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Macroeconomic stabilisation and monetary policy effectiveness in a low-interest-rate environment

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Macroeconomic stabilisation and monetary policy effectiveness in a low-interest-rate environment *

Günter Coenen† Carlos Montes-Galdón‡ Sebastian Schmidt§

Abstract

The secular decline in the equilibrium real interest rate observed over the past decades has materially limited the room for policy-rate reductions in recessions, and has led to a marked increase in the incidence of episodes where policy rates are likely to be at, or near, the effective lower bound on nominal interest rates. Using the ECB's New Area-Wide Model, we show that, if unaddressed, the effective lower bound can cause substantial costs in terms of worsened macroeconomic performance, as reflected in negative biases in inflation and economic activity, as well as heightened macroeconomic volatility. These costs can be mitigated by the use of nonstandard instruments, notably the joint use of interest-rate forward guidance and large-scale asset purchases. When considering alternatives to inflation targeting, we find that make-up strategies such as price-level targeting and average-inflation targeting can, if they are well-understood by the private sector, largely undo the negative biases and heightened volatility induced by the effective lower bound.

Keywords: Effective lower bound, monetary policy, asset purchases, forward guidance, make-up strategies

JEL-Codes: E31, E32, E37, E52, E58

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1 Introduction

Over the past decade, monetary policy in advanced economies has operated in an environment characterised by record-low nominal interest rates and disinflationary pressures that have, in most cases, kept inflation rates firmly below central banks' targets. This configuration has unfolded against the background of a secular decline in the global equilibrium real interest rate which has severely reduced the room for monetary policy to lower policy rates in recessions without hitting the effective lower bound (ELB) on nominal interest rates.[1] The persistent and global nature of these developments has lead to a broad-based re-assessment of, on the one hand, the incidence and severity of ELB episodes, and, on the other hand, the effectiveness of available monetary policy instruments and alternative monetary policy frameworks in achieving satisfying macroeconomic stabilisation outcomes in the presence of the ELB.

Our paper provides a model-based analysis of these considerations with a focus on the euro area economy. First, we quantify the impairment in macroeconomic stabilisation induced by the ELB. In so doing, we consider a set of widely-used benchmark interest-rate rules and document how the ELB gives rise to downward biases in and heightened volatility of inflation and economic activity. Second, we explore to which extent interest-rate forward guidance and large-scale asset purchases—two nonstandard monetary policy instruments that have been employed by an increasing number of central banks—can curb the distortionary effects due to the ELB. Third, and finally, we assess the capacity of make-up strategies under which the central bank promises to make up for past inflation shortfalls by generating higher inflation in the future to improve macroeconomic stabilisation in a low-interest-rate environment with an occasionally binding ELB.

The analysis is based on the recent extension of the ECB's New Area-Wide Model II (cf. Coenen et al., 2018), henceforth referred to as NAWM II. The NAWM II is an estimated dynamic, stochastic, general equilibrium (DSGE) model of the euro area as a whole. The model incorporates a rich financial sector that allows for (i) accounting for a genuine role of financial frictions in the propagation of economic shocks as well as macroeconomic policies and for the presence of shocks originating in the financial sector itself, (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.[2]

To assess the ramifications of an occasionally binding ELB constraint for macroeconomic stabilisation in a low-interest-rate environment, we conduct stochastic simulations with the NAWM II and present summary statistics of the steady-state distributions for inflation, the

[1] For empirical evidence on the persistent downward trend in equilibrium real interest rates 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 equilibrium real rates and about whether they will remain at their current low levels in the future is, however, large.

[2] A short non-technical overview of its structure is provided in Appendix A. For a detailed description of the model, see Coenen et al. (2018).

output gap and the short-term nominal interest rate. When the short-term nominal interest rate is the only effective monetary policy instrument and the monetary policy strategy is represented by a simple interest-rate feedback rule commensurate with conventional inflation targeting, the ELB can cause substantial macroeconomic costs as reflected in negative biases in inflation and the output gap, a positive bias in the interest rate, and heightened volatility in inflation and the output gap. This result is robust across a range of widely-used benchmark interest-rate rules. Under our preferred benchmark rule, the ELB is binding one-fourth of the time with an average duration of about 12 quarters, leading to a 0.5 percentage-point shortfall of the inflation mean below the central bank's target, and a doubling in the standard deviation of inflation (relative to the counterfactual case without the ELB). Likewise, the output gap has a negative mean, and is more volatile than without the ELB. When the long-run equilibrium real interest rate is lower than in our benchmark setup, the incidence of ELB episodes increases markedly, and the negative stabilisation biases and heightened economic volatility get amplified.[3,4]

Expanding the analysis to allow for the use of nonstandard monetary policy instruments, notably interest-rate forward guidance and large-scale asset purchases, we find that they can curb, albeit not fully eliminate, the stabilisation costs associated with the ELB, in particular, if they are used jointly. In our preferred specification, interest-rate forward guidance is only imperfectly-credible with the private sector. In this case, asset purchases can help to increase the credibility of forward guidance via a signalling channel. Under such enhanced interest-rate forward guidance with asset purchases, we find that the negative inflation bias is 0.2 percentage point smaller, in absolute value, and the volatility of inflation is 0.4 percentage point lower, than in the case where the central bank does not use the two nonstandard instruments. Similar improvements are achieved in terms of the output gap bias, which is 1.4 percentage points smaller, in absolute value, than in the case without nonstandard instruments, and in term of the volatility of the output gap.

