, inflation has remained higher than counterfactuals had the Fed not embarked on unconventional policies. Using our two- and three-factor shadow rates the counterfactuals indicate that inflation would have been on average about 0.8 and 0.7 percentage points lower than its actual level over 2009–2021, respectively. Notice also that the flex price output gap generated within the Smets and Wouters (2007) model has remained open and negative since the financial crisis of 2007–2008, with counterfactuals using our shadow rates suggesting that the Fed has provided stimulus through unconventional measures during the whole period to help closing the gap. In the absence of unconventional measures, output gap would have been on average about 5.6 and 5.3 percentage points more negative than otherwise over 2009–2021, when using our two- and three factor shadow rates.

We repeat the exercise using the shadow rates of Wu and Xia (2016) and Krippner (2014). According to these shadow rates, the Fed provided further monetary stimulus through unconventional measures when the ELB was a binding constraint for interest rates. Using Wu and Xia (2016) and Krippner (2014) shadow rates, results suggest that inflation would have been on average about 0.3 and 0.4 percentage points lower than its actual levels over 2009–2021, respectively. Output gap in turn would have been on average approximately 2.3 and 3.1 percentage points lower over 2009–2021, respectively.

Notice from the results described above the importance of accounting for the highly expansionary unconventional measures that continued to be in place during the lift-off period, and that were enlarged following the Covid crisis of 2020. For instance, according to our two-factor and three-factor shadow rates, inflation would have been on average about 0.8 and 0.6 percentage points lower than otherwise over 2018–2021, respectively. Results using Wu and Xia (2016) and Krippner (2014) shadow rates are considerably smaller, 0.1 and 0.2percentage points lower than actual levels over 2018–2021, respectively. In terms of output gap, results using our shadow rates suggest that this variable would have been on average about 4.8 and 4.1 percentage points lower than otherwise over 2018–2021. Results using Wu and Xia (2016) and Krippner (2014) suggest that, over 2018–2021, output gap would have been 1.2 and 1.6 percentage points lower, respectively, had unconventional policies not been used.

Results for Sweden are shown in Fig. 10, with dashed lines showing the counterfactuals for a scenario with no unconventional monetary policy. According to our two- and three-factor shadow rates, had the Riksbank relied on the repo rate only to stimulate the Swedish economy since February 2015, CPIF inflation would have been on average 0.33 and 0.33 percentage points lower than its actual levels over the period 2009–2021, respectively. Unemployment rate, in turn, would been on average about 0.59 and 0.58 percentage points higher, respectively. These results suggest that the unconventional policies conducted by the Riksbank since 2015, including its bond purchase program, have helped the Swedish economy to recover.

The paper that provides an exercise that is closest to ours is Mouabbi and Sahuc (2019). They integrate a set of shadow rates into a medium-scale DSGE model à la Smets and Wouters (2007) to gauge the macroeconomic effects of unconventional measures implemented by the ECB and the Fed. Their results for the US suggest that, without unconventional measures, year-on-year inflation and output growth would have been on average about 0.6 and 0.92 percentage points below their actual levels over the period 2008Q1–2015Q4, respectively. Results using an average of our two shadow rates for a similar period, 2008Q3–2015Q4, suggest that inflation and output growth would been on average about 0.7 and 1.1 percentage points below their actual levels, respectively. Other related papers in the literature are Wu and Zhang (2019a,b)). They propose shadow rate New Keynesian models (SRNKMs) that incorporate the shadow rate specification proposed by Black (1995), allowing their models to measure the effects of unconventional monetary policy when the lower-bound is binding. Their models capture several important features of monetary policy, including the assumption that the central bank sets monetary policy at the effective lower bound using a shadow rate Taylor rule. The results discussed in this section using our proposed shadow rates differ from those in the papers above in the sense that they do not rely on lower-bound assumptions. This has important implications for measuring the macroeconomic effects of unconventional monetary policies, as unconventional policies have become more standard and central banks have relied on a number of policy instruments to steer the economies. As discussed throughout this paper, the proposed shadow rate is able to account for these effects.

6. Concluding remarks

In this paper, we propose a shadow rate that measures the overall stance of monetary policy when the lower bound is not necessarily binding. Our specification is useful for estimating the overall stance of monetary policy at any point in time, prior and during the lower bound period, as well as in the current "New Normal" policy environment, where unconventional policies have become more standard with major central banks using forward guidance and balance sheet policies in connection with policy rates to offset disturbances to inflation and economic activity when judged necessary. This key salient feature makes our shadow rate an attractive and informative market-based monetary policy stance measure at any point in time.

Using daily yield curve data, we estimate shadow rates for the US, Sweden, the euro area and the UK, for the unconventional period starting from the financial crisis of 2007–2008. We find that our shadow rate estimates fall (rise) as monetary policy becomes more expansionary (contractionary), and market participants price monetary policy information into the yield curve. Our estimates track episodes of policy rate cuts and hikes, forward guidance, as well as balance sheet expansions and contractions, showing the ability of the shadow rate to track the stance of monetary policy.

