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Measuring Monetary Policy with Residual Sign Restrictions at Known Shock Dates*

Harald Badinger† and Stefan Schiman‡

September 2020

Abstract

We propose a novel identification strategy to measure monetary policy in a structural VAR. It is based exclusively on known past policy shocks, which are uncovered from high-frequency data, and does not rely on any theoretical a-priori restrictions. Our empirical analysis for the euro area reveals that interest rate decisions of the ECB surprised financial markets at least fifteen times since 1999. This information is used to restrict the sign and magnitude of the structural residuals of the policy rule equation at these shock dates accordingly. In spite of its utmost agnostic nature, this approach achieves strong identification, suggesting that unexpected ECB decisions have an immediate impact on the short-term money market rate, the narrow money stock, commodity prices, consumer prices and the Euro-Dollar exchange rate, and that real output responds gradually. Our close to assumption-free approach obtains as an outcome what traditional sign restrictions on impulse responses impose as an assumption.

Keywords: Structural VAR, Set Identification, Monetary Policy, ECB
JEL Classification: C32, E52, N14

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1 Introduction

Modeling and estimating the effects of monetary policy has been subject to numerous studies over the last decades. Among the various methodological approaches employed, structural vector autoregressions (SVARs) have become the predominant tool to identify the causal effects of monetary policy.

Identification of SVARs can be achieved in several ways. Imposing a triangular structure by means of a Cholesky decomposition of the error variance-covariance matrix as in the seminal contribution by Sims (1980) is still a widely used approach. It assumes a specific monetary policy rule and time lags in the effects of monetary policy. Several innovative strategies have since been developed to relax these identifying assumptions. They include, among others, so called 'proxy-VARs', using external information based on narrative accounts (Romer and Romer, 1989) or high-frequency data (Gertler and Karadi, 2015), or, alternatively, imposing widely accepted sign restrictions on impulse response functions (Uhlig, 2005), or, in addition, on the structural residuals (Antolín-Díaz and Rubio-Ramírez, 2018).[1]

Drawing on these alternative strands of the literature, the present paper suggests a novel, utmost agnostic and purely data-based, yet highly informative strategy to identify SVARs and provides an application to monetary policy using euro area data.

First, our approach builds on the 'proxy-VAR' literature in using external, high-frequency data to identify monetary policy shocks, which we also validate by an ex-post narrative analysis. But unlike existing studies that employ an instrumental variable approach based on reduced form residuals, which inevitably introduces additional noise into the model, we use the external information as an 'internal instrument' in the terminology of Stock and Watson (2018) by imposing corresponding identifying restrictions within the VAR.

Second, the approach draws on the strand of the SVAR-literature that employs commonly accepted sign restrictions. But instead of assuming outcomes of impulse responses, we remain utmost agnostic in the sense of imposing restrictions merely on the sign of the structural residuals at known shock dates. This strategy is closely related to Antolín-Díaz and Rubio-Ramírez (2018), who supplement traditional sign restrictions on impulse responses with sign and magnitude restrictions on structural residuals, which they infer from narrative accounts. We differ in two important respects: First, we drop restrictions on impulse responses entirely and achieve identification solely through sign and magnitude restrictions on structural residuals. Second, the shocks are recovered from high-frequency data rather than from narrative accounts, which insulates them more credibly from endogeneity issues.

This approach directly addresses the critique of Rudebusch (1998) that residuals of monetary VARs show little correlation with signals from forward-looking financial markets: Policy shocks are identified properly by construction; at the same time, the estimated impulse responses are not (necessarily) in conflict with the assumptions of the aforementioned, alternative identification strategies.

[1]See Ramey (2016) for a detailed overview of the literature and alternative identification strategies.

We argue that our approach combines the virtues of these alternative strands of the literature and avoids their potential limitations. It 'objectifies' the identification of shocks and minimizes endogeneity concerns by the use of high-frequency data. At the same time, it ensures that the identified shocks are economically meaningful by an ex-post narrative analysis. It uses outside, financial markets data as an internal rather than as an external instrument, thereby avoiding the introduction of additional noise into the estimation. It uses sign restrictions on structural residuals at known shock dates and avoids making assumptions on macroeconomic effects of monetary policy (impulse response functions). Finally, unlike other studies, it links and reconciles, by construction, the macroeconomic model estimates (of structural shocks) with financial market information.

In our application for the euro area, policy surprises by the European Central Bank (ECB) are uncovered from high-frequency financial markets data taken from Altavilla et al. (2019). Specifically, we use observations on interest rate swaps during time windows, in which the ECB announces its policy rate decision and this is arguably the only news affecting markets.

Over the period from 1999 to 2019, we identify fifteen sizable monetary policy shocks (interest rate surprises) by the ECB, eight of which were restrictive and seven expansive. In the ex-post narrative analysis of these shocks three chronological clusters emerge: In the early 2000s the ECB deviated from market expectations to underpin its independence and its commitment to price stability. A second series of unforeseen interest rate decisions occurred during the global financial crisis 2008 and its aftermath. A third series of shocks is associated with the change of presidency from Jean-Claude Trichet to Mario Draghi in 2011 and mounting disagreements in the Governing Council.

The proposed identification strategy yields a highly informative measure of monetary policy. Specifically, we find that an unexpectedly restrictive interest rate decision by the ECB leads to an increase of the short-term money market rate, a decline of the narrow money stock, a decline in commodity and consumer prices, an appreciation of the Euro against the US-Dollar, and a gradual negative response of output. Hence, in spite of the minimal, close to assumption-free nature of the approach, no empirical puzzles emerge.

With regard to the systematic component of monetary policy, our estimates of the ECB's policy rule suggest that it responds immediately, i.e., within the same month, to contemporaneously available data on all variables considered, which appears to exclude consumer prices. Hence, monetary policy is tightened if output, commodity prices or the money stock surge, if the US federal funds rate goes up or if the Euro depreciates against the US-Dollar. The zero result on consumer prices is likely due to publication lags, i.e., that current information is not available at the time when monetary policy is set.

A counterfactual exercise completes our empirical investigation. We examine how interest rates would have evolved, if the ECB had always acted according to the estimated policy rule, i.e., if no monetary policy shocks had occurred. We find that during the recession from 2003 to 2004, interest rates could have been lowered further and that during the subsequent recovery, they could have been raised earlier. At the onset of the global financial crisis in 2008, the policy rate was at the upper bound of the counterfactual range; the ECB could have lowered it by up to 100 basis points. In the immediate aftermath of the crisis, however, the policy stance was loose, so that the widely criticized rate hikes in 2011 appear justified. Eventually, recent negative interest rates are also found to be in line with the estimated monetary policy rule.

The remainder of the paper is structured as follows. Section 2 outlines our identification strategy and reports the results from uncovering monetary shocks in the euro area using high-frequency data. Section 3 introduces the VAR model, the data used and the identification and estimation procedure. Section 4 presents the results for the effects of monetary policy shocks, Section 5 those on systematic monetary policy. Section 6 concludes.

2 Measuring Monetary Policy Shocks

In this section, we develop the approach to uncover monetary policy shocks in the context of our overall identification strategy and report the results from its application to euro area data over the period from 1999 to 2019.

2.1 A Purely Data-Based Identification Strategy

The approach pursued in the present paper uses information on policy shocks that are uncovered from high-frequency financial markets data during a monetary policy announcement window. Existing studies that build identification of monetary policy on high-frequency information do so via an instrumental variable procedure (e.g., Gertler and Karadi, 2015; Caldara and Herbst, 2019). In contrast, we incorporate the external information as an 'internal instrument' in the terminology of Stock and Watson (2018) by imposing identifying restrictions directly within the VAR.

Moreover, we restrict our attention to a set of significant monetary policy shocks. In this respect, our strategy is close to the narrative approach pioneered by Romer and Romer (1989, 1994), which has been widely used in subsequent studies to construct external instruments. While this approach clearly has its virtues, a downside is that broadly accepted narratives are rare and that broad acceptance does not per se imply validity, i.e., that the shocks uncovered are in fact exogenous (cf. Shapiro, 1994; Leeper, 1997).[2]

Antolín-Díaz and Rubio-Ramírez (2018) incorporate the narrative information into their 'internally identified' SVAR by supplementing traditional sign restrictions on impulse responses with sign and magnitude restrictions on the structural residuals. Specifically, in their application to US monetary policy, the residual of the interest rate equation at October 1979—the month, in which the Fed adopted

[2] Romer and Romer (2004) made progress in controlling for endogenous monetary policy by purging the narrative series of information contained in real-time central bank forecasts.

an aggressive anti-inflationary policy ('Volcker shock')—is assumed to be predominantly driven by a restrictive monetary policy shock. They find that adding this narrative information strengthens inference on monetary policy shocks considerably.

Our approach is closely related but differs in two respects. First, we abandon all sign restrictions on impulse responses and build our identification solely on sign and magnitude restrictions on the structural residuals. Hence, we do not preclude any macroeconomic effects of monetary policy. This makes our approach utmost agnostic with the only remaining assumption being that restrictive monetary policy shocks are associated with an increase in interest rate expectations, which is essentially definitional.

Second, we do not use narrative accounts but infer monetary policy shocks from high-frequency financial markets data during time windows of monetary policy communications. Using intra-day data and observing an immediate response of asset prices to the announcement of a policy measure facilitates to rule out confounding factors and to establish a causal link among these incidents and, hence, the occurrence of a policy shock.

