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QUANTITATIVE TIGHTENING: LESSONS FROM THE US AND POTENTIAL IMPLICATIONS FOR THE EA

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Quantitative Tightening: Lessons from the US and Potential Implications for the EA

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Abstract

Given the decades-high inflation, central banks are complementing conventional rate hikes with quantitative tightening (QT), i.e. a reduction of the sizeable asset holdings accumulated during the quantitative easing (QE) era. In this study, we employ empirical (proxy-SVAR) and structural (medium-scale NK DSGE) frameworks to study the macroeconomic implications of QT. Our empirical findings show that the impact of QT has been relatively muted in the US, suggesting asymmetric effects of QT compared to QE. This finding is corroborated by model simulations, calibrated to the post-pandemic high inflation environment. Nevertheless, QT can partly substitute conventional rate hikes by creating some deflationary pressure and requiring less aggressive conventional policy action. QT produces smaller effects in the euro area (EA) due to the smaller share of private bonds on the ECB's balance sheet. However, a potential concern for QT in the EA is the proliferation of fragmentation risk. We empirically argue that the deployment of market-stabilisation QE can be used to stabilise sovereign spreads without creating considerable inflationary pressure in case QT leads to disorderly market dynamics.

Keywords: monetary policy, quantitative tightening, quantitative easing, proxy-SVAR, DSGE

JEL codes: C54, E31, E52, E58, G12

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1 Introduction

Given the decades-high inflation, the Federal Reserve System and the European Central Bank are complementing conventional rate hikes with quantitative tightening (QT), i.e. a reduction of the sizeable asset holdings accumulated during the quantitative easing (QE) era. By 2022, both the Federal Reserve and the ECB have accumulated close to 35% of their respective nominal GDP levels under their asset purchase programmes. The Federal Reserve already engaged in a balance sheet wind down during the previous tightening cycle from 2017 to 2019 and has resumed the balance sheet reduction from mid-2022 onward, while the ECB has started to reduce its asset holdings from the first quarter of 2023 onward.

While there is ample empirical research on the effects of QE[1], evidence on the effects of QT is much more limited given the few available observations with balance sheet unwinding before the current tightening episode.

Nevertheless, Smith and Valcarcel (2022), Crawley et al. (2022), and Wei (2022) provide important contributions to understanding the potential implications of QT. Smith and Valcarcel (2022) particularly evaluate the financial effects of QT by the Federal Reserve, implemented between 2017 and 2019, concluding that it had asymmetric effects compared to balance sheet expansion. Specifically, they find that QT surprises have limited announcement effects. However, the transmission via the duration channel remains strong in the wind down phase, resulting in tighter financial conditions, as both short- and long-term rates rise and the US dollar appreciates. However, they strongly emphasise that QT cannot be simply considered as QE in reverse as the underlying state of the economy matters to a large extent – QE is deployed at the effective lower bound (ELB) or during high financial distress episodes, which explains the asymmetries.

Crawley et al. (2022) and Wei (2022) instead focus on the substitutability between policy rate hikes and QT. The former study finds that a $2.5 trillion balance sheet reduction is equivalent to a 50 basis point (bp) policy rate hike, while the latter study estimates that a $2.2 trillion roll-off is equivalent to a 29 bps hike in tranquil market conditions. This number rises to 74 bps in states of high financial stress. To put those numbers into perspective, if the Federal Reserve reduces its balance sheet at the announced pace[2], it will be able to roll off approximately $1 trillion over the course of a year. Therefore, the potential of QT to combat high inflation appears to be limited, suggesting that central

[1]See Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), Baumeister and Benati (2013), Weale and Wieladek (2016), Swanson (2021) for evidence from the US and Altavilla et al. (2015), Andrade et al. (2016), Blattner and Joyce (2016), Garcia Pascual and Wieladek (2016), Hartmann and Smets (2018), Rostagno et al. (2019), De Santis (2020) Zlobins (2023b), Eser et al. (2023) for evidence from the euro area.

[2]See `https://www.federalreserve.gov/newsevents/pressreleases/monetary20220504b.htm` for details.

banks should primarily rely on conventional monetary policy tools to stabilise inflation away from the ELB.

Furthermore, the theoretical literature on optimal QE/QT suggests that the exit from a large balance sheet regime should be gradual. Both Harrison (2017) and Karadi and Nakov (2021) find limited macroeconomic stabilisation potential of QT but outline non-negligible financial side-effects, thus advising to favour gradualism over aggressive balance sheet reduction. However, the current literature lacks a comprehensive appraisal of QT stabilisation properties in an environment of high inflation and its interaction with traditional policy rate setting. Additionally, the potential effects of a balance sheet wind down in the euro area have not been explored yet.

Hence, we contribute to filling this gap and expand the literature on the central bank balance sheet unwinding as follows: first, we gather macro-level evidence of tightening surprises using a proxy-SVAR, estimated using both US and euro area data. Second, we utilise the model of Sims and Wu (2021) – a medium-scale New-Keynesian DSGE model – to explore the stabilisation properties of QT in response to a mix of supply and demand shocks to mimic the post-pandemic high inflation environment. In addition to using the US calibration by Sims and Wu (2021) for the US scenarios, we calibrate the model to the euro area, before using it for the euro area scenarios.

Our empirical findings demonstrate that QT has an asymmetric impact on the economy compared to a balance sheet expansion, with substantially weaker influence on output and inflation dynamics, suggesting a limited macroeconomic stabilisation potential of balance sheet policy away from the ELB. This finding is backed up by model simulations, suggesting that QT as a stand-alone policy tool is not effective in stabilising inflation. Nevertheless, the model simulations also reveal that, in conjunction with an active monetary policy interest rule, QT can partly substitute conventional rate hikes by creating some deflationary pressure and requiring less aggressive conventional policy action. Regarding the euro area, the effects of QT are likely to be even more muted due to a larger share of public bonds, as compared to private bonds, accumulated under the auspices of the ECB's asset purchase programmes. We also corroborate findings from the existing literature that balance sheet unwinding leads to a sizeable widening of spreads on financial markets. Thus, it might be advisable for the ECB to reduce its balance sheet in a moderate fashion to minimise the fragmentation risks in the euro area. In the event that such risks materialise, market-stabilisation QE via the recently announced Transmission Protection Instrument or Outright Monetary Transactions might be the more appropriate policy option since they can effectively stabilise sovereign spreads with lower inflationary pressures, as compared to conventional QE policy.

This paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the empirical framework, while Section 4 presents the empirical findings on the macroeconomic effects of QT in the US and the euro area. Similarly, Section 5 describes the structural model and its calibration, and Section 6 discusses the simulation results. Finally, Section 7 concludes.

2 Literature Review

Our paper contributes to several strands of the literature on the transmission of central bank balance sheet policies to the economy. Given the widespread adoption of QE by the central banks in light of a binding ELB constraint after the Great Recession (in the US) and the Sovereign Debt Crisis (in the euro area), a burgeoning empirical literature has emerged, documenting the implications of balance sheet expansions on financial markets and real economic activity. For the impact of the Federal Reserve's QE, see, e.g. Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), Baumeister and Benati (2013), Weale and Wieladek (2016), Swanson (2021), while for the experience of the ECB, see the studies by Altavilla et al. (2015), Andrade et al. (2016), Blattner and Joyce (2016), Garcia Pascual and Wieladek (2016), Hartmann and Smets (2018), Rostagno et al. (2019), De Santis (2020) Zlobins (2023b), Eser et al. (2023), among others. However, considering the limited implementation of QT – the Federal Reserve managed to reduce its balance sheet from 2017 to 2019 – the empirical evidence on balance sheet roll-offs remains scant. Still, Smith and Valcarcel (2022), using event studies and vector autoregressions, provides an empirical investigation of the Federal Reserve's initial balance sheet normalisation. They find that, contrary to QE, QT has weak announcements effects, but the balance sheet reduction still carries considerable impact on the prevailing financial conditions via the liquidity extraction channel. The paper also emphasises that the underlying state of the economy to a large extent explains the asymmetric impact of QT compared to QE, since the latter is deployed when the ELB constraint is binding or during high financial distress episodes.

Two closely related papers by Crawley et al. (2022) and Wei (2022) – using the semi-structural FRB/US model and preferred-habitat model of Vayanos and Vila (2021), respectively – analyse the substitutability between policy rate hikes and QT. Crawley et al. (2022) define the equivalence between policy rate hikes and QT in terms of their impact on long-term interest rates, employment, and inflation, while Wei (2022) defines it just in terms of the effect on the 10-year Treasury yield. However, both find a relatively limited potential for QT to substitute conventional policy. Crawley et al. (2022) estimate that a \$2.5 trillion balance sheet roll-off is equivalent to a 50 bps policy rate hike, Wei (2022), in addition, allows for potential non-linearity and finds that a \$2.2 trillion wind-down is equivalent to a 29 bps hike in tranquil market conditions, rising to 74 bps if high financial stress prevails. However, the aforementioned studies mostly focus on the financial implications of QT, while being silent on its macroeconomic consequences. Given the few empirical observations with actual episodes of balance sheet roll-offs, most papers rely on structural macroeconomic models to pin down the impact of QT on output and inflation.

For example, Harrison (2017) and Karadi and Nakov (2021) both utilise a New-Keynesian DSGE framework to derive optimal implementation strategies for QE/QT. Their simulations suggest a limited potential for QT in terms of additional macroeconomic stabilisation. At the same time, both studies advise to reduce the central bank balance sheet in a moderate fashion as adverse effects of aggressive balance sheet roll-offs via financial channels can be substantial.

In a recent contribution to the literature, Cantore and Meichtry (2023) concentrate on the role of a binding ELB constraint for the asymmetric transmission of QT compared to QE. They deploy a two agent New-Keynesian model with short- and long-term bonds. Therefore, when the central bank reduces the fraction of long-term bonds on its balance sheets (i.e. when the central bank implements QT), there is a larger supply of bonds available to the households so that the borrowers borrow more using short-term assets while more long-term assets are held by savers. Thus, the long-term interest rate increases, while the short-term interest rate decreases. In other words, the interest rate spread between long-term and short-term bonds increases. Thus, both households reduce consumption, and output and inflation decrease on aggregate due to households paying adjustment costs for changing the composition of their bond portfolios. There are no financial intermediaries in their model and borrowers are constrained in their borrowing decisions as the main financial friction. The effects of QE and QT are symmetric when the economy is far above the ELB, while QT is more recessionary when the economy is close to the ELB due to the short-term interest rate not falling as much, thereby decreasing the borrowing costs for borrowing households. This points to the noteworthy implication that QT should be implemented only after the conventional policy rate has been raised to avoid falling into a liquidity trap. Thus, household heterogeneity only matters when the economy is close to the ELB.

Although their focus is mostly on QE and other unconventional monetary policy tools, Sims and Wu (2021) also conduct an exercise regarding QT. They use a representative household model, but it features financial intermediaries and financial frictions on the firm and intermediary side and central bank purchases of private bonds, in contrast to Cantore and Meichtry (2023) who concentrate on aggregate economic effects originating solely from household dynamics and from the purchases and sales of public bonds. They extend their framework to a heterogeneous agent New-Keynesian (HANK) model in Sims et al. (2022) with idiosyncratic labour productivity shocks but exclusively focus on QE in that study. In Sims and Wu (2021)'s QT exercise, they concentrate on QT implementation after exogenous liquidity shocks that make the ZLB bind and endogenous QE implementation via a Taylor-type rule so that private bond holdings by the central bank increase in response to a lower inflation gap or a lower output gap. No unwinding of the central bank's balance sheet after this endogenous QE period makes the recession during the ZLB period more severe but leads to higher output after the ZLB period, while moderate and immediate unwinding does not produce very different outcomes – an immediate unwinding leads to a somewhat worse performance at the time of the ZLB exit. The difference between the dynamics with and without the expectation that QT is implemented after the ZLB period is due to higher investment during the ZLB period when some form of QT is expected to occur due to relatively better investment conditions. This leads Sims and Wu (2021) to conclude that QE is most effective when a clear QT path is announced ex ante and clearly communicated to economic stakeholders.

We use the model of Sims and Wu (2021) without any alterations but look at different ways for QT implementation and re-calibrate it to the euro area, when we study the effect of QE/QT in the euro area. The main difference is that both QE and QT shocks in our customised scenarios are exogenous and unexpected. Moreover, we shift the focus of QE/QT happening just before the COVID-19 pandemic or just after the pandemic (then only QT shocks are studied, without an initial QE period). For the former scenario we make sure that the size of balance sheet increases corresponds to the actual dynamics of the balance sheet of the Federal Reserve in our US simulations or the ECB in our euro area simulations during the pandemic.

3 Empirical framework

In this section, we describe our empirical framework to pin down potentially asymmetric effects of quantitative tightening. In particular, we split the QE shock series, identified via high frequency information methods, into easing and tightening reactions to central bank announcements. We then use those surprises as external instruments Z_t in the proxy-SVAR setup of Stock and Watson (2012) and Mertens and Ravn (2013). Let Y_t denote a vector of endogenous variables which evolve according to:

$$Y_t = C_t + \sum_{j=1}^{p} A_j Y_{t-j} + u_t, \tag{1}$$

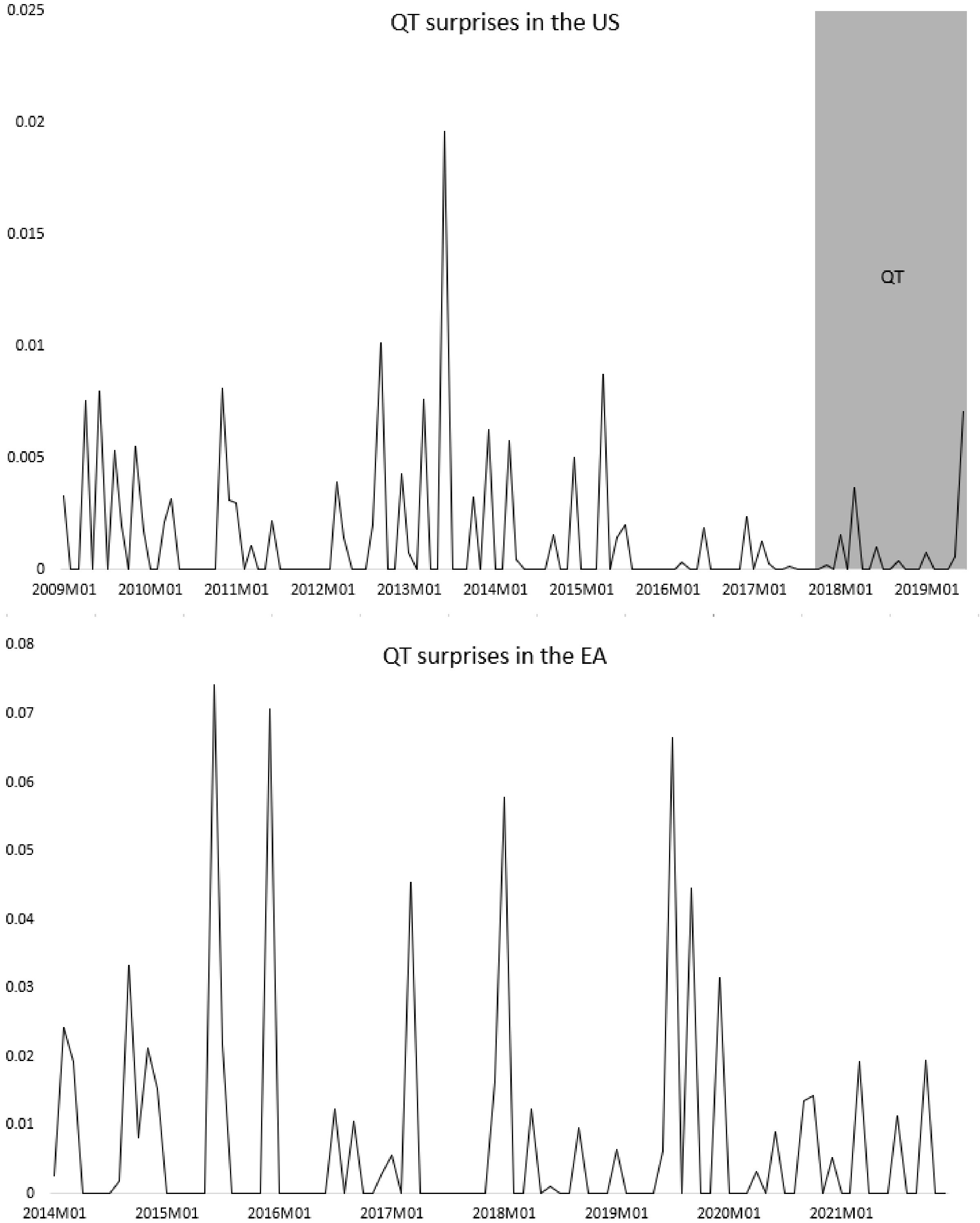
where C_t is an $n \times 1$ vector of constants, A_j $(j = 1, \ldots, p)$ is an $n \times n$ matrix of coefficients related to the j-th lag, Y_{t-j} is a set of endogenous variables, and u_t is an $n \times 1$ structural error vector with zero mean with variance-covariance matrix Σ.