Finally, we find that make-up strategies, notably price-level targeting and average-inflation targeting with a sufficiently long averaging window can largely undo the negative biases and heightened volatility induced by the ELB. For instance, under a permanent and symmetric average-inflation targeting rule with an 8-year averaging window, the negative inflation bias shrinks to 0.1 percentage point—0.4 percentage point smaller, in absolute value, than under the benchmark interest-rate rule without a make-up element—and the standard deviation of inflation is even lower than in counterfactual simulations without the ELB where interest-rate policy is governed by the benchmark rule. Likewise, the output gap bias is relatively small,

[3]The same holds true for the case where the central bank's inflation target is lower, or the level of the ELB constraint is higher, than assumed in our benchmark setup.

[4]While changes in the long-run 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.

3.0 percentage points smaller than under the benchmark rule. We also find that temporary price-level targeting and asymmetric average-inflation targeting can be about as effective as strategies with a permanent and symmetric element. The noticeable improvement in stabilisation outcomes associated with the considered make-up strategies is due to their reliance on two key expectation channels. One is that by committing to an inflation overshoot, the central bank is, in effect, committing to a lower-for-longer interest-rate policy. Expectations of future short-term interest rates should get incorporated into longer-term rates and thereby provide additional accommodation. The other channel is that by committing to overshooting, the make-up strategies should boost inflation expectations. Those higher inflation expectations reduce ex-ante real rates, again providing additional accommodation.

Our paper is related to several (interrelated) strands of the literature on monetary policy and the ELB. In light of the volume by which this literature has grown in recent years, our discussion has to be selective. First, focusing on the U.S. economy, Chung et al. (2012), and Kiley and Roberts (2017), among others, find that both the incidence and the severity of episodes with a binding ELB is higher today than prior to the Global Financial Crisis.[5]

Second, a large and growing strand of the literature assesses the capacity of alternative nonstandard monetary policy instruments to stabilise the economy when faced with the ELB. Eggertsson and Woodford (2003) show that optimal monetary policy under commitment uses state-contingent interest-rate forward guidance to steer the economy when the ELB is binding. Cúrdia and Woodford (2011), Gerali et al. (2010) and Gertler and Karadi (2011), among others, show that in the presence of financial frictions, large-scale asset purchases can mitigate economic downturns when short-term nominal interest rates are at or close to the ELB. Reifschneider (2016), Kiley (2018), Mouabbi and Sahuc (2019) and Chung et al. (2019), among others, provide quantitative, model-based assessments of the effectiveness of these nonstandard instruments. Coenen et al. (2020) is most closely related to this part of our paper. Like us, they use the NAWM II to analyse interest-rate forward guidance and large-scale asset purchases, though under a slightly different parameterisation of these policies. In contrast to our paper, they study the interactions of these nonstandard monetary policy instruments with state-contingent fiscal policy interventions.

Finally, a third strand of the literature aims to explore whether in a low-interest-rate environment alternative monetary policy frameworks could help achieve better stabilisation outcomes than the currently predominant inflation-targeting paradigm. Make-up strategies, in particular, are often considered as a possible means to improve upon the stabilisation properties of conventional inflation targeting in the presence of the ELB.[6] Reifschneider and Williams (2000) proposed an otherwise standard interest-rate feedback rule that "memorises" the sum of past shortfalls in interest-rate cuts due to a binding ELB, and aims to make up for the accumulated

[5] For model-based assessments of the degree to which the ELB may deteriorate macroeconomic stabilisation that were conducted prior to the Global Financial Crisis, see, for instance, Reifschneider and Williams (2000) and Coenen et al. (2004) for the U.S. economy, and Coenen (2003) for the euro area economy.

[6] These strategies are sometimes also referred to as history-dependent strategies.

interest-rate shortfalls by keeping interest rates low for longer. More recently, Nakov (2008), Mertens and Williams (2019), Bernanke et al. (2019), Amano et al. (2020) and Arias et al. (2020) have studied average-inflation-targeting and price-level-targeting rules in the context of the ELB, whereas Budianto et al. (2020) analyse average-inflation targeting for the case where the monetary policy strategy is formalised as an objective function.[7] These studies employ either relatively stylised macroeconomic models, or models of the U.S. economy. In contrast, we assess make-up strategies in an estimated model of the euro area. Furthermore, while most studies consider only make-up rules with a permanent and symmetric make-up element, we, like Arias et al. (2020), also consider make-up rules with either a temporary or an asymmetric make-up element.

The remainder of the paper is organised as follows. Section 2 documents, for a set of commonly used benchmark interest-rate rules, that the ELB constraint makes it more difficult for a central bank to achieve satisfactory macroeconomic stabilisation. Section 3 analyses the effectiveness of interest-rate forward guidance and large-scale asset purchases to mitigate the distortionary effects due to the ELB. Section 4 extends the analysis to make-up strategies, and Section 5 concludes. The Appendix provides a more detailed description of NAWM II and the methods used for solving and simulating the model, as well as detailed simulation results.