Summing up, our identification strategy, which is based on residual sign restrictions at known shock dates, proceeds in two steps. First, we uncover dates of interest rate surprises from high-frequency financial markets data. Second, we estimate and identify the structural VAR using (only) sign and magnitude restrictions on the structural residuals associated with these monetary policy shocks. The following subsection summarizes the results from the first step.

2.2 Monetary Policy Shocks in the Euro Area

The identification of monetary policy shocks by the ECB over the time period from 1999 to 2019 makes use of Altavilla et al. (2019), who collect high-frequency data on financial market variables before and after monetary policy decisions of the ECB. They differentiate between two time slots on days of monetary policy decisions, the first of which ranges from 13:25 to 14:10. The only material event within these three quarters of an hour is the publication of a press release at 13:45, which includes the ECB's decision on its three policy rates without any further comment.[3]

The second time window matches the duration of the subsequent press conference from 14:15 to 15:50, during which the interest rate decision is commented by the President and further information, e.g., on forward guidance or quantitative easing, is conveyed and the ECB's assessment of the stance of the economy is communicated.

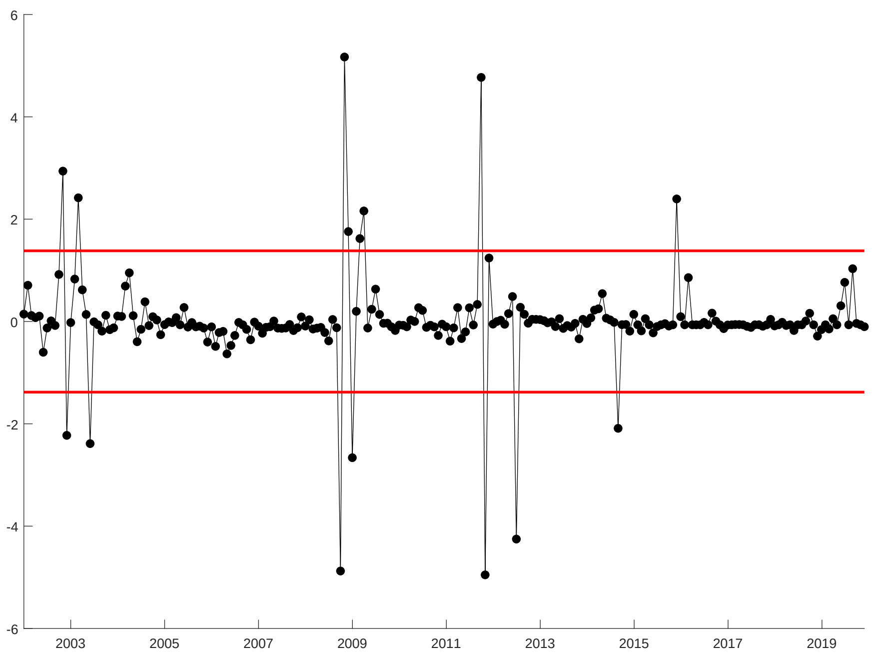
Given this clear separation in the ECB's communication policy, a key finding from a factor analysis by Altavilla et al. (2019) is that financial market responses during the first time window are solely due to interest rate surprises, whereas responses during the second time slot are due to surprises related to forward guidance, the assessment of the economic situation by the ECB, and unconventional monetary policy.

[3]Two such exemplary press releases are given in Appendix A1.

In order to identify monetary policy shocks, we focus on financial market reactions reflecting changes in interest rate expectations during the first of the two aforementioned time slots. Specifically, we consider data on changes in overnight index swap (OIS) rates with maturities of 1 week, 1 month, 3 months and 6 months during the time frame from 13:25 to 14:10 on days of monetary policy decisions.

As the ECB Governing Council usually meets once a month, this intra-day information on the (non-)occurrence of a policy shock is easily transformed into monthly observations in order to match the frequency at which the variables of our VAR are observed. In the few months, where more than one meeting took place, the cumulative change of the swap rates in the respective month is considered.

Figure 1: Monetary Policy Decisions and Financial Markets Reactions



Black dots: Average of standardized 1-week, 1-month, 3-months and 6-months overnight index swap rate changes in basis points. **Red lines:** 1.5 standard deviations.

All four resulting swap rate time series are highly leptokurtic: In $80\% - 87\%$ of the cases, swap rates do not change at all or at most by one basis point, yet the standard deviation of the series ranges from 1.9 to 2.6 basis points. This means, first, that most interest rate decisions are anticipated and financial markets hardly react to the press release; and second, that there were some significant unexpected decisions, i.e., interest rate surprises. We direct our attention to these events.

In particular, we focus on policy surprises at which financial markets were particularly startled, when the Governing Council of the ECB conveyed its interest rate decision to the public. To identify such events, we standardize the time series of the changes in the four swap rates and consider the average of them at each date. The resulting synthetic series of average changes is presented in Figure 1 together

Table 1: Monetary Policy Shocks in the Euro Area, 2002-2019

Date	*Sign*	*Description*
Nov. 7, 2002	+	Amid deteriorating economy, ECB does not bow to politicians', Fed's and public's pleas to cut rates.
Dec. 5, 2002	−	Having underpinned its independence, ECB relents in the face of the economic downturn.
Mar. 6, 2003	+	Preceding statements of ECB officials have been misinterpreted in direction of a larger rate cut.
Jun. 5, 2003	−	Markets are doubtful about a significant rate cut, so the ECB exceeds expectations.
Oct. 8, 2008	−	Globally coordinated rate cut; full allotment makes corridor system essentially a floor system.
Nov. 6, 2008	+	ECB does not meet expectations raised by BoE's sharp rate cut immediately preceding it.
Dec. 4, 2008	+	ECB intensifies monetary easing only cautiously and again lags behind BoE's rate cut.
Jan. 15, 2009	−	Restoration of pre-crisis corridor range reduces interest rate floor disproportionately.
Mar. 5, 2009	+	Similarly to late 2008, ECB fails to meet expectations raised by preceding BoE rate cut.
Apr. 2, 2009	+	The unexpectedly timid rate cut shows ECB's aversion towards a zero-interest policy.
Oct. 6, 2011	+	President Trichet's last meeting; prior statements of ECB officials misread in direction of rate cut.
Nov. 3, 2011	−	President Draghi's first meeting; rate cut despite an essentially unchanged economic environment.
Jul. 5, 2012	−	Markets did not expect the deposit facility rate to be reduced to zero.
Sep. 4, 2014	−	Rate cut a month after the ECB said rates would remain unchanged for an extended period of time.
Dec. 3, 2015	+	The ECB Governing Council does not follow President Draghi's push for a higher rate cut.

with red bands that indicate 1.5 standard deviations, which we use as threshold for the average change in swap rates to qualify as policy shock.[4] This threshold choice implies that there have been fifteen policy shocks—eight restrictive, seven expansive—in the period from 2002 to 2019.[5] Table 1 gives some narrative back-

[4] We will consider alternative thresholds in the robustness analysis in Subsection 4.3.

[5] As Altavilla et al. (2019), we use data from 2002 to 2019, because the sparsity (and, hence, increased volatility) of quotes between 1999 and 2002 impedes separating noise from true policy surprises in this period.

ground information on these monetary policy decisions and Appendix A2 provides a more detailed description based on ECB material and newspaper articles. In the next section, we outline how these monetary shocks are used in the identification of the structural VAR by means of sign and magnitude restrictions on the structural residuals.

3 VAR Implementation

We conduct our empirical analysis by means of a structural VAR model. Point of departure is the standard reduced form VAR representation

$$\boldsymbol{y}_t = \boldsymbol{c} + \sum_{i=1}^{L} \boldsymbol{A}_i \boldsymbol{y}_{t-i} + \boldsymbol{u}_t, \tag{1}$$

where $\boldsymbol{y_t}$ is the $K \times 1$ vector of observations on the endogenous variables in time period (month) t. The right-hand side includes a $K \times 1$ vector of constants, $\boldsymbol{c}$, and $i = 1, \ldots, L$ time lags of the vector of endogenous variables, $\boldsymbol{y}_{t-i}$, with corresponding $K \times K$ reduced-form parameter matrices $\boldsymbol{A}_i$. As it is standard in the literature on monetary VARs with monthly data, we set the lag length of the VAR to $L = 12$. Finally, $\boldsymbol{u}_t$ is a $K \times 1$ vector of stochastic error terms, which are assumed to be independently and normally distributed, $\boldsymbol{u}_t \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{V})$.

Having set up the standard framework for our analysis, we now turn to a description of the model specification, i.e., the variables included, the data sources and the econometric implementation of our identification strategy.