Since the proxy-SVAR framework only allows to identify one shock at a time, we choose:

$$u_t = s\epsilon_t^i, \tag{2}$$

where s is an $n \times 1$ vector corresponding to the contemporaneous effect of the shock of interest ϵ_t^i. For the external instrument Z_t to be valid, it must be correlated with the

Figure 1: QT surprises



Notes: This graph depicts tightening surprises extracted from the LSAP factor of Swanson (2021) (for the US) and the QE shock series, obtained via fusion of high frequency identification with narrative sign restrictions (for the EA).

shock of interest ϵ_t^i and orthogonal to other shocks in the system ϵ_t^j:

$$\mathbb{E}[Z_t\epsilon_t^i] \neq 0, \tag{3}$$

$$\mathbf{E}[Z_t\epsilon_t^j] = 0. \tag{4}$$

The estimation of the model proceeds in two steps: in the first stage, reduced-form residuals associated with the policy variable u_t^i are regressed on the instrument:

$$u_t^i = \beta_1 Z_t + \zeta_t, \tag{5}$$

$$\tilde{u}_t^i = \tilde{\beta}_1 Z_t. \tag{6}$$

In the second stage, reduced-form residuals of other variables u_t^j included in the system are regressed on $\tilde{u}_t^i$, which after the first stage only includes exogenous information regarding the shock of interest ϵ_t^i:

$$u_t^j = \tilde{\beta}_2 \tilde{u}_t^i + \xi_t = \frac{s^j}{s^i} \tilde{u}_t^i + \xi_t. \tag{7}$$

Regarding the instruments, for the US we use the LSAP factor of Swanson (2021), while for the EA we employ the QE shock series, obtained via the approach of Zlobins (2022). The series has now been further extended to accommodate the market-stabilisation QE shock, identified along the lines of Motto and Özen (2022) (see Appendix A for details on the identification strategy). The extracted tightening surprises[3], depicted in Figure 1, suggest that contractionary responses to central bank announcements regarding their balance sheet policy have often happened in the past, even when the respective central banks have pursued active asset purchase programmes, thus providing us with a sufficient number of observations for our empirical analysis.[4]

The model for both the US and the EA is estimated over the sample from January 2000 to December 2021 using 2 lags (see dataset description and transformations in the the F). The first stage regression on the instrument, though, is implemented over shorter sub-samples, dictated by the chosen shock series. For the US, the LSAP factor is available from January 2009 to June 2019, while the QE shock for the EA is available from January 2014 to December 2021.

4 Empirical Results

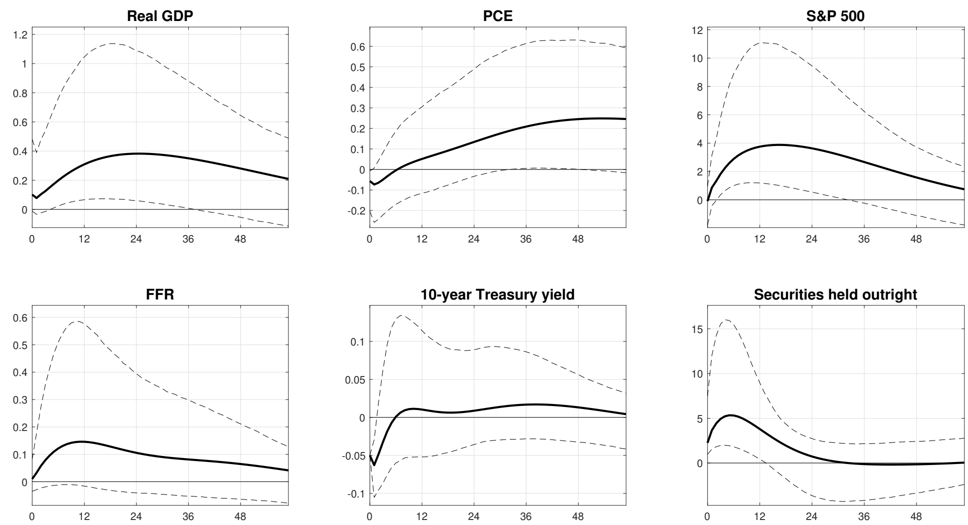
Panel (a) of Figure 2 depicts the impulse response functions obtained from the proxy-SVAR to the Federal Reserve Bank's easing surprises in the US. The results suggest that a QE announcement generates substantial macroeconomic effects in the US, as an easing surprise which lowers the 10-year Treasury yield by 5 bps,boosts output by up to 0.4%

[3]For comparison, see Appendix B for figures with extracted easing surprises.

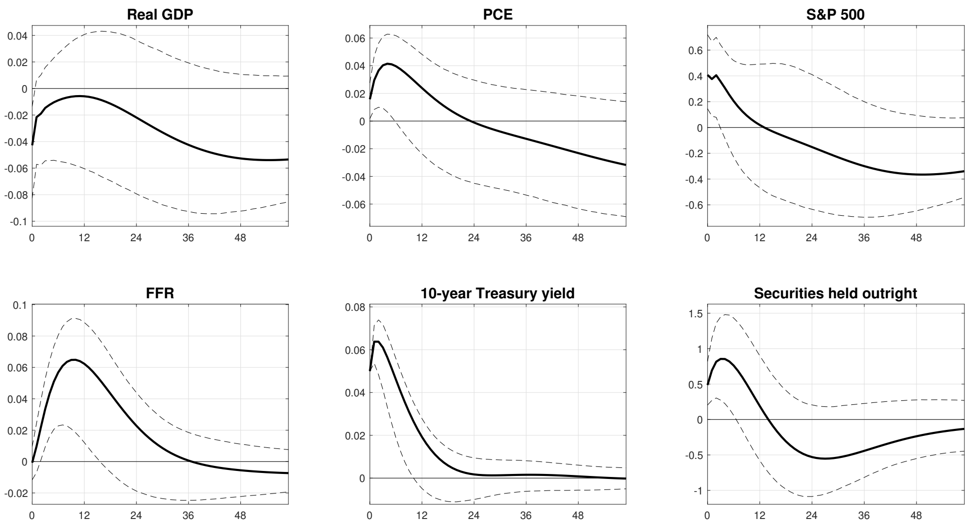
[4]We acknowledge that a considerable share of tightening surprises have occurred during periods of active QE, thus also reflecting the market response to an announcement of smaller central bank purchases than expected rather than an outright balance sheet wind down. It's also important to highlight that the high frequency identification approach primarily captures the announcement (or stock) effects rather than the impact of actual implementation of purchases (flow effects).

Figure 2: Baseline results for the US

(a) Impulse response functions to easing surprises



(b) Impulse response functions to tightening surprises



Notes: This figure depicts impulse response functions to the QE/QT shock from a proxy-SVAR. Easing/tightening surprises extracted from the LSAP factor of Swanson (2021) have been used as an external instrument for the 10-year Treasury yield with the first stage regression ran on the instrument over the sample from January 2009 to June 2019. The shock has been normalised to generate a 5 basis points decrease/increase in the 10-year yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

and the private consumption expenditure (PCE) price index by approximately 0.25% [5]. QE also leads to a sizeable increase in the balance sheet of the Federal Reserve and the S&P 500 stock price index. To ensure that our results are in line with the estimates reported in the literature on the effectiveness of QE in the US, we also estimate the

[5]Appendix D shows that QE also has sizable impact on corporate bond spreads.

proxy-SVAR with the original LSAP factor, i.e. without splitting it into easing/tightening surprises. The figure in Appendix C depicts that using the raw LSAP factor generates lower macroeconomic estimates of QE, with a 5 bps reduction in long-term interest rates leading to an increase of approximately 0.2% in output and 0.15% in prices. These elasticities are broadly similar to the ones reported in the literature on the effects of QE in the US. For example, Kim et al. (2020) also pin down the QE shock via a high frequency identification approach and estimate that a 5 bps compression in the 10-year Treasury yields boosts output and prices by about 0.3% and 0.2%, respectively. They also compare their results with existing studies and find that their estimates are similar to other empirical findings obtained via SVARs or semi-structural models (Chung et al., 2011; Weale and Wieladek, 2016; Hesse et al., 2018) but larger than evaluations done using structural DSGE models (Chen et al., 2012; Gertler and Karadi, 2013).

The results depicted in Panel (b) demonstrate that tightening surprises yield an asymmetric impact on the economy as the median responses of output and prices are significantly smaller and surrounded by wide confidence bands which do include zero, rendering them statistically insignificant. Thus, the US experience with QT suggests that balance sheet policy away from the effective lower bound can only have a limited macroeconomic stabilisation potential.[6]

Additionally, we repeat the same exercise using data for the euro area in Figure 3. These results further corroborate our findings that only easing surprises generate sizeable macroeconomic effects as the impulse responses of all variables with respect to the tightening surprises are statistically insignificant.[7] However, given that the ECB has not carried out any balance sheet reduction in the considered data sample, the results should be interpreted with caution.

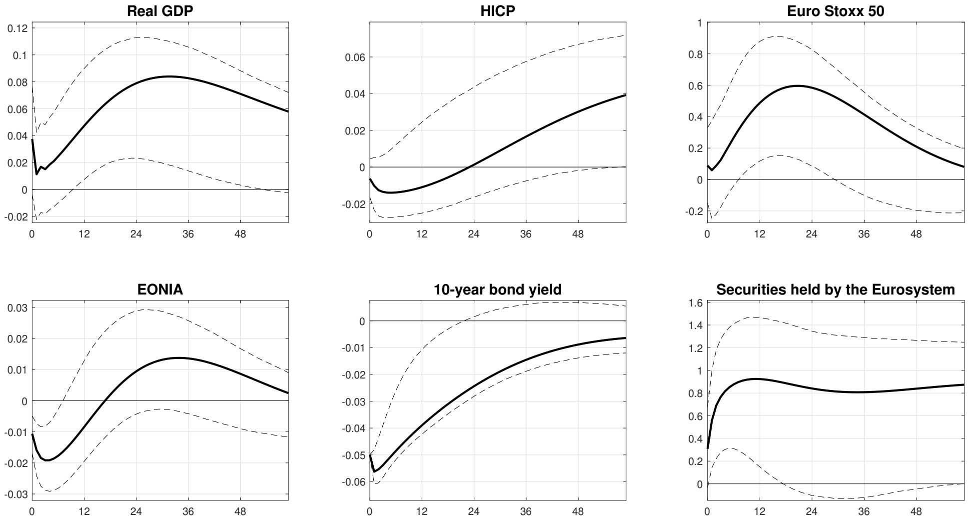
The results obtained from US data point out that QT leads to a rise in sovereign borrowing costs despite having little macroeconomic impact. Given the peculiarities of the euro area architecture, an aggressive balance sheet wind-down can potentially lead to a proliferation of fragmentation risk in sovereign bond markets. Should such risk materialise, the ECB could deploy market-stabilisation QE via the Transmission Protection Instrument or the Outright Monetary Transactions. As evidenced by the results in Figure 4, market-stabilisation QE can effectively stabilise the sovereign yields of peripheral countries and generate little inflationary pressure in the process. For this

[6]Appendix E demonstrates that the results remain unchanged when we exclude the taper tantrum episode in June 2013 during which the largest tightening realisation occurs as depicted in Figure 1.

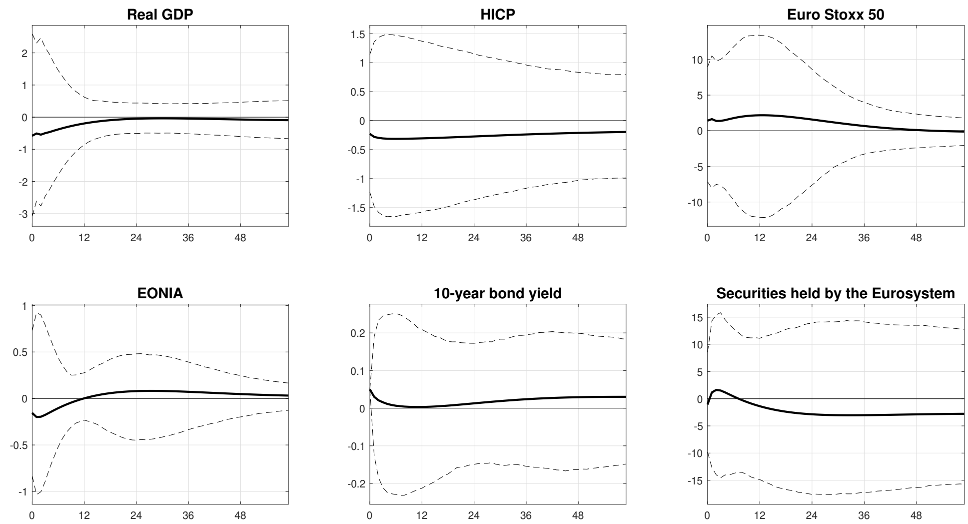
[7]Figure D.1 in Appendix C depicts that the raw QE shock series generates macroeconomic effects broadly in line with the studies on the impact of QE in the euro area, assuming that a QE shock generating a 5 bps drop in 10-year sovereign bond yields is approximately equal to a purchase of 1% of 2015 euro area nominal GDP (see Zlobins (2023a) for a reasoning behind this assumption). Existing evidence on the macroeconomic impact of QE in the euro suggests that the ECB's asset purchases, worth 1% of GDP, increase output by 0.1–0.2% and prices by 0.05–0.1%, see Garcia Pascual and Wieladek (2016), Lhuissier and Nguyen (2021), Rostagno et al. (2021), Zlobins (2023b).

Figure 3: Baseline results for the EA

(a) Impulse response functions to easing surprises



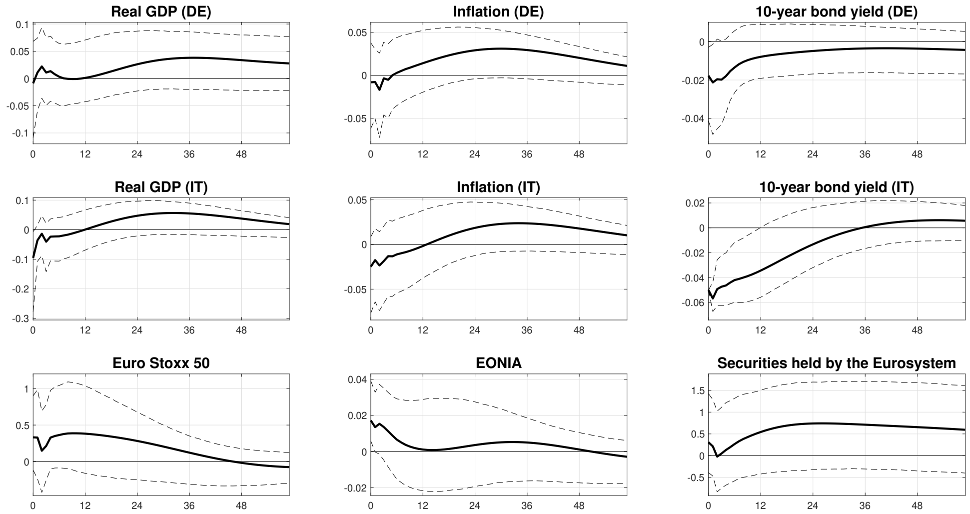
(b) Impulse response functions to tightening surprises



Notes: This figure depicts impulse response functions to the QE/QT shock from a proxy-SVAR. Easing/tightening surprises extracted from the QE shock, obtained via combination of high frequency identification with narrative sign restrictions, have been used as an external instrument for the 10-year benchmark bond yield with the first stage regression ran on the instrument over the sample from January 2014 to December 2021. The shock has been normalised to generate a 5 bps decrease/increase in the 10-year yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

exercise, we slightly modify our proxy-SVAR: we replace the aggregate euro area output, inflation and long-term yields with German and Italian counterparts, representing a core and a periphery country, respectively. The impulse response functions demonstrate that market-stabilisation QE primarily loads on the Italian 10-year yields, with substantially smaller impact on the German yields. This particular instrument also slightly increases

Figure 4: Results for the market-stabilisation QE shock



Notes: This figure depicts impulse response functions to the market-stabilisation QE shock from a proxy-SVAR. The market-stabilisation QE shock, obtained via fusion of high frequency identification with narrative sign restrictions, has been used as an external instrument for the 10-year Italian bond yield with the first stage regression ran on the instrument over the sample from May 2010 to December 2021. The shock has been normalised to generate a 5 bps decrease in the 10-year Italian yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

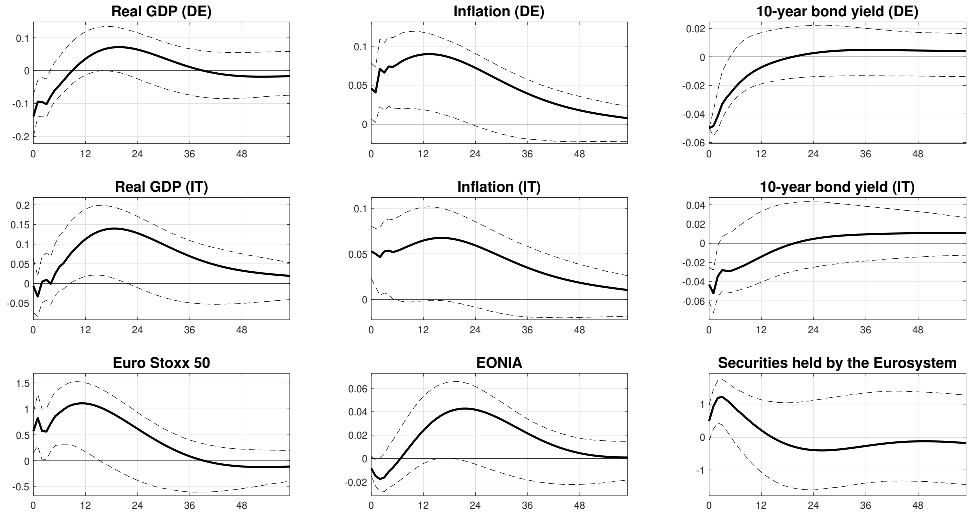
output and inflation but the median responses are small in both countries and they are surrounded with wide confidence bands, rendering them statistically not different from zero.

For comparison, we swap the market-stabilisation QE shock with a conventional QE shock in Figure 5. The impulse responses to conventional asset purchases exhibit much stronger responses – both output and inflation rise and sovereign yields fall. Also note that the reactions of these variables are rather similar in both countries, indicating a symmetric transmission of conventional asset purchase programmes among euro area jurisdictions. However, in order to compress the periphery yields by approximately 5 bps, an increase of 0.5% in the ECB's asset holdings is necessary when using conventional QE while in the case of market-stabilisation QE an increase of 0.3% is sufficient, suggesting smaller costs of this instrument to reduce fragmentation risks. Thus, in case of widening sovereign spreads in an unsustainable fashion as a result of QT, the ECB has credible policy tools in its arsenal to limit the fragmentation risk in sovereign bond markets while adding little inflationary pressure as a side effect.