2 Challenges for monetary policy in a low-interest-rate environment

In this section, we document, by means of stochastic model-based simulations, that the ELB constraint makes it more difficult for a central bank to achieve its price stability objective and to support macroeconomic stabilisation under common prescriptions of interest-rate policy and in the absence of nonstandard policy instruments. To show the robustness of this finding, we provide simulation results for four alternative interest-rate rules.

2.1 A set of benchmark inflation-targeting rules

In addition to the policy rule that was originally estimated with the NAWM II, we also consider three alternative widely-used feedback rules, as summarised in Table 1.

All four rules respond to deviations of inflation from target as well as to a measure of economic activity, and they exhibit some inertia in the adjustment of the policy rate. Unlike the other three rules, the estimated rule has been log-linearised around the intended deterministic steady state of the model. When simulating the NAWM II with the estimated rule but without imposing the ELB constraint, the model-based standard deviations of key variables such as inflation and interest rates match their historical empirical counterparts quite well. The first alternative rule listed in the table is Taylor (1999)'s inertial feedback rule. This specification has

[7] See also Svensson (2020) for conceptual discussions of monetary policy objective functions that contain an inflation average rather than period-by-period inflation.

been used by the Federal Reserve System in analytical work for its monetary policy framework review as a benchmark rule representing standard inflation targeting (see, e.g., Arias et al., 2020). In addition to the original version of the Taylor (1999) rule, we also consider a modified version of this rule that features a stronger response to deviations of inflation from target. The modified inertial Taylor rule provides a better fit in terms of model-based moments than the original version of Taylor's inertial rule. Finally, the first-difference rule shown in the final row of the table prescribes interest-rate policy in terms of the change in the policy rate. It captures the ECB's interest-rate policy up to mid-2012 quite well and is therefore often used as a benchmark for monetary policy in the euro area (see, e.g., Hartmann and Smets, 2018). When simulating the model with these alternative rules, we impose, with a view to broadly capturing the present configuration in the euro area, an inflation target of 2%, a long-run equilibrium real interest rate of 0.5% and an ELB at -0.5%.

2.2 How severe is the ELB constraint?

Figure 1 provides a quantitative assessment, based on stochastic model simulations, of the extent to which the ELB constraint hampers macroeconomic stabilisation.[8] The left panel of the figure reports the frequency and the average duration of a binding ELB constraint. The right panel reports the mean and the (normalised) standard deviation of inflation, the output gap and the policy rate.[9] Each policy rule is represented by a distinct coloured marker.

Depending on the policy rule, the ELB is binding in between 11% and 27% of the simulated periods, and the average duration of a binding ELB ranges from 6 to 12 quarters. Under all four rules, the inflation mean falls short of the central bank's 2% inflation target. This "negative inflation bias", which ranges from -1.86 percentage points to -0.13 percentage point, is a result of the asymmetry in the ability of the central bank to respond to expansionary versus contractionary shocks by means of commensurate adjustments in the policy rate. The central bank can always raise the policy rate in accordance with its interest-rate rule in response to an expansionary shock that triggers inflationary pressures, thereby containing the amount by which inflation overshoots the target. However, in the face of a large contractionary shock, the ELB may prevent the central bank from lowering the policy rate sufficiently to contain disinflationary pressures, and inflation may fall well below target. The disinflationary pressures are amplified through the model's financial sector. ELB incidences are associated with a pronounced decline in asset prices that tightens economy-wide lending conditions, and leads to an appreciation of the euro exchange rate enforced by no-arbitrage conditions in international financial markets.[10] The asymmetry in the central bank's reaction function induced by the ELB also renders the

[8] Technical details on the solution method that we use to solve the NAWM II subject to the ELB constraint are provided in Appendix B.

[9] In the model simulations, the policy rate is set equal to the value prescribed by the respective rule when the value is above the ELB, and it is set equal to the ELB otherwise.

[10] The negative inflation bias is further amplified by the private sector's anticipation that the ELB might be binding in the future in response to shocks that have not yet materialised. See, e.g., Hills et al. (2019).

inflation rate more volatile than in simulations without the ELB.

On the real side of the economy, the deterioration in inflation stabilisation is mirrored by a negative bias in the output gap, which is on average between -6.8% and -1.8%, and heightened output gap volatility.[11] Finally, since the ELB constraint truncates the steady-state probability distribution of the short-term nominal interest rate from below, accounting for the ELB results in an upward shift in the mean of the policy rate—from 2.5% without the ELB to a level ranging from 2.7% to 3.9% with the ELB—and a decline in its volatility.

