DISCUSSION PAPER SERIES

DP16050

Effects of State-Dependent Forward Guidance, Large-Scale Asset Purchases and Fiscal Stimulus in a Low-Interest-Rate Environment

Günter Coenen, Carlos Montes-Galdon and Frank Smets

MONETARY ECONOMICS AND FLUCTUATIONS

CEPR

ISSN 0265-8003

Effects of State-Dependent Forward Guidance, Large-Scale Asset Purchases and Fiscal Stimulus in a Low-Interest-Rate Environment

Günter Coenen, Carlos Montes-Galdon and Frank Smets

Discussion Paper DP16050
Published 18 April 2021
Submitted 17 April 2021

Centre for Economic Policy Research
33 Great Sutton Street, London EC1V 0DX, UK
Tel: +44 (0)20 7183 8801
www.cepr.org

Effects of State-Dependent Forward Guidance, Large-Scale Asset Purchases and Fiscal Stimulus in a Low-Interest-Rate Environment

Abstract

We study the incidence and severity of periods with a binding effective lower bound on nominal interest rates and the efficacy of three types of state-dependent policies—forward guidance about the path of future interest rates, large-scale asset purchases and spending based fiscal stimulus—in mitigating the detrimental consequences of the lower bound. Based on the ECB's New Area-Wide Model of the euro area, our findings suggest that, if unaddressed, the lower bound can cause substantial macroeconomic distortions. In the near term, forward guidance, if fully credible, is most powerful and can largely undo the distortions due to the lower bound. A combination of imperfectly credible forward guidance, asset purchases and fiscal stimulus is almost equally effective, especially when asset purchases enhance the credibility of the forward-guidance policy via a signalling effect. In the long run, with an equilibrium real rate as low as zero, a combination of all three policies is needed to materially reduce the distortions.

JEL Classification: E31, E32, E37, E52, E62

Keywords: effective lower bound, monetary policy, forward guidance, asset purchases, Fiscal policy, Euro Area

Günter Coenen - gunter.coenen@ecb.europa.eu
European Central Bank

Carlos Montes-Galdon - carlos.montes-galdon@ecb.europa.eu
European Central Bank

Frank Smets - frank.smets@ecb.int
European Central Bank and CEPR

Acknowledgements
We thank Jordi Galı, Jesper Linde, Roberto Motto, Shinichiro Okawa, Athanasios Orphanides, Sebastian Schmidt and Anders Warne for helpful discussions and suggestions. We have also benefited from presentations of earlier drafts and material at the Bank of Canada-CREI-UPF Workshop on "Recent Developments in Macroeconomic Modelling" in Barcelona, at the ESHET Conference on "Money, Banks and Finance in Economic Thought" in Lille, at a central bank expert meeting held at the Bank for International Settlements in Basel, at meetings of the Monetary Policy Committee of the European System of Central Banks (ESCB), its FORE Task Force and its Working Group on Econometric Modelling, at the 15th Dynare Conference in Lausanne, at the Swiss National Bank Research Conference on "New Normal Monetary Policy Frameworks" in Zurich, at the 3rd Workshop of the ESCB Research Cluster on Monetary Economics in London, at the virtual "The Road Ahead for Central Banks" seminar of the Hoover Institution, and at seminars at the Bank of Japan and the ECB. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the ECB.

Effects of State-Dependent Forward Guidance, Large-Scale Asset Purchases and Fiscal Stimulus in a Low-Interest-Rate Environment [*,†]

Günter Coenen, Carlos Montes-Galdón

and Frank Smets

April 17, 2021

Abstract

We study the incidence and severity of periods with a binding effective lower bound on nominal interest rates and the efficacy of three types of state-dependent policies—forward guidance about the path of future interest rates, large-scale asset purchases and spending-based fiscal stimulus—in mitigating the detrimental consequences of the lower bound. Based on the ECB's New Area-Wide Model of the euro area, our findings suggest that, if unaddressed, the lower bound can cause substantial macroeconomic distortions. In the near term, forward guidance, if fully credible, is most powerful and can largely undo the distortions due to the lower bound. A combination of imperfectly credible forward guidance, asset purchases and fiscal stimulus is almost equally effective, especially when asset purchases enhance the credibility of the forward-guidance policy via a signalling effect. In the long run, with an equilibrium real rate as low as zero, a combination of all three policies is needed to materially reduce the distortions.

JEL Classification System: E31, E32, E37, E52, E62

Keywords: Effective lower bound, monetary policy, forward guidance, asset purchases, fiscal policy, euro area

---

[*] Correspondence: Günter Coenen: European Central Bank, Sonnemannstrasse 20, 60314 Frankfurt am Main, Germany, e-mail: gunter.coenen@ecb.europa.eu; Carlos Montes-Galdón: European Central Bank, e-mail: carlos.montes-galdon@ecb.europa.eu; Frank Smets: European Central Bank and Ghent University, e-mail: frank.smets@ecb.europa.eu.

[†] We thank Jordi Galí, Jesper Lindé, Roberto Motto, Shinichiro Okawa, Athanasios Orphanides, Sebastian Schmidt and Anders Warne for helpful discussions and suggestions. We have also benefited from presentations of earlier drafts and material at the Bank of Canada-CREI-UPF Workshop on "Recent Developments in Macroeconomic Modelling" in Barcelona, at the ESHET Conference on "Money, Banks and Finance in Economic Thought" in Lille, at a central bank expert meeting held at the Bank for International Settlements in Basel, at meetings of the Monetary Policy Committee of the European System of Central Banks (ESCB), its FORE Task Force and its Working Group on Econometric Modelling, at the 15th Dynare Conference in Lausanne, at the Swiss National Bank Research Conference on "New Normal Monetary Policy Frameworks" in Zürich, at the 3rd Workshop of the ESCB Research Cluster on Monetary Economics in London, at the virtual "The Road Ahead for Central Banks" seminar of the Hoover Institution, and at seminars at the Bank of Japan and the ECB. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the ECB.

1 Introduction

The Global Financial Crisis, the secular fall in the equilibrium real interest rate,[1] and the protracted period with nominal interest rates at their effective lower bound experienced in major advanced economies have led to a re-assessment of the incidence and severity of lower-bound episodes and of the effectiveness of existing monetary policy frameworks to safeguard macroeconomic stability. At the same time, central banks have gained considerable experience with the use of non-standard monetary policy instruments such as forward guidance about the likely path of future interest rates and the conduct of large-scale asset purchases. These instruments helped to cushion the detrimental consequences of the lower bound for economic activity and were key for preserving price stability.[2]

Against this background, our paper studies quantitatively the effects of forward guidance and large-scale asset purchases in a low-interest-rate environment in which the ability of monetary policy to stave off recessionary and deflationary shocks by adjusting its standard interest-rate instrument is impaired because of the effective lower bound. In so doing, the paper contributes to the literature on the conduct and efficacy of monetary policy at the lower bound, including the recent papers by Reifschneider (2016), Kiley and Roberts (2017), Kiley (2018) and Chung et al. (2019), which however all focus on the policies of the Federal Reserve and the US economy.[3] Our paper adds to this literature by considering the euro area economy and by also examining the role of expansionary fiscal policy as an additional stabilisation instrument when the nominal interest rate has fallen to the lower bound, as called for, amongst others, by Blanchard (2019), Eichenbaum (2019) and Rachel and Summers (2019). Moreover, the quantitative analysis in our paper takes into account the state-dependent nature of the three different policies, and their possible interaction, which is crucial for appropriately capturing their macroeconomic effects.

[1]For a documentation of the downward trend in the equilibrium real interest rate over the past decades and across countries, see, e.g., Laubach and Williams (2016), Hamilton et al. (2016), Holston et al. (2017), Brand et al. (2018) and Jordà and Taylor (2019). The uncertainty around the available estimates of the equilibrium rate and about whether it will remain at its current low level in the future is however large.

[2]See Hartmann and Smets (2018) and Rostagno et al. (2019) for an account of the experience with the implementation of the ECB's asset purchase programme and its interaction with other non-standard policies, including the ECB's forward guidance about the likely path of its key policy rates. For an assessment of the respective Federal Reserve policies, see Engen et al. (2015), Chung et al. (2019) and Sims and Wu (2019).

[3]Another recent literature studies the ability of alternative monetary policy frameworks to overcome the constraint on monetary policy due to the lower bound. For example, Bernanke (2017) and Bernanke et al. (2019), examine the benefits of temporary, or permanent, switches to a price-level targeting framework, whereas Mertens and Williams (2019) study average inflation targeting. Within the common inflation-targeting framework Andrade et al. (2018) analyse the relationship between the equilibrium real interest rate and the optimal inflation objective. By contrast, our analysis remains within the existing monetary policy framework of the ECB, and focuses instead on the efficacy of its non-standard policy instruments.

Our quantitative study relies on two complementary approaches. In the first approach, we assess the consequences of the effective lower bound for the near-term economic outlook on the basis of *predictive distributions* for inflation, real GDP growth and the short-term nominal interest rate, as in Coenen and Warne (2014). These distributions are computed by conducting model-based stochastic simulations around a recent vintage of the Eurosystem staff projections, taking into account the lower-bound constraint. Importantly, the projection vintage features an interest-rate baseline path which stays close to the effective lower bound perceived to prevail over the projection horizon. This baseline path translates into a very high likelihood that monetary policy will be constrained by the effective lower bound during an unforeseen future economic downturn.[4] Within this approach, we first characterise the predictive distributions in terms of deflation and recession risks, the lower-bound incidence, and the downward biases in inflation and real GDP growth induced by the lower-bound constraint. We then assess the effectiveness of forward guidance about future interest rates and large-scale asset purchases to provide the intended monetary stimulus when the lower bound is binding and, thereby, to mitigate the deflation and recession risks and to undo the downward biases. In the same vein, we examine the efficacy of government spending-based fiscal stimulus in safeguarding the near-term outlook.

In the second approach, we take a long-run perspective independent of current economic conditions and investigate model-based *steady-state distributions* for inflation, the output gap and the short-term nominal interest rate assuming that the documented fall in the equilibrium real interest rate is permanent. As the size of the actual fall in the equilibrium real rate is subject to a high degree of uncertainty, we compute these steady-state distributions under alternative assumptions about the level of equilibrium real rate, with a lower level making it increasingly more likely that the effective lower bound on nominal interest rates will constrain monetary policy.[5] Under this approach, we first gauge the impact of a lower equilibrium real rate on the ability of monetary policy to stabilise inflation and the output gap when it can only resort to its standard interest-rate instrument subject to the lower-bound constraint. In doing so, we build on a large number of model-based studies conducted

[4]Considering such a real-time baseline scenario seems more appealing from a monetary policy point of view than a hypothetical and stylised adverse scenario resulting from a large contractionary demand shock, which is typically studied in the literature.

[5]While changes in the equilibrium real interest rate are driven by multiple structural factors such as demographic trends, a slowdown in productivity growth and shifts in wealth and income distributions, in our model, we treat shifts in the equilibrium real rate as exogenous and abstain from a more structural interpretation. Furthermore, we abstract from the uncertainty that both real-time and ex-post estimates of the equilibrium real rate are typically plagued with in practice, making the simplifying assumption that agents in the model have perfect information about changes in the equilibrium real rate.

in the years prior to the financial crisis and in its aftermath, including Reifschneider and Williams (2000), Coenen et al. (2004), Williams (2009) and Chung et al. (2012), all with a focus on the US economy, and Coenen (2003), considering the euro area economy. We then expand the scope of these studies and examine the extent to which state-dependent forward guidance, asset purchases or fiscal stimulus can ameliorate the detrimental consequences of the lower bound. Our approach is similar to the one taken by Kiley (2018), which however is limited to the analysis of non-standard monetary policy instruments.

To carry out the stochastic simulations, we employ the recent extension of the ECB's New Area-Wide Model (cf. Coenen et al., 2018), henceforth referred to as NAWM II. This model incorporates a rich financial sector with the threefold aim of (i) accounting for a genuine role of financial frictions in the propagation of economic shocks and in the transmission of macroeconomic policies, (ii) capturing the prominent role of bank lending rates and the gradual interest-rate pass-through in the transmission of monetary policy in the euro area, and (iii) providing a structural framework useable for assessing the macroeconomic impact of the ECB's large-scale asset purchases conducted in recent years. Deviating from its standard specification, the Taylor-type interest-rate rule included in the model is modified to track a shadow interest rate, which represents the notional short-term nominal interest rate which the central bank in the model would like to set given current economic conditions if it had not been constrained by the effective lower bound. The shadow rate in turn keeps track of the severity of unfolding economic downturns and ensuing shortfalls of inflation below the central bank's inflation objective, and makes the period for which the nominal interest rate is kept at the effective lower bound depend on the severity of these events. In other words, the interest-rate rule is modified to incorporate state-dependent forward guidance about the path of future interest rates once the effective lower bound is reached. In a similar vein, asset purchases and/or fiscal stimulus are triggered in a state-dependent manner whenever the short-term nominal interest rate falls to the lower bound following a sequence of adverse economic shocks.

Our two complementary approaches based on model-based stochastic simulations provide a rich laboratory for studying the efficacy of state-dependent forward guidance, state-dependent asset purchases and state-dependent fiscal stimulus in a low-interest-rate environment in which episodes during which nominal rates are stuck at their effective lower bound are much more frequent. Our findings suggest that, if unaddressed, the lower bound can cause substantial macroeconomic distortions. In the current environment with historically low nominal and real interest rates, the effective lower bound can amplify the impact of adverse shocks on inflation and GDP growth, leading to elevated deflation and recession risks and noticeable downward biases in the respective predictive distributions. Similarly, in an environment with a permanently lower equilibrium real interest rate, the lower-bound constraint can significantly impair macroeconomic stability, as reflected in inflated root mean-squared deviations (RMSDs) of the steady-state distributions for inflation and the output gap. The detrimental effects due to the lower bound are the larger, the lower the equilibrium real interest rate: As the equilibrium real rate falls from 2% to zero, the frequency of lower-bound episodes rises from 10.3% to 24.0%, and the RMSDs for inflation and the output gap increase from 2.9% and 6.0% to 4.2% and 8.6%, respectively. These inflated RMSDs reflect both sizeable shortfalls in the means of the respective steady-state distributions as well as markedly higher standard deviations.

Regarding the stabilisation effects of the different state-dependent policies in the current low-interest-rate environment, forward guidance on interest rates, if fully credible, is most powerful and can largely undo the distortions due to the lower bound. Such strong forward guidance may not be realistic, also in view of the "forward-guidance puzzle" of New Keynesian dynamic stochastic general equilibrium (DSGE) models (see Del Negro et al., 2012), which concerns the often implausibly large effects of forward guidance within this class of models. But a combination of a weaker form of forward guidance with limited credibility, large-scale asset purchases as well as fiscal stimulus is almost equally effective, especially when asset purchases can enhance the credibility of the forward-guidance policy through a signalling effect. In contrast, in the long run, with a permanently lower equilibrium real interest rate and recurrent long-lived lower-bound episodes, forward guidance is found to be less effective in itself and a combination of all three policies is needed to materially reduce the lower-bound distortions. For an equilibrium real rate equal to zero, the combination of policies results in a marked reduction in the average RMSD for inflation and the output gap from 6.4% to 4.6%, even though noticeable shortfalls in the respective means persist. In accordance with the "low-for-longer" prescription of the forward-guidance policy, the number of times the short-term nominal rate stays at the lower bound rises from 24% to about 31% and the average duration of lower-bound episodes increases from around 9.5 to 17.5 quarters. The average amount of assets purchased is reasonable, as is the average size of the fiscal stimulus, but the ultimate amount of asset purchases needed can still be substantial in extreme circumstances, with asset holdings exceeding 45% of annual GDP even when fiscal stimulus of more than 3% of GDP helps to keep them contained.