Additionally, we show two applications for our shadow rate. In the first application, we measure the pass-through of monetary policy to exchange rates using event study regressions with a decomposition of shadow rate changes around announcements

[20] Ramses II is a medium-scale open economy DSGE model that is used by the Riksbank to produce macroeconomic forecasts, to construct alternative scenarios, and for monetary policy analysis in general. For a detailed description of the model, see Adolfson et al. (2013). Its impulse responses are estimated with data from the first quarter of 1995 to the fourth quarter of 2014, and are shown in Fig. 10. They have a typical hump-shaped form, with an initial effect of a 0.25 percentage points repo rate shock on inflation and unemployment rate of approximately −0.03 percentage points and zero, respectively. The maximum effect is reached after 3–5 quarters, with a decline of 0.08 percentage points in inflation, and an increase of 0.08 percentage points in the unemployment rate.

[21] In practice we increase the Calvo parameters on prices and wages by 0.15. For more details see De Groot et al. (2021). Figure D.1 in that paper shows that this results in IRFs that are close to those coming from the FRB/US.

into conventional and unconventional monetary policy surprises. Using pooled and single exchange rate regressions, we find larger responses to conventional monetary policy. Our estimates suggest that a 10 basis points decrease in the conventional surprise measure depreciates the domestic currencies by 1.02 percent vis-à-vis foreign currencies. We find the estimated impact of unconventional policy to be lower, about 0.32 percent.

In our second application, we measure the macroeconomic effects of unconventional monetary policy in the US and Sweden. We replace the policy rates in two DSGE models, Smets and Wouters (2007) and Riksbank's Ramses II, by shadow rates, and run counterfactual experiments. We illustrate that in the US, our shadow rate continues to be a useful measure of policy stance during the entire unconventional period, as it accounts for the highly expansionary unconventional measures that continued to be in place during the lift-off period of 2016–2018, and that were enlarged following the Covid crisis of 2020. In summary, results using our shadow rates suggest that the unconventional policies implemented by the Fed since 2008 have raised inflation and the output gap by around 0.8 and 5.5 percentage points on average over 2008–2021, respectively. In addition, the measures implemented by the Riksbank since February 2015 further stimulated the Swedish economy, with CPIF inflation being on average around 0.33 percentage points higher and unemployment rate around 0.58 percentage points lower than otherwise over the period 2015–2021. This type of application is particularly appealing for monetary policy analysis, as DSGE models typically used by central banks can become overly complex when unconventional monetary policy is explicitly modeled. Furthermore, scenarios estimating the effects of further unconventional policies such as bond purchases can be easily constructed.

CRediT authorship contribution statement

Rafael B. De Rezende: Conceptualization, Methodology, Investigation, Formal analysis, Software, Data curation, Validation, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Annukka Ristiniemi:** Conceptualization, Methodology, Investigation, Formal analysis, Software, Validation, Writing – review & editing.

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Appendix A. Conventional monetary policy surprise measures

A1. US

Letting ff_t^h denote the price of the federal funds future contract expiring on day h of a given month with D days, then

$$ff_t^h = \frac{1}{D}\sum_{i=1}^{N} E_t(r_{t+i}) + \xi_t^h \tag{A.1}$$

where r_t is the effective federal funds rate and ξ_t^h is a corresponding time-varying term premium. Kuttner (2001) and Gürkaynak et al. (2005) construct monetary policy surprises using quotes of the front contract of the one-month federal funds future, ff_t^1, which are based on the average of the federal funds rate calculated over the current month. Following these studies and considering that a FOMC meeting will happen within this period, we can then write:

$$ff_{t-\triangle t}^1 = \frac{d}{D} r_0 + \frac{D-d}{D} E_{t-\triangle t}(r_1) + \xi_{t-\triangle t}^1 \tag{A.2}$$

where d denotes the day of the FOMC meeting, r_0 is the federal funds rate that has prevailed so far in the month, r_0 is the federal funds rate that has prevailed so far in the month, r_1 is the rate that is expected to prevail for the reminder of the month and $\xi_{t-\triangle t}^1$ is the corresponding term premium. We use a window $\triangle t$ of ten minutes before and twenty minutes after each monetary policy announcement. The unexpected change in the federal funds target rate is given by,

$$\triangle r_t^u = \left(ff_t^1 - ff_{t-\triangle t}^1\right)\frac{D}{D-d} \tag{A.3}$$

A2. Sweden

The surprise component of the change in the repo rate, $\triangle r_t^u$, is given by

$$\triangle r_t^u = \frac{\left(stina_t^1 - stina_{t-\triangle t}^1\right)(d1+d2)}{d2} \tag{A.4}$$

where $\left(stina_t^1 - stina_{t-\triangle t}^1\right)$ is the change in the 1-month STINA interest rate around a window of fifteen minutes before and two hours and forty five minutes after each monetary policy announcement, $d1$ is the number of days between the day the STINA contract takes effect and the repo rate implementation day, and $d2$ is the number of days within the repo rate implementation day and the day in which the contract ends. STINA is an overnight index swap contract that has the T/N STIBOR (Tomorrow Next Stockholm Interbank Offered Rate) interest rate as the underlying rate.

A3. Euro area

For constructing short-rate surprises for the euro area we use one-day interest rate changes for the front contract of the three-month Euribor future, which are based on the three-month Euribor interest rate. We do not use any scaling that takes into account the days of ECB announcements. $\triangle r_t^u$ is then given by,

$$\triangle r_t^u = ef_t^3 - ef_{t-1}^3 \tag{A.5}$$

A4. UK

For constructing short-rate surprises for the UK we use one-day interest rate changes for the front contract of the three-month short-sterling future, which are based on the three-month interbank (GBP) Libor rate. More specifically,

$$\triangle r_t^u = sf_t^3 - sf_{t-1}^3 \tag{A.6}$$

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