When comparing macroeconomic stabilisation outcomes in the presence of the ELB across policy rules, the biases in the inflation rate and the output gap turn out to be most severe under the estimated rule. Two factors contribute to the relatively poor stabilisation performance of the estimated rule when the ELB is taken into account. The first factor is the high degree of interest-rate smoothing enshrined in the rule. A high degree of interest-rate inertia implies that the policy rate is lowered only sluggishly in response to a contractionary shock which may amplify disinflationary pressures.[12] The second factor is the output gap growth term in the estimated rule. Stabilising the growth rate of the output gap requires a more rapid increase in the interest rate after an ELB incidence than otherwise. The private sector's anticipation of a less gradual interest-rate increase after the ELB incidence heightens the decline in inflation and economic activity during the ELB incidence.[13] The inertial Taylor rule is associated with smaller downward biases in inflation and the output gap than the estimated rule but exhibits by far the highest standard deviation of inflation (not shown in absolute terms), as well as the largest upward bias in the policy rate. The modified inertial Taylor rule and the first-difference rule perform relatively similar in terms of macroeconomic stabilisation outcomes, though the frequency and average duration of ELB episodes is higher under the former than under the latter rule. In the remainder, we use the modified inertial Taylor rule as our benchmark rule for standard inflation targeting. In light of the higher stabilisation costs observed under the estimated rule and the original inertial Taylor rule, this is a conservative choice. Compared to the first-difference rule, an advantage of the modified inertial Taylor rule is that it allows for a clear distinction between standard inflation targeting and make-up strategies such as average-inflation targeting and price-level targeting. The first-difference rule, instead, is tantamount to a price-level targeting rule in the absence of the ELB, and the rule is therefore not necessarily a

[11] We also explore how a change in the slope of the domestic price Phillips curve affects stabilisation outcomes. We find that a flatter (steeper) Phillips curve attenuates (heightens) the negative biases and the excess volatility of inflation and the output gap induced by the ELB. In line with the so-called paradox of flexibility (e.g. Eggertsson and Krugman, 2012), at the ELB, the drop in output in response to a contractionary shock is smaller (larger) if prices are more sticky (flexible) because the smaller (larger) decline in inflation mitigates (amplifies) the ensuing increase in the real interest rate.

[12] While some degree of interest-rate smoothing is desirable for macroeconomic stabilisation in the presence of the ELB, too much interest-rate inertia typically worsens stabilisation outcomes (Nakata and Schmidt, 2019).

[13] In contrast, in models without an ELB constraint, the trade-off between inflation and output gap stabilisation often improves when monetary policy aims to stabilise the growth rate of the output gap (Walsh, 2003). Hence, the output gap growth term in the estimated rule is likely to contribute to the substantial discrepancy in the performance of this rule in simulations with and without the ELB.

good representation of inflation targeting strategies that treat past deviations of inflation from target as bygones.

2.3 How much monetary policy space?

The incidence of ELB events, and the extent to which the ELB constraint hampers macroeconomic stabilisation are not solely determined by the central bank's monetary policy rule, they also depend on the longer-run economic conditions in which monetary policy is operating. In this respect, three key parameters are the long-run equilibrium real interest rate, the inflation target, and the level of the ELB constraint. Together, they determine the average "space" for monetary policy to reduce its policy rate in recessions.

Figure 2 shows how the model simulation results change when either the equilibrium real rate, the inflation target or the level of the ELB constraint take on a higher or lower value than in our benchmark calibration. In each case, interest-rate policy is governed by our benchmark rule (the modified inertial Taylor rule).

A decline in the long-run equilibrium real interest rate leads to an increase in the incidence of episodes where the ELB is binding, and aggravates, both, the negative stabilisation biases and economic volatility. When the equilibrium real interest rate falls from 0.5% to 0.0%, the neutral level of the policy rate falls, all else equal, from 2.5% to 2.0%, so that the central bank has less space to reduce its policy rate in response to contractionary shocks, resulting in an increase in the ELB frequency by 3.5 percentage points. The heightened asymmetry in the ability of the central bank to adjust its policy rate in response to shocks raises the negative inflation bias to 0.63 percentage point. In a similar vein, a lower inflation target of 1% results in an increase in the ELB frequency of 7.3 percentage points and raises the negative inflation bias to 0.83 percentage point. Hence, a reduction in the inflation target leads to a more than one-for-one decline in the mean of inflation.

By the same token, a higher inflation target or a lower level of the ELB attenuate the ELB incidence and improve macroeconomic stabilisation outcomes. For instance, when the NAWM II is simulated with an inflation target of 3%, rather than 2%, the negative inflation bias shrinks to 0.28 percentage point. If the numerical value of the ELB is assumed to be -1.0% instead of -0.5%, the negative inflation bias is 0.1 percentage point smaller than in the benchmark simulations.[14]

3 Nonstandard monetary policy instruments

In an attempt to soften the adverse economic consequences of the ELB constraint documented in the previous section, central banks have expanded their set of policy instruments to include,

[14]To be clear, the level of the ELB, like the level of the long-run equilibrium real interest rate, is not a policy parameter to be chosen by central banks but rather depends on factors such as storage and transportation costs associated with hoarding cash. Another factor concerns the existence of a "reversal rate" hampering financial intermediation capacity; see Brunnermeier and Koby (2018).

amongst others, interest-rate forward guidance and large-scale asset purchases. In this section, we explore the effectiveness of these two instruments in mitigating the distortionary effects associated with the presence of the ELB.