The remainder of the paper is organised as follows. Section 2 provides a brief overview of the model, while Section 3 details the three types of state-dependent policies that we consider in our study. Section 4 presents the model-based analysis of the impact of the lower-bound constraint on the risks to the near-term outlook and of the risk-mitigation capabilities of the three different policies. Section 5 presents the analysis of the consequences of the lower bound for macroeconomic stability in the long run for alternative levels of the equilibrium real interest rate and of the ability of the different policies to overcome them. Section 6 concludes. Details on the simulation and solution methods employed and other complementary material can be found in an Appendix.

2 The model: A bird's eye view

In this section we give a brief overview of the extended version of the ECB's New Area-Wide Model (NAWM) that we use in our quantitative study. As the main elements of the model's baseline version are relatively standard, including the specification of the fiscal sector, we just provide a non-technical sketch of its basic structure and highlight subsequently those features that are most relevant for understanding the enhanced role of the financial sector in the extended model and the effects of central bank asset purchases.[6]

2.1 The baseline model

The baseline NAWM is an estimated open-economy DSGE model of the euro area developed for use in the (Broad) Macroeconomic Projection Exercises regularly undertaken by ECB and Eurosystem staff and for analysis of topical policy issues; see Christoffel et al. (2008) for a detailed description of the model structure. Its design has been guided by the need to cover a comprehensive set of core projection variables, including a small number of foreign variables, which, in the form of exogenous assumptions, play an important role in the preparation of the staff projections.

The NAWM features four types of economic agents: households, firms, a fiscal authority and the central bank. Households make optimal choices regarding their purchases of consumption and investment goods, the latter determining the economy-wide capital stock. They supply differentiated labour services in monopolistically competitive markets, they set wages as a mark-up over the marginal rate of substitution between consumption and leisure, and they trade in domestic and foreign short-term bonds.

[6] For later reference, illustrative simulations of the effects of autonomous, i.e. non-state-dependent, asset purchases and spending-based fiscal stimulus are shown in Figures A.1 and A.2 of the Appendix.

As regards firms, the NAWM distinguishes between domestic producers of tradable intermediate goods and domestic producers of three types of non-tradable final goods: a private consumption good, a private investment good, and a public consumption good. The intermediate-good firms use labour and capital services as inputs to produce differentiated goods, which are sold in monopolistically competitive markets domestically and abroad. In doing so, they set different prices for domestic and foreign markets as a mark-up over their marginal costs. The final-good firms combine domestic and foreign intermediate goods in different proportions, acting as price takers in fully competitive markets. The foreign intermediate goods are imported from producers abroad, who set their prices in euro in monopolistically competitive markets, allowing for a gradual exchange-rate pass-through. A foreign retail firm in turn combines the exported intermediate goods, with aggregate export demand depending on total foreign demand.

Both households and firms face a number of nominal and real frictions, which have been identified as important in generating empirically plausible dynamics. Real frictions are introduced via external habit formation in consumption, through generalised adjustment costs in investment, imports and exports, and through fixed costs in intermediate-good production. Nominal frictions arise from staggered price and wage-setting à la Calvo (1983), in combination with (partial) dynamic indexation of price and wage contracts to past inflation. In addition, there exist stylised financial frictions which enter the model in the form of exogenous shocks that can be interpreted as domestic and foreign risk premia.

The fiscal authority purchases the public consumption good, issues short-term bonds, and levies different types of distortionary taxes at constant rates. Nevertheless, Ricardian equivalence holds because of the simplifying assumption that the fiscal authority's budget is balanced each period by means of lump-sum taxes. The central bank sets the short-term nominal interest rate according to an inertial Taylor (1993)-type rule, stabilising inflation in line with the ECB's definition of price stability as well as output.

The NAWM is closed by a rest-of-the-world block, which is represented by a structural vector-autoregressive (SVAR) model determining several foreign variables, including total foreign demand. The SVAR model does not feature spill-overs from the euro area, in line with the treatment of the foreign variables as exogenous assumptions in the ECB and Eurosystem staff projections.

2.2 The extended model

The extended version of the NAWM, which is referred to as NAWM II and described in detail in Coenen et al. (2018), includes a rich financial sector which is centered around two distinct types of financial intermediaries: (i) funding-constrained "wholesale banks" à la Gertler and Karadi (2011) which engage in maturity transformation and originate long-term loans, and (ii) "retail banks" à la Gerali et al. (2010) which distribute these loans to the non-financial private sector and adjust the interest rate on loans only sluggishly. The long-term loans are required by the non-financial private sector to finance capital investments as in Carlstrom et al. (2017). Furthermore, NAWM II includes a set of no-arbitrage and optimality conditions which determine the returns on the holdings of domestic and foreign long-term government bonds by the financial and the non-financial private sector, building on Gertler and Karadi (2013).

The incorporation of these financial extensions into the baseline model reflects the three-fold aim pursued in the development of NAWM II, namely: (i) to account for a genuine role of financial frictions in the propagation of economic shocks and in the transmission of macroeconomic policies, and for the presence of shocks originating in the financial sector itself, (ii) to capture the prominent role of bank lending rates and the gradual interest-rate pass-through in the transmission of monetary policy in the euro area, and (iii) to provide a structural framework useable for assessing the macroeconomic impact of the ECB's large-scale asset purchases which have been conducted in recent years.

In the model, central bank asset purchases of domestic long-term government bonds ease the wholesale banks' funding constraint and result in a rise in the valuation of the banks' assets. This valuation effect implies a fall in the excess returns on long-term government bonds and long-term wholesale loans; that is, a decline in their term premia. At the retail-bank level, the lower loan premium translates into a decline in the lending rate required from the non-financial private sector, stimulating loan demand for financing additional capital investments. The ensuing increase in domestic demand puts upward pressure on firms' marginal costs and leads to a rise in domestic prices in the shorter term, whereas disinflationary effects resulting from the enhanced productive capacity on the back of higher capital investments tend to prevail in the medium to longer term. On the external side, the implied decline in the premium on domestic long-term government bonds comes along with a decrease in the premium on foreign long-term government bonds which is brought about by an instantaneous depreciation of the domestic currency, boosting export demand and raising import prices.

In addition to the effects on the loan and bond premia, the model incorporates an impact of central bank asset purchases on its domestic risk premium which drives a wedge between the short-term nominal interest rate controlled by the central bank and the returns on households' deposits with the wholesale banks and short-term government bonds. In economic terms, this wedge can also be interpreted as a liquidity premium reflecting the distinct liquidity services provided by central bank assets versus wholesale bank deposits and short-term government bonds. In a situation, where the central bank massively purchases long-term nominal assets and issues large amounts of short-term excess reserves to the wholesale banks in order to finance these purchases, the liquidity premium is likely to be increasingly compressed. Because excess reserves are exchangeable with households' deposits placed to the wholesale bank, the return on these deposits is compressed as well. Thereby, asset purchases affect households' spending decisions, over and above the effects resulting from lowering the loan and bond premia. Practically, this additional channel stands in for portfolio re-balancing effects of central bank asset purchases on households' consumption decisions which are not explicitly modelled.

3 State-dependent policies at the lower bound

This section describes the specification and parameterisation of the three types of state-dependent policies that are activated when the short-term nominal interest rate has fallen to the effective lower bound: forward guidance about the path of the short-term nominal interest rate, large-scale asset purchases and spending-based fiscal stimulus. It provides the basis for the model-based assessment of their effectiveness in overcoming the macroeconomic distortions due to the lower bound in the following sections.

3.1 Forward guidance

In our assessment of the efficacy of state-dependent forward guidance about future short-term nominal interest rates, we focus on history-dependent interest-rate rules which lead to low-for-longer policy prescriptions. An early example of a rule falling in this category is the rule by Reifschneider and Williams (2000). According to this rule, current and future short-term nominal interest rates are set to make up the cumulated values of past shortfalls of the *shadow interest rate* below the effective lower bound on nominal rates. The shadow interest rate is defined as the notional interest rate which the central bank would like to set given current economic conditions if it had not been constrained by the effective lower bound. In models with forward-looking agents such as NAWM II, this rule proves to be extremely effective in overcoming the lower-bound constraint as it still succeeds to influence economic agents' forward-looking expectations in situations when the current interest rate is stuck at the lower bound because of its history-dependent element.

We consider a weaker version of this make-up rule which relates the short-term interest rate to the *lagged value* of the shadow-rate shortfall as opposed to its *cumulated past values*, like in Debortoli et al. (2018).[7] Concretely, we incorporate state-dependent forward guidance into an inertial Taylor (1993)-type interest-rate rule subject to the lower-bound constraint as follows:

$$r_t \;=\; \max[\,\tilde{r}_t,\, -100{\cdot}\log(\bar{R}) + \mathit{ELB}\,] \tag{1}$$

with

$$\tilde{r}_t \;=\; 0.9\,(\iota\, r_{t-1} + (1-\iota)\,\tilde{r}_{t-1}) + (1-0.9)\;(2.5\,\pi_{C,t} + 0.125\,y_t) + \eta_t. \tag{2}$$

In the specification of the lower-bound constraint (1), $r_t = 100\cdot\log(R_t/\bar{R})$ is the logarithmic deviation of the (gross) short-term nominal interest rate R_t from the model's steady-state (gross) nominal interest rate $\bar{R}$, which the central bank can implement subject to the effective lower bound, *ELB*, while $\tilde{r}_t$ represents the shadow interest rate. The steady-state nominal interest rate $\bar{R}$ is determined as the product of the model's steady-state (gross) real interest rate $\bar{R}^r$ and the steady-state (gross) inflation rate $\bar{\Pi}$, with the latter being pinned down by the central bank's inflation objective.

In the interest-rate rule (2), $\pi_{C,t}$ denotes the logarithmic deviation of (gross) consumer price inflation $\Pi_{C,t}$ from the steady-state inflation rate. Similarly, y_t is the logarithmic deviation of aggregate output Y_t from the trend output level, with trend output growth following a unit-root process. Finally, η_t is a transitory shock capturing temporary deviations of the short-term nominal interest rate from the systematic prescriptions of the interest-rate rule. It is worth noting that the rule has key features with the estimated interest-rate rule of NAWM II in common, namely a high degree of inertia and a strong reaction to deviations of inflation from the central bank's inflation objective. But it omits a reaction to output growth because, in the presence of the lower-bound constraint, it generally proves to be harmful to raise interest rates when growth is picking up following a recession, with the

[7] We do not consider alternative history-dependent rules such as price-level targeting rules (Vestin, 2006, Bernanke, 2017, Bernanke et al., 2019), or average-inflation targeting rules (Nessén and Vestin, 2005, Mertens and Williams, 2019). These rules imply a change in the monetary policy framework, which we do not contemplate in this paper. Similarly, we do not consider threshold-based rules (Coenen and Warne, 2014, Boneva et al., 2018, Chung et al., 2019), which rely on an alternative mechanism to induce low-for-longer policy prescriptions.

output gap still being negative and continued deflationary pressures.

In computing the value of the shadow interest rate, the parameter $\iota \in \{0, 1\}$ determines whether the shadow rate depends on the lagged realised interest rate ($\iota = 1$), or on the lagged shadow interest rate ($\iota = 0$). In the latter case, the shadow rate keeps track of a recession or a shortfall of inflation below the central bank's inflation objective and makes the period for which the interest rate is kept at the effective lower bound depend on the severity of the respective event. In other words, the interest-rate rule embeds *state-dependent forward guidance* about the future interest-rate path.[8]

The case with $\iota = 0$ can be interpreted as the case of fully credible, or *strong*, interest-rate forward guidance, with $\tilde{r}_t = \tilde{r}_t(\tilde{r}_{t-1})$. As the assumption of full credibility is arguably unrealistic, we consider two modifications. First, imperfectly credible, or *weak*, forward guidance can be thought of as a case in which private-sector agents attach only a reduced probability to the central bank's interest-rate guidance, as in Haberis et al. (2019). This is tantamount to assuming that agents base their expectations of future interest rates on a probability-weighted linear combination of two distinct interest-rate rules including either the shadow rate depending on the lagged realised rate, $\tilde{r}_t(r_{t-1})$, or the shadow rate depending on its own lag, $\tilde{r}_t(\tilde{r}_{t-1})$. And second, as a simple approach to account for the signalling channel of asset purchases, *enhanced* forward guidance can be considered as a case in which asset purchases carried out by the central bank lead to an increase in the probability attached to the bank's guidance, compared to the case of weak forward guidance.[9]

In our implementation of the two modifications concerning the way agents form their expectations of future interest rates, the actual current interest rate continues to be determined according to rule (2) with $\iota = 0$. That is, the central bank sets the interest rate period-by-period in line with its shadow rate-based forward guidance policy. Agents that do not fully believe in this policy and observe the realisation of the current-period interest

[8] Simulating NAWM II under the interest-rate rule with *state-dependent* forward guidance subject to the lower-bound constraint differs from simulating the model under a transient, but exogenous, interest-rate peg mimicking *time-dependent* forward guidance during a lower-bound episode. Whereas such simulations are typically very sensitive to keeping the interest rate fixed for an increasing period of time and can result in empirically implausible outcomes (see Del Negro et al., 2012, and Carlstrom et al., 2012, on the forward-guidance puzzle of New Keynesian DSGE models), such implausible behaviour does not arise under our augmented rule which makes future interest rates depend on the evolution of the economy. Notwithstanding this, it is worth noting that, as demonstrated in Figures A.1 and A.2 of the Appendix, the outcomes of NAWM II-based simulations of asset purchases and fiscal stimulus under an interest-rate peg remain plausible, at least for a reasonable duration of the peg, an important factor being the model's high levels of nominal and real rigidities.

[9] For a rigorous treatment, see Bhattarai et al. (2015) who argue that asset purchase policies exert their influence through signalling the central bank's commitment to maintain low interest rates in the future and provide an explicit signalling theory of asset purchases.

rate could in principle infer the true policy intentions of the central bank by solving a signal extraction problem in the presence of transitory interest-rate shocks. Yet such an element of learning is not taken into account in our implementation.

3.2 Asset purchases and fiscal stimulus

In our analysis we link the specification of state-dependent asset purchases and fiscal stimulus to the shortfall of the shadow interest rate below the effective lower bound. For asset purchases we consider the following rule:

$$a_t \;=\; \rho_{a,1}\, a_{t-1} + \rho_{a,2}\, a_{t-2} + \alpha_a\, r_t^{gap}, \tag{3}$$

where a_t denotes the central bank's asset holdings (valued at steady-state prices and expressed as a share of annual steady-state GDP), $r_t^{gap} = r_t - \tilde{r}_t(\kappa\, r_{t-1} + (1-\kappa)\,\tilde{r}_{t-1})$ represents a measure of the current interest-rate shortfall, and α_a determines the sensitivity of the initial asset purchases with respect to the interest-rate shortfall, i.e. their *strength*. The assumed AR(2) process for the dynamic propagation of the initial asset purchases, with appropriately chosen parameters $\rho_{a,1}$ and $\rho_{a,2}$, allows for a gradual build-up of overall asset holdings broadly consistent with the pattern of actual asset purchases carried out by central banks, and a gradual reduction thereafter as the assets mature.[10] Like for the counterfactual analysis of the ECB's early asset purchase programme in Coenen et al. (2018), the state-dependent asset purchases analysed in this paper comprise purchases of long-term government bonds and long-term private-sector loans.

