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Abstract

We propose a shadow rate that measures the overall stance of monetary policy when the lower bound is not necessarily binding. 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). This ability of the shadow rate to track the stance of monetary policy is identified on announcements of policy rate cuts (hikes), balance sheet expansions (contractions) and forward guidance, with shadow rates responding in a timely fashion, and in line with government bond yields. 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, a counterfactual experiment in a DSGE model suggests that inflation in Sweden would have been around half a percentage point lower had unconventional monetary policy not been used since February 2015.

Key words: Monetary policy stance, unconventional monetary policy, term structure of interest rates, short-rate expectations, term premium, exchange rates.

JEL classification: E43, E44, E58, E52.

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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 relied on a variety of unconventional policies with the objective of lowering longer-term interest rates, and further ease monetary conditions. More recently, in the face of improving economic conditions and increasing inflation, these policies started to be reversed, a process called "monetary policy normalization".

One central issue is that measuring the stance of monetary policy when various policy tools are at hand is challenging. As unconventional policies are more 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]

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's (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 lower bound (Krippner 2012, 2014; Wu and Xia 2016; Wu and Xia 2017).

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, being particularly useful for estimating the overall stance of monetary policy prior and during the lower bound period, as well as in the current "New Normal" policy environment, where major central banks are keeping interest rates low, balance sheets large, and have continued to provide guidance on their interest rate and balance sheet policies. In addition, since there is no need to make assumptions about, or

[1] As emphasized by De Rezende (2017) and Swanson (2018), 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 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 2009), the reserve-induced portfolio balance channel (Christensen and Krogstrup 2016), the signaling channel (Bauer and Rudebusch 2014), the collateral channel (D'Amico et al. 2013) and the liquidity channel.

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.

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, Sack and Swanson 2005) and inverse prediction (Graybill 1976; Osborne 1991; Graybill and Iyer 1994; Brown 1994, 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 into a conventional monetary policy surprise plus a prediction error, which can be associated with the surprise component of announced unconventional monetary policies or with

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

other news in the economy, scaled by the associated event-study regression coefficient.

We estimate shadow rates for the US, Sweden, the euro area and the UK. For illustration, 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 lie well below policy rates in the four economies, suggesting that the unconventional measures implemented after the financial crisis of 2007-2008 eased monetary conditions more than otherwise. Moreover, our estimated shadow rates rise as monetary policy becomes more contractionary, and market participants price this information into the yield curve.

This ability of the shadow rate to track the stance of monetary policy is better identified on monetary policy announcements. Our estimates are able to precisely track episodes of policy rate cuts and hikes, balance sheet expansions and contractions, forward guidance, as well as speeches, in line with the responses of government bond yields. For instance, we find that the US shadow rate fell by 82.9 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 27.2 basis points. In addition, the US shadow rate reacted positively to the tapering of QE3, as well as during the balance sheet contraction period. In Sweden, we find that our shadow rate declined by 26.9 basis points on the day the Riksbank launched its bond purchase program in February 2015, as the five- and ten-year bond yields declined by 15.6 and 11.1 basis points. In the UK, the shadow rate declined by 28.2 basis points on the announcement of the post-Brexit stimulus package in August 2016. In the euro area, the shadow rate decreased by -3.5, -1.3, -3.9 and -6.6 basis points on the announcements preceding the extension of ECB's bond purchase program on December 3, 2015. Sizable effects are also found for 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 try 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 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 1.04 percent vis-à-vis the foreign currency. The estimated impact of unconventional policy is lower, about 0.36 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; Inoue and Rossi 2019).

In our second application, we measure the macroeconomic effects of unconventional monetary policy. We replace the repo rate in the Riksbank's DSGE model Ramses II by the Swedish shadow rate and construct a counterfactual analysis for inflation and unemployment rate using the impulse responses to a policy rate shock from Ramses II (see Adolfson et al. 2013). Our results suggest that the unconventional policies implemented by the Riksbank since February 2015 further stimulated the Swedish economy, with CPIF inflation and unemployment being around 0.45 percentage points higher and 0.83 percentage points lower than otherwise by the second quarter of 2019. 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 modelled. Furthermore, scenarios estimating the effects of additional unconventional measures such as further 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, Singleton and Zhu 2011; Joslin, Le and Singleton 2013; Adrian, Crump and Möench 2013; Wu and Xia 2016; Wu and Xia 2017, 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 $\mathbb{P}$,

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

where $\varepsilon_t \sim iid\, N(0, I_p)$ 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

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

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,

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

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, $P_t^n = exp(A_n + B_n' X_t)$, 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. 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 factors that drive the government bond yield curve and its short-rate expectations component specified in (5), depending on the days on which unconventional monetary policies are present, and are announced. More specifically, our specification assumes the following form,

$$\triangle s_t = \begin{cases} \triangle r_t \quad if \quad t < t_0 \\ \varphi_1' \triangle X_t^{sr} \quad if \quad t \geq t_0 \;\; s.t. \;\; t \neq t^\star \\ \varphi_2' \triangle X_t \quad if \quad t \geq t_0 \;\; s.t. \;\; t = t^\star \end{cases} \tag{6}$$

where t_0 is the first announcement day of unconventional policy measures, $t^\star$ is a day of an unconventional monetary policy announcement, X_t is a $q \times 1$ vector of yield factors, X_t^{sr} is a $q \times 1$ vector of factors that summarize the short-rate expectations component of yields, and 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). Additionally, during periods

[3]Notice that the short-rate expectation component of yields is an affine function of the pricing factors X. By setting $p = N$, we can then obtain X^{sr} through a simple rotation of X. More specifically, we define a $N \times N$ orthogonal 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 matrix U^{sr} such that X^{sr} equals the principal components of the $N \times T$ matrix Y^{sr}. We can then use the first q rows of X^{sr} as driving factors for s_t.

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

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 may 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.

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 equation (6) forward until the last sample observation, T. More specifically,

$$s_t = r_1 + \sum_{t=2}^{t_0-1} \triangle r_t + \sum_{t=t_0}^{T,t\neq t^\star} \varphi_1' \triangle X_t^{sr} + \sum_{t=t_0}^{T,t=t^\star} \varphi_2' \triangle X_t \tag{7}$$

Note that s_t may start diverging from r_t from $t = t_0$, which we set 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. 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.

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 consider that each of the vectors X_t^{sr} and X_t in (6) have dimension equal to one, i.e. $q = 1$, and estimate event study regressions as in Kuttner (2001), Gürkaynak, Sack and Swanson (2005) and other related studies,

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

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

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_t^{sr} and X_t when only conventional monetary policy was being implemented, and the relationship between these variables clearly existed.[5]

We then translate movements in X_t^{sr} and X_t 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,

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

where $\frac{1}{\widehat{\beta}}$ and $\frac{1}{\widehat{\alpha}}$ are used as estimates for φ_1 and φ_2, and where $\frac{1}{\widehat{\beta}} \triangle X_t^{sr} = \widehat{\triangle r_t^u} = \triangle r_t^u + \frac{1}{\widehat{\beta}} \widehat{\xi}_t$ when $t \neq t^{\star}$, and $\frac{1}{\widehat{\alpha}} \triangle X_t = \widehat{\triangle r_t^u} = \triangle r_t^u + \frac{1}{\widehat{\alpha}} \widehat{\varepsilon}_t$ 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 may affect short-rate expectations on that particular day, scaled by $\frac{1}{\widehat{\beta}}$. 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 error, which can be associated with the surprise component of the unconventional monetary policies announced on that particular day, as well as other news that may affect bond yields, scaled by $\frac{1}{\widehat{\alpha}}$.

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 yield curve and its short-rate expectations component as factors, i.e. $q = 1$. Even though we abstract from the information contained in other higher dimensional factors, we show in sections 4.1 and 4.2 that our shadow rate is able to capture the observed daily movements in the yield curve with high precision. This is a common feature of the factor decomposition of the yield curve, with the level factor typically explaining over 95 percent of the cross-sectional variation of yields. The event study methodology also helps substantially in that matter, as it is a powerful way of identifying the true relationship between the short-rate, and short-rate expectations and yields (Gürkaynak and Wright

[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.

2013), and to obtain precise and consistent estimates for our parameters of interest.

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 2013; Wu and Xia 2016; Bauer and Rudebusch 2016; Lemke and Vladu 2016; Wu and Xia 2017, 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, $\underline{r}$ $\left(\underline{r_t}\right)$. More specifically, one may have,

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

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, 2014; Wu and Xia 2016; Wu and Xia 2017).