3.1 Interest-rate forward guidance

Central banks have pursued different types of interest-rate forward guidance. We model forward guidance as a state-dependent policy prescription. That is, the central bank promises to keep its policy rate at the ELB beyond the point in time where the benchmark interest-rate rule would imply an increase in the policy rate, and the length of the additional period for which the policy rate is kept low depends on the severity of the previous downturn.[15] To do so, we augment our benchmark interest-rate rule with a notional shadow rate, defined as the interest rate implied by the policy rule when the ELB constraint is ignored.[16] The actual annualised policy rate R_t then equals the annualised shadow rate $\tilde{R}_t$, when the shadow rate is above the ELB, and it equals the level of the ELB, when the shadow rate is below the ELB:

$$\tilde{R}_t = 0.85\left(\tau R_{t-1} + (1-\tau)\tilde{R}_{t-1}\right) + 0.15\left(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + 2.0(\bar{\pi}_t^{(4)} - \pi^*)\right) \tag{1}$$

$$R_t = \max\left(\tilde{R}_t, ELB\right), \tag{2}$$

where $\bar{\pi}_t^{(4)}$ is the annual consumer price inflation rate, y_t^{gap} is the output gap, r^* denotes the annualised equilibrium real rate, π^* is the central bank's inflation target, and ELB denotes the level of the ELB constraint. When $\tau = 1$, the above specification is tantamount to the benchmark rule without state-dependent forward guidance. Instead, when $\tau = 0$, then the contemporaneous shadow rate depends on the lagged shadow rate, and, hence, the path of the policy rate after an ELB incidence depends on the severity of the inflation shortfall and the recessionary pressures materialising while the ELB has been binding.

While the central bank never reneges on its interest-rate forward guidance in our model simulations so that the actual current policy rate is determined according to equations (1) and (2) with $\tau = 0$, we allow for the possibility that the central bank's state-dependent forward guidance is not fully credible with the public, and that the degree of credibility depends on the overall configuration of employed instruments. In the case of imperfect credibility, private sector agents' base their expectations of future interest rates on a probability-weighted linear combination of two distinct interest-rate rules which respond either to the lagged shadow rate or to the lagged realised policy rate.[17]

[15] Alternative forms of interest-rate forward guidance include non-state-contingent date-based forward guidance (Carlstrom et al., 2015) and threshold-based forward guidance (Coenen and Warne, 2014; Boneva et al., 2018).

[16] Our formalisation of interest-rate forward guidance follows the approach of Coenen et al. (2020).

[17] See Coenen et al. (2020), Section 2, for more details.

3.2 Large-scale asset purchases

As regards central bank asset purchases, we assume that they are initiated when the ELB constraint becomes binding and that they comprise purchases of long-term government bonds and long-term private-sector loans. In the NAWM II, asset purchases affect the economy by relieving the stressed financial intermediary sector through relaxation of funding constraints and an ensuing improvement in economy-wide lending conditions.[18] The central bank's asset holdings are governed by a feedback rule that makes the size of the asset purchases a function of the severity of the drop in inflation and economic activity as measured by the gap between the ELB and the shadow interest rate. In addition, the rule contains a persistent component that allows for a gradual build-up of overall central bank asset holdings broadly consistent with the pattern of actual asset purchases carried out by central banks, and a gradual reduction thereafter as the purchased assets mature. Formally,

$$a_t = 1.2a_{t-1} - 0.27a_{t-2} + 0.125R_t^{gap} \tag{3}$$

$$R_t^{gap} = \max\left(\tilde{R}_t, ELB\right) - \tilde{R}_t, \tag{4}$$

where a_t denotes the central bank's asset holdings. Thus, we model asset purchases as a state-dependent policy.

3.3 Effects of nonstandard instruments on macroeconomic stabilisation

Figure 3 presents results from stochastic simulations of the NAWM II on how interest-rate forward guidance and large-scale asset purchases affect stabilisation outcomes and the ELB incidence. The figure shows results for alternative configurations of forward guidance and asset purchases, as well as for the benchmark interest-rate rule without nonstandard policies. Each policy configuration is represented by a distinct coloured marker. The gray axes running from the origin outwards depict different statistics summarising the outcomes of the simulations.[19] To facilitate their comprehension, the summary statistics for a particular policy configuration are connected via lines that have the same colour as the corresponding markers.

The effectiveness of forward guidance critically hinges on its credibility with the private sector. In Figure 3, "credible forward guidance" refers to the case where the central bank's forward-guidance policy is seen by the private sector as fully credible, whereas "imperfectly-credible forward guidance" refers to the case where private-sector agents attach only a small probability to the central bank's forward-guidance policy. Credible interest-rate forward guidance reduces the negative inflation bias by about 0.2 percentage point and extends the average

[18] See Appendix A for a more detailed description of the financial sector in NAWM II.