The parameter $\kappa \in \{0, 1\}$ determines whether the shadow interest rate used in the computation of the interest-rate shortfall depends on the lagged realised rate ($\kappa = 1$, with $\tilde{r}_t = \tilde{r}_t(r_{t-1})$), or on the lagged shadow rate ($\kappa = 0$, with $\tilde{r}_t = \tilde{r}_t(\tilde{r}_{t-1})$). The value of κ does not need to coincide with the value of ι. For example, in the case that the interest-rate rule embeds forward guidance ($\iota = 0$), the interest-rate shortfall may still be more conveniently computed using the alternative shadow-rate measure based on the lagged realised interest rate ($\kappa = 1$) if the forward guidance is imperfectly credible, i.e. weak. Therefore, and in order to ensure comparability of the computation of the interest-rate shortfall across the

[10] This specification captures the idea that large-scale asset purchase programmes affect long-term yields through current and expected future purchases at announcement date and over time. Consistent with this idea, Eser et al. (2019) estimate for the euro area, based on the path of the ECB's net asset purchases envisaged in June 2018, a half-life of around 5 years for the 10-year term premium impact. This result contrasts with the finding of Greenlaw et al. (2018) for the US that, whatever the initial impact of some Fed actions or announcements, the effects of its large-scale asset purchases tended not to persist.

cases with and without forward guidance, we use uniformly the shortfall measure based on the lagged realised rate.[11]

We specify a similar state-dependent rule for providing fiscal stimulus, g_t, in a situation where the short-term interest rate is constrained by the effective lower bound:[12]

$$g_t \quad = \quad \rho_g \, g_{t-1} + \alpha_g \, \max[\, r_t^{gap} - c_g, \, 0\,], \tag{4}$$

with α_g determining the strength of the fiscal stimulus, c_g representing a possible threshold for providing stimulus, and the dynamics being restricted to an AR(1) process with parameter ρ_g. The presence of the threshold reflects the view that fiscal stimulus is likely to be enacted with less ease and immediacy than monetary stimulus. Throughout the analysis, fiscal stimulus corresponds to an increase in consumptive government spending (expressed as a share of steady-state GDP).

3.3 Parameterisation

First, regarding the formulation of the lower-bound constraint (1), we will consider alternative values for the steady-state short-term nominal interest rate, $\bar{r} = 100 \cdot \big(\log(\bar{R}^r) + \log(\bar{\Pi})\big)$, and the effective lower bound, *ELB*, depending on the nature of the two complementary model-based simulation approaches pursued in this paper. These values will therefore be discussed in the respective sections below. As we keep the model's steady-state inflation rate constant at 1.9% per annum, consistent with the ECB's price stability objective of maintaining inflation rates below, but close to, 2% over the medium term, the alternative values for the steady-state short-term nominal interest rate will ultimately reflect alternative assumptions about the level of the steady-state real interest rate, which represents the long-run equilibrium real interest rate in our model.

Second, linked to the specification of the interest-rate rule (2), we explore the consequences of alternative assumptions about the strength of state-dependent rate forward

[11] To appreciate the implications of this choice it is helpful to know that there exists an equivalence relationship between the two alternative shortfall measures for restricted parameterisations of the asset-purchase rule (3). If the autoregressive component of the rule that prescribes a response to the interest-rate shortfall defined in terms of the lagged realised rate ($\kappa = 1$, with $\tilde{r}_t = \tilde{r}_t(r_{t-1})$) is given by an AR(1) process with a parameter of 0.90, the implied path for the holdings of assets is identical to the path implied by a rule without an autoregressive component but that relates the asset holdings in a proportionate way to the interest-rate shortfall defined in terms of the lagged shadow rate ($\kappa = 0$, with $\tilde{r}_t = \tilde{r}_t(\tilde{r}_{t-1})$). The reason is that, in the latter case, the interest-rate shortfall inherits the same autoregressive component from the shadow rate-based interest-rate rule (2) with its coefficient of 0.90 on the lagged shadow rate.

[12] Our fiscal-stimulus rule is very much in the spirit of the proposal by Eichenbaum (2019) to adopt a system of asymmetric, automatic stabilisers when certain macro indicators hit pre-specified targets conformable with a binding lower-bound constraint.

guidance. Specifically, we assume that weak forward guidance results in a noticeably reduced effectiveness in mitigating the distortions due to the lower bound compared to the extreme case of strong forward guidance. To this end, we postulate that private-sector agents attach a markedly lower probability of 25% to the shadow rate-based forward guidance policy. Enhanced forward guidance then corresponds to the case that, in reaction to asset purchases carried out by the central bank, agents start to attach a higher probability to the forward guidance policy. According to this narrative, we let the probability rise from 25% for the case of weak guidance to 50% for the case of enhanced guidance.

Third, concerning the state-dependent asset-purchase rule (3), we explore the effects of alternative parameterisations of the sensitivity of central bank asset purchases to the interest-rate shortfall, with $\alpha_a = 0.5$ ("moderate") and $\alpha_a = 1$ ("strong"). Concerning the parameters of the autoregressive component of the rule we choose a pair of values equal to $\rho_{a,1} = 1.5$ and $\rho_{a,2} =$ -0.54 (with roots equal to 0.9 and 0.6 for the associated lag polynomial). If the annualised interest-rate shortfall were to equal 100 basis points for four quarters and with $\alpha_a = 1$, these values would result in a gradual build up of asset holdings reaching a peak at somewhat above 10% of annual GDP after six quarters. This pattern is broadly comparable with the scale of the initial asset purchase programme announced by the ECB at the beginning of 2015.

And finally, for the state-dependent fiscal-stimulus rule (4) we choose a sensitivity parameter of $\alpha_g = 5$, an optional threshold parameter of $c_g = 0.125$ (corresponding to an annualised interest-rate shortfall of 50 basis points), and an autoregressive parameter of $\rho_g = 0.9$ that results in a persistent but monotonically declining stimulus pattern. In the absence of the threshold, the rule would give rise to a peak stimulus of roughly 1% of GDP if the interest-rate shortfall were to equal 100 basis points for a period of four quarters.

4 Consequences of the lower bound for the economic outlook

Having specified the three different of state-dependent policies: forward guidance, asset purchases and fiscal stimulus, we now assess their effectiveness in addressing the detrimental consequences of the effective lower bound for the near-term economic outlook. In so doing, we start from the premise that future unforeseen events give rise to uncertainty and pose risks to the outlook which, if they materialise on the downside and the lower bound binds, will lead to the activation of the different policies, either individually or in combination with each other. To gauge the risk-mitigation capabilities of these policies, we analyse their impact in a probabilistic setting on the basis of model-based *predictive distributions* that comprehensively characterise the near-term outlook.

4.1 Predictive distributions and the lower bound

As policy-makers do not base their deliberations narrowly on predictions of any single model, we start from a central prediction that incorporates a wide range of data and takes into account different models and perspectives, namely the baseline projection of the December 2018 Broad Macroeconomic Projection Exercise (BMPE) conducted by Eurosystem staff. We then carry out stochastic simulations with NAWM II to obtain predictive distributions around this baseline. That is, we rely on a model-based characterisation of macroeconomic uncertainty, but account for the vastly broader information set utilised in actual policy-making. In the stochastic simulations, we allow the short-term nominal interest rate (corresponding to the 3-month EURIBOR) to react to new and unforeseen shocks that may occur over the projection horizon subject to the effective lower bound perceived to have been in place at the time of the December 2018 BMPE.[13, 14]

Figure 1 shows the December 2018 BMPE baseline paths as well as the means and the 70% and 90% confidence bands of the NAWM II-based predictive distributions for annual real GDP growth, annual consumer price inflation (measured in terms of the private consumption deflator) and the annualised short-term nominal interest rate. As can be seen in panel A of the figure, when the effective lower bound on nominal interest rates is taken into account, a larger part of the predictive distributions for real GDP growth and consumer price inflation lies below the respective baseline. Accordingly, these distributions are skewed to the downside, with their means falling noticeably below the baseline values over most of the projection horizon. The reason for the asymmetry and the resulting downward bias of the predictive distributions is that, with short-term nominal interest rates in the baseline being very close to the lower bound over the projection horizon, the reaction of monetary policy to new recessionary and deflationary shocks via standard interest-rate adjustments is severely constrained. As a consequence, the predictive distribution for the short-term nominal interest rate is piling up at the lower bound, with the short-term rate

[13] Concretely, the lower-bound constraint is imposed at a level of -31.5 basis points, equal to the value of the 3-month EURIBOR at the start of the projection horizon; that is, in 2018Q4. The value of the steady-state real interest rate is kept at the level of 2% assumed in the estimation of the model.

[14] Technical details on the stochastic simulations carried out around the December 2018 BMPE baseline and on the method that we use to solve NAWM II subject to the lower-bound constraint are provided in the Appendix.

being markedly higher on average than in the baseline.[15] By contrast, if the lower bound were not to be present, as assumed in panel B of the figure, the predictive distributions for real GDP growth, consumer price inflation and the short-term nominal interest rate would all be symmetric, and their means would be equal to the baseline values.

4.2 The efficacy of state-dependent policies in safeguarding the outlook

To assess the effectiveness of the different state-dependent policies in mitigating the distortions due to the lower bound, we computed variants of the predictive distributions that allow for the deployment of these policies once the short-term nominal interest rate has fallen to the lower bound.[16] Yet before turning to this assessment, we first illustrate how the different policies help stabilising the economy in the presence of an adverse demand shock that is superimposed on the December 2018 BMPE baseline.

4.2.1 The impact of an adverse demand shock

As is evident from the skew of the model-based predictive distributions, the lower bound can become a strong amplifier of shocks to the economic outlook. To illustrate the basic mechanism, the panels in Figure 1 also show the impact of an additional adverse demand shock that results in a decline of quarterly real GDP growth to roughly zero at the start of the December 2018 BMPE horizon. With the short-term nominal interest rate being persistently stuck at the lower bound (as shown in panel A), the ensuing fall in inflation leads to a rise of the (ex-ante) real interest rate. As a result, aggregate demand is dampened further, over and above the initial effect of the adverse demand shock, and real GDP grows more slowly than in a situation where the nominal interest rate can be lowered to partly offset the recessionary and deflationary effects of the demand shock (see panel B). The larger amount of economic slack implied by the lower-bound constraint reduces price pressures and, thus, inflation further, giving rise to an adverse feedback-loop operating in particular through the real-interest-rate channel. Additional channels in the model that contribute to the amplification of the demand shock at the lower bound include a rise in bond and loan premia and an appreciation of the real exchange rate.

[15] In principle, the economy can fall into a deflationary spiral if deflation pressures become so severe that the lower bound eventually restricts the real interest rate at a level high enough to induce a growing aggregate demand imbalance. For the simulations carried out with NAWM II, such instabilities did not occur, but at times the computational effort to obtain the solution of the model increased considerably when the lower-bound episode turned out to be very severe; see the Appendix for further discussion.

[16] The various predictive distributions are shown in Figure A.3 of the Appendix.

To discern the differences in the effectiveness of the three different state-dependent policies in mitigating the consequences of the adverse demand shock in the presence of the lower bound, Figure 3 shows the simulation outcomes for a larger set of variables, including the output gap (instead of real GDP growth) as well as the size of the asset purchases and of the spending-based fiscal stimulus triggered by the demand shock. For the sake of expositional clarity, the simulation outcomes are shown as percentage-point deviations from the December 2018 BMPE baseline paths, except for the outcomes for the short-term nominal interest rate which are displayed in levels. The two cases when the lower bound is taken into account, whilst not allowing for the deployment of state-dependent policies, and when the lower-bound constraint is disregarded (solid red lines and dashed red lines, respectively) provide benchmarks for assessing the relative effectiveness of the different state-dependent policies. Both asset purchases (solid blue lines) and fiscal stimulus (dashed blue lines) succeed in dampening the impact of the adverse demand shock on output and inflation to a comparable, albeit moderate, extent, with the impact on inflation being generally more muted.[17] At the same time, asset purchases and fiscal stimulus lead to a slightly swifter increase in the short-term nominal interest rate after its lift-off from the lower bound because of their positive effects on output and inflation. When asset purchases and fiscal stimulus are deployed jointly (dotted blue lines), the dampening impacts on output and inflation are strengthened, with the provision of fiscal stimulus modestly reducing the amount of asset purchases, and vice versa.

Strong interest-rate forward guidance (solid green lines) results in outcomes that are close to those for the unconstrained benchmark case. This finding reflects the fact that the baseline short-term interest-rate path is moderately upward sloping over the outer years of the projection horizon so that the implied low-for-longer policy prescription provides non-negligible policy support. If weak (dashed green lines), the effectiveness of forward guidance is markedly reduced, with outcomes closer to those obtained when using asset purchases or fiscal stimulus alone. However, if the effectiveness of forward guidance is enhanced because of its combination with asset purchases (dotted green lines), the outcomes are again much more favourable. In the case of strong forward guidance the interest rate lifts off from the effective lower bound about three quarters later than in the constrained benchmark case. The timing of interest-rate lift-off is broadly unchanged when forward guidance is weak or enhanced, but with the increase in the interest rate thereafter being more gradual as the

[17] The relative differences in the effects of the two policies on output and inflation are in part explained by their differential impact on the real exchange rate; see Figures A.1 and A.2 in the Appendix.

remaining output and inflation shortfalls are larger.

The above illustration of the effects of an adverse demand shock provides a qualitative indication of the efficacy of the different state-dependent policies in overcoming the impairments due to the lower-bound constraint. Below we use two different metrics to quantify both the impairments and the efficacy of the state-dependent policies on the basis of the model-based predictive distributions around the December 2018 BMPE baseline. In this context, we consider a slightly more varied set of policies with the aim of exploring the sensitivity of their effects to policy-relevant changes in their implementation.

4.2.2 Deflation and recession risks, and lower-bound incidence

We first assess the importance of downside risks to the December 2018 BMPE baseline and the efficacy of the different state-dependent policies in mitigating their amplification through the effective lower bound. We do this on the basis of quantitative *risk measures* calculated from the model-based predictive distributions, as in Coenen and Warne (2014). In particular, we associate downside risks to the baseline outlook with the emergence of *deflation*, which can be defined as the event that annual inflation falls below zero for at least four consecutive quarters, and with the slide of the economy into *recession*, which is defined, as usual, as the event that quarterly real GDP growth is negative for at least two consecutive quarters. Our definition of deflation risk is motivated by the widely-held view that negative inflation rates ought to become a concern for policy-makers only in cases where they are persistent and translate in a sustained fall in the aggregate price level.[18] In measuring deflation risk, we also consider the *severity* of the deflation event, which is calculated as the mean value of inflation conditional on the economy being in a deflation state. This measure is of interest because the severity of the deflation event, together with its probability, determines the expected loss associated with the emergence of deflation which policy-makers obviously want to keep strictly contained. Finally, we also consider a measure of conditional deflation risk, which concerns deflation events conditional on being in a recession state. This measure is more likely to capture a genuine deflation event resulting from a severe economic downturn, as opposed to a disinflation event caused by a sequence of favourable supply-side shocks. The different risk measures are complemented by a measure of the *lower-bound incidence* which is calculated as the frequency that the

[18]The confidence bands of the predictive distributions for consumer price inflation shown in Figure 1 and Appendix Figure A.3 allow for spells of inflation below zero that are shorter than four consecutive quarters. Since the shortest spell can be only one quarter, the confidence bands represent short-term as well as medium-term risks. The focus of the analysis in this paper is on the latter. Probabilities for differing definitions of deflation events can be easily obtained from the predictive distributions for inflation.

short-term nominal interest rate is constrained by the effective lower bound for at least one quarter over the BMPE horizon.