Specifications (6) and (11) have similarities, such as that both are driven by yield curve information, and inform about the overall stance of monetary policy. There are also differences. The first difference is that specification (6) does not impose a lower bound constraint on nominal interest rates, and does not necessarily equal the short-rate when the lower-bound is not binding. We consider this to be particularly appealing as (6) is able to measure the overall stance of monetary policy from any point in time, i.e. $t \geq t_0$. In addition, (6) is able to capture the interest rate effects of unconventional policies that are still present when the central bank exits the lower bound. This is particularly relevant in the current “New Normal” policy environment, where major central banks are keeping interest rates low, balance sheets large, and have continued to provide guidance on their interest rate and balance sheet policies.[7] Another 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). Another aspect is that formulation (6) does not take term premium information into the measurement of the shadow rate at all times, as we consider that term premium tends to carry substantial information that is not particularly related to the stance of monetary policy, which may add noise to the shadow rate measurement. It is also worth mentioning that specification (6) can be used in conjunction with any term structure model.

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

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

use a range of indicators including interest rates, monetary aggregates and balance sheet variables. In their approach, a shadow rate is obtained by treating the short-term interest rate as a missing variable during the zero-lower bound period in the US. Therefore, it also respects the lower bound period. Our shadow rate also differs in terms of specification, data frequency and estimation method.

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, Sack and Wright (2007). These are constructed using a smooth discount function based on the Svensson (1995) 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 September 30, 2019. This sample is consistent with other studies in the literature (Wright 2011; Bauer, Rudebusch and Wu 2012; Adrian, Crump and Moench 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, Galí and Gertler 2000; Galí, Lopez-Salido and Valles 2003; Kim and Nelson 2006, among others).[9]

Swedish zero-coupon government bond yields are also constructed using the Svensson (1995) 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 September 30, 2019, which is consistent with the introduction of the inflation targeting regime by the Riksbank in 1995.

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 September 30, 2019, and spread-adjusted

[8]The Svensson (1995) 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.

[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.

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 September 30, 2019, 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; Wu and Xia 2016; Bauer and Rudebusch 2016). The decompositions of the five-year yields for the four economies are shown in Figures 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.

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, Sack and Swanson (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, Relleen and Sorensen (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 Table 1, and include announcements that involved balance sheet expansions, forward guidance, tapering as well as balance sheet contractions. We also include the last 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.

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 Table 2, in addition to its conventional monetary policy tool, the repo rate, the Riksbank has been using at least three unconventional policy instruments: government bond purchases, communication, and forward guidance, which has been provided mainly through its published repo rate path.[12] As can be seen, the Riksbank has announced conventional and unconventional monetary policies concurrently. In Section 5, we decompose the shadow rate into conventional and unconventional surprises, which helps to disentangle the effects of the two types of policy.

[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.

[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.

The ECB has provided unconventional stimulus through a number of measures (see Table 3). 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.

A large part of the unconventional measures in the UK was 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, and those in which the Bank of England provided some guidance on the reduction of its stock of purchased assets (see Table 4).

4 Shadow rate estimates

4.1 Shadow rate estimates and their responses to monetary policy announcements

In this section, we describe the estimated shadow rates for the four economies. Table 5 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 $\triangle X_t^{sr}$ and $\triangle X_t$ respond significantly to short-rate surprises for all economies, with R2 values ranging from 0.20 to 0.74. These determine the link between the short-rate, the yield curve and its short-rate expectations component, and are used to compute the shadow rates, as described in section 2.3.

4.1.1 United States

The estimated shadow rates using the two and three-factor models for the US are shown in Figure 3. As can be seen, the two 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 and the last interest rate cuts, and rise as market participants expect monetary policy to become more contractionary, as around the announcements of tapering, interest rate hikes and balance sheet contractions.

In order to better identify how the stance of monetary policy has changed with these policies, we look at how the shadow rates responded to the unconventional policy announcements that are listed in Table 1. These are shown in Table 6. 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 6, following government bond yields, the shadow rates increased following Bernanke's speech and the first forward-guidance announcement, but dropped by 27.2 basis points after the Fed announced that it would keep the fed funds target rate at zero until mid-2013. As shown in Figure 3, shadow rates remained low and stable after that event, suggesting 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.

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. However, the responses of our shadow rates to the first four expansionary announcements made by the Fed are more pronounced, suggesting that QE was particularly expansionary at its start. Our shadow rates are also able to track quite well 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 balance sheet contractions and further policy rate increases that were announced later on. As the alternative estimates respect the lower bound constraint, they necessarily equal the observed short-rate as soon as the lower bound is no longer binding.

4.1.2 Sweden

The shadow rate estimates for Sweden are shown in Figure 3. 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 in Table 7.

We start by looking at the announcement of February 12, 2015, which 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 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 government bond yields, leading the shadow rates to decline by 22.7 and 21.1 basis points. The other two announcements affected mostly the long-end of the Swedish yield curve, with shadow rates declining by 6.7 and 7.8 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.

[13] Information about QE expectations is collected from market newletters 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.

Contractionary announcements can be seen on April 29, 2015, April 21, 2016, and December 20, 2018, 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 lower 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, with shadow rates raising by 14.7 basis points.

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 that clearly involved 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 7, $\triangle s_{t^\star} - \triangle r_{t^\star}^u$, and scale them in terms of a suprise of SEK 10 billion in purchases obtained from market newsletters and also provided in Table 7. 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 introduced 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 Figure 4. 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 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 8, we see the shadow rate responses to a series of unconventional announcements by the ECB. The European swap rates moved little following most announcements, with the shadow rates also moving accordingly. Interestingly, on October 6, 2011 the shadow rates increased by 17.1 basis points, which can be largely attributed to the surprise in the short-rate that strongly affected the short-end of the yield curve with the two-year yield increasing by 20.4 basis points. The first extension of the Expanded Asset Purchase Program (EAPP) announced in December 2015 also led the European shadow rates to increase by 21.1 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 abount its reinvestment strategy, the euro area shadow rates increased continuously, as can be seen from Figure 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.

4.1.4 United Kingdom

The shadow rates for the UK are shown in Figure 4. As for other economies, the UK shadow rate shows a downward trend, as a result of the highly expansionary measures provided by the Bank of England, reaching the values of -2.53 (two-factor model) and -2.05 (three-factor model) percent in September 30, 2019.

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 the unconventional period. As can be seen from Table 9, there were five announcements that can be considered strongly expansionary - October 8, 2008, February 11, 2009, March 5, 2009, June 24, 2016 and August 4, 2016 - and four that can be considered strongly contractionary - July 9, 2009, June 13, 2014, July 15, 2017 and September 14, 2017.

On February 11, 2009 the Bank of England suggested that it could buy assets in the near-future. This led yields on Gilts to fall sharply, with the UK shadow rates responding accordingly, and lowering by 46 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 35.7 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 and 10.3 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 28.2 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 11.4, 10.3 and 11.5 basis points, respectively.

The most important contractionary announcements happened on July 9, 2009, June 13, 2014, July 15, 2017 and September 14, 2017. On the first date, UK shadow rates increased by 19.8, 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 17.5 basis points, after Mark Carney stated that Bank Rate would be increased sooner than expected by market participants. The last two announcements are characterized by the Bank of England signaling that Bank Rate could be increased soon, which led market participants to quickly price in this information, leading shadow rates to increase by 16.7 and 15.5 basis points, respectively. After that, shadow rates continued rising as monetary policy started being normalized in the UK.

4.2 Monetary policy normalization across economies: discussion

As described above, our shadow rate increases as monetary policy becomes more contractionary. In this context, it is useful to compare the shadow rates estimated for the four economies to shed light on the interest rate effects of monetary policy shifting towards the "New Normal" environment. One important aspect is the differences in communication and use of the set of policy tools by different central banks.

The Fed was the first central bank to start normalizing monetary policy following the highly expansionary measures adopted in response to the global financial crisis of 2007-2008. Its strategy followed a sequence of events, with (i) the announcement of tapering of its open-ended QE policy, (ii) communication of the reinvestment of the principal payments from its asset holdings, with the aim of using asset holdings as a passive monetary policy instrument, (iii) policy rate increases, and (iv) balance sheet contraction. The interest rate effects of this strategy can be seen in Figure 3, with the announcement made by Bernanke on May 22, 2013 marking its beginning. Although market participants became aware of the potential tapering of QE3, the US shadow rates did not rise significantly. In fact, we observe a sharp increase in long-term Treasury term premia right after, resulting from the higher uncertainty regarding the upcoming policy (see Figure 1). This uncertainty was only resolved after December 2013, when a series of tapering announcements lowered uncertainty about Fed's balance sheet policy, and brought term premia back to lower levels. As a result, the US shadow rate responded promptly, rising continuously from the end of 2013. Interestingly, we see a sharp rise around October 28, 2015, when the Fed communicated that the first policy rate hike could happen in December 2015, and from mid-2017, when the Fed's balance sheet started contracting.