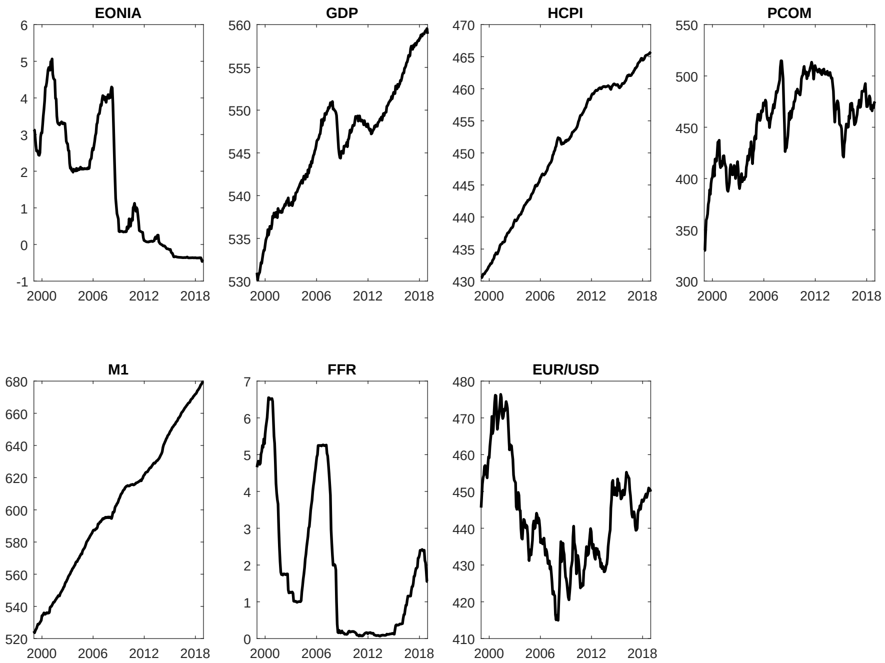
3.1 Variables and Data

The long tradition of modeling US monetary policy has produced a consensus on a set of variables to be included that is considered rich enough to adequately capture the macroeconomic effects of monetary policy. This set includes real output, economy-wide prices, commodity prices, non-borrowed reserves, total reserves and the federal funds rate.

There is no corresponding standard for modeling monetary policy in the euro area. To make the results (and our identification strategy) comparable with previous studies and alternative methodological approaches, we follow the US modeling canon, yet with two modifications: First, we use $M1$ as a measure of the money stock.[6] Second, we add the US federal funds rate (FFR) as a foreign interest rate and the nominal Euro-Dollar exchange rate (EUR/USD) to account for euro area interactions with the US economy and US monetary policy. Kim and Roubini (2000) use the same set of variables to study monetary policy in G7 countries.

[6] In doing do, we stick to applied work on monetary policy in the euro area that incorporates money in its specification, in particular Georgiadis (2015), Barigozzi et al. (2014), Rafiq and Mallick (2008), and Peersman (2004).

Figure 2: Model Variables



Notes: The data were retrieved from Macrobond, primary data sources are: European Money Markets Institute ($EONIA$), Eurostat (GDP, Industrial Production), Hamburg Institute of International Economics ($PCOM$), the Federal Reserve Bank of New York (FFR) and the ECB ($HCPI$, $M1$, EUR/USD).[7]

In our euro area data set, comprising monthly data over the period from 1999m1 to 2019m12, real output is measured in terms of real GDP.[8] As economy-wide price indicator we use the harmonized consumer price index ($HCPI$), since it is the ECB's explicit policy target and highly correlated with the GDP deflator. Commodity prices are measured by the overall commodity price index ($PCOM$) of the Hamburg Institute of International Economics in Euro. The money stock $M1$ includes overnight deposits and cash. As short-term money market rate we use the European OverNight Index Average ($EONIA$), defined as average of interest rates on overnight unsecured lending between banks.

$EONIA$, FFR and EUR/USD are all measured at monthly averages. All variables are in natural logs except for $EONIA$ and FFR. Hence, our vector of endogenous variables in Equ. (1) is of dimension 7×1 and given by

$$\boldsymbol{y}_t \equiv (EONIA_t, GDP_t, HCPI_t, PCOM_t, M1_t, FFR_t, (EUR/USD)_t)'.$$

[7] Note that the officially published time series of $M1$ exhibits a jump in May 2005, which is related to the fact that Spanish non-MFI savings accounts were re-classified and included in $M1$ from then on. We have eliminated this break by adding Spanish non-MFI savings accounts to $M1$ also prior to May 2005.

[8] Monthly data are obtained through interpolation using industrial production data and the method proposed by Chow and Lin (1971).

The sample starts at 1999m1 with the formation of the euro area as a monetary union and goes through 2019m12, which makes 252 observations. The time series are presented in Figure 2.

Modeling US interest rate policy often stops in 2008, when the policy rate hit the zero lower bound and was complemented by unconventional measures. In the euro area such a lower bound has arguably not been reached during the sample period. The deposit facility rate and $EONIA$ became negative in 2014 and declined further thereafter. Therefore, and in accordance with Hartmann and Smets (2018), we use the full sample in the estimation.

3.2 Identification

Having uncovered a set of fifteen monetary policy shocks from high-frequency data in Subsection 2.2, we now outline how we use this information to identify the following structural VAR associated with the reduced form given by Equ. (1):

$$\boldsymbol{B}\boldsymbol{y}_t = \boldsymbol{c}^* + \sum_{i=1}^{L} \boldsymbol{A}_i^* \boldsymbol{y}_{t-i} + \boldsymbol{w}_t, \tag{2}$$

where $\boldsymbol{c}^* = \boldsymbol{B}\boldsymbol{c}$, $\boldsymbol{A}_i^* = \boldsymbol{B}\boldsymbol{A}_i$, $\boldsymbol{w}_t = \boldsymbol{B}\boldsymbol{u}_t$ and $\boldsymbol{w}_t \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{I})$. The matrix $\boldsymbol{B}$ is the structural parameter matrix that governs the instantaneous relationships between the model variables. It is chosen such the following sign restrictions are satisfied:

$$\hat{w}_{1,t} > 0, \tag{3}$$

where $\hat{w}_{1,t}$ is the structural residual of the first equation of the SVAR in Equ. (2)[9] for $t =$ 2002m11, 2003m03, 2008m11, 2008m12, 2009m03, 2009m04, 2011m10, and 2015m12, i.e., months of restrictive policy shocks, and

$$\hat{w}_{1,t} < 0 \tag{4}$$

for $t =$ 2002m12, 2003m06, 2008m10, 2009m01, 2011m11, 2012m07, and 2014m09, i.e., months of expansive policy shocks (see Table 1).

The sign restrictions given by Expression (3) and (4) are complemented by magnitude restrictions to make sure that the identifying shocks are economically meaningful. Specifically, we require that each of them exceeds (in absolute terms) half the standard deviation of the series of structural residuals of the policy equation—a choice that is motivated by computing time considerations. These additional magnitude restrictions rule out that structural residuals of a negligible size are misinterpreted as policy shocks and sharpen our identification, but they are not crucial for the results. Estimates based on sign restrictions only are provided in Appendix A3.

[9]Without loss of generality we identify the monetary policy rule in the first equation of the SVAR.

3.3 Estimation

The model is estimated with standard Bayesian techniques, employing an independent Normal-Wishart prior with Minnesota-style shrinkage of the prior parameter variance-covariance matrix $\boldsymbol{V_A}$, where $\boldsymbol{A} = (\boldsymbol{c}, \boldsymbol{A}_1, \ldots, \boldsymbol{A}_L)$ with dimension $K \times (KL+1)$ and $\boldsymbol{V_A}$ assumed diagonal, implying independent parameters. With regard to the K^2L+K diagonal elements $v_{ii,\boldsymbol{A}}$ (i.e., the prior values of the variance), we set a flat prior variance on intercepts, $v_{ii,\boldsymbol{A}} = 100$, and decreasing prior variances on lag parameters, $v_{ii,\boldsymbol{A}} = \kappa_1 \cdot l^{-2}$ for own lag l and $v_{ii,\boldsymbol{A}} = \kappa_2 \cdot l^{-2} \cdot \hat{\sigma}^2_{ii}/\hat{\sigma}^2_{jj}$ for lags of other variables, where the scaling parameter $\hat{\sigma}^2_{ii}/\hat{\sigma}^2_{jj}$ is the ratio of estimated residual variances of univariate AR(12) models for variables i and j. The hyperparameters are set to $\kappa_1 = 0.1$ and $\kappa_2 = 0.01$ to achieve sufficient shrinkage, but the results are robust to increasing these values and, hence, the prior variance, to, e.g., $\kappa_1 = 1$ and $\kappa_2 = 0.1$.[10]

The prior mean of AR(1) parameters in the VAR is set to one, while all other slope parameters, including the constant, are set to zero. Hence, the model estimates are shrunk towards a multivariate random walk, which is a reasonable assumption given the non-stationary nature of the variables at hand (see Figure 2); but the results are robust if we choose prior values smaller than one for the AR(1) parameters.

In selecting structural parameter matrices $\boldsymbol{B}$ that satisfy the sign and magnitude restrictions we apply the well-established procedure proposed by Rubio-Ramírez et al. (2010) for set-identified models.[11] Specifically, we randomly draw a square orthogonal matrix from a multivariate Normal distribution and multiply it with the Cholesky factor of $\boldsymbol{V}$ to obtain independent shocks. If a candidate draw does not satisfy the sign and magnitude restrictions on the structural residuals, it is discarded, otherwise it is retained. We stop sampling when we have collected 5,000 valid draws.

4 Effects of Monetary Policy Shocks

In this section, we report the impulse responses of our model variables to a restrictive monetary shock. We compare them to those obtained using a traditional sign restriction approach and explore the robustness of our results with respect to the number of identifying monetary policy shocks.