[19] Figure 3 presents the same summary statistics as Figure 2, except that it depicts the inflation and output gap biases, rather than their means. The inflation bias is defined as the difference between the inflation mean and the central bank's inflation target, whereas the output gap bias coincides with the output gap mean (which would be zero in the absence of the ELB constraint).

duration of ELB episodes by 5 quarters. The increase in the average duration of ELB episodes reflects the "low for longer" element of forward guidance. Credible forward guidance is also successful in mitigating the output gap bias, and in reducing economic volatility. If, instead, forward guidance has low credibility, the improvement in stabilisation outcomes is much more muted. For instance, under low credibility, forward guidance reduces the negative inflation bias only by 0.08 percentage point. Credibility is essential for interest-rate forward guidance to effectively steer private-sector expectations about future policy and, thus, about future inflation and economic activity. At the ELB, a credible announcement by the central bank that interest-rate policy will remain accommodative beyond the expected duration of the contractionary shock raises private-sector inflation expectations. Higher expected inflation lowers the real interest rate and stimulates aggregate demand, thereby mitigating the downward pressure on current inflation and economic activity.[20] For inflation expectations to rise in response to the forward guidance announcement, the private sector thus has to understand that the announcement signals a more accommodative stance rather than a worsened macroeconomic outlook.[21]

Next, we consider the effects of central bank asset purchases. Large-scale asset purchases, on their own, have a rather small effect on inflation in the model simulations. The use of asset purchases as an additional policy instrument reduces the negative inflation bias by 0.04 percentage point and the volatility of inflation by 0.11 percentage point. Central bank asset purchases, while inflationary in the short run, give rise to dis-inflationary pressures over the medium term that prevent a more sizeable reduction in the negative inflation bias. These dis-inflationary pressures arise because asset purchases stimulate investment, leading to a gradual increase in the physical capital stock and a decline in the rental rate of capital that, in turn, puts downward pressure on firms' marginal costs. The output gap bias, on the other hand, shrinks by 0.91 percentage point.[22] Finally, the incidence of a binding ELB, notably its duration, is somewhat reduced by the asset purchases, as the improved stabilisation outcomes tend to support a more timely normalisation of the policy rate.

Apart from the direct effect that asset purchases have on the macroeconomy, they may also help the central bank to enhance the credibility of interest-rate forward guidance when both nonstandard instruments are used together and, thereby, increase the capacity of monetary policy to stabilise the economy. This effect materialises when, as is often argued, an increasing central bank balance sheet is interpreted by the private sector as a signal for accommodative future interest-rate policy. To account for this signalling channel in the simulations, we assume that the asset purchases carried out by the central bank lead to an increase in the probability that private-sector agents attach to the central bank's forward guidance when compared to the

[20] Interest-rate forward guidance also improves stabilisation outcomes by attenuating the decline in asset prices at the ELB, thereby counteracting the amplification of ELB incidences through the financial sector. See Table C in the Appendix.

[21] See Andrade et al. (2019).

[22] The cumulated size of asset purchases can be as large as 42% of GDP (corresponding to the 95th percentile of their probability distribution obtained from the stochastic simulations).

"imperfectly-credible forward guidance" scenario without large-scale asset purchases.[23] Under this configuration, referred to as "enhanced forward guidance with asset purchases" in Figure 3, the two nonstandard instruments together reduce the negative inflation bias by 0.16 percentage point, and lower the volatility of inflation by 0.4 percentage point. Similar improvements are achieved in terms of the output gap bias and volatility.

3.4 Nonstandard instruments in a counterfactual recession scenario

We close this section with an illustrative example that shows how interest-rate forward guidance and large-scale asset purchases can help to mitigate the contraction in output and inflation in a recession scenario where interest rates are ex ante close to the ELB. The simulation shown in Figure 4 is centered on the baseline projection of the December 2019 Broad Macroeconomic Projection Exercise (BMPE) conducted by Eurosystem staff, that we augmented with a model-based extension (grey solid line with filled circles), and the recession is induced by a large contractionary demand shock.[24] All variables, except for the policy rate, are presented in deviations from the baseline.

The negative demand shock leads to a gradual and persistent decline in the output gap and inflation. The economic downturn is most severe when the central bank completely refrains from using nonstandard instruments. With the policy rate already close to the ELB, the very small cut in the interest rate prescribed by the benchmark interest-rate rule is insufficient to offset the negative effects of the shock. When, instead, the central bank uses forward guidance about the likely path of future policy rates in addition to conventional interest-rate policy, and the policy announcement is credible, the decline in the output gap and inflation is substantially mitigated. With credible forward guidance, private-sector agents anticipate that the central bank will keep the policy rate low beyond the point in time where the standard interest-rate rule would prescribe a normalisation of monetary policy. This raises expectations about higher inflation and output in the future. Forward-looking households and firms account for higher expected output and inflation by increasing, respectively, their spending and prices already today. When large-scale asset purchases are part of its toolbox, the central bank responds to the demand shock and the ensuing ELB incidence by starting to buy public and private-sector bonds, which leads to a gradual expansion of its balance sheet. The central bank's asset purchases provide relief to the stressed balance sheets of the economy's banking sector, thereby contributing to an improvement of lending conditions (not shown). The improved lending conditions, in turn, have a positive, albeit small, effect on economic activity. Finally, when interest-rate forward guidance and large-scale asset purchases are used together, and asset purchases help to dispel private-sector doubts about the credibility of the forward-guidance policy, then the two policies together are almost as effective in stabilising the economy as fully-credible forward guidance.

[23] Woodford (2012) provides an overview of the empirical evidence for a signalling channel of central bank asset purchases. For a model-based assessment, see Bhattarai et al. (2015).

[24] The assumptions underlying the model-based extension of the BMPE are broadly consistent with the conditioning assumptions of the BMPE.