Our findings regarding the importance of downside risks to the outlook and the relative efficacy of non-standard-policies in mitigating their amplification through the lower bound are summarised in Table 1. As benchmarks for our assessment, we use the values of the risk measures obtained for the two cases when the lower bound is taken into account, whilst not allowing for additional state-dependent policies, and when the lower bound is disregarded; see the two items in the bottom panel of the table. In the constrained benchmark case, the short-term nominal interest rate is found to be stuck at the lower bound with an incidence of 34.8% (computed as an average across all quarters of the BMPE horizon). Evidently, this heightened incidence is in large part caused by the fact that the short-term interest rate in the baseline is expected to stay close to the lower bound over the BMPE horizon. It comes along with elevated downside risks to the inflation outlook, with a deflation probability of 9.5% and a conditional inflation mean of -1.7%. The recession probability is found to equal 20.9% and implies a conditional deflation probability of 7.8%, which is almost 2 percentage points lower than the unconditional deflation probability, suggesting that supply-side shocks are relatively important in causing deflation spells. If the lower-bound constraint were non-existent, the values of these risk measures would be markedly lower. In particular, the conditional deflation risk would be less than half as large as the risk for the constrained benchmark case, supporting the view that the consequences of the lower-bound constraint are particularly severe in the event of recessionary shocks.

As regards the risk-mitigation effects of state-dependent policies, panel A in Table 1 reports the risk measures and the lower-bound incidence when asset purchases and fiscal stimulus are deployed in the absence of state-dependent forward guidance. Asset purchases carried out alone are found to lower deflation and recession risks the more, the more sensitive they are to emerging interest-rate shortfalls, although the reduction of the deflation and recession risk measures remains modest and barely exceeds, respectively, 0.4 and 0.6 percentage point even when asset purchases respond strongly to interest-rate shortfalls, underpinning the case for sizeable purchases to bring about substantive effects. In relative terms, the mitigating effect on the conditional deflation risk is notably larger, suggesting that asset purchases prove particularly effective in case a deflation event is demand-driven. At the same time, asset purchases lead to a decline in the lower-bound incidence as they tend to bring forward the lift-off of the interest rate from the effective lower bound. Spending-based fiscal stimulus is found to result in broadly comparable risk-mitigation effects, at least if its deployment is not subject to a threshold. This suggests that the timely provision of fiscal stimulus in an economic downturn with interest rates at their lower bound is important to reap its full effect. If strong asset purchases and timely fiscal stimulus are deployed jointly, the risk-mitigation effects are noticeably enhanced.

Details on the size of the asset purchases carried out (measured in terms of the central bank's accumulated asset holdings as a percentage of annual GDP) and of the fiscal stimulus provided (measured as a percentage of GDP) are reported in panel A of Table 2. The reported values are the means and the 95th percentiles of their predictive distributions, which are calculated for each individual calendar year covered by the BMPE horizon.[19] Both asset holdings and fiscal stimulus are rising over time, as the lower-bound constraint is increasingly often binding and the implied interest-rate shortfall widens. Obviously, asset purchases are more sizeable if the sensitivity of their response to the interest-rate shortfall is higher. Nevertheless, even if the response is strong, the central bank's asset holdings by the final year of the BMPE horizon remain contained, with a mean of slightly above 5% of GDP. Similarly, the average fiscal stimulus barely exceeds 0.3% of GDP. However, in extreme circumstances, as measured by the 95th percentiles of the distributions, both asset holdings and fiscal spending can be very sizeable, amounting to roughly 20% and 1.2% of GDP. If deployed together, asset holdings and fiscal spending are somewhat reduced and reach, respectively, around 18.5% and 1.1% of GDP.

Finally, turning to the effects of state-dependent forward guidance, panel B of Table 1 shows that the risk measures are substantially reduced and only moderately higher than in the unconstrained benchmark case if the forward guidance policy is strong. It is noteworthy that the implied lower-bounded incidence of roughly 44% is markedly higher, in line with the low-for-longer prescription for the interest rate. If interest-rate forward guidance is weak, the risk measures are reduced considerably less, and the lower-bound incidence rises further to 46.7% as the central bank needs to keep interest rates low for even longer ex post. In the case that forward guidance is enhanced through central bank asset purchases the effectiveness is largely restored. When fiscal stimulus is provided in addition, the values of the risk measures diminish further and can get even close to those for the unconstrained benchmark case. As can be seen in panel B of Table 2, the provision of interest-rate forward guidance further reduces the amount of state-dependent asset purchases and fiscal spending, both on average and in extreme circumstances.

[19] The results for the year 2018 are not shown as they are quantitatively negligible.

4.2.3 Effects on the means of inflation and growth

As a second metric in our assessment of the efficacy of the different state-dependent policies in the near term, Table 3 reports the effects of the lower-bound constraint on the means of the model-based predictive distributions for consumer price inflation and real GDP growth. As a benchmark for the assessment, we consider the case where the lower bound is taken into account, but without state-dependent policies; see the bottom panel of the table. In this case, the means of the predictive distributions fall persistently below the baseline paths over the full horizon of the December 2018 BMPE. The corresponding downward bias in inflation builds up gradually and reaches, in absolute value, 0.2 percentage point in the final year of the BMPE, whereas the bias in real GDP growth rises, in absolute value, to a level of 0.4 percentage point in the middle year of the BMPE.[20]

The results presented in the upper two panels of Table 3 broadly confirm the findings based on the model-based risk measures, as reported in Table 1. First, asset purchases and fiscal stimulus, regardless of whether they are deployed individually or jointly, can diminish the downward biases in inflation and GDP growth due to the lower bound, but only to a limited extent. Second, strong forward guidance succeeds in substantially reducing the absolute maximum of the biases to, respectively, 0.01 and 0.13 percentage point. Third, weak forward guidance is noticeably less effective in reducing the biases. And lastly, enhanced forward guidance with strong asset purchases, and possibly combined with fiscal stimulus, is about as effective as strong forward guidance.

5 Macroeconomic stability in a low-real-interest-rate world

Following the analysis of the near-term consequences of the lower bound on the basis of NAWM II-based predictive distributions around the December 2018 BMPE baseline, we now adopt a long-run perspective and analyse the impact of a permanent fall in the equilibrium real interest rate on the efficacy of monetary policy in safeguarding macroeconomic stability. To this end, we study the unconditional probability distributions for inflation, the output gap and the short-term nominal interest rate under alternative assumptions for the equilibrium real rate in the presence of the lower bound. These distributions are obtained by conducting stochastic simulations with NAWM II around its respective non-stochastic steady state subject to the lower-bound constraint. Based on the model-based *steady-state distributions*, we first gauge the ability of monetary policy to stabilise inflation

[20] As in Table 2, the results for the year 2018 are not shown as they are quantitatively negligible.

and the output gap when it can only resort to its standard interest-rate instrument. We then proceed and examine the extent to which state-dependent forward guidance, asset purchases and fiscal stimulus can overcome the distortions due to the lower bound and restore macroeconomic stability.

5.1 The equilibrium real interest rate and macroeconomic stability

Our analysis of the consequences of a fall in the equilibrium real interest rate for macroeconomic stability is carried out for alternative values of the model's annualised steady-state real interest rate, $r^* = 400 \cdot \log(\bar{R}^r)$. Specifically, we consider values for r^* equal to 2%, 1% and 0%, which roughly span the range of values circumscribing the documented secular decline in the long-run equilibrium real interest rate over the past two decades.

As benchmarks for assessing the efficacy of the different state-dependent policies, Table 4 presents a set of summary statistics characterising the steady-state distributions obtained for the three alternative values of r^* under the assumption that monetary policy can only use its standard interest-rate instrument, either with or without taking into account the lower-bound constraint. These statistics provide information on the lower-bound incidence, which is measured by the frequency (i.e. the number of times, the short-term nominal interest rate is at the lower bound) and by the average duration of lower-bound events (in terms of quarters), and on the means, the standard deviations and the root mean-squared deviations (RMSDs) of inflation and the output gap.[21] The latter statistics are computed with respect to the non-stochastic steady-state values of 1.9% for inflation (equal to the assumed inflation objective) and of zero for the output gap.

Comparing the summary statistics for the two cases with and without the lower-bound constraint, the results in Table 4 suggest that, in an environment with a permanently lower long-run equilibrium real interest rate, the lower-bound constraint, if unaddressed, is likely to lead to a significant deterioration of macroeconomic stability, as reflected in the inflated RMSDs of the steady-state distributions for inflation and the output gap. The detrimental consequences of the lower bound are the larger, the lower the equilibrium real interest rate is: As the equilibrium real rate falls from 2% to zero, the lower-bound frequency rises from 10.3% to 24.0%, while the average duration of the lower-bound episodes increases from 7.0 to 9.6 quarters. In parallel with the increase in the lower-bound incidence, the RMSDs for

[21] In conducting the stochastic simulations for obtaining the model's steady-state distributions, the lower-bound constraint is imposed at a level of -45 basis points, accounting for a small spread between the EURIBOR and the ECB's deposit facility rate, which has been equal to -50 basis points at the time when the simulations were conducted. For further details on the stochastic simulations see the Appendix.

inflation and the output gap rise from 2.9% and 6.0% to 4.2% and 8.6%, respectively. These inflated RMSDs reflect both sizeable shortfalls in the means of the respective distributions, i.e. downward biases, as well as markedly higher standard deviations.

5.2 The efficacy of state-dependent policies in restoring macroeconomic stability

Table 5 reports the same set of summary statistics for the steady-state distributions obtained for different configurations of state-dependent asset purchases, fiscal stimulus and forward guidance. As shown in panel A of the table, when deployed individually, state-dependent asset purchases and fiscal stimulus can redress a noticeable part of the distortions due to the lower-bound constraint.[22] That is, both asset purchases and fiscal stimulus succeed in lowering the RMSDs for inflation and the output gap relative to the constrained benchmark case (see Table 4). However, the shortfalls in inflation and the output gap and the magnitude of the standard deviations remain sizeable, notably for values of the equilibrium real rate below 1%. Fiscal stimulus turns out to be more effective than asset purchases in offsetting the shortfall of inflation, whereas asset purchases have a stronger offsetting effect on the output-gap shortfall, especially if the equilibrium real rate equals zero and the consequences of the lower-bound constraint are particularly severe. The effects of the two policies on the respective standard deviations are more even. Within our model, these findings can be explained by the dominant impact of asset purchases on investment and the associated disinflationary effects over the medium term. These effects eventually result in an increase in the real interest rate and an appreciation of the real exchange rate when the lower-bound constraint binds, curbing aggregate demand and inflation. In contrast, the impact of fiscal stimulus on aggregated demand is weakened over the medium term because of crowding out of private spending, with more contained effects on inflation.[23]

When asset purchases are combined with fiscal stimulus, the shortfalls of inflation and the output gap can be reduced more substantially and in a broadly balanced manner. Focusing on the case with an equilibrium real rate of zero, the average of the RMSDs for inflation and the output gap drops from 6.4% for the constrained benchmark case (see Table 4) to 4.8%, even though noticeable shortfalls in the respective means persist. This

[22] Note that the results shown in panel A focus on the cases of strong asset purchases and fiscal stimulus without a threshold. Complementary analysis concerning alternative specifications of the asset-purchase and fiscal-stimulus policies is summarised in Section 5.3.

[23] Figures A.1 and A.2 in the Appendix show illustrative simulations of the effects of (autonomous) asset purchases and fiscal spending. For a more extensive discussion of the transmission channel of asset purchases in the model, see Section 2.

involves substantial asset purchases by the central bank resulting in asset holdings of, on average, 11.4% of annual GDP and a sizeable fiscal stimulus of, on average, 0.8% of GDP. In extreme circumstances, however, the size of the asset holdings and the amount of fiscal stimulus can become far larger, as indicated by the 95th percentile of the respective distribution with values of around 60% and 4%, respectively. It is noteworthy that the provision of fiscal stimulus lessens the need for carrying out very large asset purchases, with the mean and the 95th percentile of the central bank's asset holdings being reduced by more than one fourth compared to case when asset purchases are carried out individually.

As shown in panel B of Table 5, strong forward guidance also succeeds in mitigating the distortions due to lower bound. In line with the implied low-for-longer prescription for the short-term nominal interest rate, the lower-bound incidence rises, both in terms of frequency and duration. In particular, for an equilibrium real rate of zero the lower-bound frequency increases from 24% for the constrained benchmark case to 31.8%, while the duration rises from around 9.5 quarters to 18.3 quarters. However, the reduction in the average RMSD for inflation and the output gap is only moderate and similar in size to that found for asset purchases and fiscal stimulus on their own. In particular, the means of inflation and the output gap continue to fall markedly short of the means for the unconstrained benchmark case (see Table 4) and, accordingly, the difference in the average RMSDs of, respectively, 5.2% and 4.4% remains substantial. This finding reflects the fact that, following recurrent and long-lived lower-bound episodes, the amount of monetary stimulus implied by strong forward guidance is eventually insufficient to overcome the upward pressure on the real interest rate from persistent deflationary shocks even when the short-term nominal interest rate is expected to stay at the lower bound over a significantly extended period.

Obviously, weak forward guidance is less effective than strong forward guidance and results in larger RMSDs. In contrast, enhanced forward guidance with asset purchases can become even more effective than strong forward guidance, especially as regards output stabilisation, whereas the inflation shortfall persists and eventually worsens for increasingly lower levels of the equilibrium real rate. If additional fiscal stimulus is provided, macroeconomic stability is further increased, eventually getting close to the unconstrained benchmark case. When all policies are combined, the average amount of assets purchased is reasonable, as is the average size of the fiscal stimulus. But the amount of asset purchases can still be substantial, with the 95th percentile of central bank asset holdings moderately exceeding 45% of GDP even when fiscal stimulus of more than 3% of GDP helps to keep them contained. All in all, with increasingly lower equilibrium real interest rates, a combination of all three policies is needed to materially reduce the lower-bound distortions.

To visualise the key findings of our quantitative study of the efficacy of the three different state-dependent policies in a low-real-interest-rate world, Figure 3 depicts the average RMSDs of the respective steady-state distributions for inflation and the output gap in the form of bar charts. In these charts, the RMSDs are shown as percentage deviations from the RMSDs of the unconstrained benchmark case, whereas the red squares indicate the relative RMSDs of the constrained benchmark case without state-dependent policy support. As can be seen, the state-dependent policies succeed individually in more than halving the distortions due to the lower bound. In contrast, when deployed in combination they can basically eliminate the lower-bound distortions for values of the equilibrium real interest rate as low as 1%, whereas the distortions are reduced to less than one-twentieth for an equilibrium real rate of zero.

5.3 Complementary analysis

With a view to corroborating the findings of our quantitative study of the efficacy of state-dependent policy support in a low-real-interest-rate world, this section summarises complementary analysis provided in the Appendix of this paper. First, regarding the specification of the state-dependent asset-purchase and fiscal stimulus rules outlined in Section 3.2, panels A and B in Appendix Table A.1 show that implementing merely moderate asset purchases and fiscal stimulus subject to a threshold (equal to a one percentage-point interest-rate shortfall) leads to a noticeable deterioration in stabilisation performance for low equilibrium real rates. At the same time, the central bank's accumulated asset holdings and the amount of fiscal spending turn out to be markedly smaller, whereas the lower-bound incidence is generally somewhat higher. This suggests that carrying out merely timid asset purchases and delaying the deployment of fiscal stimulus in a situation where the standard interest-rate instrument has reached the lower bound is not conducive.

Second, panel C in Appendix Table A.1 considers the case of strong asset purchases when the state-dependent rule features an AR(1) component with autoregressive parameter $\rho_a = 0.9$, instead of the benchmark AR(2) specification. This specification is of interest because the implied pattern of central bank asset holdings is fully synchronised with the path of the shadow interest rate (see footnote 11 for details). Under this specification, and in the absence of a persistent interest-rate shortfall, the peak effect on the central bank's asset holdings is already reached in the initial period without any further increase. Hence, the overall amount of asset purchases is smaller and the stabilisation performance of the rule is worse compared to the benchmark rule with the AR(2) component. In the light of this finding, panel C also reports the outcomes for an AR(1) rule resulting in "very strong" initial asset purchases (with sensitivity parameter $\alpha_a = 2.0$). For this rule, the stabilisation performance is closer to the performance under the benchmark AR(2) rule, while the implied asset holdings are still somewhat smaller.