Normalization of monetary policy in other economies started later. The ECB started communicating a reduction 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, as well as on the level of its key interest rates, which would remain at low levels well past the horizon of its asset purchases. The interest rate effects of the ECB's strategy can be seen in Figure 4, with the shadow rates for the euro area starting to increase around October 2016, when market participants speculated that the ECB would provide extensions of its EAPP, but with a gradual reduction in the pace of purchases.[14] When these speculations started to materialize in December 2016, with a series of less expansionary (or contractionary) announcements by the ECB, we see a continuing increase of the shadow rate. In Sweden and the UK, shadow rates indicated a contraction in monetary conditions only when policy rates were about to start rising. This differs from the US and euro area cases, where the stance of monetary policy became more contractionary at the time that the pace of asset purchases was reduced.

5 Applications

This section presents two 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 by replacing the repo rate in the Riksbank's DSGE model Ramses II by the Swedish shadow rates shown in Figure 3, and by running a counterfactual experiment to evaluate the effects of unconventional monetary policy on inflation and unemployment.

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, $\triangle r^u_{t^\star}$, from shadow rate changes and obtain a measure of unconventional monetary policy surprise, $\triangle ump^u_{t^\star} = \triangle s_{t^\star} - \triangle r^u_{t^\star}$, which may include information about monetary policy that affects the whole term structure of interest rates, and that is unrelated to $\triangle r^u_{t^\star}$.[15] This decomposition, which is

[14] See for instance, https://www.ft.com/content/4867052a-d5f6-334c-901e-b5d3010ab02d.

[15] 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, as well as other news that may affect bond yields, scaled by $\frac{1}{\alpha}$.

shown in Figures 6 and 7, can be used to 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,

$$\triangle e_{t^\star} = \eta + \gamma \triangle r^u_{t^\star,d} + \vartheta \triangle ump^u_{t^\star,d} + \omega \triangle s_{t^\star,f} + \varepsilon_{t^\star} \tag{12}$$

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 minutes before and 30 minutes 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 10. 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 -0.091 to -0.206, compared to -0.022 to -0.123 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 all the announcements listed in Tables 1 to 4.[16] On average, a 10 basis point drop in the conventional surprise measure depreciates the domestic currencies by 1.04 percent vis-à-vis foreign currencies. The estimated impact of unconventional monetary policy is lower, about 0.36 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; Inoue and Rossi 2019).

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

5.2 The macroeconomic effects of unconventional monetary policy

As a second application we measure the macroeconomic effects of unconventional monetary policy. We construct a counterfactual analysis by replacing the repo rate in the Riksbank's DSGE model Ramses II with the Swedish shadow rates, and by computing what inflation and unemployment rates would have been had unconventional monetary policy not been conducted since February 2015.[17] In practice, negative monetary policy shocks are fitted to the difference between the repo rate and the shadow rates shown in Figure 3. The gist of the exercise is that there were other shocks with negative effects on inflation and economic activity hitting the economy, and the appropriate response to those would be to lower the repo rate to the shadow rate. In case the Riksbank had not done that, monetary policy would have been tighter, which would have led to lower inflation and higher unemployment in Sweden. For the analysis we use the impulse responses from Ramses II, estimated with data from the first quarter of 1995 to the fourth quarter of 2014. These are shown in Figure 7, and have a typical hump-shaped form. As the economy responds with a lag, the initial effect of a 0.25 percentage points repo rate shock on inflation and unemployment rate is 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.

5.2.1 Results

Results are shown in Figure 7, with dashed lines showing the counterfactuals for a scenario with no unconventional monetary policy. As suggested by our estimates, had the Riksbank relied on the repo rate only to stimulate the Swedish economy since February 2015, CPIF inflation would have been 0.46 (0.43) percentage points lower in second quarter of 2019, according to the two-factor (three-factor) model shadow rate. Unemployment, in turn, would be 0.83 (0.83) percentage points higher, according to the two-factor (three-factor) model shadow rate. 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.

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 interest rate effects of unconventional monetary policy prior and during the lower bound period, as well as in the

[17] Ramses II is a medium-scale open economy DSGE model that is currently 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).

current "New Normal" policy environment, where major central banks are keeping interest rates low, balance sheets large, and have continued to provide guidance about their interest rate and balance sheet policies. Additionally, there is no need to make assumptions or estimate the lower bound value in our specification, making it 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). These salient features make our shadow rate an attractive and informative market-based monetary policy stance measure in conventional and unconventional times.

Using daily yield curve data, we estimate shadow rates for the US, Sweden, the euro area, and the UK. For illustration, we set the day in 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. We find that our estimates fall (rise) as monetary policy becomes more expansionary (contractionary), and market participants price monetary policy information into the yield curve. Our estimates are able to precisely track episodes of policy rate cuts and hikes, balance sheet expansions and contractions, forward guidance, as well as speeches. These events identify the ability of the shadow rate to track the stance of monetary policy.

Additionally, we show two applications for the 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 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 1.04 percent vis-à-vis foreign currencies. We find the estimated impact of unconventional policy to be lower, about 0.36 percent.

In our second application, we measure the macroeconomic effects of unconventional monetary policy in Sweden by replacing the repo rate in the Riksbank's DSGE model Ramses II with the Swedish shadow rates, and by running a counterfactual experiment. Our estimates suggest that the unconventional policies conducted in Sweden since 2015 have further stimulated the Swedish economy, with CPIF inflation and unemployment being around 0.45 percentage points higher and 0.83 percentage points lower than otherwise by the second quarter of 2019, respectively. 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 modelled. Furthermore, scenarios estimating the effects of further unconventional policies such as bond purchases can be easily constructed.

Appendix. Conventional monetary policy surprise measures

A.1. 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

$$ff_t^h = \frac{1}{D}\sum_{i=1}^{N} E_t\left(r_{t+i}\right) + \xi_t^h \tag{13}$$

where r_t is the effective federal funds rate and ξ_t^h is a corresponding time-varying term premium. Kuttner (2001) and Gürkaynak, Sack and Swanson (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:

$$ff_{t-\triangle t}^1 = \frac{d}{D} r_0 + \frac{D-d}{D} E_{t-\triangle t}\left(r_1\right) + \xi_{t-\triangle t}^1 \tag{14}$$

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,

$$\triangle r_t^u = \left(ff_t^1 - ff_{t-\triangle t}^1\right)\frac{D}{D-d} \tag{15}$$

A.2. Sweden

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

$$\triangle r_t^u = \frac{\left(stina_t^1 - stina_{t-\triangle t}^1\right)(d1+d2)}{d2} \tag{16}$$

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.

A.3. 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,

$$\triangle r_t^u = ef_t^3 - ef_{t-1}^3 \tag{17}$$

A.4. 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,

$$\triangle r_t^u = sf_t^3 - sf_{t-1}^3 \tag{18}$$

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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
Nov 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
Nov 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
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
Nov 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%
Sep 18, 2019	Fed lowers the fed funds target rate to the range of 1.75% - 2.0%

Table 2: 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 per cent, 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
Feb 13, 2019	Repo rate unchaged at −0.25 per cent. Next repo rate rise is likely to occur during the second half of 2019
Apr 25, 2019	Repo rate unchaged at −0.25 per cent. 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 per cent. 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 per cent. Next repo rate rise is likely to occur at the end of 2019, or early 2020

Table 3: 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
	Reinvestmest 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

Table 4: 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
Nov 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
Nov 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
Nov 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, 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
Nov 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%

Table 5: Regression results

Notes: This table shows estimation results for the regressions $\triangle X_{t^\diamond} = \alpha \triangle r^u_{t^\diamond} + \varepsilon_{t^\diamond}$ and $\triangle X^{sr}_{t^\diamond} = \beta \triangle r^u_{t^\diamond} + \varepsilon_{t^\diamond}$, where $\triangle X_{t^\diamond}$ and $\triangle X^{sr}_{t^\diamond}$ are the changes in the first principal components of the yield curve and its short-rate expectations component. $\triangle r^u_{t^\diamond}$ 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