5 Utilised Model and Calibration

In this section, we first briefly describe the utilised model in Section 5.1. In Section 5.2, we re-calibrate the model to euro area data for the use in scenario analyses pertaining to

Figure 5: Transmission of the conventional QE shock: Core vs. periphery country



Notes: This figure depicts impulse response functions to the conventional QE shock from a proxy-SVAR. The QE shock, obtained via fusion of high frequency identification with narrative sign restrictions, has been used as an external instrument for the 10-year German bond yield with the first stage regression ran on the instrument over the sample from January 2014 to December 2021. The shock has been normalised to generate a 5 bps decrease in the 10-year German yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

the euro area in Section 6.2.

5.1 Brief Description of the Utilised Model

For our model-based simulations to evaluate the equilibrium effects of QT on macroeconomic and financial quantities, we make use of the well-established model by Sims and Wu (2021) that features all three unconventional monetary policy tools – quantitative easing, forward guidance (FG), and negative interest rate policy (NIRP) – that became popular in many economies during and in the aftermath of the Global Financial Crisis of 2007–2009 and again during the COVID-19 pandemic of 2020–2022. While the model is developed for and calibrated to the US economy, the model framework is also well suitable to apply in the context of the euro area economy, as the implementation of the aforementioned unconventional monetary policy tools are quite similar across both sides of the Atlantic Ocean, after a suitable re-calibration of the model to euro area data that we will discuss in Section 5.2 below. In what follows, we briefly outline the model of Sims and Wu (2021).

First, we review the relatively standard ingredients of their New-Keynesian DSGE model. It is a closed economy with a representative household and all the usual real and nominal rigidities. Both wages and prices are rigid and subject to Calvo-style price- and wage-setting rigidity. The wages and prices can be partly indexed to past inflation if they are not allowed to be set optimally. The intermediate goods are produced with a standard Cobb-Douglas production function with capital and labour as inputs, subject to exogenous total factor productivity shocks. Building capital is subject to investment adjustment costs. Capital utilisation is endogenously chosen with lower capital utilisation leading to lower capital depreciation. The household sector allows for a representative household that maximises its lifetime utility by choosing optimal consumption of final goods, subject to internal habit formation, and labour supply, which generates disutility. The fiscal authority is modelled in a very simplistic way. It consumes an exogenously specified amount of final goods (wasteful public consumption) by collecting the profits from the central bank, issuing public bonds, and levying a lump-sum tax on households. The public bonds supply is assumed to be fixed so that the lump-sum tax on households adjusts in such a way that the government budget constraint holds every period.

Second, we discuss the financial sector, the frictions it is exposed to, and the role of the central bank in Sims and Wu (2021). The financial sector is modelled similarly to Gertler and Karadi (2011, 2013). Therefore, the financial intermediaries finance the purchases of private and public bonds by issuing deposits to households and using their own net worth. Private bonds are issued by the final goods producer. Both types of bonds are assumed to be long-term bonds with a decaying coupon structure, following Woodford (2001). The financial intermediaries are subject to an incentive compatibility constraint so that they do not divert with a fraction of their assets. Shocking the fraction of their assets with which financial intermediaries could abscond with when the incentive compatibility constraint would not hold is a proxy for liquidity or credit shocks in the model. This absconding rate is allowed to differ for private and public bonds as a means to construct a spread between the private bond return to the public bond return. Every period a constant fraction of financial intermediaries has to exit and transfer the remaining net worth to households. Every period new financial intermediaries are born that start their business with some funds from the households (start-up funds). Differently from Gertler and Karadi (2013), the financial intermediaries can also invest in interest-bearing reserves issued by the central bank. Moreover, the second constraint that financial intermediaries potentially face is a minimum reserve requirement.

The central bank's monetary policy tool set consists of conventional monetary policy, where the short-term nominal interest rate is set according to a Taylor-type interest rule with interest rate smoothing, endogenous adjustments to the inflation gap and the output gap, and exogenous monetary policy shocks. In normal times, this short-term nominal interest rate is equal to both the deposit interest rate and the interest rate on reserves. The zero lower bound (ZLB) constraint in the model implies that these three interest rates cannot become negative, unless the negative interest rate policy is employed as one of the unconventional monetary policy tools. Then, it is assumed that the deposit interest rate can still not get negative but the interest rate on reserves can become negative and equal to the (negative) short-term interest rate set via the Taylor rule. Forward guidance is modelled by introducing a shock to the underlying short-term policy rate during a binding ZLB constraint. This implies a lower rate on reserves and, in turn, deposits after the ZLB period is over. Credibility of forward guidance announcements is added in reduced form by scaling the shock size. This form of modelling forward guidance allows the model not to be subject to the "forward guidance puzzle".

The most important tool in the unconventional monetary policy toolkit in this model for our purposes and also in the real world is quantitative easing. In the model, QE is modelled as the central bank buying private and/or public bonds from the financial intermediaries in exchange for interest-bearing central bank reserves. Via this channel bonds are transferred from the balance sheet of financial intermediaries to the balance sheet of the central bank, which provides liquidity to the financial sector and loosens the incentive compatibility constraint and thus the stringency of financial frictions the financial sector is exposed to.

5.2 Calibration of the utilised model to the EA

In terms of the calibration strategy, we follow the approach laid out in Section 4.1 of Sims and Wu (2021) but obtain information on the empirical moments for the euro area from two statistical databases and the website of the ECB that we use instead of the US counterparts for the calibration of the model. The statistical databases we use are Eurostat for macroeconomic variables and the ECB Statistical Data Warehouse for data on the financial sector and other financial variables. The website of the ECB is used to obtain information on the annual profits of the ECB by studying the annual reports of the ECB and on the bond purchases made within the asset purchase programmes of the ECB. As the economic entity we use the EA-19, i.e. the euro area with 19 countries, throughout our calibration exercise. The time period chosen for the data collection ranges from the first quarter of 1999 to the fourth quarter of 2019, but some variables are collected on a monthly or annual frequency during this time horizon. The monthly series are made quarterly by averaging three monthly observations per quarter, as none of these time series are growth rates. In Appendix G, we provide additional information on the data used for the calibration of the model. Moreover, for some parameters we adopt the parameters estimated by Coenen et al. (2018) using their New Area Wide Model II. All the parameters are reported in Table 1.

For a couple of parameters, we do not make any adjustments, relative to the calibration of Sims and Wu (2021), since they have been set there to conventional values in the literature and there is no divergent guidance from the literature for calibrations of models to the euro area. Specifically, in line with Gertler and Karadi (2011, 2013), the survival probability for financial intermediaries σ is also set to 0.95. The capital depreciation rate and the parameters governing the capital utilisation dynamics are left unchanged, relative to Sims and Wu (2021), and the same is true for the coupon decay parameter κ and the steady-state gross inflation Π.[8] The labour disutility scaling parameter is chosen to adhere to the conventional choice to have a steady-state labour supply of $L = 1$.

There are some sizeable differences in EA data regarding empirical moments pertaining to the financial sector and the government statistics that we take into account in our re-calibration exercise. The government statistics display a significantly higher government debt to GDP ratio for the euro area in the considered data sample, relative to the target value of 41% for the US chosen by Sims and Wu (2021). Thus, a value of 80% is targeted for that moment in the steady state. Computing the government consumption to GDP ratio for the EA reveals a similar value as for the original target, i.e. the target for the EA implied by this data is only 40 bps higher at 20.4%.[9] Turning to the private financial sector, there is a lower private debt to GDP ratio in the EA relative to the US. As reported in Table 2, the target value is around 105% whereas the original target of Sims and Wu (2021) is 168%. We choose a lower fraction of investment that needs to be financed by debt to match this ratio in the model, i.e. $\psi = 0.50$ instead of $\psi = 0.81$. Moreover, there is slightly higher leverage in the euro area's financial intermediary sector, i.e. the new financial intermediary start-up fund is chosen to imply a steady-state financial sector leverage of 4.6 (instead of 4). The spread between the private bond and the risk-free rate is on average similar in the EA and the US (the EA empirical counterpart stands at 3.07 percentage points (pps), see Table 2). Thus, we choose the same target in the model as Sims and Wu (2021) and target 3 pps. The public bond premium is, however, more than twice as high in the EA than Sims and Wu (2021)'s target of 1pp (i.e. 2.38 pps). We calibrate $\Delta = 2/3$ so that the model-implied value for the public bond premium will be 2 pps. Finally, after the Global Financial Crisis and the Euro Area Sovereign Debt Crisis, the balance sheet of the ECB is composed of both private and public bonds at the end of 2019, just before the COVID-19 pandemic hit the world economy. Thus, we calibrate the balance sheet of the central bank in the model to feature the central bank's holdings of public bonds in the order of 17.33 and of private bonds in the order of 3.82 (both as % of GDP) in line with the data average for the period ranging from the first quarter of 2018 to the fourth quarter of 2019.

[8]The data in both the US and the EA is clearly at odds with an average gross inflation of 1. However, we simulate the models also with a (quarterly) steady-state gross inflation of 1.00475 so that the model is in line with the central bank targets across both sides of the Atlantic Ocean (steady-state gross inflation of around 1.02). However, due to using a first order perturbation method to simulate the model, the differences in moments and the scenarios are negligible. The results for these non-zero inflation models are available upon request from the authors.

[9]Note that total government spending in the EA is higher than in the US. Using that data would give a ratio to GDP of around 48%. However, since other forms of government spending like public investment or social security spending is not considered in the model, we use the data on final consumption expenditure of the general government and not the total general government expenditure.

Table 1: Parameters for US and EA calibrations

Symbol	Description	US value/target	EA value/target
	Household sector and labour markets		
β	Time discount factor	0.995	0.998
b	Internal habit formation	0.7	0.62
η	Inverse Frisch labour elasticity	1	2
χ	Labour disutility scaling parameter	$L = 1$	$L = 1$
ϵ_w	Elasticity of substitution for labour types	11	1.3/0.3
ϕ_w	One minus probability to reset wage	0.75	0.78
γ_w	Wage indexation	0	0.37
	Production sector and price rigidity		
α	Physical capital share	0.33	0.36
δ_0	Steady-state capital depreciation rate	0.025	0.025
δ_1	Capital utilisation linear term	$u = 1$	$u = 1$
δ_2	Capital utilisation quadratic term	0.01	0.01
κ_I	Investment adjustment cost parameter	2	2
Π	Steady-state gross inflation	1	1
ϵ_p	Elasticity of substitution for intermediate goods	11	1.35/0.35
ϕ_p	One minus probability to reset price	0.75	0.82
γ_p	Price indexation	0	0.23
ρ_A	AR(1) persistence of productivity shocks	0.95	0.92
s_A	Volatility of productivity shocks	0.0065	0.007
	Fiscal authority		
$\bar{b}_G$	Steady-state government debt	$B_G Q_B/(4Y) = 0.41$	$B_G Q_B/(4Y) = 0.80$
G	Steady-state government spending	$G/Y = 0.2$	$G/Y = 0.204$
ρ_G	AR(1) persistence of government spending shocks	0.95	0.95
s_G	Volatility of government spending shocks	0.01	0.0035
	Financial sector and central bank		
κ	Coupon decay parameter	$1 - 40^{-1}$	$1 - 40^{-1}$
ψ	Fraction of investment financed by debt	0.81	0.50
σ	Financial intermediary survival probability	0.95	0.95
θ	General absconding rate	$400(R^F - R) = 3$	$400(R^F - R) = 3$
X	New financial intermediary start-up fund	Leverage = 4	Leverage = 4.6
Δ	Public bond relative absconding rate	1/3	2/3
ρ_t	AR(1) persistence of liquidity shocks	0.98	0.98
s_t	Volatility of liquidity shocks	0.04	0.04
ρ_r	Interest rate smoothing in Taylor rule	0.8	0.93
ϕ_π	Inflation gap parameter in Taylor rule	1.5	2.74
ϕ_y	Output gap parameter in Taylor rule	0.25	0.10
s_r	Volatility of monetary policy shocks	0	0
b_{cb}	Steady-state CB holdings of public bonds	0.06	0.1733
f_{cb}	Steady-state CB holdings of private bonds	0	0.0382
ρ_b	AR(1) persistence of public bond QE	0.8	0.8
ρ_f	AR(1) persistence of private bond QE	0.8	0.8

Notes: This table reports the parameters used in the calibration for the economy of the euro area. The original calibration of Sims and Wu (2021) is reproduced in column 3 to ensure comparability of our calibration to theirs.

As for the parameters borrowed from Coenen et al. (2018), we choose a slightly higher time discount factor of $\beta = 0.998$, a slightly lower habit formation parameter of $b = 0.62$,

Table 2: Empirical EA moments and simulated moments for US and EA calibrations

Moment	Description	EA data	EA model	US model
$\sigma(dy)$	Output growth volatility	0.60	0.62	0.73
$\sigma(dc)$	Consumption growth volatility	0.37	0.25	0.24
$\sigma(di)$	Investment growth volatility	2.33	2.77	3.40
$\sigma(dL)$	Labour growth volatility	0.95	0.65	0.67
$\sigma(\pi)^*$	Inflation rate volatility	0.92	0.40	0.79
$\sigma(R_t^F - R_{t-1}^D)^*$	Private bond spread volatility	0.67	1.02	1.35
$\sigma(R_t^B - R_{t-1}^D)^*$	Public bond spread volatility	1.10	0.76	0.95
$\sigma(R_t^F - R_t^B)^*$	Private to public bond spread volatility	0.71	0.28	0.45
$\sigma(dc)/\sigma(dy)$	Relative consumption growth volatility	0.61	0.40	0.33
$\sigma(di)/\sigma(dy)$	Relative investment growth volatility	3.86	4.47	4.64
$\sigma(dL)/\sigma(dy)$	Relative labour growth volatility	1.57	1.05	0.92
$\sigma(\pi)^*/\sigma(dy)^*$	Relative inflation rate volatility	1.53	0.21	0.30
$\sigma(R_t^F - R_{t-1}^D)/\sigma(dy)$	Relative private bond spread volatility	1.11	0.56	0.48
$\sigma(R_t^B - R_{t-1}^D)/\sigma(dy)$	Relative public bond spread volatility	1.81	0.39	0.33
$\sigma(R_t^F - R_t^B)/\sigma(dy)$	Relative public to private bond spread volatility	1.17	0.20	0.17
$\text{corr}(dc, dy)$	Consumption and output growth correlation	0.70	0.23	0.16
$\text{corr}(di, dy)$	Investment and output growth correlation	0.45	0.97	0.95
$\text{corr}(dL, dy)$	Labour and output growth correlation	0.27	0.31	0.50
$\text{corr}(\pi, dy)$	Inflation rate and output growth correlation	-0.12	-0.15	-0.06
$\text{corr}(R_t^F - R_{t-1}^D, dy)$	Private bond spread and output growth correlation	-0.24	-0.32	-0.28
$\text{corr}(R_t^B - R_{t-1}^D, dy)$	Public bond spread and output growth correlation	-0.16	-0.23	-0.12
$\text{corr}(R_t^F - R_t^B, dy)$	Private to public bond spread and output growth correlation	0.02	-0.51	-0.57
$\mathbb{E}[(fQ)/(4Y)]$	Average private debt to GDP ratio	104.64	104.64	168.38
$\mathbb{E}[R_t^F - R_{t-1}^D]$	Average private bond spread	3.07	2.98	2.96
$\mathbb{E}[R_t^B - R_{t-1}^D]$	Average public bond spread	2.38	1.99	0.99
$\mathbb{E}[\text{leverage}]$	Average financial sector leverage	4.66	4.59	3.99
$\mathbb{E}[(b_G Q_B)/(4Y)]$	Average government debt to GDP ratio	79.10	79.99	41.00
$\sigma(dG)$	Government spending growth volatility	0.32	0.36	1.01
$\mathbb{E}[\pi]$	Average inflation rate	1.72	0.00	0.00
$\mathbb{E}[I/Y]$	Average investment to GDP ratio	21.02	21.70	20.79
$\mathbb{E}[C/Y]$	Average consumption to GDP ratio	55.24	57.90	59.20
$\mathbb{E}[G/Y]$	Average government spending to GDP ratio	20.41	20.41	20.01
$\mathbb{E}[T_{cb}/(4Y)]$	Average central bank profits to GDP ratio	0.01	0.11	0.01
$\mathbb{E}[(F_{cb}Q)/(4Y)]$	Average central bank's private bond holdings to GDP ratio	3.82	3.82	0.00
$\mathbb{E}[(B_{cb}Q_B)/(4Y)]$	Average central bank's public bond holdings to GDP ratio	17.33	17.33	6.00

Notes: This table reports the empirical moments for the euro area, the simulated moments of the euro area calibrated model, and the moments using the original calibration of Sims and Wu (2021). The empirical moments for the euro area are computed using the time period ranging from the first quarter of 1999 to the fourth quarter of 2019 (at least when available for the whole time period) with two exceptions – private and public bond holdings by the central bank as fractions of GDP – for which the utilised time period is from the first quarter of 2018 to the fourth quarter of 2019. The model moments are obtained by using first order perturbation methods in `dynare 4.5.4` for 100000 quarters. Unless otherwise noted by an asterisk next to the moment, volatilities and correlations are reported as quarterly moments and expectations as annual moments. If there is an asterisk next to a volatility, annual volatilities are reported.

and a slightly higher share of physical capital in production $\alpha = 0.36$. In line with less flexible labour supply dynamics in the EA, as compared to the US, the inverse

Frisch labour elasticity is chosen to be 2 instead of 1. Due to the ECB having a single mandate but the Federal Reserve being obliged to a dual mandate, a larger focus is placed on fighting inflation in the Taylor rule, i.e. $\phi_\pi = 2.74$ instead of $\phi_\pi = 1.5$, and a smaller focus on the output gap, i.e. $\phi_y = 0.10$ instead of $\phi_y = 0.25$. The interest rate smoothing parameter is also higher in the EA calibration, i.e. $\rho_r = 0.93$ instead of $\rho_r = 0.8$.[10] The largest changes to the parameters are, however, made to the wage and price rigidity calibration. There is now both wage indexation ($\gamma_w = 0.37$)[11] and price indexation ($\gamma_p = 0.23$)[12], slightly lower probabilities of being allowed to re-optimise the wage ($\phi_w = 0.78$) or to re-optimise the price ($\phi_p = 0.82$), and at the same time lower elasticities of substitution (i.e. higher mark-ups) for labour unions ($\epsilon_w = 1.3/0.3$ or a wage mark-up of $\epsilon_w/(\epsilon_w - 1) = 1.3$) and intermediate goods producers ($\epsilon_p = 1.35/0.35$ or a price mark-up of $\epsilon_p/(\epsilon_p - 1) = 1.35$). As in Sims and Wu (2021), we assume the absence of exogenous monetary policy shocks ($s_r = 0$) to produce the simulated moments.