Lastly, Appendix Table A.2 reports the outcomes for the two benchmark cases of constrained and unconstrained interest-rate policy under the model's estimated interest-rate rule. This rule differs from the calibrated rule used in our study by allowing for a marked reaction to output growth, over and above a small reaction to the output gap. The reported outcomes show that the performance of the two rules is broadly comparable in the absence of the lower-bound constraint. Yet, in the presence of the lower bound, the performance of the estimated rule deteriorates sharply, with the average RMSD for inflation and the output gap reaching double-digit levels for an equilibrium real rate of zero. This very poor performance reflects the fact that, in periods with a binding lower-bound constraint, it can be highly detrimental to raise interest rates when growth is picking up following a recession, with the output gap still being negative and continued deflationary pressures.

6 Conclusions

The end of the Great Moderation and the secular fall in the equilibrium real interest rate have increased the frequency and the length of periods with nominal interest rates at their effective lower bound and have challenged the flexible inflation targeting regimes with an inflation target of around 2%, which prevail in many advanced economies. In this paper we address this challenge quantitatively by conducting stochastic simulations with the ECB's NAWM II under a Taylor-type interest-rate rule consistent with the ECB's monetary policy framework aimed at keeping inflation close to, but below, 2%.

The paper has two main findings. First, it shows that the effective lower bound, if unaddressed, can have substantial macroeconomic costs. In the current low-interest-rate environment, the lower bound amplifies the impact of adverse shocks on inflation and GDP growth, leading to elevated deflation and recession risks and a downward bias in the respective predictive distributions. Following the Covid-19 pandemic, these costs might be exacerbated because of an increase in precautionary savings in response to the heightened level of uncertainty and because of lasting behavioural changes, putting further downward pressure on the equilibrium real interest rate. Similarly, in the long run with a permanently lower equilibrium real rate, the lower-bound constraint impairs macroeconomic stability by substantially inflating the standard deviations of the steady-state distributions for inflation and the output gap and causing noticeable shortfalls in their means. And second, the paper finds that state-dependent forward guidance, asset purchases and fiscal stimulus that set in when the short-term nominal interest rate reaches its lower bound can largely undo these distortions. In the current low-interest-rate environment, fully credible forward guidance, whereby the short-term rate is kept low for longer depending on the severity of economic downturns and inflation shortfalls, is found to be most powerful. While this finding may be affected by the forward-guidance puzzle of New Keynesian DSGE models, the paper also shows that a combination of imperfectly credible forward guidance, asset purchases and fiscal stimulus is almost equally effective, in particular when the conduct of asset purchases enhances the credibility of the forward-guidance policy through a signalling effect. In the long run, with a permanently lower equilibrium real rate, a combination of all three policies is needed to materially reduce the lower-bound distortions.

Our findings are of relevance for the review of monetary policy frameworks that some major central banks have recently embarked on. On the one hand, they suggest that it is of utmost importance that central banks maintain their approximate 2% inflation buffer in order not to compound the distortions resulting from the effective lower bound in a lasting low-interest-rate environment. On the other hand, with effective non-standard monetary policy instruments and appropriate fiscal policies there may be no need to raise the prevailing inflation targets from around 2% to higher values, as suggested by a number of renowned economists. More analysis is, however, needed to investigate the robustness of our findings using different modelling approaches. In particular, our analysis based on NAWM II assumes forward-looking rational expectations, which enhance the effectiveness of systematic state-dependent monetary and fiscal policies. Examining the performance of such policies under alternative expectation formation mechanisms is an important item on central banks' research agenda. Moreover, NAWM II assumes a particular, though empirically plausible, transmission channel of asset purchases and has a relatively simple account of the effects of fiscal policy. Hence, the robustness of the findings with respect to alternative transmission channels of, and synergies between, the different state-dependent policies also needs to be investigated. We leave this for future research.

References

Andrade, P., J. Galí, H. Le Bihan, and J. Matheron (2018). The optimal inflation target and the natural rate of interest. Banque de France Working Paper No. 670.

Bernanke, B. S. (2017). Monetary policy in a new era. Paper prepared for "Rethinking Macroeconomic Policy", a conference held at the Peterson Institute for International Economics, Washington, DC, October 12.

Bernanke, B. S., M. T. Kiley, and J. M. Roberts (2019). Monetary policy strategies for a low-rate environment. *AEA Papers and Proceedings 109*(May), 421–426.

Bhattarai, S., G. Eggertsson, and B. Gafarov (2015). Time consistency and the duration of government debt: A signalling theory of quantitative easing. National Bureau of Economic Research, Working Paper 21336.

Blanchard, O. J. (2019). Public debt and low interest rates. *American Economic Review 109*(4), 1197–1229.

Boneva, L., R. Harrison, and M. Waldron (2018). Threshold-based forward guidance. *Journal of Economic Dynamics and Control 90*(C), 138–155.

Brand, C., M. Bielecki, and A. Penalver (2018). The natural rate of interest: Estimates, drivers, and challenges to monetary policy. European Central Bank, Occasional Paper Series No. 217.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics 12*(3), 383–398.

Carlstrom, C. T., T. S. Fuerst, and M. Paustian (2012). Inflation and output in New Keynesian models with a transient interest rate peg. Federal Reserve Bank of Cleveland, Working Paper 12-34.

Carlstrom, C. T., T. S. Fuerst, and M. Paustian (2017). Targeting long rates in a model with segmented markets. *American Economic Journal: Macroeconomics 9*(1), 205–242.

Christoffel, K., G. Coenen, and A. Warne (2008). The New Area-Wide Model of the euro area: A micro-founded open-economy model for forecasting and policy analysis. European Central Bank, Working Paper Series No. 944.

Chung, H. T., É. Gagnon, T. Nakata, M. Paustian, B. Schlusche, J. Trevino, D. Vilán, and W. Zheng (2019). Monetary policy options at the effective lower bound: Assessing the Federal Reserve's current policy toolkit. Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2019-003.

Chung, H. T., J.-P. Laforte, D. Reifschneider, and J. C. Williams (2012). Have we underestimated the likelihood and severity of zero lower bound events? *Journal of Money, Credit and Banking 44*(1), 47–82.

Coenen, G. (2003). Zero lower bound: Is it a problem in the euro area? European Central Bank, Working Paper Series No. 269.

Coenen, G., P. Karadi, S. Schmidt, and A. Warne (2018). The New Area-Wide Model II: An extended version of the ECB's micro-founded model for forecasting and policy analysis with a financial sector. European Central Bank, Working Paper Series No. 2200.

Coenen, G., A. Orphanides, and V. Wieland (2004). Price stability and monetary policy effectiveness when nominal interest rates are bounded at zero. *Advances in Macroeconomics 4*(1), Article 1.

Coenen, G. and A. Warne (2014). Risks to price stability, the zero lower bound and forward guidance: A real-time assessment. *International Journal of Central Banking 10*(2), 7–54.

Debortoli, D., J. Galí, and L. Gambetti (2018). On the empirical (ir)relevance of the zero lower bound constraint. Centre for Economic Policy Research, Discussion Paper DP12691.

Del Negro, M., M. Giannoni, and C. Patterson (2012). The forward guidance puzzle. Federal Reserve Bank of New York, Staff Report No. 574.

Eichenbaum, M. S. (2019). Rethinking fiscal policy in an era of low interest rates. Northwestern University, Maunscript.

Engen, E. M., T. Laubach, and D. Reifschneider (2015). Effects of the Federal Reserve's unconventional monetary policies. Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2015-005.

Eser, F., W. Lemke, K. Nyholm, S. Radde, and A. L. Vladu (2019). Tracing the impact of the ECB' asset purchase programme on the yield curve. European Central Bank, Working Paper Series No. 2293.

Gerali, A., S. Neri, L. Sessa, and F. M. Signoretti (2010). Credit and banking in a DSGE model of the euro area. *Journal of Money, Credit and Banking 42*(S1), 107–141.

Gertler, M. and P. Karadi (2011). A model of unconventional monetary policy. *Journal of Monetary Economics 58*(1), 17–34.

Gertler, M. and P. Karadi (2013). QE 1 vs. 2 vs. 3 . . .: A framework for analyzing large-scale asset purchases as a monetary policy tool. *International Journal of Central Banking 9*(1), 5–53.

Greenlaw, D., J. D. Hamilton, E. Harris, and K. D. West (2018). A skeptical view of the impact of the Fed's balance sheet. NBER Working Paper No. 24687.

Haberis, A., R. Harrison, and M. Waldron (2019). Uncertain policy promises. *European Economic Review 111*(January), 459–474.

Hamilton, J. D., E. S. Harris, J. Hatzius, and K. D. West (2016). The equilibrium real funds rate: Past, present and future. *IMF Economic Review 64*(4), 660–707.

Hartmann, P. and F. Smets (2018). The first 20 years of the European Central Bank: Monetary policy. *Brookings Papers on Economic Activity Fall*(49), 1–146.

Holston, K., T. Laubach, and J. C. Williams (2017). Measuring the natural rate of interest: International trends and determinants. *Journal of International Economics 108*(S1), S59–S75.

Jordà, Ò. and A. A. Taylor (2019). Monetary policy divergence. Paper prepared for the Jackson Hole Economic Policy Symposium on "Challenges for Monetary Polciy", hosted by the Federal Reserve Bank of Kansas City, August 22-24.

Kiley, M. T. (2018). Quantitative easing and the "new normal" in monetary policy. Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2018-004.

Kiley, M. T. and J. M. Roberts (2017). Monetary policy in a low interest rate world. *Brookings Papers on Economic Activity 48*(Spring), 317–372.

Laubach, T. and J. C. Williams (2016). Measuring the natural rate of interest redux. Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2016-011.

Mertens, T. M. and J. C. Williams (2019). Tying down the anchor: Monetary policy rules and the lower bound on interest rates. Federal Reserve Bank of San Francisco Working Paper 2019-14.

Nessén, M. and D. Vestin (2005). Average inflation targeting. *Journal of Money, Credit and Banking 37*(5), 837–863.

Rachel, L. and L. H. Summers (2019). On falling neutral real rates, fiscal policy, and the risk of secular stagnation. *Brookings Papers on Economic Activity Spring*(50), 1–76.

Reifschneider, D. (2016). Gauging the ability of the FOMC to respond to future recessions. Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series 2016-068.

Reifschneider, D. and J. C. Williams (2000). Three lessons for monetary policy in a low-inflation era. *Journal of Money, Credit and Banking 32*(4), 936–966.

Rostagno, M., C. Altavilla, G. Carboni, W. Lemke, R. Motto, A. Saint Guilhem, and J. Yiangou (2019). A tale of two decades: The ECB's monetary policy at 20. European Central Bank, Working Paper Series No. 2346.

Sims, E. and J. C. Wu (2019). Evaluating central banks' tool kit: Past, present, and future. Paper presented at the FedListens Conference on "Monetary Policy Strategy, Tools & Communication Practices", hosted by the Federal Reserve Bank of Chicago, June 4-5.

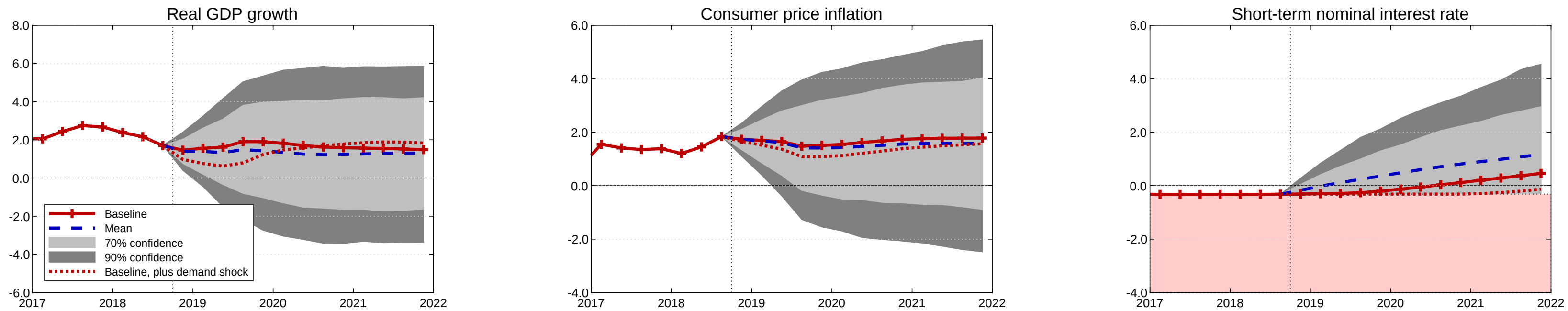
Taylor, J. B. (1993). Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy 39*(1), 195–214.

Vestin, D. (2006). Price-level versus inflation targeting. *Journal of Monetary Economics 53*(7), 1361–1376.

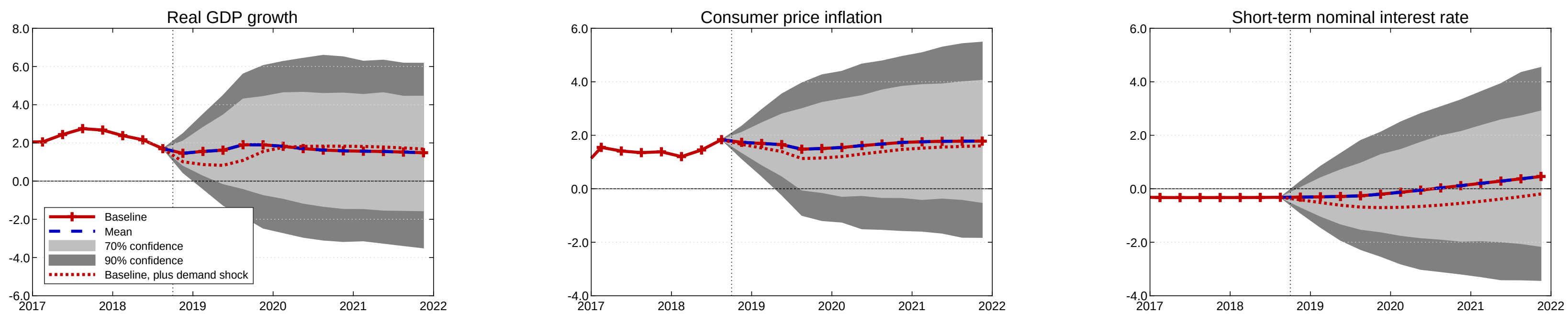
Williams, J. C. (2009). Heeding Daedalus: Optimal inflation and the zero lower bound. *Brookings Papers on Economic Activity 40*(Fall), 1–49.