Table 6: 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 Table 1. 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 $(\triangle r^u_{t^*})$	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	-112.8
Nov 25, 2008	0.0	-1.0	-14.3	-22.5	-21.4	-37.9
Dec 1, 2008	0.0	-1.0	-11.9	-21.4	-21.5	-33.5
Dec 16, 2008	-75.0	-16.0	-10.7	-16.3	-17.5	-32.3
Mar 18, 2009	0.0	0.0	-26.4	-47.1	-51.9	-82.9
Aug 10, 2010	0.0	0.4	-2.7	-7.1	-6.9	-8.4
Aug 27, 2010	0.0	0.0	5.4	12.3	16.6	19.0
Sep 21, 2010	0.0	0.0	-3.7	-9.6	-10.7	-11.3
Oct 15, 2010	0.0	0.0	-1.2	2.6	8.6	4.6
Nov 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	22.1
Aug 9, 2011	0.0	-0.7	-8.6	-19.1	-20.5	-27.2
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	-8.7
Aug 31, 2012	0.0	0.0	-3.7	-6.4	-7.0	-10.5
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	6.3
Dec 18, 2013	0.0	0.0	-1.5	2.6	4.6	6.5
Jan 29, 2014	0.0	0.0	-2.0	-5.9	-7.7	-8.5
Mar 19, 2014	0.0	0.0	10.6	18.4	9.8	24.3
Apr 30, 2014	0.0	0.0	-2.4	-4.8	-3.5	-7.8
Jun 18, 2014	0.0	0.0	-1.3	-4.9	-4.7	-5.1
Jul 30, 2014	0.0	-0.5	2.7	7.5	10.2	18.4
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	11.2
Oct 28, 2015	0.0	-0.5	8.5	9.2	5.3	13.1
Dec 16, 2015	25.0	2.2	4.3	5.0	2.9	4.7
Dec 14, 2016	25.0	0.0	9.9	10.1	5.4	15.4
Mar 15, 2017	25.0	0.5	-6.3	-10.6	-9.5	-17.3
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	-6.9
Jul 26, 2017	0.0	0.0	-4.3	-6.2	-4.1	-8.5
Sep 20, 2017	0.0	0.0	4.9	5.0	3.7	5.7
Dec 13, 2017	25.0	0.5	-4.6	-5.7	-4.2	-7.7
Mar 21, 2018	25.0	0.9	-2.0	-0.5	1.2	-0.9
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	-4.0
Nov 8, 2018	0.0	0.3	2.2	2.6	1.6	4.8
Dec 19, 2018	25.0	3.6	-1.3	-3.5	-5.8	-5.3
Jan 30, 2019	0.0	0.0	-4.9	-5.1	-0.5	-6.2
Mar 20, 2019	0.0	1.5	-6.0	-7.9	-6.1	-11.6
Jul 31, 2019	-25.0	0.0	4.1	0.0	-3.7	4.4
Sep 18, 2019	-25.0	0.6	3.4	2.1	-0.5	1.8

Table 7: 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 Table 2. 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 ($\triangle r^u_{t^\star}$)	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	-22.7
Apr 29, 2015	0.0	7.3	10-20 bn	5.5	6.7	6.9	11.0
Jul 2, 2015	-10.0	-8.5	45 bn	-11.2	-13.1	-8.9	-21.1
Sep 3, 2015	0.0	5.3	0 bn	2.6	-2.2	-3.6	-0.4
Oct 28, 2015	0.0	4.5	30 bn	-2.2	-7.5	-8.2	-6.7
Dec 15, 2015	0.0	-0.4	0 bn	3.1	6.4	8.4	7.7
Feb 11, 2016	-15.0	-7.9	0 bn	-4.1	-4.0	-4.1	-7.5
Apr 21, 2016	0.0	1.0	-15 bn	-0.3	3.8	8.3	4.3
Jul 6, 2016	0.0	1.2	0 bn	0.4	1.5	-0.2	-0.6
Sep 7, 2016	0.0	0.0	0 bn	0.3	1.7	0.8	1.2
Oct 27, 2016	0.0	0.2	0 bn	-2.6	0.8	6.0	0.5
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	-1.6
Apr 27, 2017	0.0	-0.6	15 bn	-3.4	-6.4	-7.3	-7.8
Jul 4, 2017	0.0	1.0	0 bn	-4.1	-4.3	-3.6	-5.8
Sep 7, 2017	0.0	0.0	0 bn	-2.6	-4.4	-3.6	-5.3
Oct 26, 2017	0.0	-0.8	0 bn	-3.2	-3.7	-3.8	-5.1
Dec 20, 2017	0.0	0.0	0 bn	1.2	2.6	1.8	2.6
Feb 14, 2018	0.0	-1.3	0 bn	1.3	2.0	1.8	2.2
Apr 26, 2018	0.0	1.1	0 bn	-2.8	-4.9	-3.9	-5.4
Jul 3, 2018	0.0	0.9	0 bn	2.9	3.3	2.0	4.2
Sep 6, 2018	0.0	-2.1	0 bn	3.4	0.4	-0.4	1.6
Oct 24, 2018	0.0	-3.1	0 bn	-1.5	-2.2	-1.3	-1.0
Dec 20, 2018	15.0	0.8	0 bn	4.8	0.7	-0.5	7.4
Feb 13, 2019	0.0	0.0	0 bn	2.8	3.2	2.3	3.9
Apr 25, 2019	0.0	0.0	0 bn	-7.0	-7.8	-8.3	-11.3
Jul 3, 2019	0.0	0.6	0 bn	1.6	0.1	-2.1	0.4
Sep 5, 2019	0.0	2.1	0 bn	9.5	10.7	9.9	14.7

Table 8: 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 3. 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 ($\triangle r^u_{t^\star}$)	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	7.9
May 10, 2010	0.0	-15.5	5.0	8.5	13.2	7.9
Oct 6, 2011	0.0	10.5	20.4	7.7	5.6	17.1
Dec 8, 2011	0.0	10.5	-5.9	2.6	-7.9	-4.7
Sep 6, 2012	0.0	1.0	3.3	2.9	7.6	5.8
Jun 5, 2014	-10.0	-2.0	0.5	-4.2	-3.1	-3.8
Sep 4, 2014	-10.0	-4.0	-6.3	-4.6	1.0	-8.5
Dec 4, 2014	0.0	0.5	1.5	1.1	2.4	0.3
Jan 2, 2015	0.0	-1.0	-1.2	-2.2	-6.0	-3.5
Jan 22, 2015	0.0	0.0	-0.8	-1.9	-1.3	-1.3
Sep 3, 2015	0.0	0.0	-0.9	-3.7	-5.5	-3.9
Oct 22, 2015	0.0	-3.5	-4.3	-5.2	-4.9	-6.6
Dec 3, 2015	0.0	7.5	12.7	18.1	16.6	21.2
Jan 21, 2016	0.0	-2.5	-3.2	-5.1	-3.2	-5.6
Feb 18, 2016	0.0	-1.0	-2.1	-2.9	-5.8	-4.5
Mar 10, 2016	-5.0	1.5	6.5	5.3	3.7	7.7
Apr 21, 2016	0.0	0.0	1.0	3.9	6.3	3.7
Sep 8, 2016	0.0	1.0	2.5	4.0	6.9	5.1
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	7.8
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	-3.5
Jun 14, 2018	0.0	0.0	-3.4	-4.8	-4.5	-5.1
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	-1.0
Mar 7, 2019	0.0	0.0	-2.5	-4.5	-5.8	-4.7
Jun 18, 2019	0.0	-4.0	-5.8	-6.9	-6.7	-8.4
Jul 25, 2019	0.0	2.0	0.2	-1.1	-1.1	0.4
Sep 12, 2019	0.0	4.5	8.5	9.0	7.0	13.0