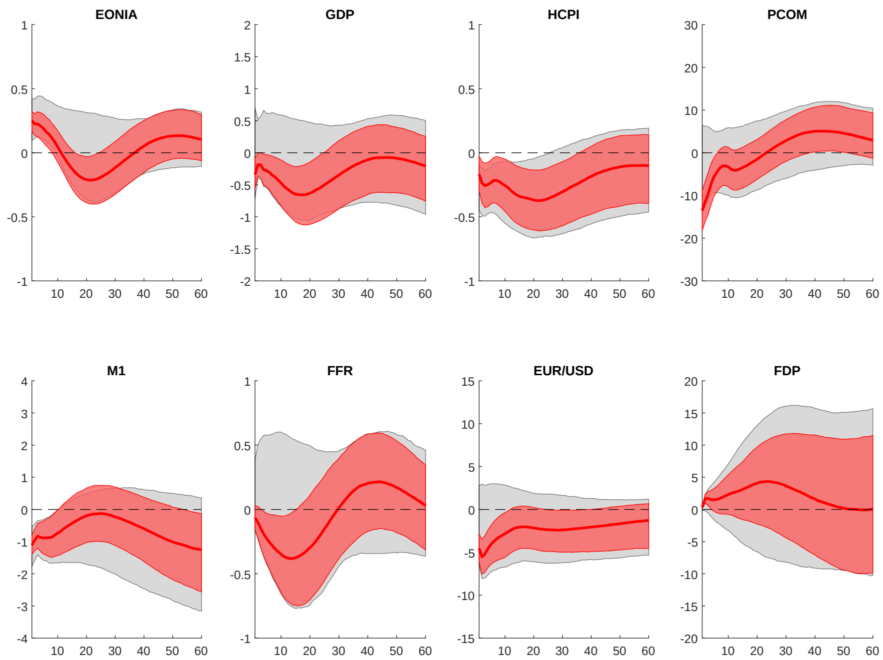
4.1 Basic Results

Figure 3 shows the impulse responses of our seven model variables to a restrictive monetary policy shock over a 5-year period. It also plots the impulse response of

[10]We do not consider the diffuse prior $\boldsymbol{V_A}^{-1} = \boldsymbol{0}$, because it is subject to overfitting due to the relatively high number of parameters to be estimated. Our findings do not hinge on the use of the Minnesota prior, however. We obtain qualitatively similar results when we apply the diffuse prior and reduce the parameters to be estimated by lowering the lag length to, e.g., $L = 4$.

[11]See Kilian and Lütkepohl (2017) for a textbook treatment.

Figure 3: Impulse Responses, 68% Credible Sets



Red: Sign and magnitude restrictions on structural residuals. **Gray:** Sign restrictions on impulse responses analogous to Uhlig (2005).

the forward discount premium (FDP), which is implied by the results for $EONIA$, the federal funds rate and the exchange rate.[12]

As baseline, we report posterior medians and 68% credible sets.[13] Notice that $EONIA$ responds on impact to the monetary policy shock, i.e., within the same month. This does not come as a surprise, given that our identification of monetary policy shocks is related to interest rate expectations reflected in high frequency data on overnight interest rate swaps. Hence, $EONIA$ is a natural anchor for the scaling of the shock and so we normalize the median impact response of it to 25 basis points.

A number of interesting results emerge, all of which are consistent with standard macroeconomic theory. To begin with, there is a negative effect on output and it intensifies gradually. The effect reaches its maximum after one and a half to two years and then levels off. The effects on consumer prices are clearly on the negative side on impact and they remain so in the medium-run. In contrast, while commodity prices also respond negatively on impact, there is no systematic medium-run effect. This suggests that the medium-run price effects of restrictive monetary

[12]Specifically, the impulse response (IR), calculated as $IR_{FDP,k} = IR_{EUR/USD,0} - IR_{EUR/USD,k} + \sum_{t=0}^{k}(IR_{EONIA,t} - IR_{FFR,t})$, measures the arbitrage gain from holding a short position in USD and a long position in EUR while $EONIA$ rises unexpectedly due to a monetary policy shock.

[13]Results for 100% credible sets based on posterior means of the reduced-form coefficients are presented in Appendix A4.

policy shocks materialize mainly through core inflation. The stock of narrow money responds negatively on impact but the effect levels off in the medium-run.

Regarding the international value of the Euro we observe an appreciation following a restrictive shock, while the federal funds rate tends to fall initially. These effects suggest that the demand for euro-denominated assets increases and that the demand for dollar-denominated assets correspondingly decreases. Finally, the median response of the forward discount premium remains close to zero, suggesting that the unexpected interest rate hike does not provide a notable arbitrage gain from a long position in Euro and a short position in US-Dollar.

4.2 Comparison with Traditional Sign Restrictions

Kerssenfischer (2019) suggests that studies that find puzzling effects of US monetary policy shocks do so because they miss important information in their empirical setup rather than suffering from an invalid identification. In turn, one might ask, whether our textbook results on euro area monetary policy are sample-driven rather than identification-driven and whether we would achieve similar results when we apply a conventional identification scheme.

Therefore, we compare our results with those obtained using traditional sign restrictions on impulse responses in line with Uhlig (2005), which require consumer prices and the money stock to move in the opposite direction of the short-term interest rate over five consecutive months beyond impact.

First, notice that imposing these sign restrictions on top of the restrictions on the structural residuals leaves our results virtually unchanged. This is not surprising: As can be seen from Figure 3, the traditional sign restrictions—a negative co-movement of $EONIA$ with $M1$ and $HCPI$—are not binding for the posterior median and the credible sets in the first five months. In other words, we obtain as an estimation result what is imposed as an assumption by Uhlig (2005).

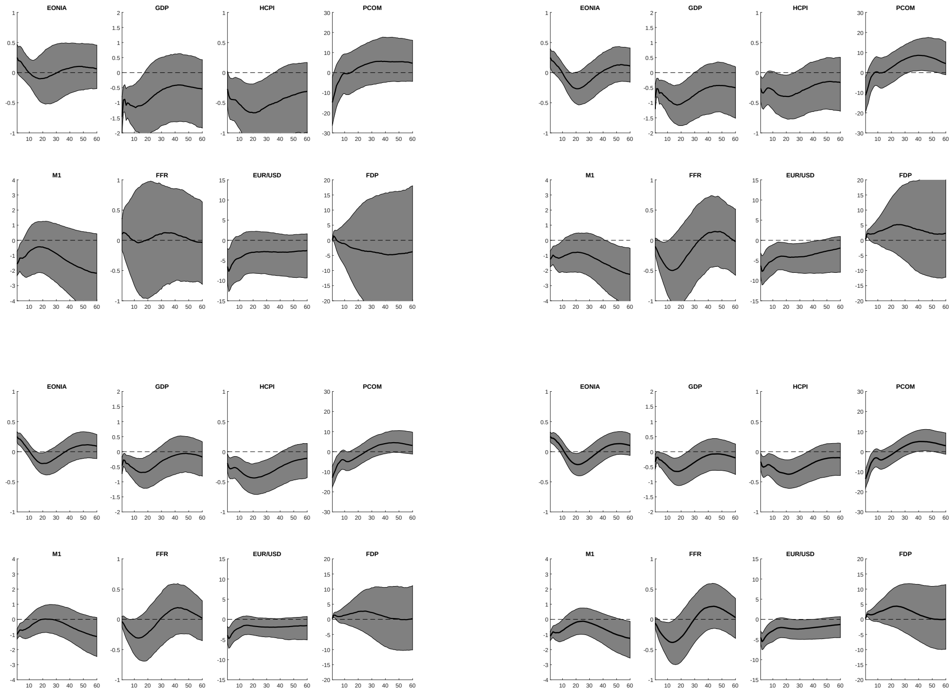
Second, the impact on unrestricted variables remains largely inconclusive with the traditional sign restriction approach. Real output seems to not respond systematically on impact or even positively, echoing Uhlig's original findings on US monetary policy. This holds analogously for the federal funds rate. Also for commodity prices and the Euro-Dollar exchange rate, many draws indicate positive responses.

We conclude that the clear findings on the effects of monetary policy are not sample-driven. They rather result from the strength of the identification procedure that we propose.

4.3 Number of Identifying Shocks

Our overall identification strategy builds on uncovering monetary shocks from high-frequency data; these are defined as policy incidents that are surprising and of a 'sizable magnitude' (see Subsection 2.2). In our baseline scenario, a 'sizable magnitude' is understood as leading to an average change of the considered swap rates that exceeds 1.5 standard deviations. This definition leads to a set of fifteen monetary policy shocks.

Figure 4: Impulse Responses, Alternative Numbers of Identifying Shocks



Top left (5σ-scenario): 2008m10, 2008m11, 2011m10, and 2011m11. **Top right** (3σ-scenario): 5σ plus 2002m11 and 2012m07. **Bottom left** (2.5σ-scenario): 3σ plus 2003m03, 2003m06, 2009m01, and 2015m12. **Bottom right** (baseline specification): 2.5σ plus 2002m12, 2008m12, 2009m03, 2009m04, and 2014m09.

The rationale for the choice of a relatively large number of shocks in the baseline scenario is that it essentially rules out the theoretical possibility of the coincidental occurrence of other than monetary policy shocks with the same sign at the same dates. In the following, we consider more stringent definitions of 'sizable shocks', namely those where the average change of the considered swap rates exceeds two and a half, three and five standard deviations. These alternative definitions, which we refer to as 2.5σ-, 3σ-, and 5σ-scenario, lead to an identification of ten, six, and four monetary policy shocks, respectively. The implied impulse responses are given in the panels of Figure 4.