4 Make-up strategies

In the previous sections, we maintained the assumption that the use of the central bank's interest-rate policy is guided by a standard inflation targeting framework as enshrined in our benchmark interest-rate rule. In this section, we consider an alternative class of strategies, so-called make-up strategies, with a view to improving macroeconomic stabilisation outcomes in the presence of the ELB. The common feature of these alternative strategies is that the central bank seeks to compensate, at least in part, for past episodes of too low (high) inflation by temporarily aiming for a rate of inflation above (below) the central bank's inflation target. A credible make-up strategy that is well-understood by the public thus allows inflation expectations to operate as "automatic stabilisers", for whenever inflation is too low (high), future inflation should be expected to temporarily overshoot (undershoot) the target, which, if private sector decisions depend on their expectations about future economic conditions, can help to improve current stabilisation outcomes. This property of make-up strategies is not shared by standard inflation targeting which renders past inflation realisations by and large immaterial for the contemporaneous monetary policy stance ("bygones are bygones").

4.1 Interest-rate rules with make-up elements

As in the case of standard inflation targeting, we specify the make-up strategies in form of interest-rate feedback rules. Table 2 lists the five make-up rules that we consider in our analysis as possible alternatives to the benchmark rule. Under price-level targeting (PLT), the central bank aims to keep the price level close to a pre-announced target path that grows at a rate consistent with the inflation target. Under average-inflation targeting (AIT), the central bank aims to stabilise an average rate of inflation over a pre-specified time window. The longer the averaging window, the more similar AIT becomes to PLT. In addition to rules with a symmetric and permanent make-up element, we also consider specifications with either an asymmetric or a temporary make-up element. Under the asymmetric average-inflation targeting (AAIT) rule, the policy rate responds to an average rate of inflation whenever average inflation is below target, and it responds to annual inflation, in accordance with the benchmark rule, otherwise. Under the temporary price-level targeting (TPLT) rule, the central bank switches to price-level targeting whenever the ELB becomes binding. Once the price level is realigned with its target path, monetary policy will switch back to the benchmark rule. The AAIT and TPLT rules are thus specifically designed with a view to addressing the economic impairments resulting from the ELB. All rules feature some sluggishness in the adjustment of the policy rate, and they are "flexible" in that they also respond to a measure of the output gap.

4.2 Effects of make-up strategies on macroeconomic stabilisation

Figure 5 presents results from stochastic simulations of the NAWM II on how the different make-up rules affect stabilisation outcomes and the ELB incidence. Results are compared to

the benchmark inflation-targeting rule and based on the benchmark assumptions for the inflation target, the equilibrium real interest rate and the ELB, respectively (see Section 2). Each policy rule is represented by a coloured marker, as in Figure 3.

The make-up rules attenuate, to a varying degree, the negative inflation and output gap biases, reduce economic volatility, and lower the incidence of a binding ELB. The PLT and AAIT rules fully eliminate the negative inflation bias, though the AAIT rule is somewhat less successful in reducing the volatility of inflation when compared to the other rules. As regards the two AIT rules, the inflation bias is smaller, in absolute value, for the rule with the longer averaging window (of eight, as opposed to four, years). The TPLT rule does not lead to a material stabilisation improvement, except for the reduction in the inflation bias of 0.2 percentage point. This may be partially explained by the small response coefficient to the price level in the TPLT rule. All in all, the PLT rule performs best in terms of minimising both the biases and the volatility of inflation and the output gap. The standard deviation of inflation is 2.3 percentage points lower than under the benchmark rule, and the standard deviation of the output gap is 1.1 percentage points lower, reflecting an improved stabilisation trade-off arising from the history dependence of the PLT rule.[25] Remarkably, although all make-up rules exhibit the property that after an ELB episode policy rates are kept "lower for longer" than would be warranted by the path of annual inflation, the average frequency of ELB incidences and, in most cases, the average duration of ELB incidences is lower than under the benchmark rule. This result is testifying to the strong general equilibrium effects associated with an effective management of expectations.

4.3 Make-up strategies in a counterfactual recession scenario

To illustrate the functioning of make-up rules in an ELB environment, we again make use of the recession scenario considered in Section 3. Figure 6 shows the simulated paths for alternative make-up rules as well as for the benchmark inflation-targeting rule. Like in Figure 4, the simulation is conducted around the baseline of the December 2019 BMPE augmented with a model-based extension, and the recession is induced by a large contractionary demand shock.[26] In so doing, we assume that the make-up rules account for the emerging marginal inflation shortfalls due to the simulated contractionary shock, but do not account for past shortfalls induced by previous shocks as enshrined in the initial conditions and the shortfalls implied by the extended baseline values themselves. All variables, except for the policy rate, are presented in deviations from the baseline.

[25] Even in the absence of the ELB constraint, make-up strategies can reduce the volatility of inflation and economic activity relative to standard inflation targeting in models with price mark-up shocks. See, for instance, Vestin (2006). Indeed, when simulating the model under the PLT rule without the ELB constraint, the standard deviations of both inflation and the output gap are lower than under the benchmark rule without the ELB constraint.

[26] For expositional convenience, Figure 6 focuses on a subset of make-up rules. At the ELB, the TPLT rule (not shown) leads to similar dynamics as the PLT rule, and dynamics under the AAIT rule (not shown) are similar to those under the AIT rules.