Table 9: 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 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	Short-rate surprise ($\triangle r^{u}_{t^{\star}}$)	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	-23.4
Feb 11, 2009	0.0	-7.0	-29.8	-25.2	-20.4	-46.0
Mar 5, 2009	-50.0	5.0	-2.0	-18.0	-31.7	-36.0
May 7, 2009	0.0	-4.0	1.3	4.6	5.7	5.7
Jul 9, 2009	0.0	2.0	8.9	14.6	17.1	19.8
Aug 6, 2009	0.0	-6.0	-3.4	-11.1	-7.3	-9.7
Nov 5, 2009	0.0	2.0	0.6	4.5	6.9	5.0
Sep 9, 2010	0.0	-1.0	3.1	4.7	6.7	7.1
Mar 10, 2011	0.0	-3.0	-5.8	-8.1	-8.2	-11.4
Oct 6, 2011	0.0	0.0	4.1	3.2	4.5	6.4
Dec 8, 2011	0.0	0.0	-1.8	-8.4	-10.2	-9.3
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	-11.7
Aug 2, 2012	0.0	4.0	-4.0	-6.9	-7.9	-8.6
Nov 7, 2013	0.0	-1.0	-5.1	-5.8	-3.9	-7.6
Feb 6, 2014	0.0	0.0	2.5	4.7	5.9	5.4
Jun 13, 2014	0.0	3.0	12.6	8.5	2.8	17.5
Jun 4, 2015	0.0	1.0	-3.6	-5.7	-6.0	-7.4
Nov 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	-43.0
Jun 30, 2016	0.0	-6.0	-5.5	-5.2	-3.7	-10.3
Aug 4, 2016	-25.0	-2.0	-8.3	-15.8	-16.8	-28.2
Jun 15, 2017	0.0	0.5	8.1	11.0	10.2	16.7
Aug 3, 2017	0.0	-2.0	-4.9	-6.8	-8.2	-11.5
Sep 14, 2017	0.0	-0.5	8.2	8.8	7.1	15.5
Nov 2, 2017	25.0	-1.5	-8.9	-10.4	-8.4	-8.3
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	6.6

Table 10: 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 to 4. 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.	0.058	0.045	0.168	−0.066	−0.053	−0.121**
	(0.107)	(0.077)	(0.135)	(0.088)	(0.053)	(0.057)
$\triangle r^{u}_{t^{\star},d}$	−0.122***	−0.091***	−0.095***	−0.091***	−0.095***	−0.094***
	(0.036)	(0.021)	(0.018)	(0.034)	(0.018)	(0.016)
$\triangle ump^{u}_{t^{\star},d}$	−0.044***	−0.037***	−0.022***	−0.044***	−0.042***	−0.048***
	(0.005)	(0.005)	(0.006)	(0.005)	(0.011)	(0.011)
$\triangle s_{t^{\star},f}$	0.028	0.039	0.025	0.003	0.007	0.010
	(0.025)	(0.033)	(0.016)	(0.024)	(0.026)	(0.011)
$\overline{R2}$	0.68	0.64	0.28	0.78	0.78	0.77
	ECB			Bank of England		
	EUR/USD	EUR/SEK	EUR/GBP	GBP/USD	GBP/SEK	GBP/EUR
const.	0.182	0.145*	0.172*	0.148	0.341	0.078
	(0.144)	(0.079)	(0.100)	(0.092)	(0.117)	(0.088)
$\triangle r^{u}_{t^{\star},d}$	−0.168***	−0.093***	−0.144***	−0.197***	−0.206***	−0.118**
	(0.048)	(0.021)	(0.028)	(0.066)	(0.074)	(0.046)
$\triangle ump^{u}_{t^{\star},d}$	−0.123***	−0.064***	−0.084***	−0.037***	−0.050***	−0.054***
	(0.033)	(0.023)	(0.029)	(0.011)	(0.012)	(0.009)
$\triangle s_{t^{\star},f}$	0.001	0.021	0.004	−0.007	−0.004	0.054**
	(0.021)	(0.030)	(0.023)	(0.012)	(0.019)	(0.021)
$\overline{R2}$	0.57	0.41	0.59	0.63	0.61	0.66

Figure 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 September 30, 2019. The US sample ranges from January 2, 1987 to September 30, 2019. The decompositions are obtained using the Joslin, Singleton and Zhu (2011) model with two ($p = 2$) and three ($p = 3$) pricing factors.

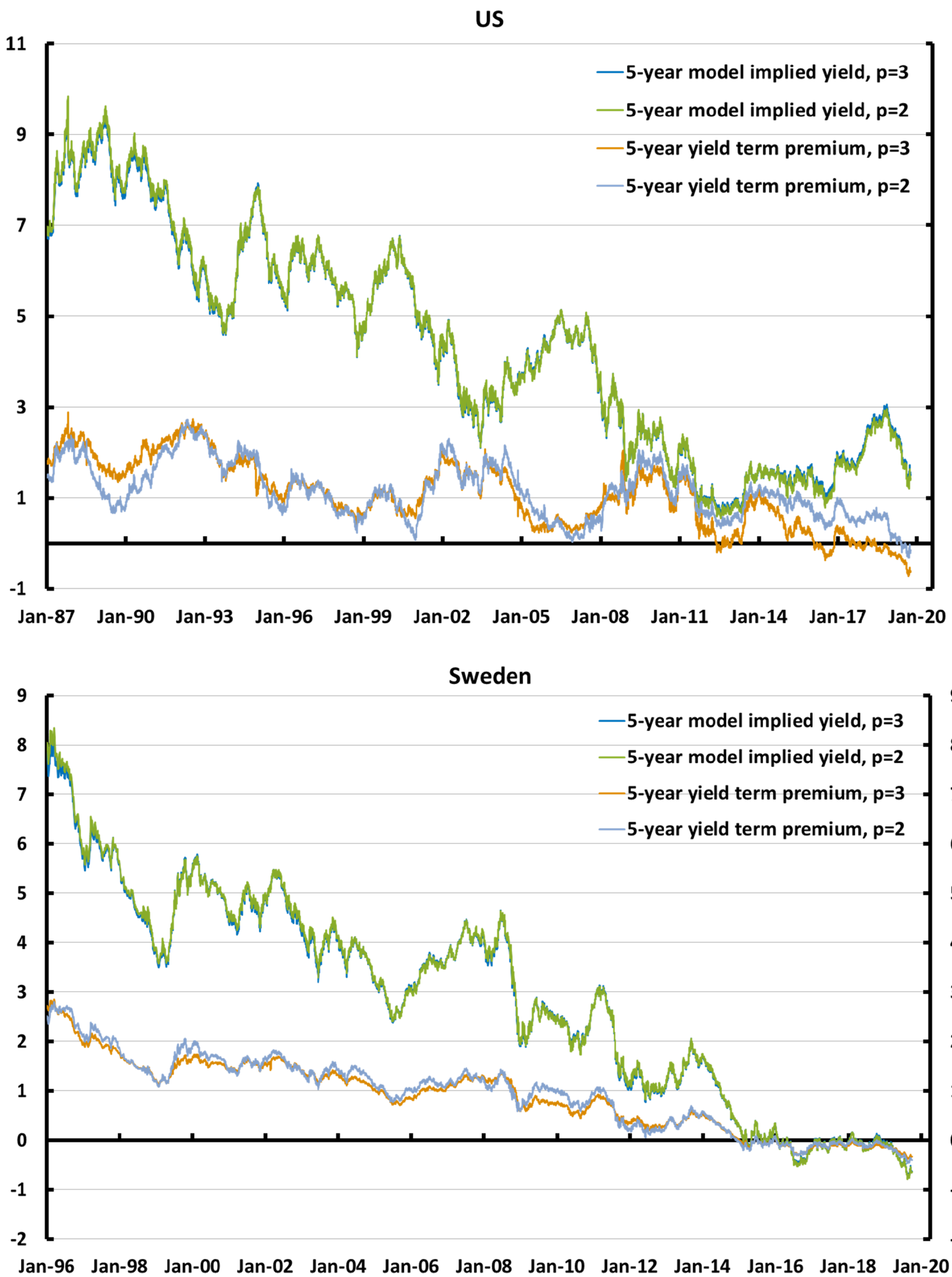
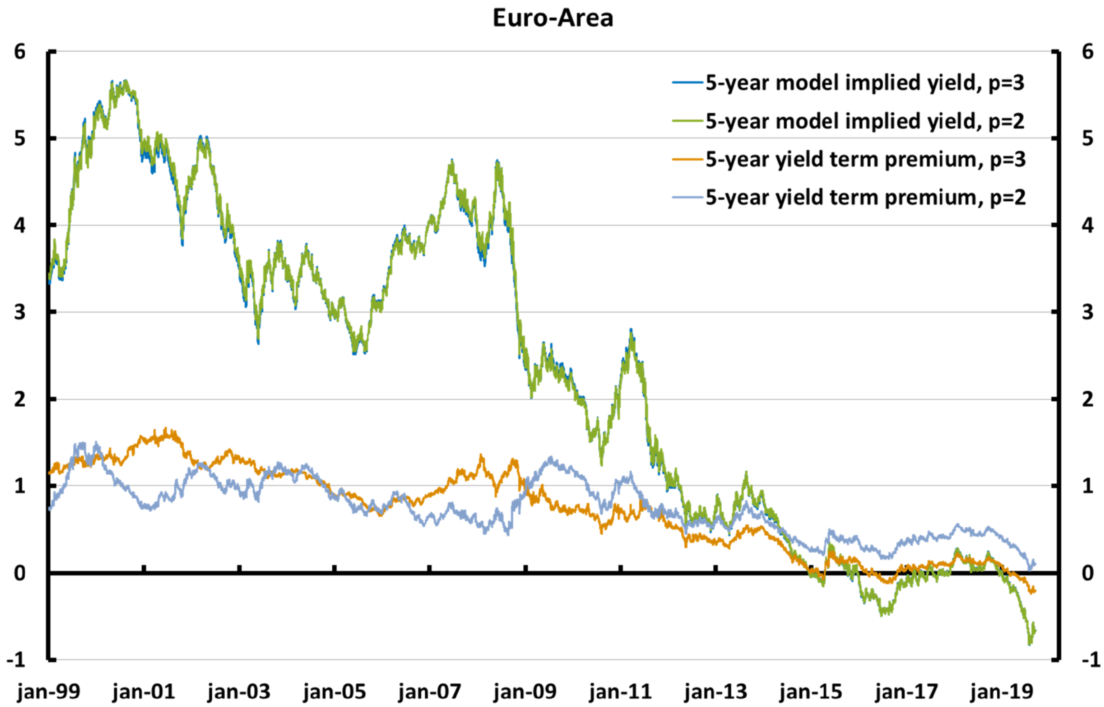