In order to match the empirical volatilities of macroeconomic variables in EA data in the best possible manner, we change some shock standard deviations. Specifically, the standard deviation of productivity shocks s_A is increased to 0.007 for the EA calibration and the standard deviation of government spending shocks s_G decreased to 0.0035, while the standard deviation of liquidity shocks s_t remains unchanged.

Closely inspecting Table 2, the model does a decent job in replicating the key macroeconomic and financial moments of the euro area. Quarterly output and government spending growth volatilities are essentially exactly matched due to the appropriate choices for the exogenous shock standard deviations. The values for consumption growth volatility, investment growth volatility, and labour growth volatility are also close to their empirical counterparts. Inflation rate volatility is less than a half in the model relative to the data. The return spread volatilities are close in magnitude to the data, but there is higher private bond spread volatility in the model, as compared to public bond spread volatility, which is contrary to the data, and the private to public bond spread volatility is only about a third of the data-implied value. Only the correlations between labour growth and output growth, between the inflation rate and output growth, and between the private (public) bond spreads and output growth are close to the empirical counterparts, while there is too little (much) correlation produced between consumption (investment) growth and output growth in the model. The correlation between the private to public bond return and output growth is completely at odds in the model with a value of -0.51,

[10] Note that the Taylor rule in Coenen et al. (2018) features two more terms: a term for adjusting the policy rate in response to a change in inflation and a term for adjusting the policy rate in response to a change in the output gap. We thus just choose a Taylor rule and its calibration similar to theirs.

[11] Their value for wage indexation to inflation is chosen.

[12] Since the NAWM II model features several goods with several Calvo-style price rigidity calibrations, we have chosen to take their values for the price rigidity with respect to domestic prices for our calibration.

relative to the noticeable absence of any correlation in the data. As discussed previously, the model fails to produce any positive average inflation, which is visible in the data however. Thus, the average interest rate on reserves and its volatility are too low. The shares of investment, consumption, and government spending to GDP are on average matched perfectly, while the model produces 11 times higher profits for the central bank than the data would allow for, but it is still negligible on aggregate.

6 Scenario Results

In this section, we utilise the Sims and Wu (2021) model to produce predictions for the economic effects of QT shocks, i.e. a reduction of the central bank's balance sheet, in the EA. We analyse the predictions the model delivers in Sections 6.1 (US model with original calibration[13] of Sims and Wu, 2021) and 6.2 (EA model after re-calibration of the model, as summarised in Table 1). We will compare the model-based predictions with the empirical evidence obtained in Section 4.

6.1 Economic effects of QT shocks in the US

In this section, we utilise the original calibration of Sims and Wu (2021) since their model is calibrated to the US economy already and does a good job in matching both macroeconomic and financial dynamics. However, we re-calibrate the steady-state balance sheet, as their original calibration corresponds to the period before QE and thus features no private bond holdings on the Federal Reserve's balance sheet and only 6% of GDP of public bond holdings. We will perform two scenarios (see Figures 6 and 7). In the first one, the central bank holds 20.9% of GDP in public bonds and 12.4% of GDP in private bonds, while in the second scenario the central bank holds 8.5% of GDP in public bonds and 10.3% in private bonds. These figures correspond to the Federal Reserve's balance sheet average between the second quarter of 2020 and the first quarter of 2022 and between the first quarter of 2018 and the fourth quarter of 2019, respectively. Therefore, in the first scenario the central bank's balance sheet corresponds to the holdings during and just after the COVID-19 pandemic and in the second scenario to the holdings just before the COVID-19 pandemic. From these numbers, note that the US has accumulated much more public bonds during the pandemic QE period than in the QE period during and after the Great Recession.

[13]Since we will look at QT shocks and not QE shocks like in their original paper, the initial state will not be the beginning of QE after the Global Financial Crisis, where the balance sheet of the Federal Reserve was different, but – depending on the scenario we analyse – equal to the Federal Reserve's balance sheet just before the COVID-19 pandemic (the fourth quarter of 2019) or just after the COVID-19 pandemic (the first quarter of 2022). Thus, the bond holdings of the central bank will be chosen differently from the original calibration. For the original calibration of Sims and Wu (2021), see Table 1 where it is reproduced to ensure comparability of our EA calibration to theirs.

In the first scenario, we assume the economy's steady state is the first quarter of 2022 and we feed the economy with a series of inflationary positive government spending and negative total factor productivity (TFP) shocks from period 1 onward in order to make the economy experience a high-inflation regime. In the data, this regime results from the resurgence of economic activity after the lifting of pandemic restrictions and the negative effects that rippled through the world economy resulting from Russia's war against Ukraine from February 2022 onward. Due to the normalisation of monetary policy that has started in 2022, a switch from QE to QT was also announced and implemented. Therefore, we feed in QT shocks as the third type of shocks in these scenarios. For the baseline scenario, we normalise the QT shocks to induce a *permanent* reduction of the central bank's balance sheet of 13.5 percentage points (as a fraction of GDP), which corresponds roughly to the increase in the total balance sheet during the pandemic, over 20 quarters, with the balance sheet reduction evenly split across these quarters, and from period 5, which corresponds to the first quarter of 2023, onward.[14]

We vary the details of these QT shocks across the size, the speed, and the start date dimensions. Regarding different sizes (Panel A in the figures in this section and the next one), we also analyse a larger QT programme, i.e. 1.5 times the size of the baseline QT programme, and a smaller QT programme, i.e. half the size of the baseline QT scenario. Regarding different speeds (Panel B), we look at a fast QT programme, i.e. only 12 quarters are used to achieve the reduction of 13.5 pps, and at a slow QT where 28 quarters are used to achieve the same reduction. Regarding different start dates of the QT shocks (Panel C), we study a slightly delayed start of QT, i.e. from period 9 or the first quarter of 2024 onward, and a significantly delayed start of QT, i.e. from period 13 or the first quarter of 2025 onward.

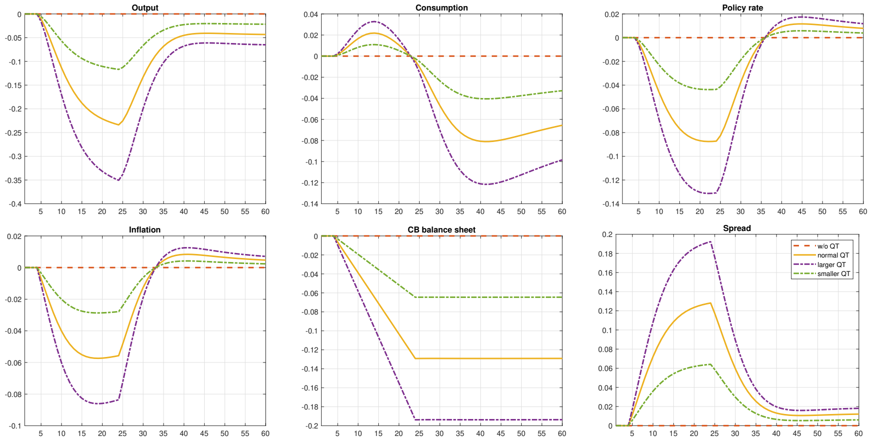
Moreover, in all scenarios, the reduction is implemented proportionally to the shares of private and public bonds on the balance sheet. For the US, the share of public (private) bonds is 62.76% (37.24%) after the pandemic.

Since all impulse response functions are expressed relative to the scenario without any QT shocks (i.e. only inflationary negative TFP shocks and positive government spending shocks), we can directly read off the effect QT shocks have on the economy from the graphs. All scenarios induce persistent, yet temporary effects on macroeconomic quantities. Only the central bank balance sheet is permanently reduced due to the QT shocks at the end due to assuming that the QT shocks are of permanent nature. Looking at the baseline QT scenario (yellow solid lines in all panels), QT implies a reduction in output, a decline in consumption over the longer run, lower inflation for up to 30 quarters and then mildly higher inflation afterwards relative to the baseline scenario without QT, but also higher private bond return spreads with a peak around quarter 25. Interestingly,

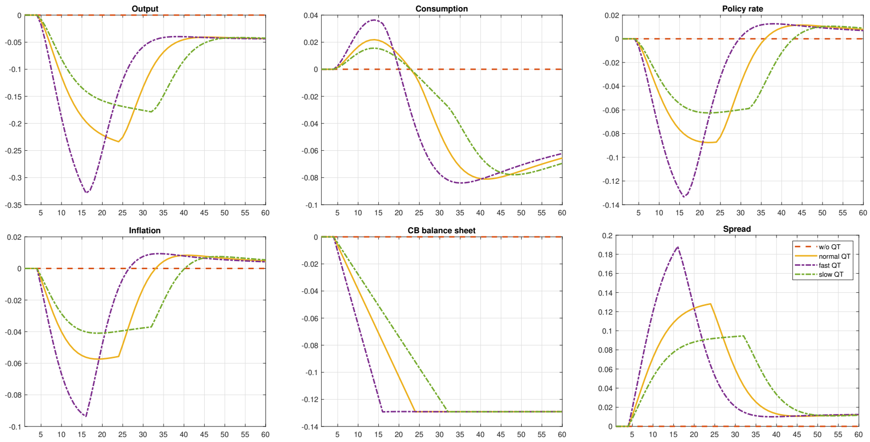
[14] As a technical remark, the permanent reduction of the central bank's balance sheet is achieved by setting the persistence parameter in the process of central bank holdings to a value of 1.

Figure 6: Inflationary shocks + QT – US model

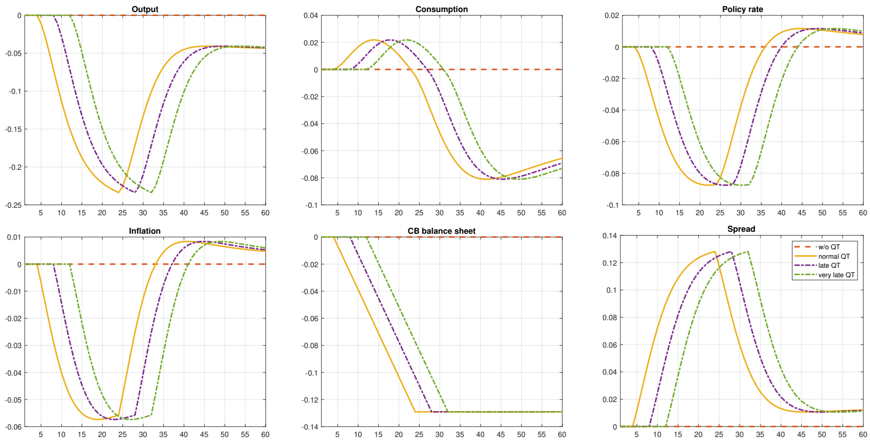
Panel A: Different QT sizes



Panel B: Different QT speeds



Panel C: Different QT start date



Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 5–24 and applied proportionally according to the central bank's steady-state private and public bonds holdings (62.76% of the balance sheet reduction pertain to public bonds and 37.24% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

there is an interaction between conventional monetary policy and the implementation of QT. Thus, the conventional monetary policy rate does not have to be increased as much as in the baseline scenario without QT, while still observing lower inflation rates in the economy. In quarter 24, when the divergence in the policy rate with and without QT shocks is the highest, the policy rate is around 8 basis points lower with QT. Therefore, QT can partly serve as a substitute to conventional monetary policy rate hikes. Due to the significantly higher private bond return spread that originates from lower liquidity in the market due to the central bank's asset sales, the output is lower with QT shocks, up to around 0.25 pps in quarter 24, which puts a price tag on QT implementation. Given the high benefits of QE during times of a binding ZLB, this price tag seems mild though. The huge balance sheets of central banks should be reduced at times of conventional monetary policy being able to take over the main tasks of the central bank. In this way, policy space can be built up for the future use of QE, when it is needed again.

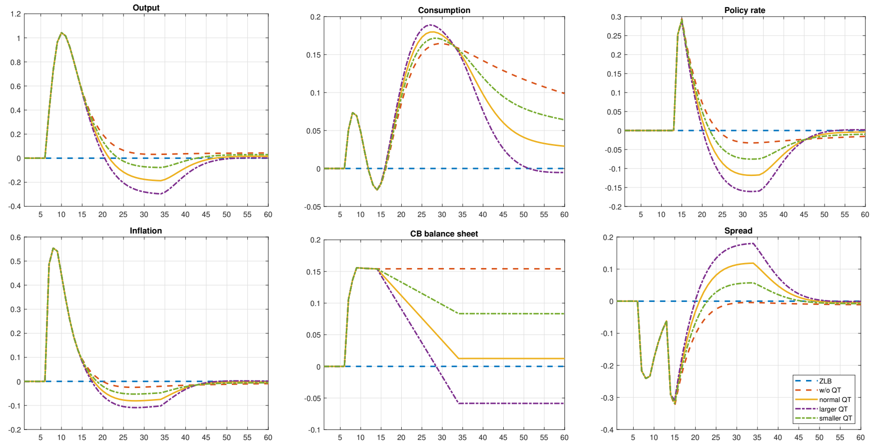
Due to the model being solved at first order[15], the different size scenarios (see Panel A of Figure 6 of 50% larger QT shocks and 50% smaller QT shocks translate one-to-one to 50% larger and smaller economic effects. The different QT speeds scenarios are more interesting to study (Panel B). Faster QT increases the magnitude of effects in the short run, while reducing the longer-run effects, and vice versa for slower QT implementation. Thus, the output decrease is more pronounced but less long-lived, while the spread increases much more in the short run and reverts back to steady-state levels earlier. The policy rate differential also becomes bigger during the fast QT implementation but converges back to the baseline scenario levels earlier. Since one of the main concerns against using QT is the reaction of financial market returns which could lead to financial instability, our results indicate that calibrating speed and size carefully is paramount to smooth the reactions of the private return spreads to a level and persistence that does not raise stability concerns on financial markets at any time. The scenarios that study different QT start dates (Panel C) do not reveal any major insights as the impulse response functions are just shifted to later dates. However, to build up unconventional policy space, one should not delay QT forever, as the ELB might get binding earlier than foreseeable. One should keep in mind that the model is linearised, implying that these results might ignore important non-linearities. Specifically, QT is probably less costly, the higher the conventional monetary policy rate is.

The second set of results, depicted in Figure 7, assumes a steady state for the central bank balance sheet consistent with pre-pandemic figures and simulates first a series of liquidity shocks that leads to a binding ZLB. Then, several exogenous QE shocks are fed in that approximately reproduce the observed balance sheet dynamics of the Federal Reserve during the pandemic, followed by QT shocks that are the same as in the previous

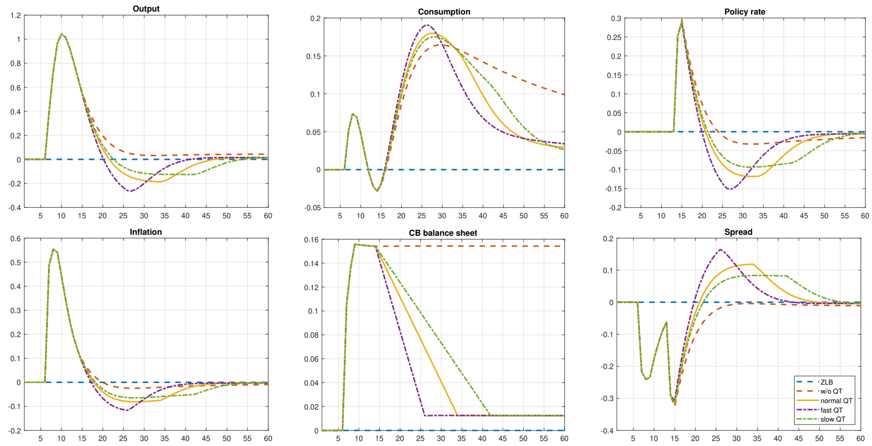
[15]Since the ZLB is not binding at any time, the model is fully linearised, and using the Occbin toolbox by Guerrieri and Iacoviello (2015) – which we do – does not matter.

Figure 7: Liquidity shocks + QE + QT – US model

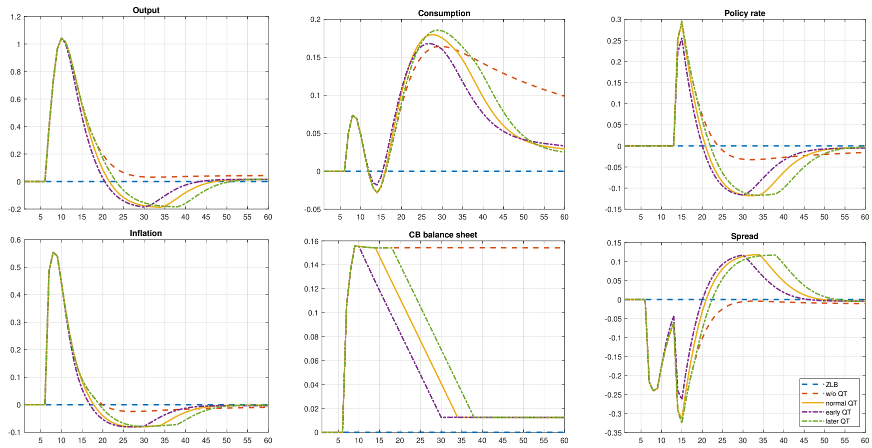
Panel A: Different QT sizes



Panel B: Different QT speeds



Panel C: Different QT start date



Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of liquidity and QE shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The liquidity shocks happen in quarters 1–6 with size $1.5s_t$ each. In periods 7–9, QE shocks are fed in to replicate the Federal Reserve's increase in bond holdings during the COVID-19 pandemic. The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 15–35 and applied proportionally according to the central bank's steady-state private and public bonds holdings (62.76% of the balance sheet reduction pertain to public bonds and 37.24% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

set of results. Note that there is a small difference in the set of different QT start date scenarios, as the baseline scenario starts in quarter 15, but there is also an early QT scenario that starts in quarter 11 and a late QT scenario that starts in quarter 19. Thus, the baseline scenario is not the earliest QT scenario anymore, but rather in the middle of the two other QT start date scenarios. Again, only the incremental effects on variables by unconventional monetary policy are shown, i.e. the effects of QE and QT shocks. Note that both QE and QT shocks are assumed to be *permanent* by assuming a persistence parameter of 1 in the central bank bond holding processes.