Figure 1: Predictive distributions around the December 2018 BMPE baseline for real GDP growth, consumer price inflation and the short-term nominal interest rate

A. Effective lower bound imposed

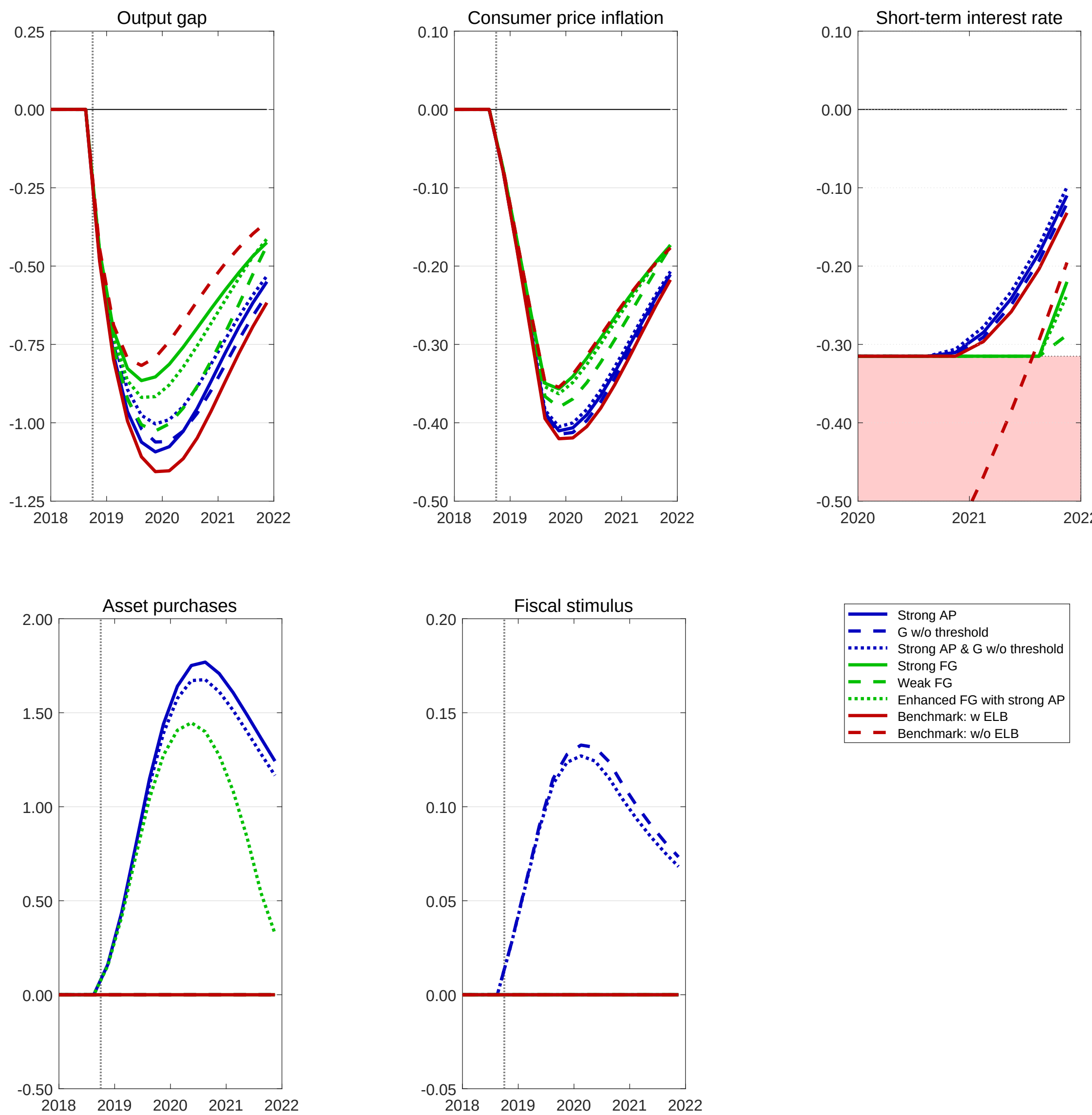


B. Effective lower bound not imposed



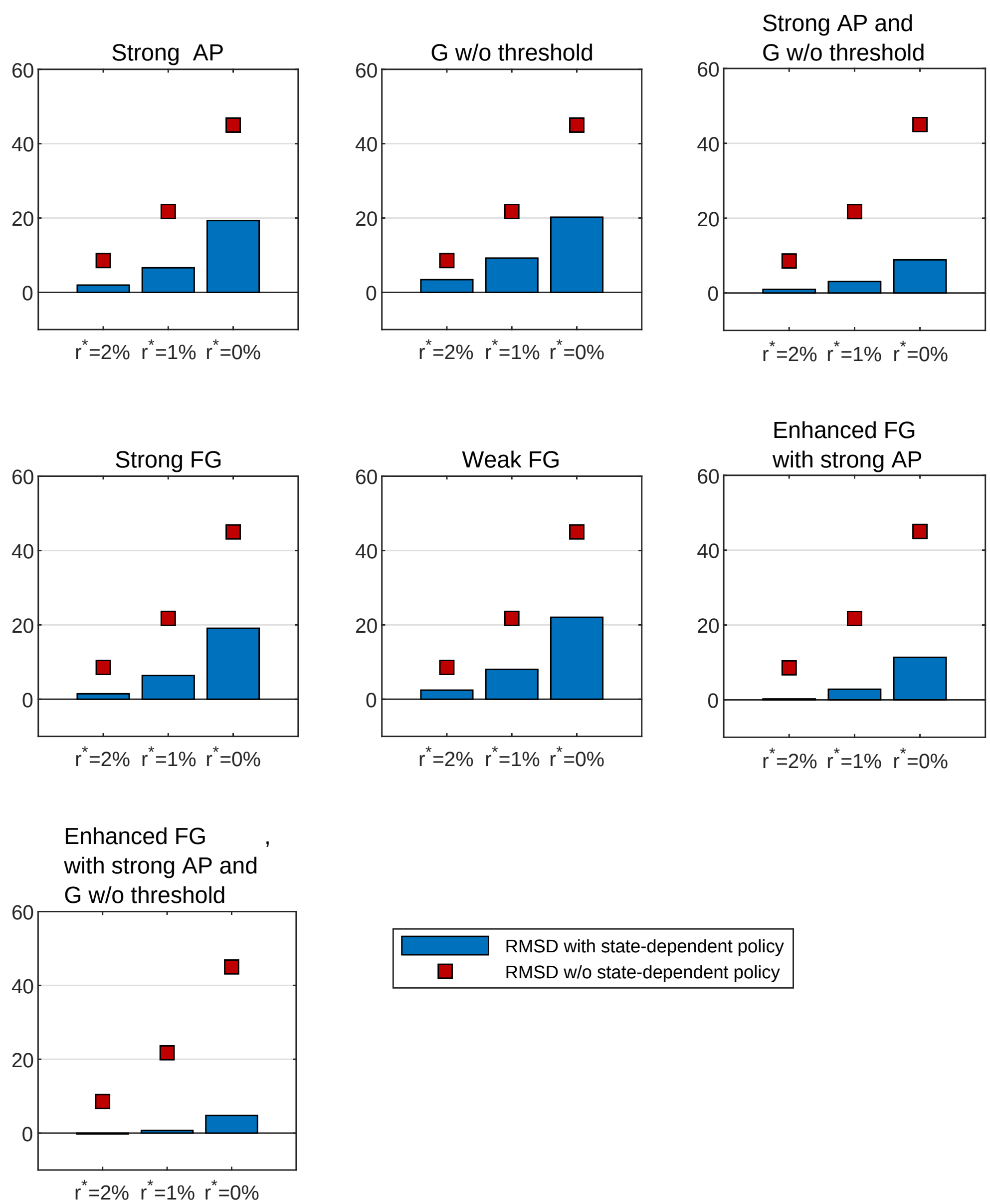
Note: This figure depicts predictive distributions for real GDP growth, consumer price inflation and the short-term nominal interest rate derived from stochastic simulations with NAWM II. The predictive distributions are centred on the structural shocks and the initial states that the model has identified for the December 2018 BMPE baseline projection. Real GDP growth and consumer price inflation (measured in terms of the private consumption deflator) are expressed as annual percentages. The short-term nominal interest rate corresponds to the 3-month EURIBOR, in percent. In the simulations that take into account the effective lower bound, the corresponding constraint is imposed at an interest-rate level of -31.5 basis points, equal to the value of the EURIBOR at the start of the December 2018 BMPE horizon; that is, 2018Q4. The simulated additional adverse demand shock corresponds to a one-off domestic risk premium shock of size equal to 1.5 standard deviations and occurs in 2018Q4.

Figure 2: Impact of an additional adverse demand shock on the December 2018 BMPE baseline under state-dependent policies



Note: This figure shows NAWM II-based deterministic simulations of an additional adverse demand shock superimposed on the December 2018 BMPE baseline, taking into account the effective lower bound (ELB) constraint and allowing for different state-dependent policies governing asset purchases (AP), fiscal stimulus (G) and forward guidance on interest rates (FG); see Section 3 for details on their specification. The shock corresponds to a one-off domestic risk premium shock of size equal to 1.5 standard deviations and occurs in 2018Q4. Asset purchases are measured by the central bank's holdings of assets, expressed as a share of annual steady-state GDP, in percent, whereas fiscal stimulus is measured by the amount of government spending, expressed as a share of quarterly steady-state GDP, in percent. The outcomes of the simulations are reported as percentage-point deviations from BMPE baseline values, except for the outcomes for the short-term nominal interest rate which are displayed in levels, expressed as annualised percentages.

Figure 3: Overall stabilisation performance of state-dependent policies for alternative values of the equilibrium real interest rate



Note: For alternative values of the annualised steady-state short-term real interest rate $r^* = 400 \cdot \log(\bar{R}^r)$ (expressed as a percentage), the blue bars in this figure show the average root mean-squared deviations (RMSDs) of the NAWM II-based steady-state distributions for inflation and the output gap for the state-dependent asset-purchase (AP), fiscal-stimulus (G) and forward guidance (FG) policies considered in Table 5. The red squares represent the RMSDs of the benchmark case with the effective lower bound being taken into account but without state-dependent policies. The RMSDs are plotted as percentage deviations from the RMSDs of the benchmark case without the lower bound.

Table 1: Effects of state-dependent policies on deflation and recession risks and on the lower-bound incidence

	Deflation risk	Severity of deflation	Recession risk	Conditional deflation risk	Lower-bound incidence
A. No forward guidance on interest rates					
Asset purchases:					
moderate	9.36	-1.67	20.58	7.31	34.46
strong	9.18	-1.65	20.26	6.73	34.13
Fiscal stimulus:					
with threshold	9.49	-1.69	20.76	7.46	34.73
w/o threshold	9.34	-1.67	20.56	7.09	34.33
Strong asset purchases and fiscal stimulus w/o threshold	9.02	-1.62	20.00	6.23	33.61
B. Forward guidance on interest rates					
Strong guidance	7.28	-1.49	19.28	4.24	44.05
Weak guidance	8.03	-1.55	19.57	5.37	46.67
Enhanced guidance with strong asset purchases	7.38	-1.50	19.15	4.24	46.22
Enhanced guidance with strong asset purchases and fiscal stimulus w/o threshold	7.31	-1.49	19.14	4.06	46.01
C. No state-dependent policies (benchmark)					
Lower bound imposed	9.54	-1.70	20.87	7.79	34.84
Lower bound not imposed	7.05	-1.45	18.84	3.60	—

Note: This table reports risk measures which are computed from NAWM II-based predictive distributions for consumer price inflation, real GDP growth and the short-term nominal interest rate. The distributions are derived from stochastic simulations which are centred on the structural shocks and the initial states that the model has identified for the December 2018 BMPE baseline projection. These simulations take into account an effective lower bound on nominal interest rates and are conducted for different specifications of the state-dependent asset-purchase and fiscal-stimulus rules (see equations (3) and (4) in Section 3.2), as well as under alternative assumptions about the effectiveness of state-dependent forward guidance on short-term nominal rates (see equation (2) in Section 3.1). Details on the parameterisation of the different state-dependent policies are provided in Section 3.3. Consumer price inflation is measured in terms of the private consumption deflator. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and the lower-bound constraint is imposed at an interest-rate level of -31.5 basis points, equal to the value of the EURIBOR at the start of the December 2018 BMPE horizon. All risk measures represent relative frequencies and are expressed in percent, except for the measure of the severity of deflation which equals the inflation mean conditional on being in a deflation state.

Table 2: Size of state-dependent asset purchases and state-dependent fiscal stimulus

	Asset purchases						Fiscal stimulus					
	2019		2020		2021		2019		2020		2021	
	Mean	95th	Mean	95th	Mean	95th	Mean	95th	Mean	95th	Mean	95th
A. No forward guidance on interest rates												
Asset purchases:												
moderate	0.84	3.12	1.93	7.34	2.68	10.17	—	—	—	—	—	—
strong	1.67	6.16	3.80	14.35	5.22	19.73	—	—	—	—	—	—
Fiscal stimulus:												
with threshold	—	—	—	—	—	—	0.03	0.18	0.07	0.40	0.10	0.55
w/o threshold	—	—	—	—	—	—	0.14	0.52	0.25	0.96	0.31	1.21
Strong asset purchases and fiscal stimulus w/o threshold	1.63	6.00	3.65	13.79	4.97	18.62	0.13	0.50	0.24	0.90	0.29	1.14
B. Forward guidance on interest rates												
Enhanced guidance with strong asset purchases	1.40	5.64	2.70	11.79	3.30	15.42	—	—	—	—	—	—
Enhanced guidance with strong asset purchases and fiscal stimulus w/o threshold	1.36	5.48	2.59	11.31	3.12	14.61	0.11	0.45	0.16	0.76	0.18	0.87

Note: This table reports the size of the central bank's accumulated asset holdings and of governing spending (expressed as a percentage of annual steady-state GDP) according to state-dependent rules that become active when the short-term nominal interest has fallen to the effective lower bound. The sizes of the asset holdings and government spending are measured by the means and the 95th percentiles of the respective predictive distributions. The results for the year 2018 are not shown as they are quantitatively negligible. See Table 1 for further explanations.

Table 3: Effects of state-dependent policies on the means of consumer price inflation and real GDP growth

	Consumer price inflation			Real GDP growth		
	2019	2020	2021	2019	2020	2021
A. No forward guidance on interest rates						
Asset purchases:						
moderate	-0.05	-0.14	-0.18	-0.31	-0.37	-0.20
strong	-0.05	-0.13	-0.16	-0.28	-0.33	-0.17
Fiscal stimulus:						
with threshold	-0.05	-0.15	-0.19	-0.31	-0.39	-0.22
w/o threshold	-0.05	-0.14	-0.17	-0.24	-0.36	-0.22
Strong asset purchases and fiscal stimulus w/o threshold	-0.04	-0.11	-0.14	-0.19	-0.28	-0.15
B. Forward guidance on interest rates						
Strong guidance	-0.00	-0.01	-0.01	-0.09	-0.13	-0.09
Weak guidance	-0.02	-0.05	-0.05	-0.21	-0.22	-0.11
Enhanced guidance with strong asset purchases	-0.01	-0.02	-0.02	-0.12	-0.12	-0.07
Enhanced guidance with strong asset purchases and fiscal stimulus w/o threshold	-0.01	-0.02	-0.02	-0.03	-0.10	-0.07
C. No state-dependent policies (benchmark)						
Lower bound imposed	-0.06	-0.15	-0.19	-0.34	-0.42	-0.24

Note: This table reports the mean effects on the NAWM II-based predictive distributions for consumer price inflation and real GDP growth due to the effective lower bound on nominal interest rates. All effects are expressed as percentage-point deviations from December 2018 BMPE baseline values. The results for the year 2018 are not shown as they are quantitatively negligible. See Table 1 for further explanations.

Table 4: Deterioration of macroeconomic stability due to the lower-bound constraint for alternative values of the equilibrium real interest rate

	Lower-bound incidence		Inflation			Output gap			Inflation and output gap
	Frequency	Duration	Mean	Std	RMSD	Mean	Std	RMSD	Average RMSD
A. Lower bound imposed									
$r^* = 2\%$	10.29	7.02	1.69	2.84	2.85	-1.24	5.91	6.04	4.44
$r^* = 1\%$	16.49	8.02	1.47	3.35	3.38	-2.50	6.45	6.92	5.15
$r^* = 0\%$	24.00	9.56	1.14	4.09	4.16	-4.56	7.30	8.61	6.38
B. Lower bound not imposed									
$r^* = 2\%$	—	—	1.90	2.40	2.40	0.00	5.77	5.77	4.09
$r^* = 1\%$	—	—	1.90	2.47	2.47	0.00	5.99	5.99	4.23
$r^* = 0\%$	—	—	1.90	2.54	2.54	0.00	6.25	6.25	4.40

Note: For alternative values of the equilibrium real interest rate $r^* = 400 \cdot \log(\bar{R}^r)$ (expressed as a percentage), this table reports summary statistics of the NAWM II-based steady-state distributions: the incidence of the lower-bound constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the effective lower bound, in percent, and the average duration of a lower-bound event, in quarters); and the mean, the standard deviation (std) and the (average) root mean-squared deviation (RMSD) of inflation and the output gap. The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with and without taking into account the lower bound. Inflation is measured in terms of the private consumption deflator. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and the lower-bound constraint is imposed at an interest-rate level of -45 basis points, accounting for a small spread between the EURIBOR and the ECB's deposit facility rate, which was equal to -50 basis points at the time when the simulations were conducted.