We find that the main qualitative results are already obtained when only the four largest shocks—two restrictive (November 2008 and October 2011) and two expansive (October 2008 and November 2011)—are used for identification (5σ-scenario, top left panel of the figure): a significant response of output, consumer prices, commodity prices, the money stock and the exchange rate.

When the threshold is lowered to three standard deviations, two more shocks are captured, a restrictive one in November 2002 and an expansive one in July 2012.

This improves identification further (top right panel of the figure). The shape of the impulse responses are already very close to those of the baseline specification, which are reproduced in the bottom right panel of the figure, while the credible sets are wider.

Lowering the threshold further to 2.5 standard deviations provides four more shocks. The corresponding impulse responses are shown in the bottom left panel of Figure 4. They basically match those of the baseline specification both in shape and width. We conclude that there is a minimum number of restrictions required to achieve a strong identification, though this number appears to be reasonably small to allow for enough flexibility of the model to fit the data.

5 Systematic Monetary Policy

Having analyzed the response of the economy (our key macroeconomic variables) to unpredictable monetary policy decisions in Section 4, we now turn to the predictable component of monetary policy and discuss the implied estimates of the ECB's policy rule. Moreover, we evaluate how the short-term interest rate would have evolved if monetary policy had been set in a fully predictable way according to the estimated policy rule.

5.1 Policy Rule Estimates

Assuming that the short-term interest rate is a suitable indicator for monetary policy, which is standard since Bernanke and Blinder (1992), the structural VAR in Equ. (2) provides a measure of systematic monetary policy, i.e., the responses of the interest rate to changes in the other (macroeconomic) model variables.

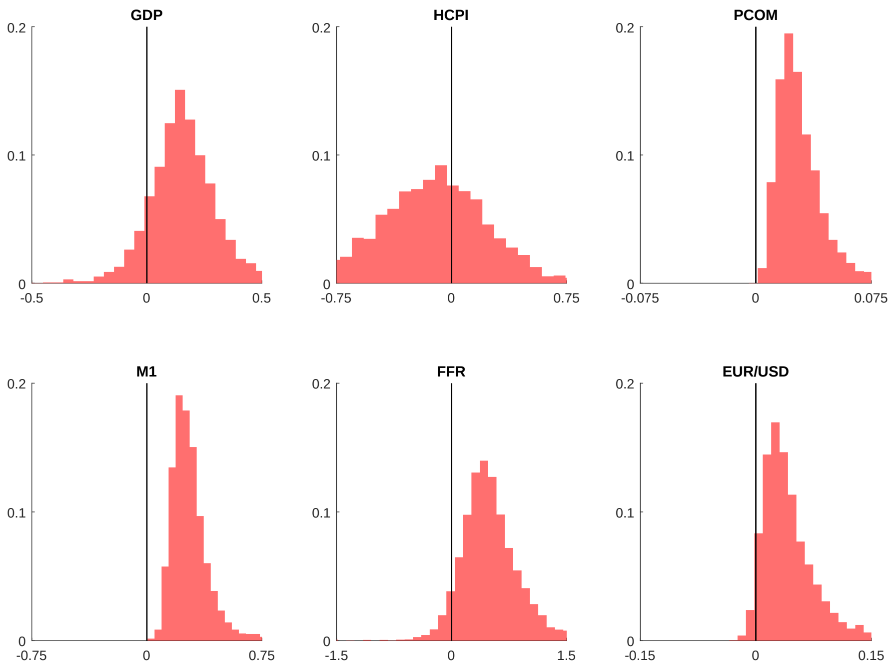
Specifically, the contemporaneous (i.e., within-a-month) response of the interest rate ($EONIA$) to model variable y, denoted as φ_y, can be recovered from the structural parameters in Equ. (2) according to $\varphi_y = -b_{1,y}/b_{1,1}$, where $b_{1,y}$ and $b_{1,1}$ are the contemporaneous structural parameters of variable y and $EONIA$ in the monetary policy equation.

Existing studies differ widely in their assumptions regarding the specification of the policy rule, in particular on which variables enter the reaction function and which parameters are set to zero. The triangular approach (recursive identification) imposes—corresponding to monetary policy rules along the lines of Taylor (1993)—that output and prices enter the policy rule and that the money stock does not (cf., e.g., Christiano et al., 1999). In recent work, using a non-recursive approach, Arias et al. (2019) construct sign and zero restrictions on the contemporaneous parameters φ_y based on the same assumptions.

However, traditional non-recursive identification schemes abstain from Taylor-rule reasoning and instead focus on the information available to the monetary authority within the same month (Leeper et al., 1996; Sims and Zha, 2006). This practically exchanges the sets of variables with and without zero restrictions, as output and consumer prices are published with delay, while the amount of outstanding cash and overnight deposits is known on a daily basis.

This methodological difference pertains to other variables beyond output, prices and money. Recursive identification of non-US monetary policy, for example, assumes that the US (i.e., the foreign) interest rate is part of the reaction function, while the exchange rate is not (Dallari and Ribba, 2020; Peersman, 2004). In contrast, in a non-recursive scheme, Kim and Roubini (2000) deploy the assumption that the monetary authority responds to exchange rate fluctuations and that changes in the foreign interest rate are not relevant beyond the extent to which they are caused by exchange rate fluctuations.

Figure 5: Contemporaneous Monetary Policy Rule Coefficients, Baseline Specification



Our results on the policy rule are summarized by means of histograms in Figure 5, which show the estimated contemporaneous monetary policy rule coefficients. According to these distributions, which cover the entire set of identified draws, real-time data availability seems to play an important role for the conduct of monetary policy. The majority of draws show that the ECB responds contemporaneously to fluctuations of commodity prices, narrow money, the exchange rate and the federal funds rate, all of which are available on a daily basis. Furthermore, the results are consistent with standard theory: Interest rates are raised when commodity prices surge, when narrow money growth accelerates, when the Euro depreciates against the US-Dollar or when the US interest rate goes up.

The ECB also appears to take the most recent development of output into account, thereby acting counter-cyclically. In contrast, coefficients of the $HCPI$ are distributed over a wide range of positive and negative values, which is a striking result, since consumer price inflation is the ECB's key target variable. This lack of a clear response to contemporaneous consumer prices might therefore be due to publication lags, since current information on consumer prices is not available at the time when monetary policy is set.

With regard to existing approaches we conclude that real time data availability is a crucial element in identifying systematic monetary policy. Furthermore, caution is required if Taylor-rule inspired restrictions are applied to SVARs, as there seems to be no monetary policy response to contemporaneous consumer prices—probably because they are not observable in real time. However, this finding does not speak against the use of Taylor rules per se, as they usually involve a richer specification than the VAR framework, in particular future projections of (output and) prices.

5.2 Counterfactual Monetary Policy

We complete our empirical analysis by exploring how interest rates, in particular $EONIA$, would have evolved over time if monetary policy had been set in a purely systematic way according to the estimated policy rule. We construct a counterfactual range of $EONIA$ that excludes fluctuations due to monetary policy shocks (red area in Figure 6) and compare it with the actual outcome (red line). Hence, the red area can be interpreted as a target range for $EONIA$, if monetary policy had been set in a fully predictable way according to our estimated policy rule.

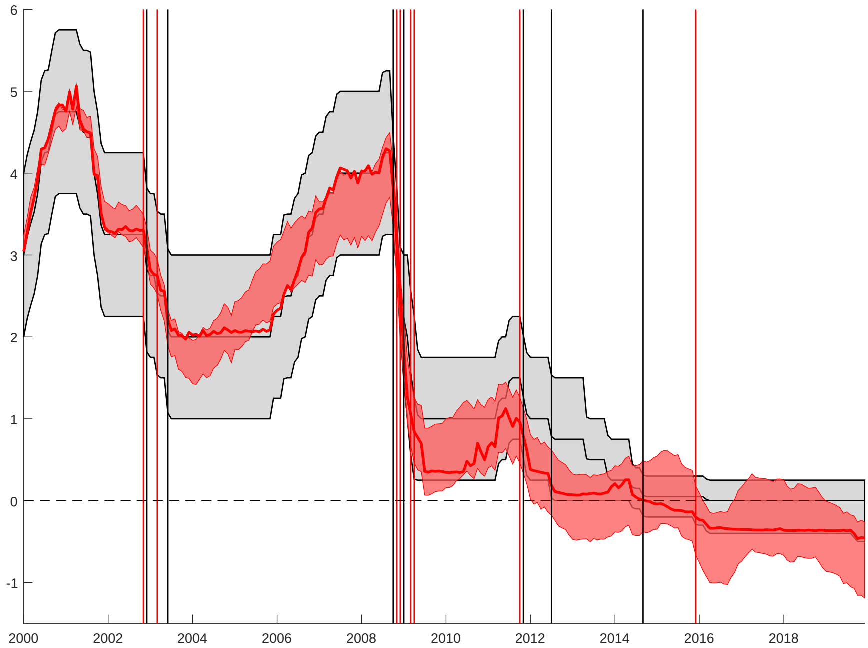
Figure 6 also plots the three policy rates of the ECB, i.e., the main refinancing rate, usually referred to as 'the policy rate' or the 'key interest rate', the marginal lending facility rate and the deposit facility rate. $EONIA$ followed the main refinancing rate closely until October 2008, when the ECB changed its procedure of providing liquidity to the banking system from a variable-rate bidding to a fixed-rate full allotment procedure. This led to mounting excess liquidity and made $EONIA$ converge to the deposit facility rate (see the discussion of these measures in Appendix A2).