We first analyse the effects of QE which naturally resemble the insights obtained by Sims and Wu (2021) and other studies on the topic. QE leads to higher output, somewhat higher consumption, higher inflation, and lower private bond return spreads during the ZLB period, all relative to the no QE and no QT baseline scenario (i.e. the effects of only liquidity shocks). If one would not implement QT after QE (see the red dashed lines in Figure 7), output would be consistently higher than in the different QT scenarios and private bond return spreads lower and never above steady-state levels. These positive effects from not implementing QT come at the cost of higher inflation, somewhat lower consumption in the medium run between quarters 15 and 30, and a larger central bank balance sheet, i.e. less policy space for unconventional monetary policy.

Therefore, as the second observation from this analysis, the effects of QT after the QE period are similar to what we find above in Figure 6. Output is reduced by QT, spreads are increased, but inflation is reduced. Additionally, the considerable gain in policy space comes at a mild cost: output is reduced by 0.2 pps at the peak in the baseline QT scenario (yellow solid lines) where 0.2 pps can be read off by comparing the yellow solid line to the red dashed line, the spread increases by up to 10 bps, and inflation is reduced by about 5 bps.

The different size scenarios (Panel A) yield again the insight that effects scale one-to-one in magnitude with the QT programme size, while different choices for the speed of QT (Panel B) allow the central bank to control the distribution of the economic effects of these shocks over time (larger/smaller effects in the short run vs. smaller/larger effects in the long run). The different QT start date scenarios (Panel C) become interesting to discuss in these cases, as running an inflated central bank balance sheet for a longer time implies more persistent inflationary effects from the QE period while allowing for higher output levels over a longer period. Delaying QT induces that the private bond return spreads stay lower for longer, but imply that the total distance between the lowest observed spread (around quarter 15 for all QT start date scenarios) and the highest observed spread (around quarter 40 in the 'later QT' scenario) is the largest. This could be considered worrisome by financial market participants.

These results are in line with our empirical findings where we also find a GDP decline and an increase in spreads in response to tightening shocks.

As an additional exercise in the model, we let conventional monetary policy be as inactive as possible without compromising the stability of the model (i.e. we set the inflation coefficient in the Taylor rule to 1.001 and the output gap coefficient to 0). We then compute the impulse responses to the same sequence of shocks. These results are summarised in Appendix H, Figures H.1 and H.2. This is done to see what QT without conventional monetary policy can achieve.[16] This variation in the model provides some noteworthy observations. For the scenarios with inflationary shocks followed by QT, we find, first, that the effects of QT become bigger for output with the additional loss of output in the baseline QT scenario reaching almost 0.3 pps (vs. around 0.23 pps with a normal Taylor rule specification). Second, there are lower effects for the policy rate and inflation in the shorter run but larger effects in the longer run. Essentially, the short-run effects are exactly offset by the long-run effects now as inflation decreases as much in the short run as it increases in the long run. This finding is in line with the findings by Airaudo (2023), who finds little effect on inflation in a fiscally-led regime where the monetary authority does not strongly fight inflation. Third, the spread increases a bit less and even slightly decreases in the long run with QT. The same observations on the effects of QT shocks can be made also in the scenarios where liquidity shocks are followed by QE and QT shocks. In essence, since conventional monetary policy is rather inactive, there is less interaction between these two monetary policy instruments and QT becomes less effective as a consequence. Therefore, using two monetary policy tools contemporaneously with one being QT and one being interest rate policy yields benefits.

6.2 Economic effects of QT shocks in the EA

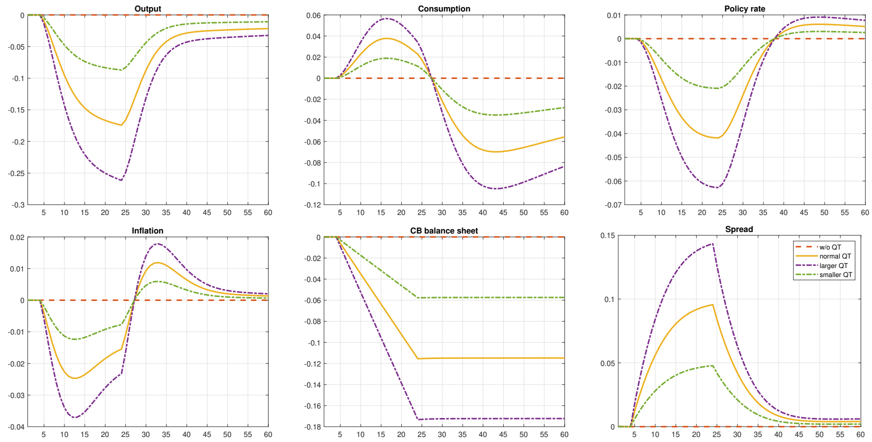
To analyse the potential effects of QT in the EA, we make use of the discussed re-calibration of the Sims and Wu (2021) model. The scenarios, depicted in Figures 8 and 9, are very similar to the two scenarios we have analysed in the previous section for the US. The steady-state balance sheets of the central bank, however, correspond to the ECB's holdings. The ECB has accumulated much more public bonds and very few private bonds during the periods of QE in both the last decade and during the COVID-19 pandemic. The public bond holdings correspond to 17.3% (of GDP) and the private bond holdings to 3.8% on average for the period ranging from the first quarter of 2018 to the fourth quarter of 2019, i.e. the pre-pandemic period. During the COVID-19 pandemic, additional bonds were accumulated and thus these numbers increase to 26.8% and 5.2%, respectively, for the period ranging from the second quarter of 2020 to the first quarter of 2022.

The QT scenarios are calibrated to induce a reduction of 11.5 pps over their run,

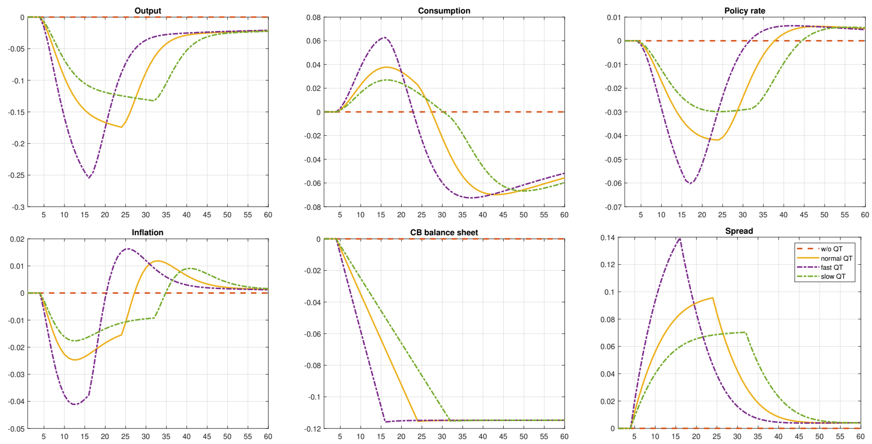
[16] The Taylor rule is not fully inactive though. Conventional monetary policy is still operational, but it does relatively little to fight inflation. Since inflation weights in the Taylor rule below 1 violate the Taylor principle and compromise the model's stability, this policy is as close as possible to an inactive monetary policy.

Figure 8: Inflationary shocks + QT – EA model

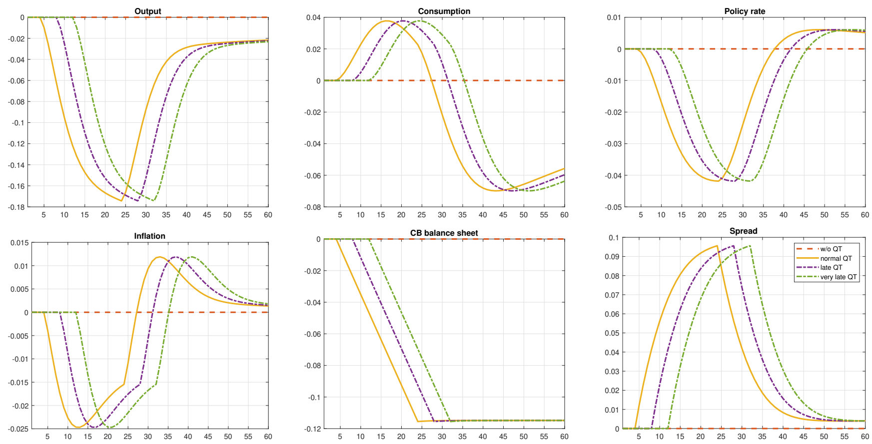
Panel A: Different QT sizes



Panel B: Different QT speeds



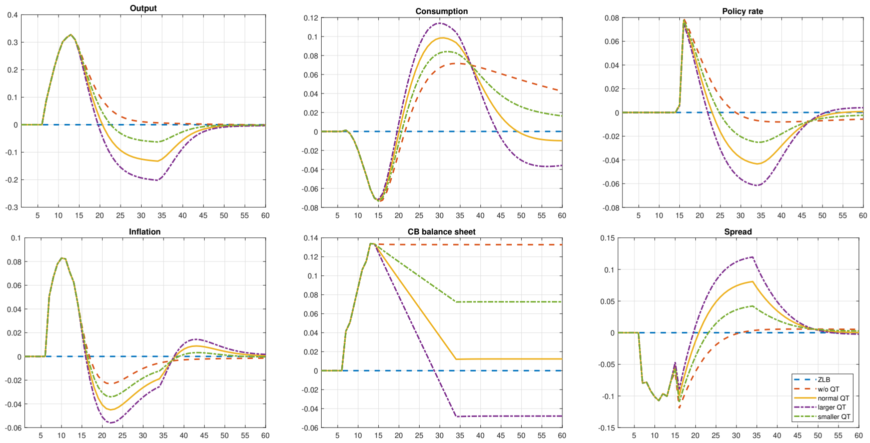
Panel C: Different QT start date



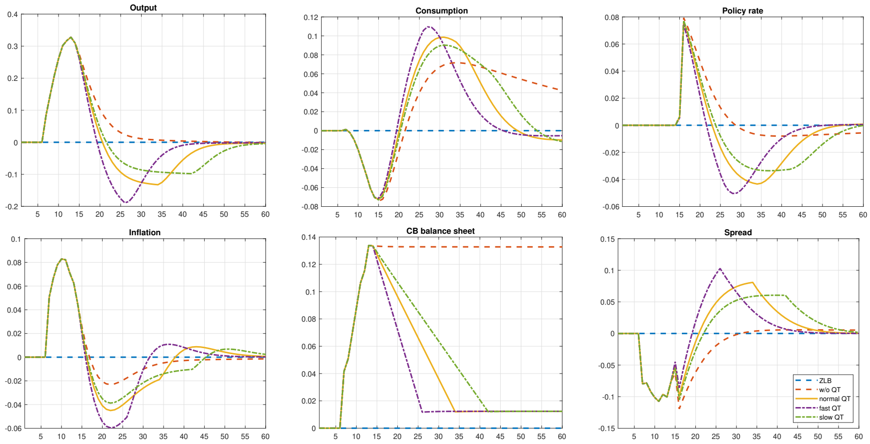
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the EA model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 11.5 pps (as % of GDP), evenly split over quarters 5–24 and applied proportionally according to the central bank's steady-state private and public bonds holdings (83.75% of the balance sheet reduction pertain to public bonds and 16.25% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

Figure 9: Liquidity shocks + QE + QT – EA model

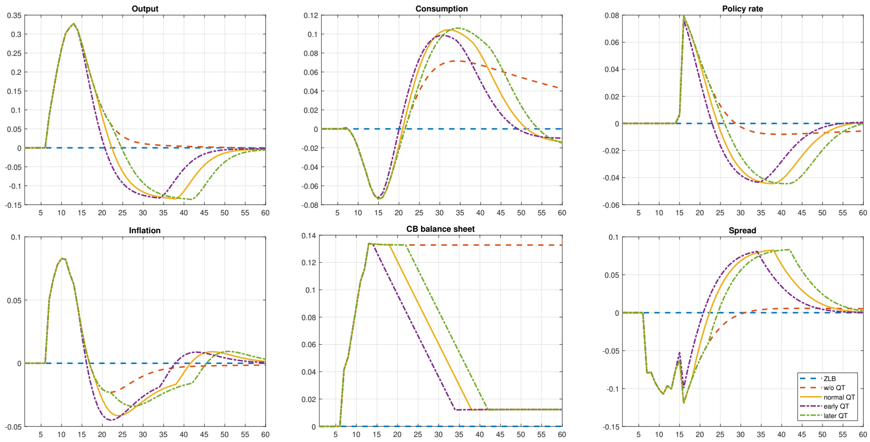
Panel A: Different QT sizes



Panel B: Different QT speeds



Panel C: Different QT start date



Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of liquidity and QE shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The liquidity shocks happen in quarters 1–6 with size $1.5s_t$ each. In periods 7–13, QE shocks are fed in to replicate the ECB's increase in bond holdings during the COVID-19 pandemic. The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 19–35 and applied proportionally according to the central bank's steady-state private and public bonds holdings (83.75% of the balance sheet reduction pertain to public bonds and 16.25% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

corresponding to the increase in the ECB's balance sheet during the pandemic. Moreover, due to the larger share of public bonds, the proportionality assumption in these scenarios implies that the bond sales are split in the following way: 83.75% of the total reduction each quarter is applied to public bonds and only 16.25% to private bonds. Note that this is a significantly smaller share of QT applied to private bonds in the EA scenarios, as compared to the US scenarios of the last section. Most other details in the different scenarios are the same. There are two additional differences. In the second set of results, QT starts four quarters later, since the ECB has started to do QT later than the Federal Reserve. Moreover, it has increased its balance sheet during the pandemic for a longer period than the US (i.e. the period with QE shocks is not only three quarters but seven quarters in the EA scenarios).

Studying the impulse response functions in Figures 8 and 9 and comparing them to the impulse response functions in Figures 6 and 7 reveals that QT shocks in the EA induce smaller effects. There is a lower relative output loss and a smaller increase in spreads. This can be explained by noting that the share of private bonds is much smaller on the ECB's balance sheet. The observed differences in consumption and inflation dynamics, and consequently in the dynamics of the policy rate, are also partly due to the differences in the calibrations of the US and EA model. Studying unreported simulations in which the steady-state values of the EA model's central bank balance sheet and the same QT scenario as in the EA model is used in the US calibration of the model, reveals that the responses of output and spread are essentially the same as in the EA model (Figure 8), while some quantitative differences in consumption, inflation, and policy rate dynamics persist, which are due to different structural parameters related to the price and wage rigidities and the financial sector. Thus, the effects in the model are less pronounced, as public bonds carry a lower risk premium and thus affect the liquidity of financial intermediaries to a smaller extent. Even though public bonds have a larger risk premium in the EA than observed in the US, this argument still explains the observed smaller effect of QT shocks. In reality, the transmission mechanism of central bank sales of private or public bonds might be more involved, as spillover effects from lower yields on public bonds to private bond yields may occur, for example. In the model, such a spillover mechanism is absent and the effect of reduced impact of QT in the EA, relative to the US, is essentially a mechanic consequence of how the model works and how it is calibrated.[17] Moreover, the heterogeneity of public bond yields in the EA is not taken into account by the model. There is basically no effect on inflation from QT shocks. This is not only due to a smaller share of public bonds sold in the QT programmes, but also due to the conventional monetary policy calibration in the model that fights inflation much more aggressively than the original US Taylor rule calibration of Sims and Wu (2021). As in

[17]In the data and thus the calibration, public bonds have lower yields, as compared to private bonds.

the previous section, when QT follows QE, the same observations can be made.

The results are also in line again with our empirical results. Although being insignificant there, the output reaction in the data is somewhat negative, and this is present in the model. Similar observations hold for financial return spreads. The empirical results predict an inflation decrease (though highly statistically insignificant) for the EA. Given our model results that predict a much more muted inflation response to QT shocks, we can provide a structural explanation for this empirical finding. The single mandate of the ECB that makes the ECB's conventional monetary policy more reactive to the inflation dynamics in comparison to the Federal Reserve's Taylor rule and its dual mandate might thus be behind the less significant finding for the EA.

In Appendix H, Figures H.3 and H.4, we also repeat the additional exercise with a muted Taylor rule for the EA model. The insights from this exercise are again similar to what we have discussed for the US model. The differential effects of QT shocks are also smaller there due to the higher share of public bonds on the central bank's balance sheet.

Additionally, Figures H.5 and H.6 depict a variation of the QT scenarios for both the US model and the EA model. In particular, the benchmark QT scenario now entails reducing the balance sheet of the central bank in both the US and the EA by 5% and by exclusively selling private bonds.[18] In this way, the implementation of QT is the same in both the US and the EA and any quantitative differences across the graphs in these two figures must result from differences in the calibrations of the US and the EA model. We find that the effects of QT in the EA are still significantly smaller in the EA than in the US. Using additional unreported simulations, this can be traced back mostly to one difference in the calibration of the models: the choice of Δ. In the US version, the relative absconding rate of public bonds is set to $\Delta = 1/3$; while in the EA version, this parameter is chosen to be $\Delta = 2/3$ due to higher sovereign bond risk premia in the EA. If one sets $\Delta = 1/3$ in the EA model version and keeps all other parameter differences intact, the quantitative differences in Figures H.5 and H.6 essentially disappear. Therefore, the difference in the return spreads of public and private bonds to deposits plays a key role in determining the magnitude of the effects of QT in the model. The larger the difference, the larger the effect on private bond spreads, output, and inflation triggered by selling (private) bonds from the central bank's balance sheet due to a larger portfolio composition effect, as it is harder to adjust to a smaller balance sheet when private bonds are sold that are relatively riskier in one model calibration than in the other.

[18] We do not compute different size scenarios for this exercise but keep the familiar variations regarding speed and timing of QT in Panels A and B.