Table 5: Stabilisation performance of state-dependent policies for alternative values of the equilibrium real interest rate

	Lower-bound incidence		Inflation			Output gap			Inflation and output gap	Asset purchases		Fiscal stimulus	
	Frequency	Duration	Mean	Std	RMSD	Mean	Std	RMSD	Average RMSD	Mean	95th	Mean	95th
A. No forward guidance on interest rates													
Strong asset purchases													
$r^* = 2\%$	9.74	6.36	1.76	2.65	2.65	-0.70	5.64	5.68	4.17	3.81	22.91	—	—
$r^* = 1\%$	15.88	7.41	1.57	3.01	3.03	-1.41	5.82	5.99	4.51	7.84	45.15	—	—
$r^* = 0\%$	23.85	8.98	1.18	3.67	3.74	-2.73	6.18	6.76	5.25	15.42	80.59	—	—
Fiscal stimulus w/o threshold													
$r^* = 2\%$	9.68	6.49	1.78	2.69	2.69	-0.91	5.69	5.76	4.23	—	—	0.29	1.75
$r^* = 1\%$	15.44	7.38	1.67	3.04	3.05	-1.80	5.92	6.19	4.62	—	—	0.55	3.23
$r^* = 0\%$	22.43	8.66	1.50	3.52	3.54	-3.26	6.24	7.04	5.29	—	—	0.95	5.02
Strong asset purchases and fiscal stimulus w/o threshold													
$r^* = 2\%$	9.26	6.05	1.81	2.59	2.59	-0.57	5.63	5.66	4.13	3.14	19.14	0.22	1.32
$r^* = 1\%$	15.00	6.93	1.70	2.86	2.87	-1.12	5.74	5.85	4.36	6.15	35.27	0.42	2.44
$r^* = 0\%$	22.37	8.24	1.49	3.30	3.33	-2.08	5.90	6.26	4.79	11.38	58.69	0.78	4.07

Note: For alternative values of the equilibrium real interest rate $r^* = 400 \cdot \log(\bar{R}^r)$ (expressed as a percentage), this table reports summary statistics of the NAWM II-based steady-state distributions: the incidence of the lower-bound constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the effective lower bound), in percent, and the average duration of a lower-bound event, in quarters); the means, the standard deviations (std) and the (average) root mean-squared deviations (RMSD) of inflation and the output gap; and the sizes of the central bank's accumulated asset holdings and of government spending (measured by the means and the 95th percentiles of the respective steady-state distributions and expressed as a percentage of annual and quarterly steady-state GDP, respectively). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state. These simulations take into account the lower bound and are conducted for different specifications of the state-dependent asset-purchase and fiscal-stimulus rules (see equations (3) and (4) in Section 3.2), as well as under alternative assumptions about the effectiveness of state-dependent forward guidance on short-term nominal interest rates (see equation (2) in Section 3.1). Details on the parameterisation of the different state-dependent policies are provided in Section 3.3. Inflation is measured in terms of the private consumption deflator. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and the lower-bound constraint is imposed at an interest-rate level of -45 basis points, accounting for a small spread between the EURIBOR and the ECB's deposit facility rate, which was equal to -50 basis points at the time when the simulations were conducted.

Table 5: Stabilisation performance of state-dependent policies for alternative values of the equilibrium real interest rate (cont'd)

	Lower-bound incidence		Inflation			Output gap			Inflation and output gap	Asset purchases		Fiscal stimulus	
	Frequency	Duration	Mean	Std	RMSD	Mean	Std	RMSD	Average RMSD	Mean	95th	Mean	95th
B. Forward guidance on interest rates													
Strong guidance													
$r^* = 2\%$	13.44	12.02	1.85	2.57	2.57	-0.58	5.70	5.73	4.15	—	—	—	—
$r^* = 1\%$	21.65	14.24	1.77	2.88	2.88	-1.30	5.97	6.11	4.50	—	—	—	—
$r^* = 0\%$	31.81	18.31	1.58	3.42	3.43	-2.70	6.51	7.05	5.24	—	—	—	—
Weak guidance													
$r^* = 2\%$	14.08	12.81	1.83	2.62	2.62	-0.67	5.71	5.75	4.19	—	—	—	—
$r^* = 1\%$	22.53	15.13	1.72	2.95	2.96	-1.46	6.01	6.18	4.57	—	—	—	—
$r^* = 0\%$	32.84	19.32	1.51	3.51	3.53	-2.93	6.58	7.20	5.37	—	—	—	—
Enhanced guidance with strong asset purchases													
$r^* = 2\%$	13.46	11.90	1.85	2.54	2.54	-0.41	5.65	5.66	4.10	2.09	13.73	—	—
$r^* = 1\%$	21.85	14.22	1.74	2.81	2.81	-0.91	5.81	5.88	4.35	4.74	31.19	—	—
$r^* = 0\%$	32.42	18.60	1.47	3.36	3.39	-1.93	6.11	6.41	4.90	10.41	62.41	—	—
Enhanced guidance with strong asset purchases and fiscal stimulus w/o threshold													
$r^* = 2\%$	13.09	11.44	1.88	2.50	2.50	-0.34	5.65	5.66	4.08	1.74	11.73	0.12	0.83
$r^* = 1\%$	21.18	13.57	1.82	2.71	2.71	-0.74	5.77	5.82	4.26	3.77	25.18	0.26	1.75
$r^* = 0\%$	31.25	17.49	1.67	3.09	3.10	-1.51	5.93	6.12	4.61	7.78	46.95	0.53	3.26

Note: See above.

Appendix

A.1 Simulation and solution methods

In order to obtain the predictive distributions around the December 2018 BMPE baseline projection, we first computed the structural shocks and the state variables of NAWM II for the historical data extended with the projection data. To this end we solved the model for its reduced form using the AIM implementation (Anderson and Moore, 1985, and Anderson, 1987) of the Blanchard and Kahn (1980) method for solving linear rational expectations models and applied the Kalman filter to its (log-)linear state-space representation. Based on the population covariance matrix of the structural shocks and the conditional covariance matrix of the states at the origin of the projection horizon, we then generated 2,500 sequences of random shocks with a sample length corresponding to the projection horizon and 2,500 random realisations of the states.[1] We added the sequences of the random shocks (except for the shocks to the model's interest-rate rule which we set to zero) to the sequence of shocks computed over the projection horizon and used the resulting shock sequences, along with the random realisations of the states, to conduct stochastic simulations around the December 2018 BMPE baseline, while imposing the effective lower bound constraint on nominal interest rates and, where applicable, taking into account the threshold condition in the specification of the fiscal-stimulus rule.[2]

For obtaining the steady-state distributions of NAWM II we follow a similar approach. Based on the population covariance matrix of the structural shocks and the conditional covariance matrix of the states computed at the model's non-stochastic steady state, we first generated 2,500 sequences of random shocks with a sample length equal to 150 quarters and 2,500 random realisations of initial states. With these ingredients, we then conducted stochastic simulations around the non-stochastic steady state of the model, while imposing the lower-bound constraint and taking into account the fiscal-stimulus threshold. In order to ensure that the steady-state initialisation of the stochastic simulations does not materially influence the properties of the resulting steady-state distributions, we discarded the first

[1] That is, we only consider a fixed set of parameters, namely the posterior mode estimates of the model's structural parameters. Accounting for parameter uncertainty by drawing from the posterior distribution of the structural parameters would have been computationally too burdensome.

[2] As the stochastic simulations are centred on the structural shocks and the initial states which have been identified with the model for the BMPE projection baseline, it is actually not relevant that the model's (log-)linear state-space representation was used for that purpose even though the effective lower bound was eventually constraining the short-term nominal interest rate in recent years and over the projection horizon. Our simulation method also implies that all previous and expected policy measures of the ECB, including its asset purchases, are reflected in the shock sequences and the initial states for the BMPE baseline.

50 realisations of each of the simulated paths for the endogenous variables of interest and retained only the final 100 realisations.

We solved the non-linear model with the lower-bound constraint and the stimulus threshold using a computationally efficient and robust algorithm which is implemented in TROLL and based on work by Laffargue (1990), Juillard (1994) and Boucekkine (1995).[3] It is related to the Fair and Taylor (1983) extended-path algorithm. In the simulations, the lower-bound constraint and the threshold also apply to the expectations of future interest rates and fiscal stimulus. A limitation of the algorithm is that the expectations of economic agents are computed under the counterfactual assumption that *certainty equivalence* holds in the non-linear model being simulated. This means, when solving for the dynamic paths of the endogenous variables from a given period onwards, the algorithm sets future shocks equal to their expected value of zero. Thus the variance of future shocks has no bearing on the formation of expectations and, hence, on current conditions. This would be correct in a linear model. However once we introduce the lower bound on nominal interest rates into the model, the variance of future shocks introduces a small bias in the average levels of various variables, including interest rates.[4]

Another caveat of our solution approach relates to the fact that an exogenous nominal interest-rate will normally cause equilibrium indeterminacy in a model with forward-looking expectations such as NAWM II. So at some time in the future the nominal rate must become endogenous for a well-behaved equilibrium to result. The same reasoning applies to episodes with a binding lower-bound constraint. However, with all future shocks set to zero in our solution approach, we can ensure determinacy by choosing a sufficiently long horizon when solving for the dynamic paths of the endogenous variables such that there is an anticipated switch back to the model's interest-rate rule in the far future as well as convergence towards the model's non-stochastic steady state with inflation equal to the central bank's inflation objective. This excludes self-fulfilling declines in inflation expectations and convergence to a steady state in which the nominal interest rate is near the lower bound and inflation is possibly negative; see Benhabib et al. (2001).

[3]TROLL is an integrated econometric modelling and time-series management tool used by many central banks and international organisations. If it were not for the non-linearities, we could use the (log-)linear state-space representation of the model to compute the predictive distributions of the endogenous variables of interest without having to resort to a non-linear solution algorithm and to stochastic simulations.

[4]It should be noted that the variance of shocks has both a direct and an indirect effect on the simulation results. The direct effect is that a greater variance of shocks implies that the effective lower bound on nominal interest rates binds with greater frequency, the indirect effect is that all agents in the model should be taking this effect of the variance into account when they form their expectations. Our employed solution algorithm captures the direct effect but not the indirect one.

There are other solution algorithms for non-linear rational expectations models that do not impose certainty equivalence or account for possible self-fulfilling equilibria at the lower bound. But these alternative algorithms would be prohibitively costly to use with NAWM II, which has more than one hundred state variables. Even with the algorithm we are using, stochastic analysis of non-linear rational expectations models with a large number of state variables remains fairly costly in terms of computational effort.

References

Anderson, G. (1987). A procedure for differentiating perfect-foresight-model reduced-form coefficients. *Journal of Economic Dynamics and Control 11*(4), 465–481.

Anderson, G. and G. Moore (1985). A linear algebraic procedure for solving linear perfect foresight models. *Economics Letters 17*(3), 247–252.

Benhabib, J., S. Schmitt-Grohé, and M. Uribe (2001). The perils of Taylor rules. *Journal of Economic Theory 96*(1-2), 40–69.

Blanchard, O. J. and C. M. Kahn (1980). The solution of linear difference models under rational expectations. *Econometrica 48*(5), 1305–1311.

Boucekkine, R. (1995). An alternative methodology for solving nonlinear forward-looking models. *Journal of Economic Dynamics and Control 19*(4), 711–734.

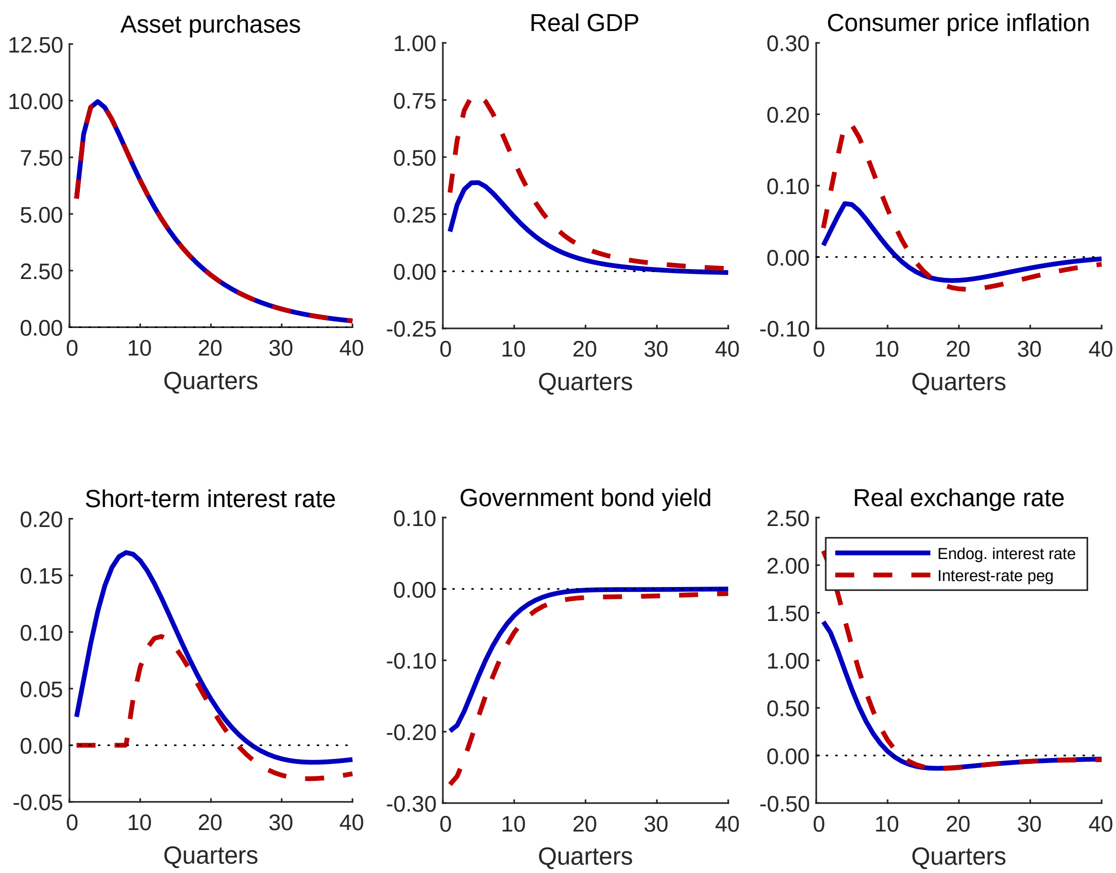
Fair, R. and J. B. Taylor (1983). Solution and maximum likelihood estimation of dynamic nonlinear rational expectations models. *Econometrica 51*(4), 1169–1185.

Juillard, M. (1994). DYNARE – A program for the resolution of non-linear models with forward-looking variables. Release 1.1, CEPREMAP, Manuscript.

Laffargue, J.-P. (1990). Résolution d'un modèle macroéconomique avec anticipations rationnelles. *Annales d'Économie et de Statistique 17*(Jan-Mar), 97–119.