Figure 2: Decomposition of five-year government bond yield for the euro area and the UK

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 September 30, 2019. The UK sample ranges from October 1, 1992 to September 30, 2019. The decompositions are obtained using the Joslin, Singleton and Zhu (2011) model with two ($p = 2$) and three ($p = 3$) pricing factors.



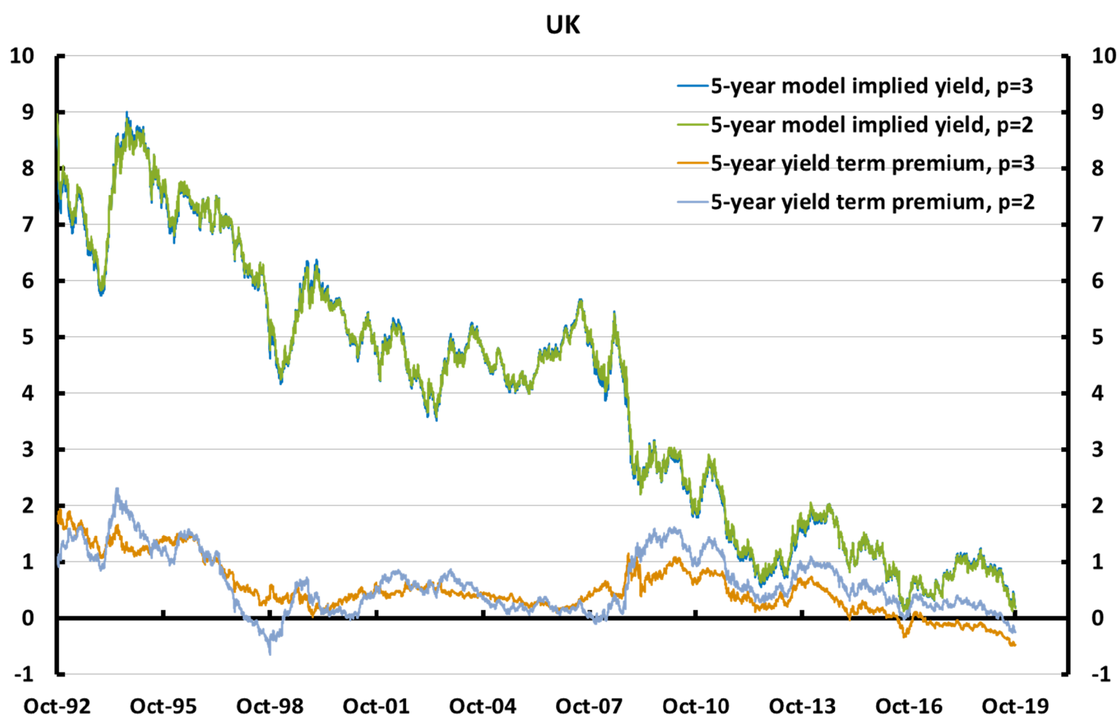
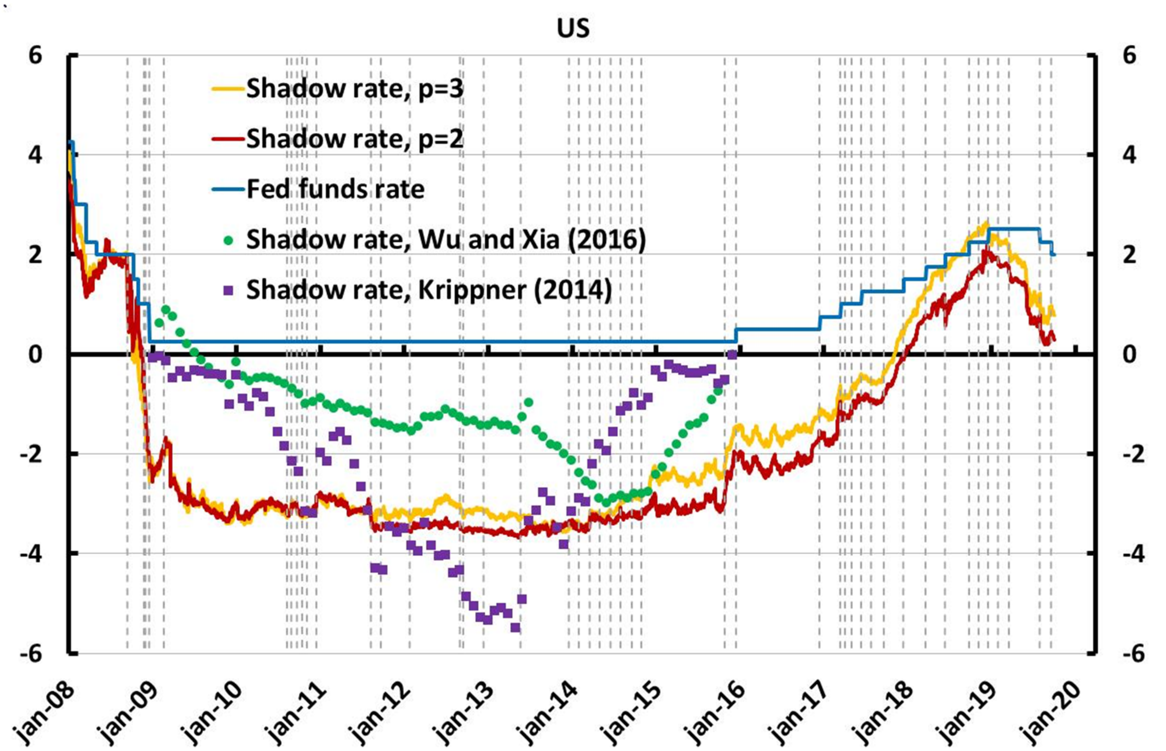


Figure 3: Shadow rate estimates for the US and Sweden

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 and 2.