7 Conclusion

After roughly a decade of monetary policy implemented mostly via quantitative easing programmes in both the US and the EA, the high inflation has prompted the Federal Reserve System and the European Central Bank to implement a series of monetary policy rate hikes which they complement with quantitative tightening. For the ECB it is the first experience with QT in history, while the Federal Reserve already engaged in a balance sheet wind-down between 2017 and 2019.

In this study, we contribute to the understanding of the macroeconomic effects of QT by employing both an empirical framework (proxy-SVAR) and a structural framework (medium-scale NK DSGE); particularly, because the implications of QT for the EA are difficult to estimate empirically due to the lack of QT episodes in EA data and also because this allows us to see whether the empirical predictions hold in the model and to shed additional light on the economic channels involved.

Our empirical findings suggest that QT has a smaller impact on the economy than QE, thereby providing evidence of asymmetric effects of QT compared to QE. These findings are corroborated by our model-based simulations. They suggest that QT as a stand-alone policy is not able to stabilise inflation. Nevertheless, QT can partly substitute conventional rate hikes by creating some deflationary pressure and requiring less aggressive conventional policy action. For the EA, the effects are found to be even smaller and surrounded by substantial statistical uncertainty due to the lack of QT episodes in EA data. The effects of QT in model-based simulations for the EA are found to be smaller due to the larger share of public bonds on the balance sheet of the ECB, as compared to the Federal Reserve's balance sheet.

We also find evidence in line with the existing literature that balance sheet reductions lead to a sizeable widening of spreads on financial markets. Thus, for the ECB it might be advisable to reduce its balance sheet in a moderate fashion to minimise the risks of fragmentation in EA sovereign yield spreads. In case of disorderly market dynamics, we find that market-stabilisation QE is able to effectively stabilise sovereign spreads without creating sizeable inflationary pressure.

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A Identification via HFI + Narrative Sign Restrictions

The identification of the QE shock series in the euro area largely follows the approach described in Zlobins (2022), i.e. by augmenting the high frequency identification approach with narrative sign restrictions of Antolín-Díaz and Rubio-Ramírez (2018) which allows for capturing multiple monetary policy shocks in policy announcements. However, in this paper we further extend the approach to also accommodate the identification of the market-stabilisation QE shock in the spirit of Motto and Özen (2022).

In the first step, we gather high frequency reactions of the risk-free yield curve and stock prices around the ECB policy announcements from the Euro Area Monetary Policy Event-Study Database (EA-MPD) of Altavilla et al. (2019). We use the press release window surprises for conventional policy shocks and press conference window reactions for all unconventional policy innovations. Then we include high frequency surprises into the VAR and ensure that they do not depend on their own lags:

$$m_t = a_0 + \sum_{j=1}^{p} 0 \, m_{t-j} + \epsilon_t, \tag{A.1}$$

where m_t are the high frequency reactions of the 3-month, 1-year, and 10-year OIS rates, the 10-year Italian bond yield and the Eurostoxx 50 stock price index to ECB policy announcements (both in the press release and press conference windows). Our choice of these particular OIS maturities is motivated by the evidence from Altavilla et al. (2019) and Rostagno et al. (2021) showing that each instrument targets a specific region of the yield curve. For instance, QE predominantly loads on the back-end of the term structure, while forward guidance (FG) loads on medium-term maturities. Regarding the negative interest rate policy (NIRP), we assume that it has the largest impact on short-term rates, similar to conventional policy. However, instead of the press release, it primarily operates in the press conference window, given the resemblance to an FG-type shock. The 10-year Italian yield is included to capture the effects of market-stabilisation QE (MS-QE) instruments, aimed to minimise the fragmentation risk in the EA sovereign bond markets, such as the Outright Monetary Transactions (OMT), Securities Market Programme (SMP), one dimension of the Pandemic Emergecy Purchase Programme (PEPP), and the recently announced Transmission Protection Instrument (TPI). The VAR is estimated on a monthly basis from January 2002 to March 2021 with standard Bayesian techniques by specifying an independent Normal-Wishart prior.[19]

In the second step, we apply a set of traditional sign restrictions, summarised in Table A.1. All restrictions are imposed to hold on impact only. The identification of the market-stabilisation QE shock largely follows Motto and Özen (2022) who show that this type of

[19] We set the AR coefficient of the prior to 0, overall tightness to λ_1=0.1, cross-variable weighting to $\lambda_2 = 0.5$, the lag decay to $\lambda_3 = 1$, and block exogeneity shrinkage to λ_5=0.001.

shock moves periphery-country yields in opposite direction to risk-free and core-country yields. In addition to the identification of conventional and unconventional monetary policy disturbances, we also control for the effects of information shocks following the logic put forth in Jarociński and Karadi (2020) by assuming that the release of central bank information during policy announcements entails a positive co-movement between interest rates and stock prices.

Table A.1: Set of traditional sign restrictions used to distinguish monetary policy instruments

Shock	3-month OIS (press release)	3-month OIS (press conference)	1-year OIS	10-year OIS	10-year IT	Euro Stoxx 50
CMP	−					+
NIRP		−				+
FG			−			+
QE				−	−	+
MS-QE				+	−	+
Information		−	−	−		−

Notes: This table summarises the traditional sign restrictions used for the identification of monetary policy disturbances.

However, given that policy shocks of Odyssean nature induced by different monetary policy tools move surprises in the same direction, pure sign restrictions alone are insufficient to clearly distinguish the effects of multiple monetary policy instruments. Mechanical orthogonalisation via zero restrictions, on the other hand, would be too restrictive as the ECB has often announced and/or recalibrated several instruments in its toolkit during the same meeting of the Governing Council. Hence, we augment traditional sign restrictions with narrative information about the respective shocks, using the approach of Antolín-Díaz and Rubio-Ramírez (2018), which allows for implementing narrative information by placing restrictions on the structural disturbances and historical decompositions in addition to sign restrictions on the impulse response functions and structural parameters, sharpening the inference. In particular, we supplement our identification strategy with the following narrative information to tell apart the effects of different monetary policy measures:

- **Narrative Sign Restriction I.** *An expansionary conventional monetary policy (CMP) shock took place in November 2011.*

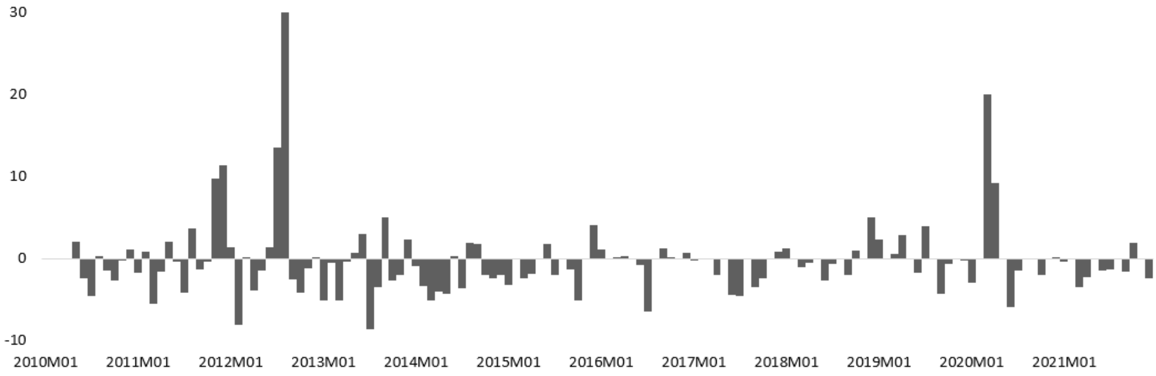
- **Narrative Sign Restriction II.** *For November 2011, the CMP shock was the overwhelming driver of the unexpected movement in the 3-month OIS (press release window).*

- **Narrative Sign Restriction III.** *An expansionary NIRP shock took place in June 2014.*
- **Narrative Sign Restriction IV.** *For June 2014, the NIRP shock was the overwhelming driver of the unexpected movement in the 3-month OIS (press conference window).*
- **Narrative Sign Restriction V.** *An expansionary FG shock took place in July 2013.*
- **Narrative Sign Restriction VI.** *For July 2013, the FG shock was the overwhelming driver of the unexpected movement in the 1-year OIS.*
- **Narrative Sign Restriction VII.** *An expansionary QE shock took place in January 2015.*
- **Narrative Sign Restriction VIII.** *For January 2015, the QE shock was the overwhelming driver of the unexpected movement in the 10-year OIS.*
- **Narrative Sign Restriction IX.** *An expansionary market-stabilisation QE shock took place in September 2012.*
- **Narrative Sign Restriction X.** *For September 2012, the market-stabilisation QE shock was the overwhelming driver of the unexpected movement in the 10-year Italian yield.*

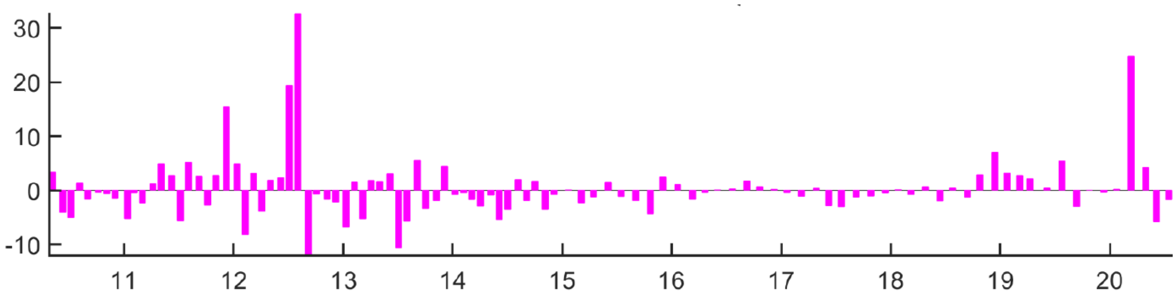
To sum up, for each of the five monetary policy shocks we identify, we restrict both the sign of the structural disturbance as well as the historical decomposition of the corresponding maturity surprise on which the respective instrument primarily loads. For the NIRP, FG, and QE shocks, the choice of dates is straightforward as the selected Governing Council meetings are the ones in which the respective instruments were first officially announced. For the MS-QE, however, the date is motivated by the evidence in Motto and Özen (2022) who show that the largest expansionary realisation of the shock took place in September 2012 when the ECB announced details of the OMT programme. Figure A.1 demonstrates that the MS-QE shock, obtained with our approach, is broadly consistent with the one of Motto and Özen (2022). Finally, our choice of the specific date for the CMP shock is motivated by the largest recorded easing surprise in the 3-month OIS rate (in the press release window) in the considered sample period and the fact that this conventional policy action was the last one before the ECB switched to a mix of unconventional policy tools, aiding the identification.

Figure A.1: Market-stabilisation QE shock series

Panel A: Market-stabilisation QE shock obtained via HFI + narrative sign restrictions



Panel B: Market-stabilisation QE shock of Motto and Özen (2022)

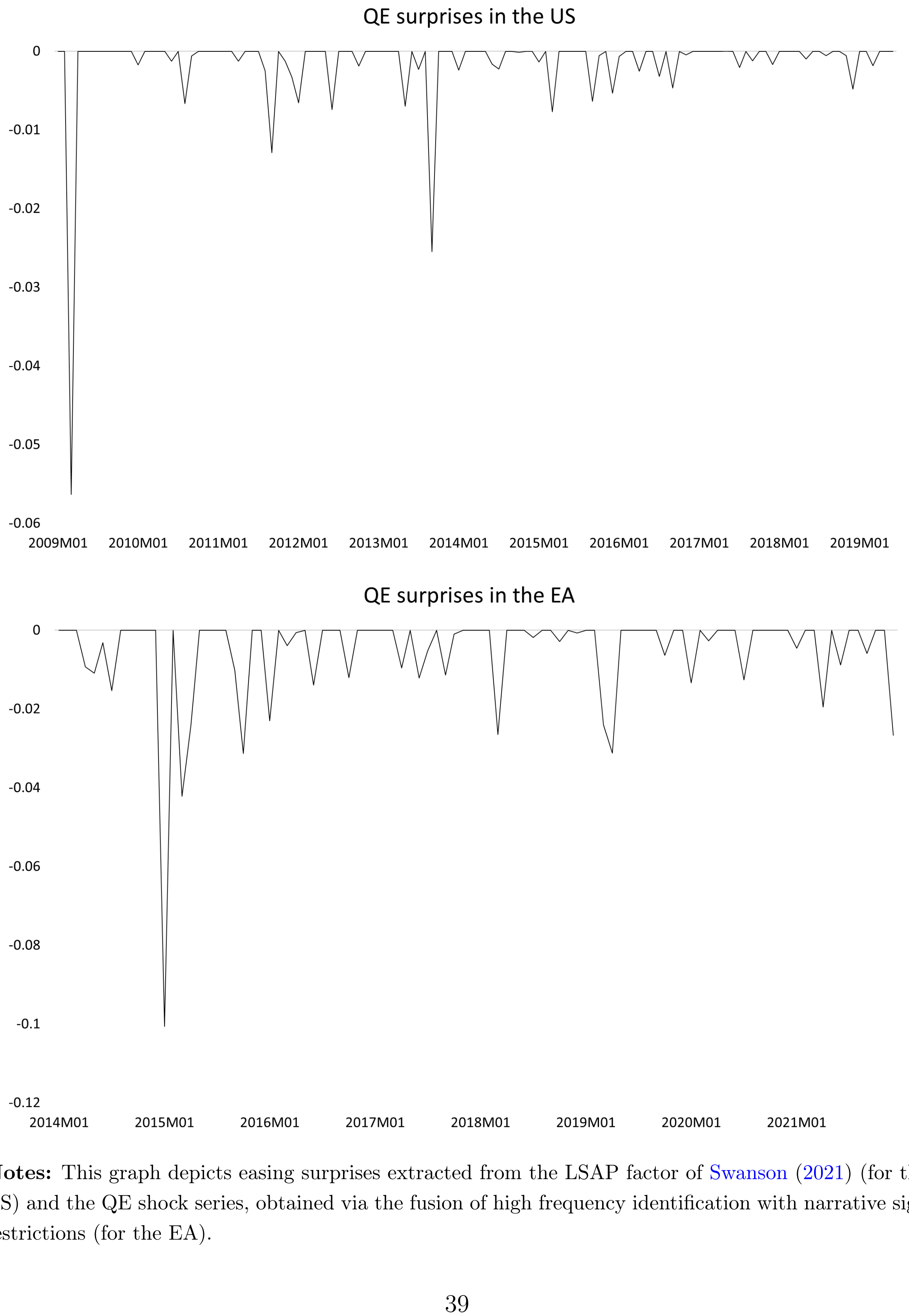


Notes: This figure depicts the time series for the market-stabilisation QE shock obtained via HFI and narrative sign restrictions in Panel A and from Motto and Özen (2022) in Panel B.

B Extracted Easing Surprises

Figure B.1 in this appendix depicts the easing surprises extracted from the LSAP factor and the QE shock series.

Figure B.1: QE surprises



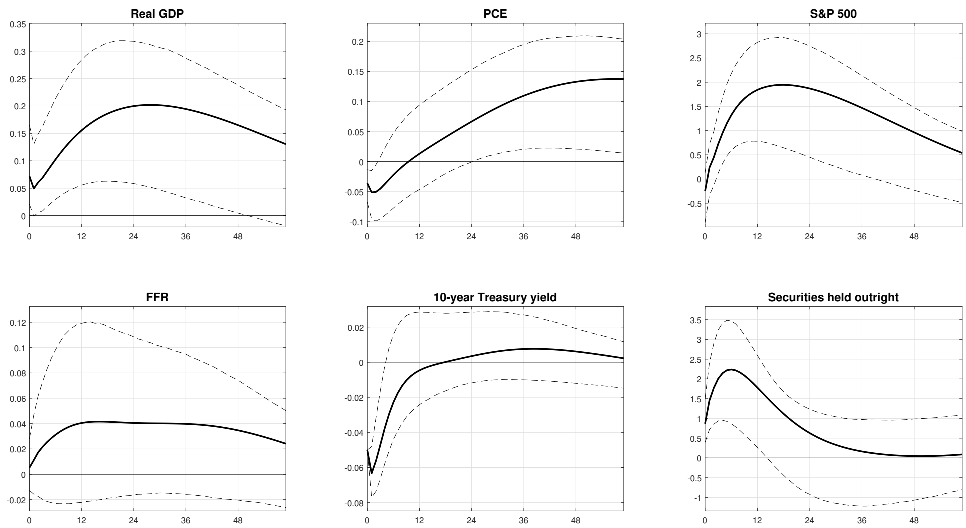
Notes: This graph depicts easing surprises extracted from the LSAP factor of Swanson (2021) (for the US) and the QE shock series, obtained via the fusion of high frequency identification with narrative sign restrictions (for the EA).

C Impulse Responses to the Original Shock Series

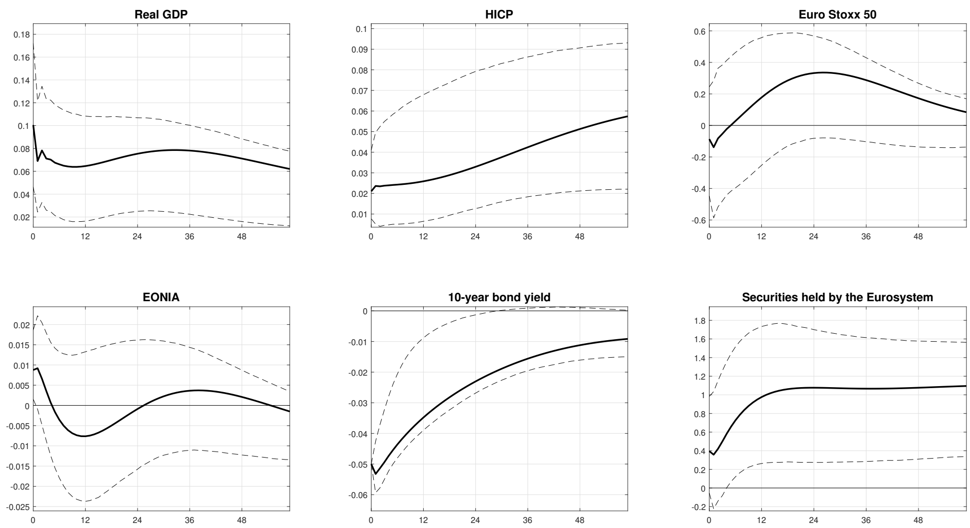
In this appendix, we report the impulse responses to the original shock series, i.e. without splitting them into easing and tightening reactions, in order to compare our results with the estimates reported in the existing literature.