The interest rate hikes and cuts in the first three years of the monetary union seem to be well in line with the estimated policy rule. In 2002, we observe that monetary policy was relatively loose, which is in accordance with the assessment of Hartmann and Smets (2018, p. 78).

In the following downturn, the ECB could have reduced the main refinancing rate further and in the subsequent expansion, it could have raised rates more gradually. Instead, it stopped the rate cut at 2%, but kept the main refinancing rate unchanged for a relatively long period of time.

The following sequence of rate hikes, in turn, was swift. The policy rate and $EONIA$ moved from the lower (expansive) edge of the counterfactual range in late 2005 to the upper bound in mid-2007. Hence, at the dawn of the global financial crisis, euro area monetary policy was particularly restrictive.

Figure 6: Actual Interest Rates and Counterfactuals without Monetary Policy Shocks



Red line: Realized *EONIA*. **Red area:** Counterfactual *EONIA* (68% credible set). **Gray area:** Corridor of standing facilities. **Upper/middle/lower black line:** Marginal lending facility/main refinancing/deposit facility rate. **Red bars:** Dates of restrictive monetary policy shocks. **Black bars:** Dates of expansive monetary policy shocks.

In July 2008, when the crisis was unfolding, the ECB raised its interest rates even further. Hartmann and Smets (2018, p. 78) concluded that this did *"not appear to be justified by the ECB's own outlook for growth and inflation"*. Our model, instead, suggests that the rate hike can be justified, as the upper and lower bound of the counterfactual range shift upwards.[14] But as the monetary policy stance had been particularly restrictive for over a year and had not yet reacted to the unfolding crisis, the interest rate hike in July 2008 seems provocative as it prolonged an extraordinary restrictive policy stance.

During the global financial and economic crisis—a period of high economic and policy uncertainty—several monetary policy shocks occurred (marked by vertical bars in Figure 6). The deposit facility rate had become the new benchmark policy rate and monetary policy was less restrictive than before the crisis.

In the first half of 2011, the ECB raised interest rates again and Hartmann and Smets (2018, p. 79) argue that the *"interest rate increases in 2011 do not show up as a major policy mistake, but seem delayed as the inflation and growth projections*

[14]The different assessment might result from the fact that Hartmann and Smets (2018) use real-time forecasts to estimate the policy rule, while our assessment is based on current and past observations.

suggested an earlier tightening move." We also do not find that the interest rate hikes in 2011 moved policy towards a particularly restrictive stance, but rather that it had been relatively loose before these rate hikes.

In the following years, interest rates lie well within the counterfactual range. In particular, the decisions to cut interest rates to below zero were well in line with the estimated policy rule. During the business cycle downturns in 2016 and 2019, the negative rates could have been lowered even further.

6 Conclusions

In this paper we show that information on dates of a reasonably small number of monetary policy shocks and their direction is sufficient for strong SVAR identification. This requires identification of these shocks through outside information in a first step, which can be obtained using a narrative approach as done in previous studies, or—as we suggest—purely data-based, using high-frequency information from financial markets. Whereas the present paper uses this approach to study the ECB's monetary policy, it is sufficiently general and flexible to be applicable in a wide range of VAR settings.

The main advantage of this approach is its utmost agnostic nature. No theoretical a-priori assumptions regarding any outcome (e.g., as through traditional sign restriction on impulse responses) are required. External information is used only to restrict the sign of the structural residuals at dates when significant shocks have occurred. This also implies that policy shocks are identified properly by construction.

In our application to monthly euro area data over the period from 1999 to 2019, we uncover fifteen significant interest rate surprises by the ECB. The implied results regarding the effects of monetary policy shocks are all economically meaningful. The domestic economy responds immediately to an unexpected interest rate decision in many important dimensions. The clarity of the results pertains even if we allow for the full set of identified draws or other alterations of the model. Another remarkable result is that several qualitative findings are already obtained by using only the four largest of the fifteen shocks. Intriguingly, we obtain as an outcome what traditional sign restrictions impose as an assumption.

A1 ECB Press Releases

A representative example of a press release of the ECB Governing Council, when policy rates were kept unchanged, is from November 7, 2002 (emphasis added):

"At today's meeting the Governing Council of the ECB decided that the minimum bid rate on the main refinancing operations and the interest rates on the marginal lending facility and the deposit facility will remain unchanged at 3.25%, 4.25% and 2.25% respectively.

The President of the ECB will comment on the considerations underlying these decisions at a press conference starting at 2.30 p.m. today." (ECB Governing Council, 2002)

A representative example of a press release announcing interest rate changes is from July 5, 2012:

"At today's meeting the Governing Council of the ECB took the following monetary policy decisions:

1. *The interest rate on the main refinancing operations of the Eurosystem will be decreased by 25 basis points to 0.75%, starting from the operation to be settled on 11 July 2012.*
2. *The interest rate on the marginal lending facility will be decreased by 25 basis points to 1.50%, with effect from 11 July 2012.*
3. *The interest rate on the deposit facility will be decreased by 25 basis points to 0.00%, with effect from 11 July 2012.*

The President of the ECB will comment on the considerations underlying these decisions at a press conference starting at 2.30 p.m. CET today." (ECB Governing Council, 2012)

A2 Narrative Accounts of Monetary Policy Shocks in the Euro Area

In this Appendix we study the monetary policy shocks employed in the analysis in more detail using ECB material and press articles. The eight months in which the ECB surprised financial markets with an exceptionally restrictive interest rate decision were November 2002, March 2003, November 2008, December 2008, March 2009, April 2009, October 2011, and December 2015. The seven months in which it surprised with an exceptionally expansive interest rate decision were December 2002, June 2003, October 2008, January 2009, November 2011, July 2012, and September 2014. Below we discuss these events in chronological order.

November 2002 (+)

At its meeting on November 7, 2002, the Governing Council decided to leave interest rates unchanged. But this decision was not unanimous. President Duisenberg declared at the press conference later that day (being put into writing in the ECB's Monthly Bulletin, ECB, 2002) that there was an extensive discussion, with several members obviously arguing in favor of a rate cut. The economy was in a business cycle downturn, but consumer price inflation was still elevated. The Economist (2002a) commented that *"the ECB's stance is hard to understand. Partly it reflects the ECB's single-minded focus on inflation"*.

What preceded this contentious interest rate decision? The main refinancing rate stood at 3.25%. The last interest rate cut had been a year ago, in November 2001 following the New York terror attacks, which had aggravated the downturn amid the burst of the stock market. In November 2002 the Fed had cut its policy rate significantly by 50 basis points the day before the ECB Governing Council met and many market participants expected it to follow the Fed.

But it didn't. *"Alan cuts, Wim refuses to follow"*, commented The Economist (2002a) in an allusion to the then chairman of the Fed, Alan Greenspan, and the president of the ECB, Wim Duisenberg. This restrictive monetary policy decision had a political-economic background. It can be interpreted as an attempt by the still young central bank to demonstrate and thus consolidate its independence.

In the run-up of the meeting, politicians from Germany, France and other countries urged the bank to cut rates in order to support the economy. With respect to these pleas, Ernst Welteke, president of the German Bundesbank and member of the ECB Governing Council, said some days before the meeting: *"In such a situation, it is more difficult for us to reduce interest rates. The people and financial markets would get the impression that we are giving in to political pressure"* (Der Spiegel, 2002, translation by the authors).[15]

[15] While a substantial share of financial market participants did not expect interest rates to remain unchanged, this does not mean that nobody expected it. In an article posted in the morning of November 7, just before the meeting of the Governing Council, the Frankfurter Allgemeine Zeitung (2002) noted that *"analysts had recently pointed out that the ECB would probably not*

December 2002 (−)

Two days before the meeting of the ECB Governing Council on December 5, 2002, The Economist (2002b) conjectured that *"boldness has not been one of the characteristics of the European Central Bank. So few people expect the bank to throw caution to the wind and announce a cut of half a percentage point in European interest rates"*.

This was all the more likely since *"central bankers have proved resistant to outside pressure before"* (ibid.), which was an allusion to the previous interest rate decision in November 2002. The ECB, however, relented in the face of slowing growth and easing inflationary pressure and surprised markets once again by cutting rates by 50 basis points.

March 2003 (+)

In a speech at a G7 meeting of finance ministers and central bank governors in Paris two weeks before the ECB Governing Council met on March 6, 2003, president Duisenberg said that uncertainties had increased lately and that the perspective for an economic recovery was no longer supported by the most recent data available to the bank (The Guardian, 2003). Importantly, *"this weaker outlook, as we see it, should contribute to lower inflationary pressure. And as you know, price stability is our aim"*.

Many market participants interpreted this assessment, together with similar statements of other members of the Governing Council, as evidence for a more substantial rate cut, given that policy rates had been unchanged for two consecutive months. *"Why so small?"*, The Economist (2003) and, according to the newspaper, many economists asked after the ECB announced its interest rate decision. To them, the decrease of the main refinancing rate by only 25 basis points came as a disappointment.