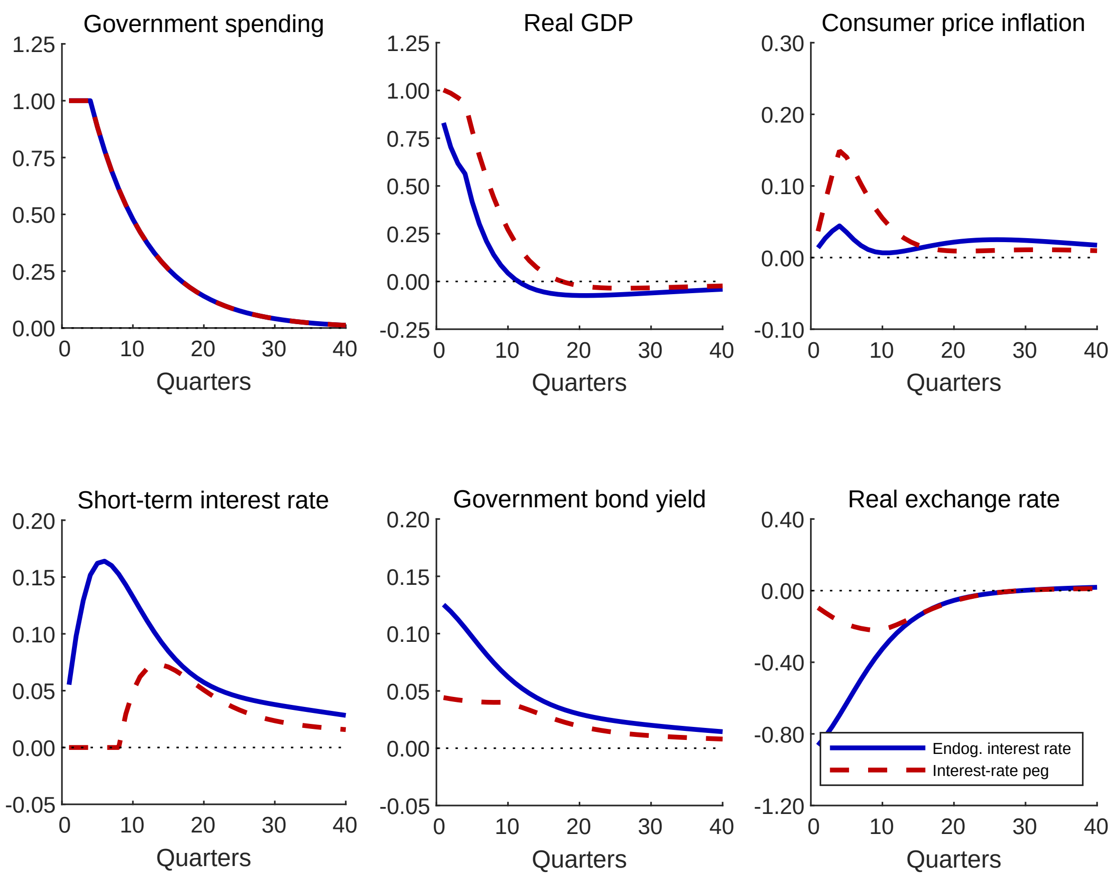
A.2 Additional figures and tables

Figure A.1: Effects of autonomous asset purchases



Note: This figure depicts the effects of a one-off asset-purchase shock, which follows an AR(2) process, as described in equation (3) of Coenen, Montes-Galdón and Smets (2021, Section 3.2). The size of the shock is calibrated such that the central bank's asset holdings reach a peak of 10% of annual steady-state GDP after 4 quarters. The effects are shown for the cases with an endogenous interest-rate reaction and with interest rates unchanged for 8 quarters and full credibility of the central bank's announcement thereof. The effects are reported as percentage deviations from the model's steady state, except for the effects on inflation and interest rates which are reported as annualised percentage-point deviations.

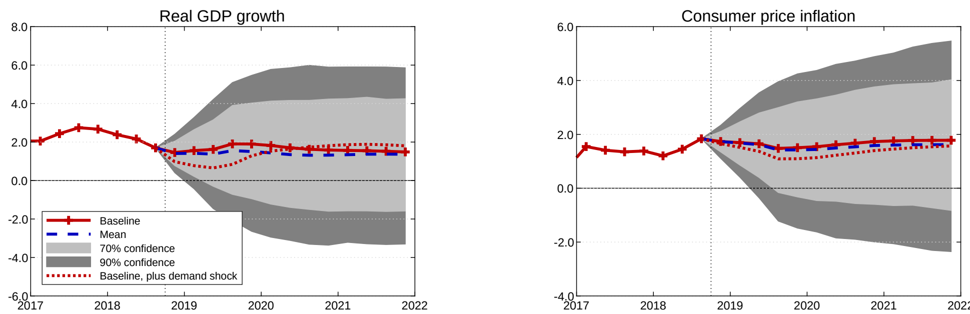
Figure A.2: Effects of autonomous fiscal stimulus



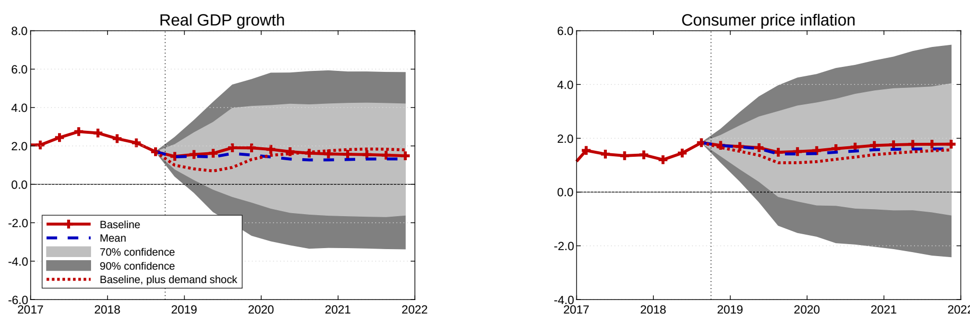
Note: This figure depicts the effects of an anticipated increase in autonomous government spending equal to 1% of steady-state GDP, which lasts 4 quarters and gradually decays thereafter following an AR(1) process, as described in equation (4) of Coenen, Montes-Galdón and Smets (2021, Section 3.2). The effects are shown for the cases with an endogenous interest-rate reaction and with interest rates unchanged for 8 quarters and full credibility of the central bank's announcement thereof. The effects are reported as percentage deviations from the model's steady state, except for the effects on inflation and interest rates which are reported as annualised percentage-point deviations.

Figure A.3: Predictive distributions around the December 2018 BMPE baseline for real GDP growth and consumer price inflation under different state-dependent policies

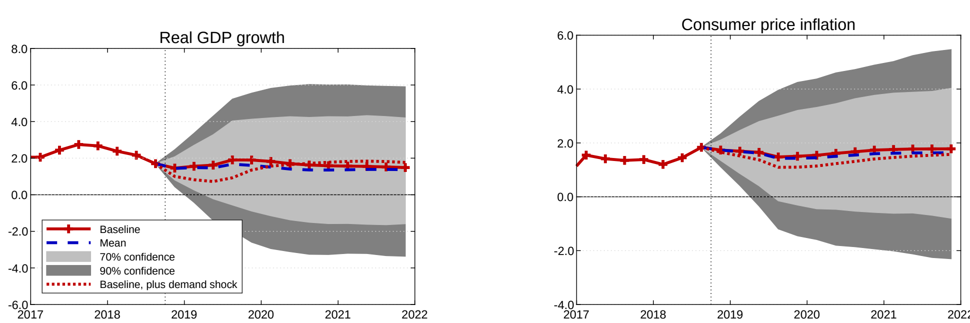
A. Strong asset purchases



B. Fiscal stimulus w/o threshold



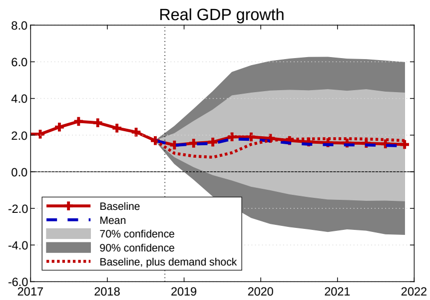
C. Strong asset purchases and fiscal stimulus w/o threshold

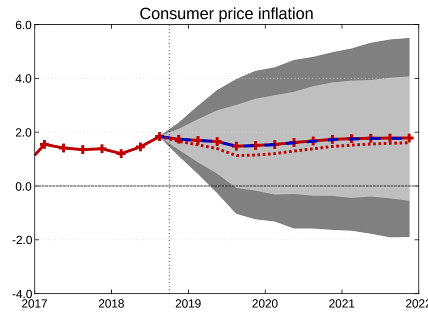


Note: This figure depicts predictive distributions for real GDP growth and consumer price inflation derived from stochastic simulations with NAWM II. The predictive distributions are centred on the structural shocks and the initial states that the model has identified for the December 2018 BMPE baseline projection. Real GDP growth and consumer price inflation (measured in terms of the private consumption deflator) are expressed as annual percentages. In carrying out the simulations, the effective lower bound is taken into account. The simulated additional adverse demand shock corresponds to a one-off domestic risk premium shock of size equal to 1.5 standard deviations and occurs in 2018Q4.

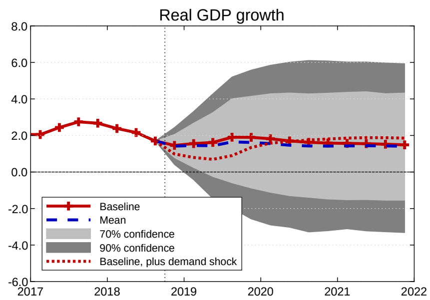
Figure A.3: Predictive distributions around the December 2018 BMPE baseline for real GDP growth and consumer price inflation under different state-dependent policies (cont'd)

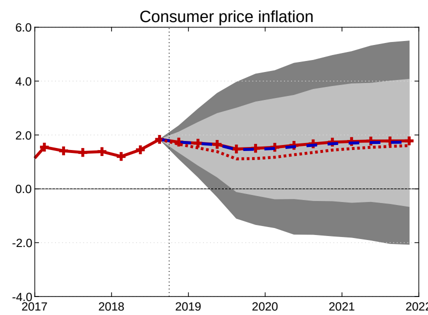
D. Strong forward guidance



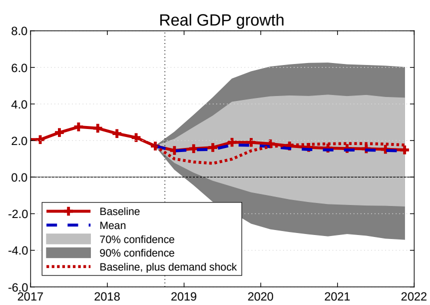


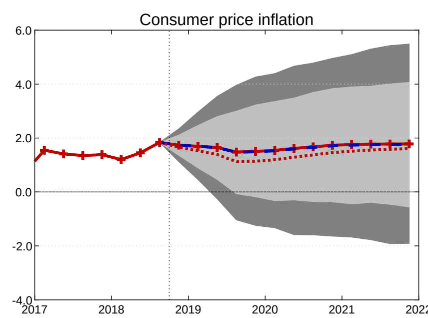
E. Weak forward guidance





F. Enhanced forward guidance with strong asset purchases





Note: See above.

Table A.1: Additional results on the stabilisation effects of state-dependent asset purchases and fiscal stimulus under the lower-bound constraint for alternative values of the equilibrium real interest rate

	Lower-bound incidence		Inflation			Output gap			Inflation and output gap	Asset purchases		Fiscal stimulus	
	Frequency	Duration	Mean	Std	RMSD	Mean	Std	RMSD	Average RMSD	Mean	95th	Mean	95th
A. Moderate asset purchases ($\alpha_a = 0.5$)													
$r^* = 2\%$	10.00	6.66	1.73	2.72	2.73	-0.91	5.71	5.78	4.25	2.26	13.61	—	—
$r^* = 1\%$	16.19	7.73	1.53	3.14	3.16	-1.86	6.00	6.28	4.72	4.58	26.77	—	—
$r^* = 0\%$	23.98	9.23	1.17	3.83	3.90	-3.51	6.55	7.43	5.67	8.61	45.27	—	—
B. Fiscal stimulus with threshold ($c_g = 0.25$)													
$r^* = 2\%$	10.11	6.84	1.74	2.76	2.76	-1.06	5.73	5.83	4.30	—	—	0.14	0.76
$r^* = 1\%$	16.15	7.78	1.58	3.15	3.17	-2.08	6.01	6.36	4.76	—	—	0.31	1.98
$r^* = 0\%$	23.43	9.14	1.36	3.71	3.75	-3.72	6.43	7.43	5.59	—	—	0.61	3.65
C. Asset purchases with AR(1) component ($\rho_a = 0.9$)													
Strong purchases ($\alpha_a = 1.0$)													
$r^* = 2\%$	10.10	6.80	1.72	2.75	2.76	-0.99	5.74	5.82	4.29	1.91	11.56	—	—
$r^* = 1\%$	16.33	7.82	1.51	3.20	3.22	-2.01	6.09	6.41	4.82	3.88	23.00	—	—
$r^* = 0\%$	24.07	9.32	1.15	3.91	3.98	-3.77	6.70	7.69	5.83	7.20	38.37	—	—
Very strong purchases ($\alpha_a = 2.0$)													
$r^* = 2\%$	9.92	6.54	1.74	2.69	2.69	-0.80	5.66	5.72	4.21	3.36	20.25	—	—
$r^* = 1\%$	16.13	7.65	1.54	3.10	3.12	-1.64	5.89	6.11	4.62	6.91	40.44	—	—
$r^* = 0\%$	24.09	9.19	1.15	3.79	3.86	-3.14	6.33	7.07	5.46	13.34	70.83	—	—

Note: For explanations, see Coenen, Montes-Galdón and Smets (2021), Section 3.2 and Table 5.

Table A.2: Deterioration in macroeconomic performance due to the lower-bound constraint for alternative values of the equilibrium real interest rate under the estimated interest-rate rule with output-growth term

	Lower-bound incidence		Inflation			Output gap			Inflation and output gap
	Frequency	Duration	Mean	Std	RMSD	Mean	Std	RMSD	Average RMSD
A. Lower bound imposed									
$r^* = 2\%$	6.06	5.04	1.23	2.84	2.92	-2.35	8.07	8.41	5.66
$r^* = 1\%$	10.45	5.57	0.36	4.40	4.67	-5.59	11.56	12.84	8.75
$r^* = 0\%$	15.87	6.08	-1.15	6.97	7.61	-11.44	17.21	20.67	14.14
B. Lower bound not imposed									
$r^* = 2\%$	—	—	1.90	1.75	1.75	0.00	5.62	5.62	3.69
$r^* = 1\%$	—	—	1.90	1.76	1.76	0.00	5.75	5.75	3.76
$r^* = 0\%$	—	—	1.90	1.77	1.77	0.00	5.91	5.91	3.84

Note: The estimated interest-rate rule is specified as follows: $r_t = 0.92\, r_{t-1} + 0.08\left(r^*_{t|t} + 2.75\, \pi_{C,t} + 0.03\, y_t\right) + 0.04\,(\pi_{C,t} - \pi_{C,t-1}) + 0.1(y_t - y_{t-1}) + \eta_t$, where r_t denotes the logarithmic deviation of the gross short-term nominal interest rate from its deterministic steady-state value, and $\pi_{C,t}$ is the logarithmic deviation of (gross) consumer price inflation from the steady-state inflation rate. y_t is the logarithmic deviation of aggregate output from the trend output level, with trend output growth in the model following a shock process which is the composite of a persistent and a transitory component; and $r^*_{t|t}$ represents the central bank's estimate of medium-run fluctuations in the logarithmic deviation of the equilibrium real interest rate from its long-run value due to the persistent component of trend output growth in the model. η_t is a transitory shock capturing temporary deviations of the short-term nominal interest rate from the systematic prescriptions of the interest-rate rule. For further explanations, see Coenen, Montes-Galdón and Smets (2021), Table 4.