Figure C.1: Results using the raw shock series

(a) Results for the US



(b) Results for the EA



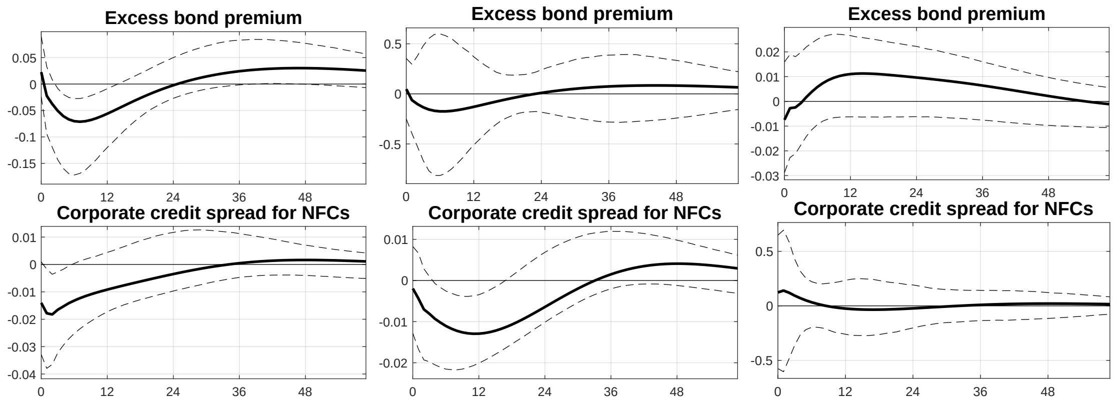
Notes: This figure depicts impulse response functions to the original LSAP factor of Swanson (2021) for the US and the QE shock series for the EA from a proxy-SVAR. The shock series have been used as an external instrument for the 10-year bond yield with the first stage regression ran on the instrument over the sample from January 2009 to June 2019 for the US and from January 2014 to December 2021 for the EA. The shock has been normalised to generate a 5 bps decrease in the 10-year yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

D Impulse responses of private sector credit spreads

In this appendix, we show the reaction of corporate bond spreads to the QE/QT innovations. For the US, we use the excess bond premium of Gilchrist and Zakrajsek (2012), while for the EA – corporate credit spreads for non-financial corporations as constructed by Gilchrist and Mojon (2018).

Figure D.1: Results for the corporate spreads

(a) Original shock series **(b)** Easing surprises **(c)** Tightening surprises

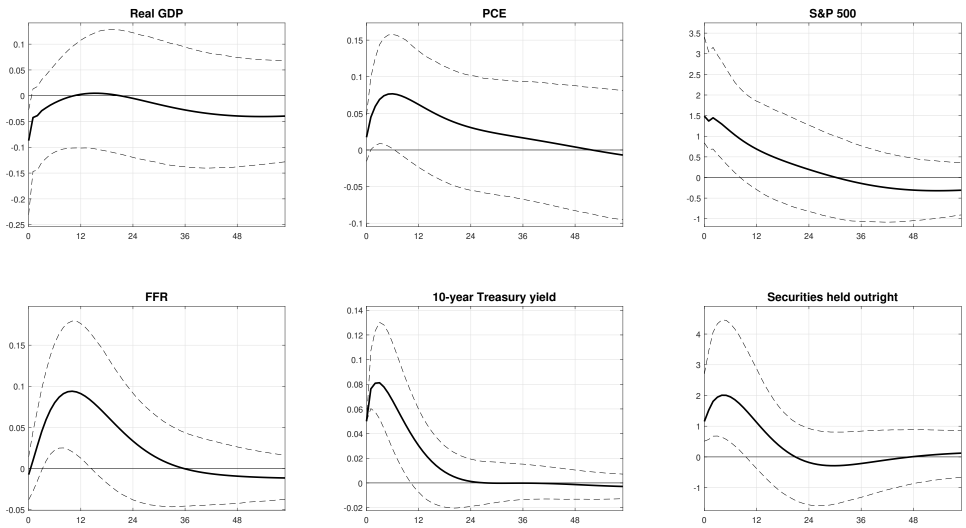


Notes: This figure depicts impulse response functions of the US and EA corporate credit spreads to the QE/QT shocks. Easing/tightening surprises extracted from the LSAP factor of Swanson (2021) and the QE shock series have been used as an external instrument for the 10-year bond yield with the first stage regression ran on the instrument over the sample from January 2009 to June 2019 for the US and from January 2014 to December 2021 for the EA. The shock has been normalised to generate a 5 bps decrease in the 10-year yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

E Results for the US without the Taper Tantrum

In this appendix, we depict the impulse response functions to the tightening surprises, from which the observation during the taper tantrum in June 2013 has been removed from the series.

Figure E.1: Impulse response functions to tightening surprises



Notes: This figure depicts impulse response functions to the QT shock from a proxy-SVAR. Tightening surprises extracted from the LSAP factor of Swanson (2021) have been used as an external instrument for the 10-year Treasury yield with the first stage regression ran on the instrument over the sample from January 2009 to June 2019, with the exception of June 2013. The shock has been normalised to generate a 5 bps decrease/increase in the 10-year yield. The dashed region depicts the 90% confidence interval obtained via the Wild bootstrap.

F Data Details for the Proxy-SVAR Model

In this appendix, we describe the data used in the estimation of the proxy-SVAR model. All variables enter the model as log-levels $\times$ 100, except those expressed as percentages which enter the model without transformation.

US macroeconomic variables

1. Real GDP – real gross domestic product, billions of chained 2012 dollars, seasonally adjusted data. Monthly series are obtained by performing the Litterman temporal disaggregation procedure using the industrial production index as indicator series, from FRED.

2. PCE – personal consumption expenditures, chain-type price index, 2012=100, seasonally adjusted data, from FRED.

3. S&P 500 – stock price index, from FRED.

4. FFR – federal funds effective rate, from FRED.

5. 10-year Treasury yield – market yield on US Treasury securities at 10-year constant maturity, quoted on an investment basis, from FRED.

6. Securities held outright – the amount of securities held by Federal Reserve Banks, from FRED.

7. EBP – excess bond premium of Gilchrist and Zakrajsek (2012). Downloaded from https://www.federalreserve.gov/econresdata/notes/feds-notes/2016/files/ebp_csv.csv.

Euro area macroeconomic variables

1. Real GDP – real gross domestic product, chain linked volumes index, 2015=100, seasonally adjusted data. Monthly series are obtained by performing the Litterman temporal disaggregation procedure using the industrial production index as indicator series, from Eurostat.

2. HICP – all-items HICP price index, 2015=100, seasonally adjusted data, from ECB.

3. Euro Stoxx 50 – Dow Jones Euro Stoxx 50 stock price index, from ECB.

4. EONIA – money market interest rate, from Eurostat.

5. 10-year bond yield – 10-year government benchmark bond yield (for the aggregate euro area), EMU convergence criterion bond yields (for Germany and Italy), from ECB and Eurostat.

6. Securities held by the Eurosystem – securities of euro area residents denominated in euro held by the Eurosystem, from ECB.

7. Corporate credit spread for NFCs - credit spreads of non-financial corporations in the euro area as constructed by Gilchrist and Mojon (2018). Downloaded from https://publications.banque-france.fr/sites/default/files/media/2022/10/07/gm_ea_credit_risk_indicators.xlsx

G Data Details for the Calibration of the DSGE Model

In this appendix, we describe the data utilised for the re-calibration of the model to the euro area economy.

Macroeconomic variables All macroeconomic growth rates dx are calculated by computing the quarterly log growth rate using the following data:

1. real GDP Y – "gross domestic product at market prices";
2. consumption C – "household and NPISH final consumption expenditure";
3. investment I – "gross fixed capital formation".

All these variables are measured using chain linked volumes (2015), millions of euro, seasonally and calendar adjusted data, euro area – 19 countries (from 2015) and have been downloaded from Eurostat. The ratios I/Y and C/Y are computed using the same data.

Labour growth dL is the quarterly log growth rate of labour hours L, which is identified in the data by "index of total actual hours worked in the main job by sex and age group ($2021 = 100$), seasonally adjusted data, not calendar adjusted data, from 20 to 64 years", which is only available from the first quarter of 2009 onward though from Eurostat.

Inflation π is given by the monthly data series "harmonised index of consumer prices (HICP) - all items, measured by growth rate on previous period (t/t-1), neither seasonally adjusted nor calendar adjusted data, euro area – 19 countries (from 2015)", from Eurostat.

Fiscal data Government consumption growth dG is the quarterly log growth rate of "final consumption expenditure of general government" from Eurostat, measured by chain linked volumes (2015), million euro, seasonally and calendar adjusted data, euro area – 19 countries (from 2015). The ratio G/Y is computed using the just described data and the output data described in the previous paragraph.

The debt to annualised GDP ratio $b_G Q_B/(4Y)$ is identified by using the annual time series "government consolidated gross debt, general government, percentage of gross domestic product (GDP), euro area – 19 countries (from 2015)" from Eurostat between 1999 and 2019.

Financial time series The deposit interest rate R^D_{t-1} is identified in the data by using the monthly time series "euro area (changing composition), annualised agreed rate (AAR)/narrowly defined effective rate (NDER), credit and other institutions (MFI except MMFs and central banks) reporting sector – Overnight deposits, total original maturity, new business coverage, non-financial corporations and households (S.11 and S.14 and

S.15) sector, denominated in euro", available at the ECB Statistical Data Warehouse, only from 2003:M1 onward though.

The private bond interest rate R_t^F is identified in the data by using the monthly time series "euro area (changing composition), annualised agreed rate (AAR) / narrowly defined effective rate (NDER), credit and other institutions (MFI except MMFs and central banks) reporting sector – loans, total original maturity, outstanding amount business coverage, non-financial corporations (S.11) sector, denominated in euro", available at the ECB Statistical Data Warehouse, only from 2003:M1 onward though.

The private bond interest rate R_t^B is identified in the data by using the monthly time series "long term government bond yields – Maastricht definition (average), neither seasonally adjusted nor calendar adjusted data, euro area (EA11–1999, EA12–2001, EA13–2007, EA15–2008, EA16–2009, EA17–2011, EA18–2014, EA19–2015)", available at the ECB Statistical Data Warehouse.

The private debt to annualised GDP ratio $(fQ)/(4Y)$ is computed using quarterly data for nominal GDP Y, i.e. "gross domestic product at market prices, current prices, millions of euro, seasonally and calendar adjusted data, euro area – 19 countries (from 2015)", from Eurostat and quarterly data on "euro area (changing composition), outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector – loans, total maturity, all currencies combined – domestic (home or reference area) counterpart, non-MFI sector, denominated in euro, data neither seasonally nor working day adjusted, end of period (E), millions of euro" from the ECB Statistical Data Warehouse.

Leverage of financial intermediaries is computed as the weighted average leverage ratio of MFI and non-MFI leverage using quarterly data from Eurostat on "Financial balance sheets".

Central bank data The central bank transfer to the fiscal sector as a ratio to annualised GDP $T_{cb}/(4Y)$ is identified by using the ECB's reported profits from the annual reports, available on the ECB's websites[20] for the period 1999–2019, and then divided by nominal quarterly GDP times 4.

The stocks of private bonds $F_{cb}Q$ and public bonds $B_{cb}Q_B$ on the central bank balance sheet are computed using data on "History of cumulative net purchases under the APP" available at https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html from 2014:M10 onward. The stocks are constructed by computing the cumulative sum of these purchases. Public bonds are the purchases made within the "public sector purchase programme" under the APP, while private bonds are the purchases within the "asset-backed securities purchase programme", the "covered bond purchase programme 3", and the "corporate sector purchase programme" under the APP. Public and private bond

[20]See, for example, https://www.ecb.europa.eu/pub/annual/html/index.en.html for the annual report of 2022.

purchases under the PEPP are added from 2020:M3 onward as well to the central bank stocks of public and private bonds. These stocks are then divided by nominal quarterly GDP times 4 to obtain the ratios of these central bank's bond holdings to (annualised) GDP.

H Additional Figures

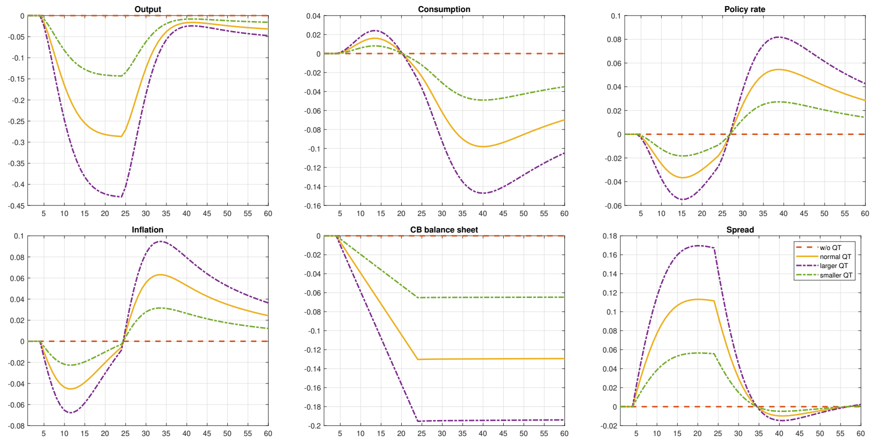
This appendix contains additional impulse response functions for a model variation that mutes as much as possible the reaction of the central bank to economic developments without compromising the stability of the model. Specifically, the Taylor rule is re-calibrated to feature no reaction to the output gap $\phi_y = 0$ and a weakened reaction to the inflation gap $\phi_\pi = 1.001$ in all simulations below.

Otherwise, Figures H.1–H.4 correspond exactly to the scenarios depicted in Figures 6–9.

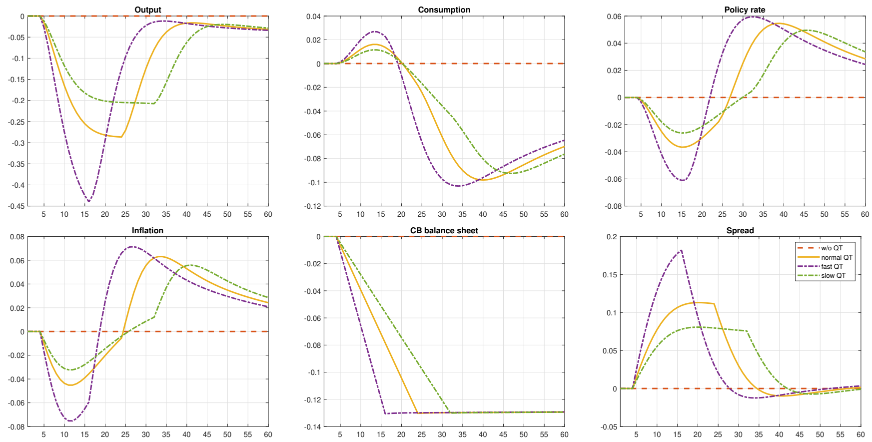
Moreover, Figures H.5 and H.6 depict modified QT scenarios, utilising the original calibrations, where QT is implemented exclusively by selling private bonds, and the size of the balance sheet reduction is the same in both the US model and the EA model (i.e. the magnitude of the balance sheet reduction equals 5 pps as % of the respective region's GDP).