June 2003 (−)

At that time, a substantial interest rate cut was considered necessary by many observers. But equally many remained skeptical about the ECB: *"Even though most forecasters had agreed that a 50 basis point cut was the best outcome, the ECB's record of extreme caution had led many to fear a different outcome"*, the BBC (2003) noted.

"But in the event, the smoke signals emanating from Frankfurt turned out to be accurate" (ibid.): On June 5, 2003, interest rates were cut by 50 basis points, as many had hoped but not believed.

be forced to take action and therefore the key rates would probably not change despite the Fed's decision. According to the experts, the desire expressed by politicians for lower interest rates and the recent discussion about the EU Stability Pact will delay a rate cut in the euro area at least until December" (translation by the authors). This was exactly what happened.

Mid-2003 to mid-2008

The five years preceding the global financial crisis, from mid-2003 to mid-2008, were a period of almost perfect monetary foresight. No significant policy shock occurred. Each of the nine interest rate hikes, one in late 2005, five in 2006, two in 2007 and another one in 2008, in the amount of 25 basis points each, were well anticipated in timing and magnitude.

Especially for the last one in July 2008 this might seem surprising, with the financial crisis already unfolding and economic growth losing momentum. In its explanation of the interest rate decision, the ECB acknowledged a *"weakening of real GDP growth"*, but at the same time saw inflation rates to *"have continued to rise significantly"* and to *"remain well above the level consistent with price stability for a more protracted period than previously thought"* (ECB, 2008a). So, worries over price stability guided the ECB once again and markets anticipated the interest rate hike accordingly.

October 2008 (–)

The collapse of Lehman Brothers in September 2008 severely aggravated the crisis of financial markets. Central banks all over the world took measures to counteract the freezing of interbank lending. Nonetheless, the ECB left interest rates unchanged in its regular meeting on October 2 (ECB Governing Council, 2008a).

Assuming that inflation would remain too high due to inflation-indexed wage-setting (*"nominal increases which are abnormal in our view"*, ECB, 2008b), the Governing Council stressed the crucial importance of keeping inflation expectations firmly anchored. This was perceived restrictive by financial markets, the short-term swap rates increased by up to 2.4 basis points. However, the Financial Times (2008a) noted that *"Mr. Trichet carefully left room for manoeuvre and did not rule out possibly co-ordinating a cut in interest rates with the US Federal Reserve—if consistent with combating inflation."*

This coordinated rate cut was orchestrated less than a week later. The monetary policy committees of the main central banks in the world met on October 8 and collectively cut policy rates by 50 basis points (ECB Governing Council, 2008b). This surprised financial markets, given the ECB's dogmatic position on price stability. The Financial Times (2008b) cited the then Chief European Economist at Goldman Sachs, Erik Nielson, who described as *"breath-taking the U-turn in ECB thinking"*. The ECB might have *"had little choice but to fall into line with action taken by other central banks"*.

While the magnitude of the rate cut from 4.25% to 3.75% was not extraordinary, another measure, announced in a separate press release (ECB Governing Council, 2008c), enhanced the expansive shock: The procedure for providing liquidity to the banking system was changed from a variable-rate bidding to a fixed-rate full allotment procedure.

Excess liquidity started to build up for the first time in the bank's history. The net recourse to the deposit facility increased from a long-term average of almost zero to 155 bn. Euro in the second week of October, when the measure was announced and implemented, and to 240 bn. Euro in the following week. The mounting excess liquidity pushed $EONIA$ from the middle of the policy rate corridor (i.e., from close to the main refinancing rate) to the bottom (the deposit facility rate), making the deposit facility rate the effective policy rate (Hartmann and Smets, 2018, p. 54).

In the same press release, the ECB announced that it would decrease the corridor of standing facilities from 200 to 100 basis points, implying a re-increase of the deposit rate by 50 basis points and, hence, to its previous level of 3.25%. This means that the change of the allotment procedure constituted a policy rate cut of 50 basis points, from 3.75% (the main refinancing rate) to 3.25% (the deposit facility rate).

Hence, the overall measures taken on October 8 amounted to a monetary easing of 100 basis points, half of which is attributable to the collective rate cut and half to the change in the allotment procedure. As a consequence, short-term swap rates fell by up to 20 basis points, which far outweighed the restrictive decision of October 2. Altogether, October 2008 was a month of significantly and unexpectedly expansive monetary policy.

November 2008 (+)

Less than an hour before the ECB announced its interest rate decision on November 6, 2008, the Bank of England surprised financial markets by cutting the bank rate from 4.50% to 3.00%. This amounted to the largest single rate cut since 1981, and in turn placed high expectations on the ECB.

Many expected a cut of the main refinancing rate from 3.75% to at least 3.00% because the British bank rate had never been lower than the main refinancing rate of the ECB. Moreover, financial market turmoil was still broadening and intensifying, while upside risks to price stability were alleviating.

But the disappointment followed swiftly: Although the Governing Council considered a 75 basis points cut in the debate (ECB, 2008c), rates were cut by only 50 basis points. Meanwhile, president Trichet urged others, especially the banking sector, to help restore confidence.

December 2008 (+)

Again, the ECB appears to have been preempted by the interest rate decision of the Bank of England. Although the Governing Council on December 4, 2008, decided to cut interest rates by 75 basis points, this was less than the 100 basis points bank rate cut by the BoE.

The Handelsblatt (2008) noted that *"hopes of a 1.00 percentage point cut in the key interest rate by the European Central Bank (ECB) drove the markets significantly upwards [...] When the ECB cut the key interest rate by 'only' 0.75 percentage points, this initially led to disappointment among investors"* (translation by the authors). The Financial Times (2008c) asserted that while *"the ECB's move was still the biggest in its history [...] there had been hopes of even bigger reductions"*.

January 2009 (−)

The international press predominantly concluded that the monetary policy decision of January 15, 2009, was too tentative. Referring to the cut of the main refinancing rate by 50 basis points, The Economist (2009) assessed that *"the ECB is not hurrying to cut interest rates—mostly for the wrong reasons"*. The Financial Times (2009a) asserted that *"the European Central Bank is not cutting rates fast enough"* and that *"that, at least, is what markets believe. [...] Currency and bond markets are in a tizzy about such relative inaction, worrying that the ECB is behind the curve"*.

This was, however, not what markets believed. As described above, the change from a flexible-rate bidding procedure to fixed-rate full allotment in October 2008 led to an immediate and substantial increase of excess liquidity, which made the ECB's corridor system, with short-term money market rates fluctuating around the main refinancing rate, essentially a floor system, with market rates hovering just above the deposit facility rate.

In the January meeting, the Governing Council not only decided to cut the main refinancing rate by 50 basis points, but also to restore the width of the corridor of standing facility rates from 100 to 200 basis points. This implied that the deposit facility rate fell by another 50 basis points, from 2.00% to 1.00% overall.

This decrease, not the 50 basis points decrease of the main refinancing rate, was the relevant rate cut and closely followed by $EONIA$. When the decisions came into effect a week later, the Financial Times (2009b) re-assessed that *"overnight market rates moved sharply lower, as the full force of last week's interest rate decision came into effect"*.

March 2009 (+)

Similar to November and December 2008, the Bank of England somewhat raised expectations of the ECB that it did not meet. The bank rate was cut by 50 basis points in February and another 50 basis points in March. The ECB paled in comparison, as it lowered its interest rates in March by only the same amount (50 basis points), after it had not changed them in February.

"The Bank of England and the European Central Bank interest rate-setting committees both met on Thursday [March 5, 2009, A/N]. *They face similar economic crises but gave very different answers to the problems facing them. The UK central bank is acting in proportion to the severity of the crisis. The eurozone's monetary authority is doing far too little"*, the Financial Times (2009c) asserted.

April 2009 (+)

By that time, several central banks had reduced their policy rates to zero or almost zero, while the deposit facility rate of the ECB was 0.50% and the main refinancing rate was 1.50%. *"Many had expected the European Central Bank to slash its main interest rate on Thursday and join the quantitative easing club"*, the Financial Times (2009d) noted. *"A big cut is what markets had expected. Instead, the ECB* *trimmed its main rate by just 25 basis points to 1.25 per cent. The euro rose sharply immediately afterwards, further squeezing the eurozone economy."*

The Handelsblatt (2009) suggested that the decision was motivated by the ECB's reluctance to adopt a zero-interest policy. *"The decision to cut the key interest rate by a quarter of a percentage point [...] delays the inevitable move to a zero-interest policy. [...] For some time now, it has been clear to all market participants that the ECB cannot maintain its reluctance to lower key rates"* (translation by the authors).

October 2011 (+)

In April and July 2011 rates were raised due to rising inflation. According to Hartmann and Smets (2018) *"the interest rate increases in 2011 do not show up as a major policy mistake"*.

But in October 2011, markets, amid a deteriorating business cycle outlook, predominantly expected a rate cut which did not materialize. This expectation was fed by statements of Governing Council members. Yves Mersch from Luxemburg said that rate cuts could be considered if the economic situation worsened considerably more than expected (Reuters, 2011). Erkki Liikanen from Finland suggested that the deterioration may have been already happening (ibid.).