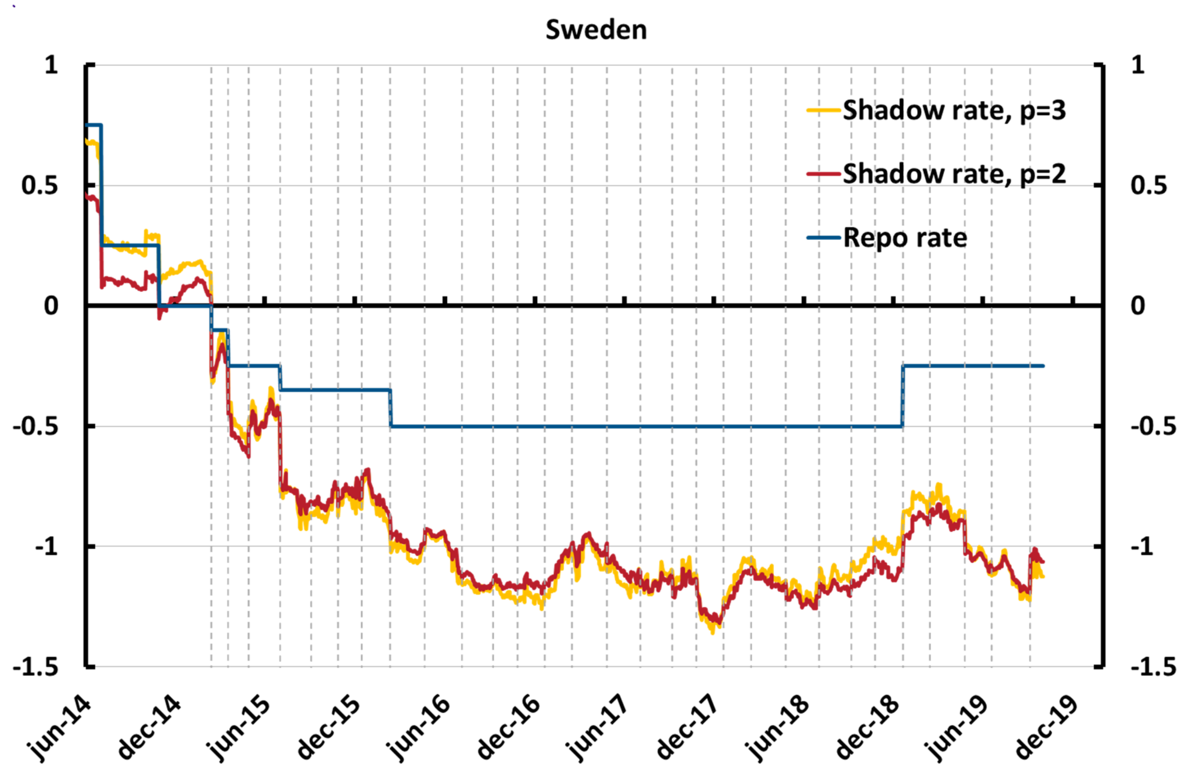
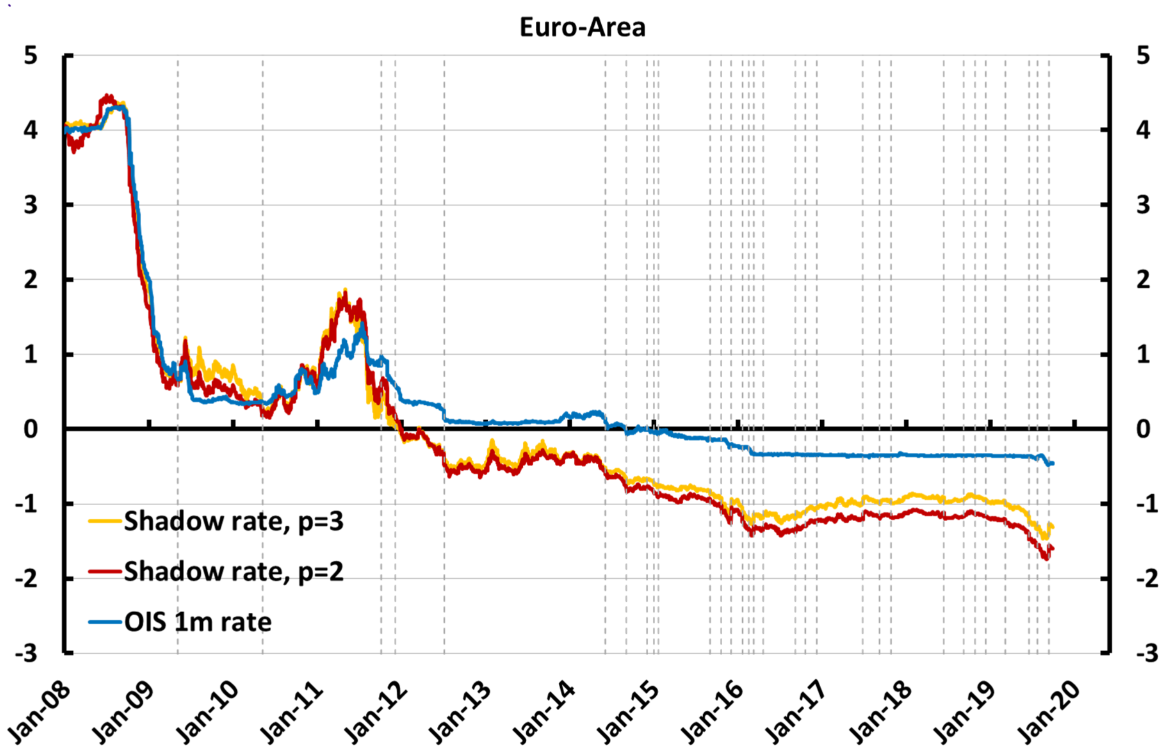


Figure 4: Shadow rate estimates for the euro area and the UK

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 3 and 4.



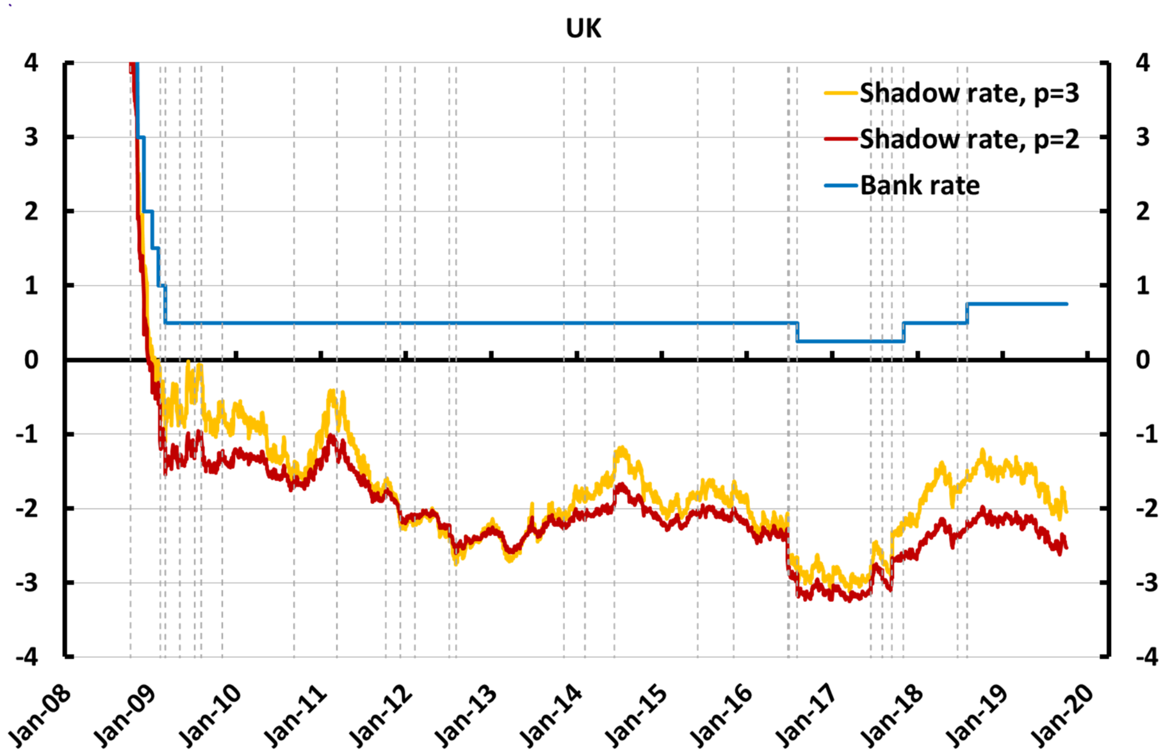
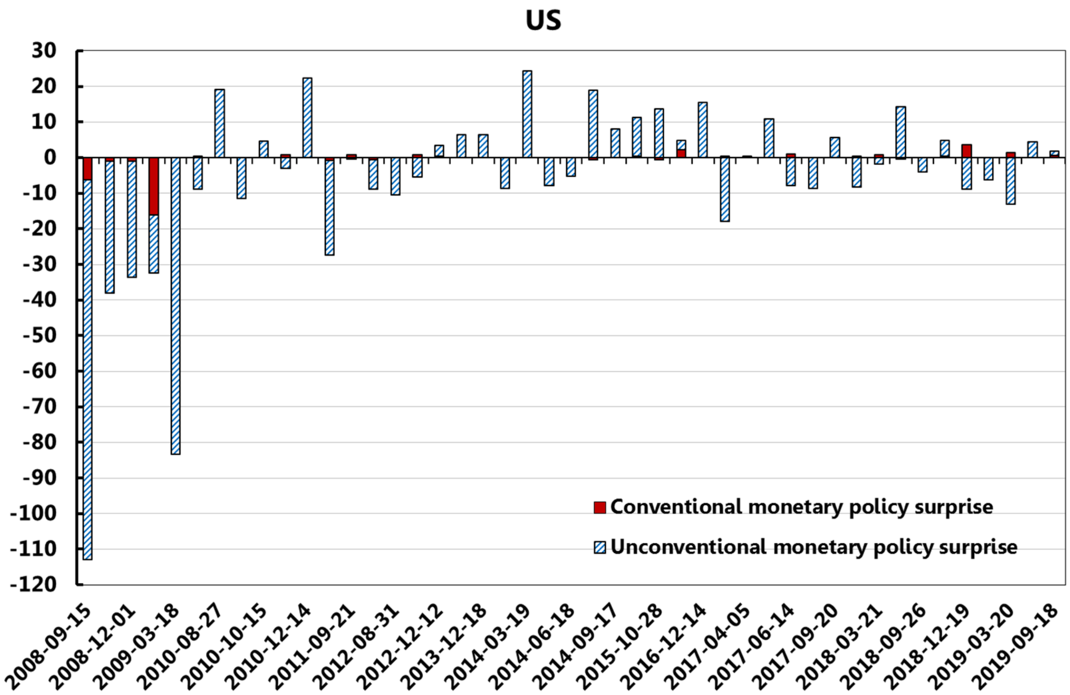