Figure H.1: Inflationary shocks + QT – US model (muted Taylor rule)

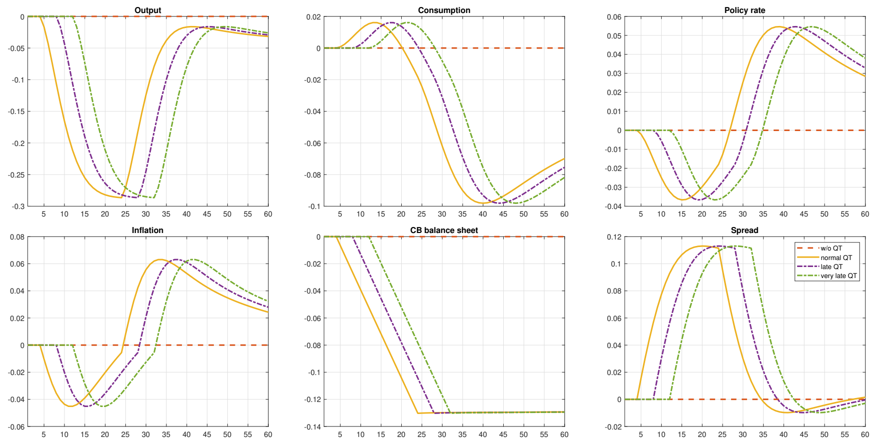
Panel A: Different QT sizes



Panel B: Different QT speeds



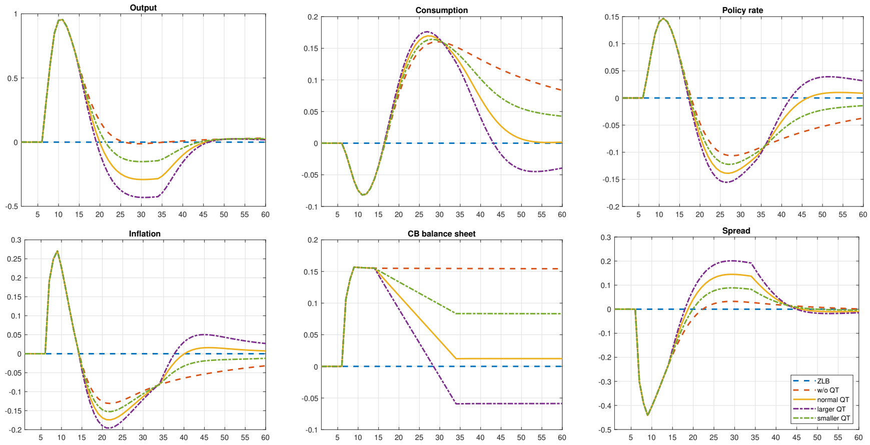
Panel C: Different QT start date



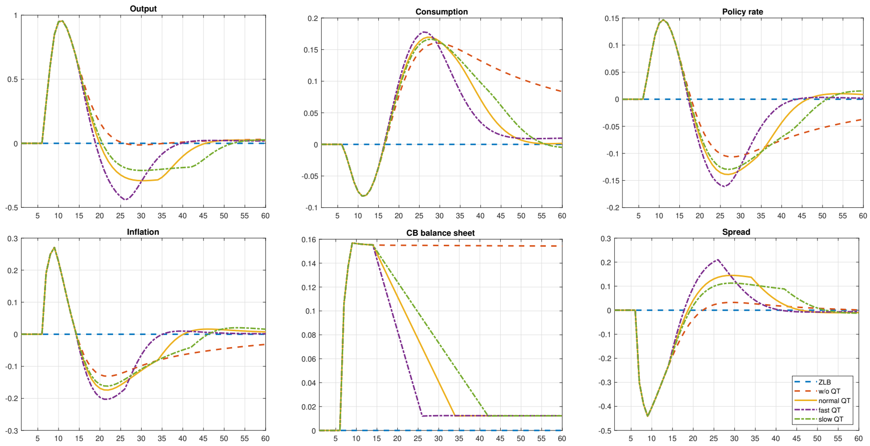
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 5–24 and applied proportionally according to the central bank's steady-state private and public bonds holdings (62.76% of the balance sheet reduction pertain to public bonds and 37.24% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

Figure H.2: Liquidity shocks + QE + QT – US model (muted Taylor rule)

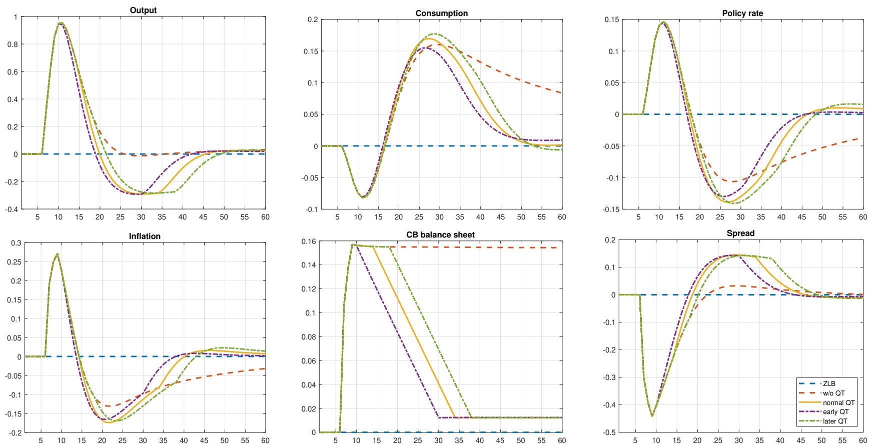
Panel A: Different QT sizes



Panel B: Different QT speeds



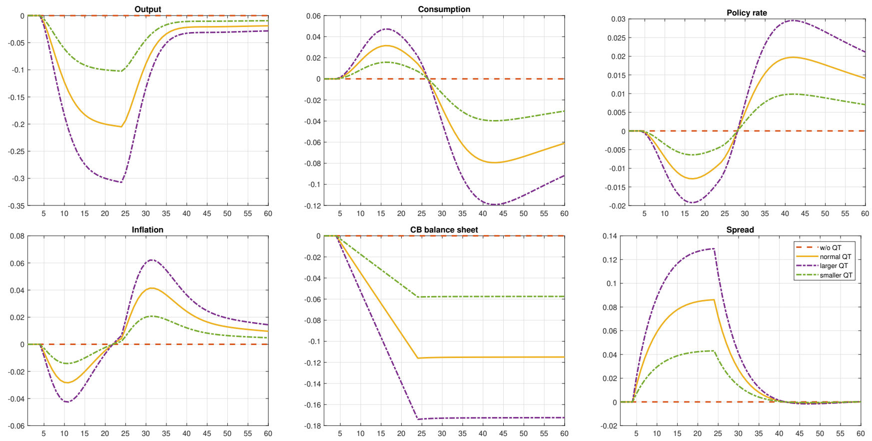
Panel C: Different QT start date



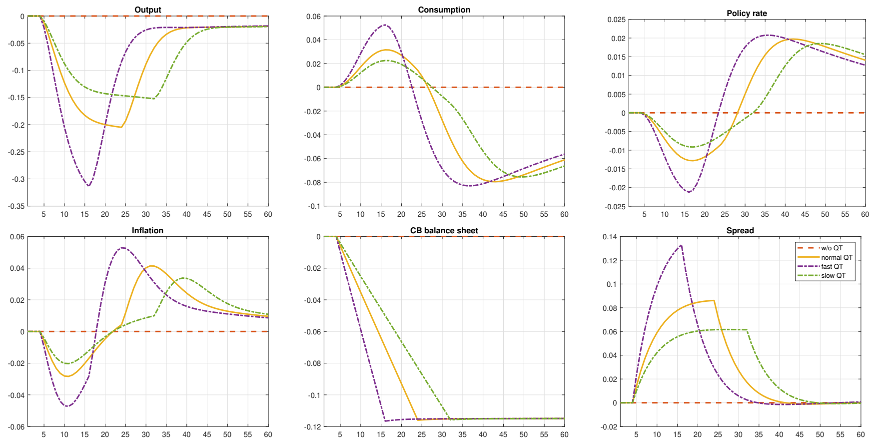
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of liquidity and QE shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The liquidity shocks happen in quarters 1–6 with size $1.5s_t$ each. In periods 7–9, QE shocks are fed in to replicate the Federal Reserve's increase of bond holdings during the COVID-19 pandemic. The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 15–35 and applied proportionally according to the central bank's steady-state private and public bonds holdings (62.76% of the balance sheet reduction pertain to public bonds and 37.24% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

Figure H.3: Inflationary shocks + QT – EA model (muted Taylor rule)

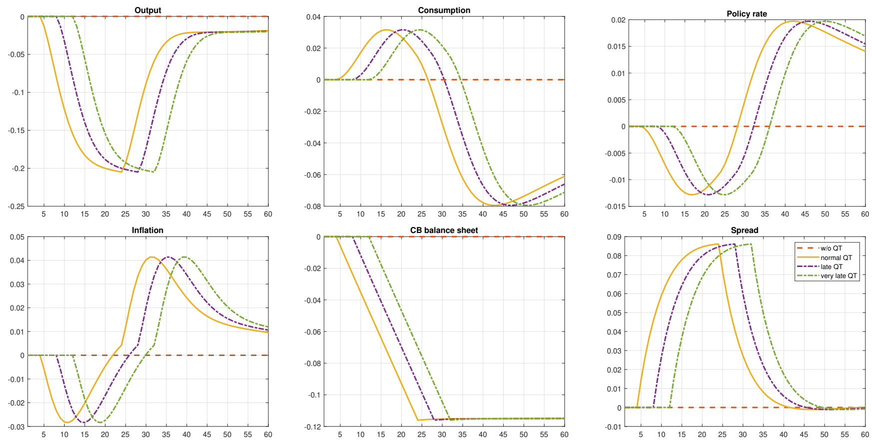
Panel A: Different QT sizes



Panel B: Different QT speeds



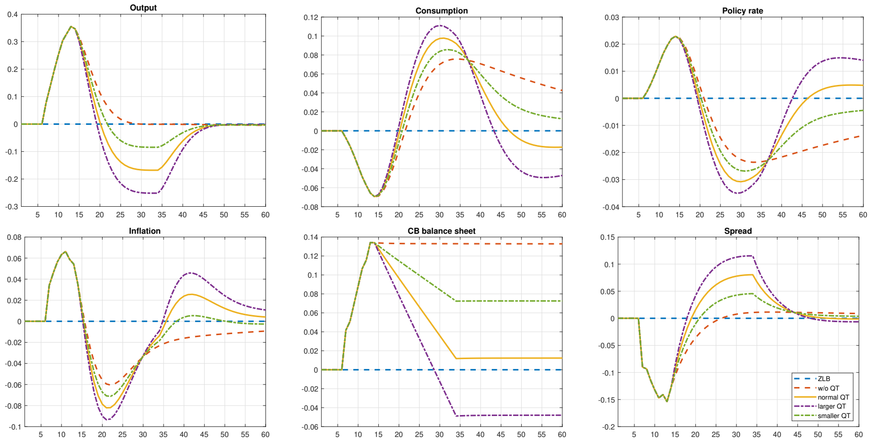
Panel C: Different QT start date



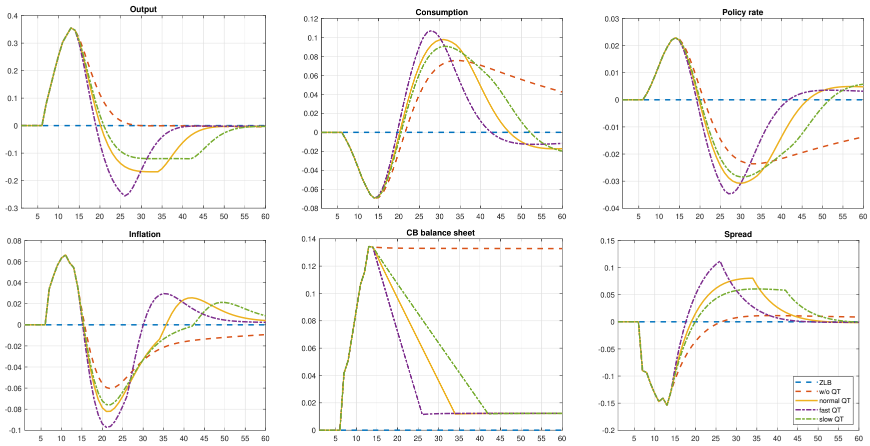
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the EA model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 11.5 pps (as % of GDP), evenly split over quarters 5–24 and applied proportionally according to the central bank's steady-state private and public bonds holdings (83.75% of the balance sheet reduction pertain to public bonds and 16.25% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

Figure H.4: Liquidity shocks + QE + QT – EA model (muted Taylor rule)

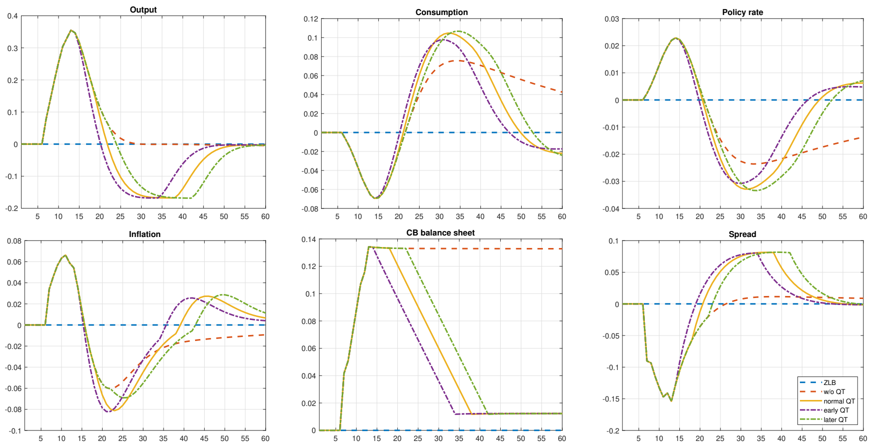
Panel A: Different QT sizes



Panel B: Different QT speeds



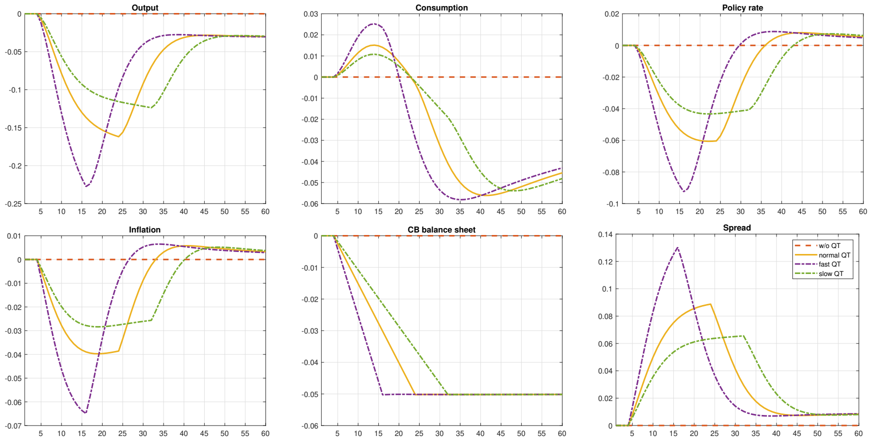
Panel C: Different QT start date



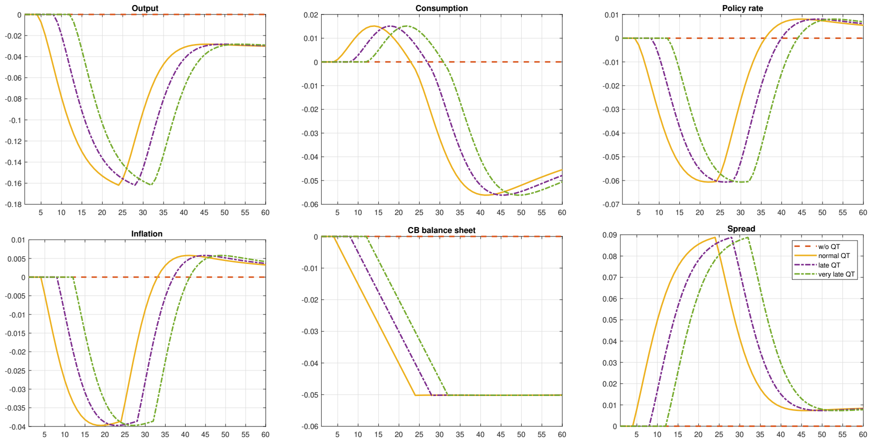
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of liquidity and QE shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The liquidity shocks happen in quarters 1–6 with size $1.5s_t$ each. In periods 7–13, QE shocks are fed in to replicate the ECB's increase in bond holdings during the COVID-19 pandemic. The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 13.5 pps (as % of GDP), evenly split over quarters 15–35 and applied proportionally according to the central bank's steady-state private and public bonds holdings (83.75% of the balance sheet reduction pertain to public bonds and 16.25% to private bonds). Across the panels, we modify the total size, the speed, and the start date of QT shocks.

Figure H.5: Inflationary shocks + private normalised QT – US model

Panel A: Different QT speeds



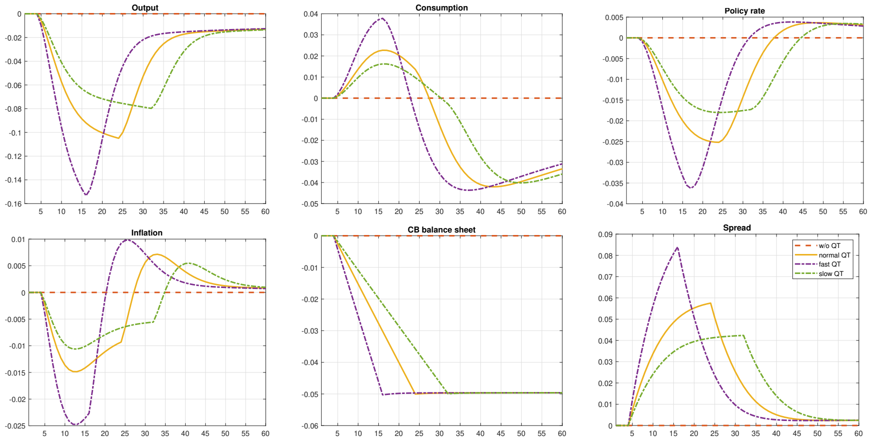
Panel B: Different QT start date



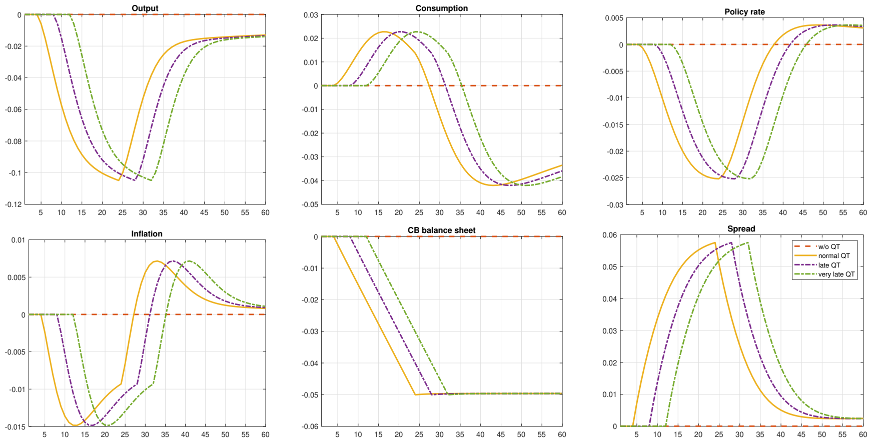
Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the US model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 5 pps (as % of GDP), evenly split over quarters 5–24 and applied only to the central bank's private bonds holdings. Across the panels, we modify the speed and the start date of QT shocks.

Figure H.6: Inflationary shocks + private normalised QT – EA model

Panel A: Different QT speeds



Panel B: Different QT start date



Notes: This figure depicts *relative* impulse response functions (IRFs) for different QT scenarios after a series of inflationary shocks in the EA model version, i.e. all IRFs are expressed relative to the baseline IRFs without any QT shocks and only inflationary shocks. The inflationary shocks consist of a series of negative productivity and positive government spending shocks, with size $0.5s_A$ ($0.55s_A$, $0.45s_A$) and $-0.5s_G$ ($-0.55s_G$, $-0.45s_G$) in quarters 1–4 (5–8, 9–12). The benchmark QT scenario (yellow solid line in all graphs) induces a balance sheet reduction of around 5 pps (as % of GDP), evenly split over quarters 5–24 and applied only to the central bank's private bonds holdings. Across the panels, we modify the speed and the start date of QT shocks.