However, consumer price inflation was still above 2% and it was Jean-Claude Trichet's last meeting as ECB president. Reversing the interest rate increases from earlier that year could have been seen as an admission of a policy mistake. Hence, the ECB surprised many financial market participants by keeping rates unchanged at its meeting on October 6.

November 2011 (−)

Interest rates were not only kept unchanged in October 2011, outgoing president Trichet also offered no indication that an interest rate move could be due in the near future (CNN Money, 2011). Furthermore, there was no striking new assessment of the economic situation: Inflation was at elevated levels, growth was very moderate and subject to heightened downside risks.

Against this backdrop, the rate cut of 25 basis points announced after the meeting on November 3, 2011, may be seen as a demonstration of the new president, Mario Draghi, to follow a more accommodative policy than his predecessor. The Economist (2011) wrote accordingly that *"'Super Mario' takes charge. [...] Jean-Claude Trichet liked to prepare the ground for interest-rate changes by signalling them before they were actually decided. [...] The decision came as a surprise to financial markets partly because it departed from Mr Trichet's way of doing things."*

July 2012 (−)

The surprising rate cut in November 2011 was followed by another cut in December 2011 which had been expected. Subsequently rates were kept unchanged until July 5, 2012.

At this meeting, all three policy rates were cut by 25 basis points. According to the press, the uniformity of these cuts surprised markets. *"As expected, the ECB has cut its main refinancing rate by 25 basis points to 0.75% and the marginal lending facility (emergency funds) by 25 basis points to 1.50%. In a less expected move they also cut the deposit rate to zero"*, noted the Financial Times (2012) and concluded: *"It's clear the ECB has gone into experimental mode."*

This mode shift not only surprised the press, but also financial markets. The Handelsblatt (2012) quoted a money market trader in Frankfurt with the words: *"The reduction in the interest rate on the deposit facility comes as a complete surprise to us. I am curious how the money market will deal with it. After all, many had recommended that the ECB should not cut the interest rate to zero"* (translation by the authors).

September 2014 (−)

In line with forward guidance introduced in July 2013, the Governing Council in August 2014 announced that interest rates would remain unchanged for an extended period of time (ECB, 2014). Only a month later, at its meeting on September 4, 2014, it decided to cut interest rates by 10 basis points.

Moreover, in June of this year, when the deposit rate had been cut to below zero for the first time, the ECB had indicated to have reached the lower bound. *"Speaking on that occasion, Mario Draghi, the bank's president, said that 'for all practical purposes, we have reached the lower bound.' [...] Today he insisted that whatever he might have said in June the ECB had now definitely reached the lower bound"* (The Economist, 2014). He also conceded that the interest rate decision was not unanimous.

December 2015 (+)

"Draghi has over promised and under delivered." This quote, cited by BBC (2015), sums up the situation on December 3, 2015. As consumer price inflation had remained well below its target for several years, *"Mario Draghi had sent strong signals in recent weeks that he and his colleagues on the ECB's governing council were prepared to 'do what we must to raise inflation as quickly as possible'"* (The Guardian, 2015).

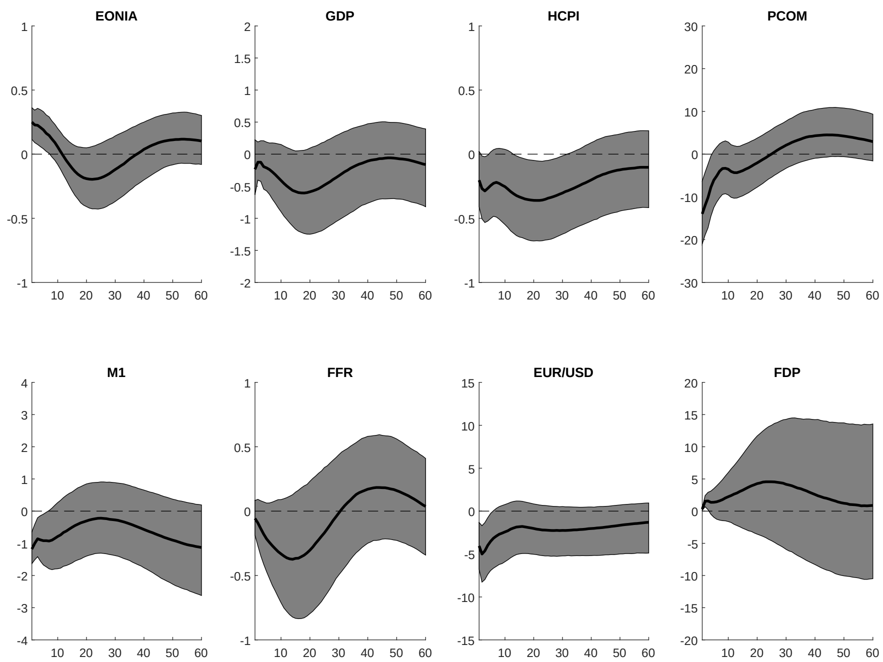
An investor, quoted by Handelsblatt (2015), suggested that *"Draghi had deliberately raised expectations too high in order to exert pressure on the Governing Council"* (translation by the authors). The newspaper maintained that the views in the Governing Council must have diverged considerably. In the end, *"many in the markets had been looking for a bigger reduction in the deposit rate"* (Financial Times, 2015) than from −0.20% to −0.30%.

The Wall Street Journal (2015) concluded that *"the ECB's moves were a major disappointment from a central bank whose actions have typically exceeded investors' expectations"*—interestingly, a view that differs dramatically from the perception of the ECB in the early years of its existence.

A3 Results without Magnitude Restrictions

In the baseline specification, we impose magnitude restrictions on top of the sign restrictions on structural residuals. In the following, we consider the results when these magnitude restrictions are dropped and only sign restrictions are used for identification.

Figure A1: Impulse Responses, No Magnitude Restrictions



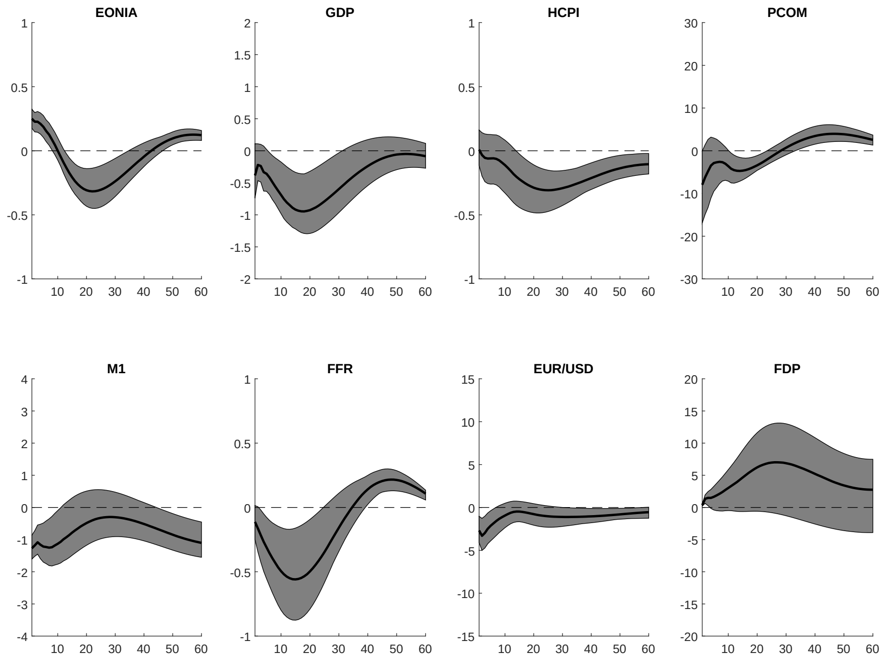
As can be seen from Figure A1, omitting magnitude restrictions hardly affects the results. Our qualitiative findings are virtually identical, the only implication is that the credible sets become wider. Hence, magnitude restrictions do not only ensure that the identifying shocks are economically meaningful, they also sharpen inference, which motivates their use in the baseline estimation.

A4 Model versus Estimation Uncertainty

Baumeister and Hamilton (2020) put forth a fundamental objection to the use of conventional credible sets in the case of set identification. Credible sets (or confidence intervals) are means to highlight estimation uncertainty in a finite sample. Estimation uncertainty can be reduced by increasing the sample size.

Set identification, however, entails another source of uncertainty, which is due to the variety of models for which the identifying restrictions hold. This kind of uncertainty is inherent to (and a benefit of) set identification. It cannot be altered by increasing the sample size but only by changing the identifying assumptions. As demonstrated by Baumeister and Hamilton (2020), the use of conventional credible sets may exclude valid model specifications and, in the worst case, lead to spurious results.

Figure A2: Impulse Responses, Full Model Variety



Therefore, they propose to present the full set of identified draws—i.e., 100% credible sets—based on the OLS estimates of the reduced-form coefficients, $\hat{\boldsymbol{A}}_{\boldsymbol{i}}$ and $\hat{\boldsymbol{V}}$. This means to ignore estimation uncertainty and to solely but fully capture the amount of model uncertainty. Figure A2 shows that the basic results remain intact when we apply this concept to our case.[16]

[16]Instead of OLS estimates we use the posterior means of the reduced-form coefficients. The OLS estimates are equivalent to the posterior means under the diffuse Normal-Wishart prior. For other priors—like Minnesota, as in our case—using the posterior means is the proper generalization.

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