Figure 5: Decomposition of shadow rate changes around announcements for the US and Sweden

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.



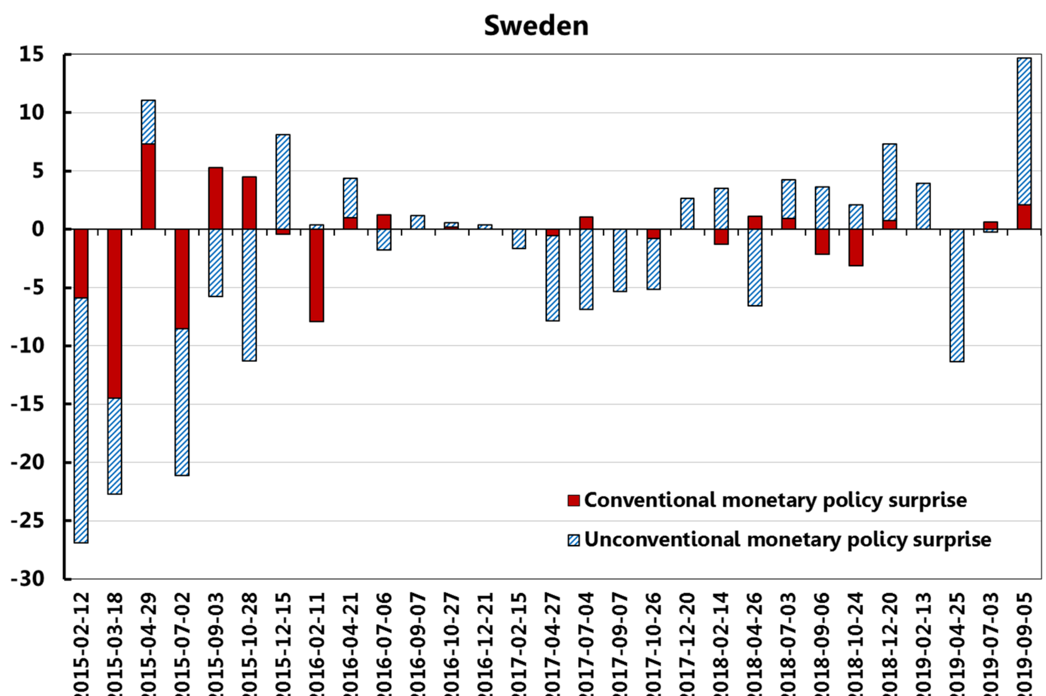
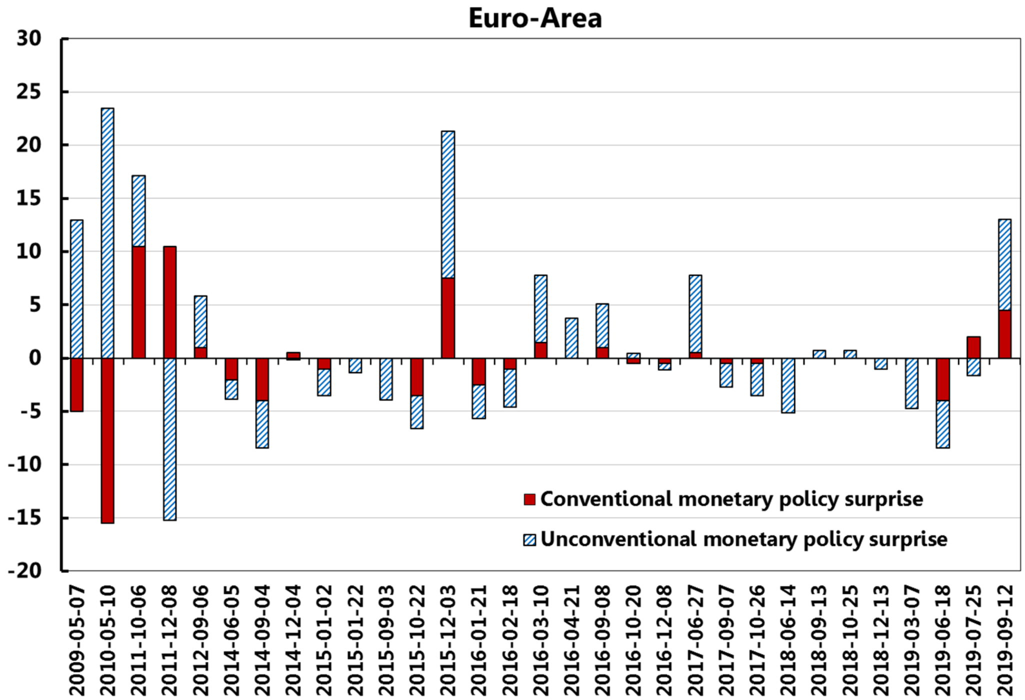


Figure 6: Decomposition of shadow rate changes around announcements for the euro area and the UK

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. $\triangle ump^u_{t^\star} = \triangle s_{t^\star} - \triangle r^u_{t^\star}$. Values are provided in basis points.



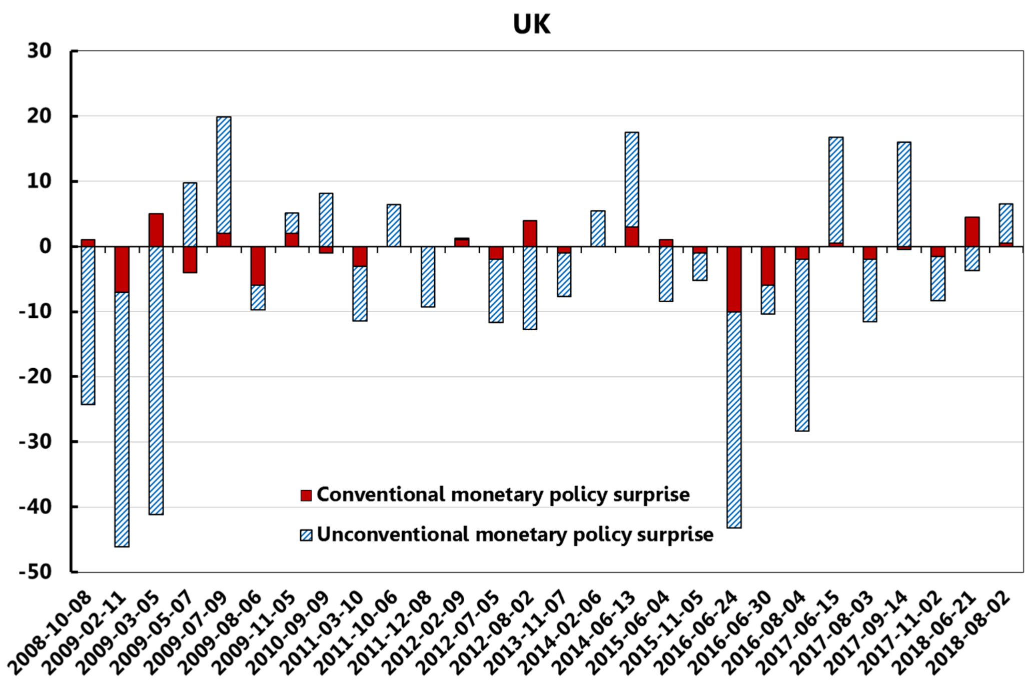


Figure 7: The macroeconomic effects of unconventional monetary policy

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.