The drop in aggregate demand induced by the shock leads to a gradual and persistent decline in the output gap and inflation. With the policy rate already close to the ELB, the central bank has, at least in the short run, little room for further interest-rate cuts, independently of the monetary policy rule. Yet, the decline in inflation and economic activity in response to the shock is much more muted under the make-up rules than under the benchmark rule. When monetary policy is governed by the PLT rule, the private-sector anticipates that monetary policy will remain accommodative after the shock has receded until the price level is fully realigned with its baseline path. This requires annual inflation to temporarily rise above the baseline path. Higher expected future inflation lowers real interest rates and thereby stimulates household spending and firms' investment. Likewise, firms respond to the increase in expected future inflation by curbing the reduction in current goods prices.[27] Despite the large magnitude of the shock, the amount by which the inflation rate temporarily overshoots its baseline path is moderate and drawn-out over several quarters. Because higher expected future inflation mitigates the decline in current inflation, there is, in equilibrium, a smaller inflation shortfall to be compensated for after the ELB incidence. Thus, in equilibrium, the path of the nominal interest rate under the PLT rule deviates only slightly from the nominal interest-rate path under the benchmark rule.[28] Dynamics under the AIT rules are similar to those under the PLT rule, except that the inflation shortfall induced by the shock is only partially, as opposed to fully, undone, implying a downward level-shift in the path of the price level and, therefore, a somewhat weaker cushioning of the decline in inflation and the output gap than under the PLT rule. All in all, the simulations show that make-up strategies, if credible and well understood by the public, can improve macroeconomic stabilisation outcomes in a low-interest-rate environment with an occasionally binding ELB.

5 Conclusion

In the current environment of persistently low equilibrium real interest rates, the presence of an effective lower bound severely impairs the ability of standard interest-rate policy to achieve satisfying macroeconomic stabilisation outcomes. The new environment does, however, not render monetary stabilisation policy per se ineffective. Using the ECB's New Area-Wide Model II, we show that the central bank can alleviate the distortions induced by the lower bound if it has recourse to interest-rate forward guidance and large-scale asset purchases. An even stronger reduction in the stabilisation costs can be obtained when the central bank's monetary policy strategy contains a make-up element so that monetary policy aims to compensate for past inflation shortfalls by generating temporarily above-target inflation in the future.

The considered remedies to the distortions induced by the effective lower bound are of course not without practical limitations. The efficacy of asset purchases is likely to be state-dependent

[27] The make-up rule also attenuates the amplification of ELB incidences associated with a deterioration of the financial sector's lending conditions by mitigating the decline in asset prices (not shown). See Table D in the Appendix.

[28] There is, of course, a more severe difference in the paths of real interest rates (not shown).

on, e.g., the severity of prevailing financial impairments, and central bank asset purchases may face quantitative limits. The stabilising macroeconomic effects of forward guidance hinge on its credibility with the private sector and on the importance of forward-looking private-sector planning, in general.[29] While we have proposed a practical way to deal with these issues in our simulations, developing alternative approaches, with a stronger theoretical foundation, would be an important area for future work.

In a similar vein, if a central bank decides to adpot a make-up strategy it may face practical challenges that we abstract from in our model-based analysis. The effectiveness of a make-up strategy hinges on people's understanding of how it makes future monetary policy and macroeconomic outcomes contingent on current economic conditions. Coherent and transparent central bank communication of the strategy is therefore pivotal for the make-up element to steer private-sector expectations in the desired way. This is likely to be particularly challenging in the initial transition phase when people still have to learn and build trust into the new strategy.[30] We leave a model-based assessment of these transitional aspects for future work.

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[29] See, for instance, Gabaix (2019) for an analysis of interest-rate forward guidance in a model with boundedly-rational expectations.

[30] See Bodenstein et al. (2019) for an analysis of the transition from an inflation-targeting rule to a price-level targeting rule in a model environment where agents learn only gradually about the new policy rule.

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Table 1: Interest-rate rules

Estimated rule in NAWM II (log-linearised)	$\hat{r}_t = 0.92\hat{r}_{t-1} + 0.08\left(\hat{r}^r_{t\|t} + 2.75\hat{\pi}_t + 0.03\hat{y}_t\right) + 0.04\left(\hat{\pi}_t - \hat{\pi}_{t-1}\right) + 0.1(\hat{y}_t - \hat{y}_{t-1})$
Inertial Taylor (1999) rule	$R_t = 0.85R_{t-1} + 0.15\left(r^* + \bar{\pi}^{(4)}_t + y^{gap}_t + 0.5\left(\bar{\pi}^{(4)}_t - \pi^*\right)\right)$
Modified inertial Taylor (1999) rule	$R_t = 0.85R_{t-1} + 0.15\left(r^* + \bar{\pi}^{(4)}_t + y^{gap}_t + 2.0\left(\bar{\pi}^{(4)}_t - \pi^*\right)\right)$
First-difference rule	$R_t = R_{t-1} + 0.5\left(\bar{\pi}^{(4)}_t - \pi^*\right) + 0.5\left(y^{gap}_t - y^{gap}_{t-1}\right)$

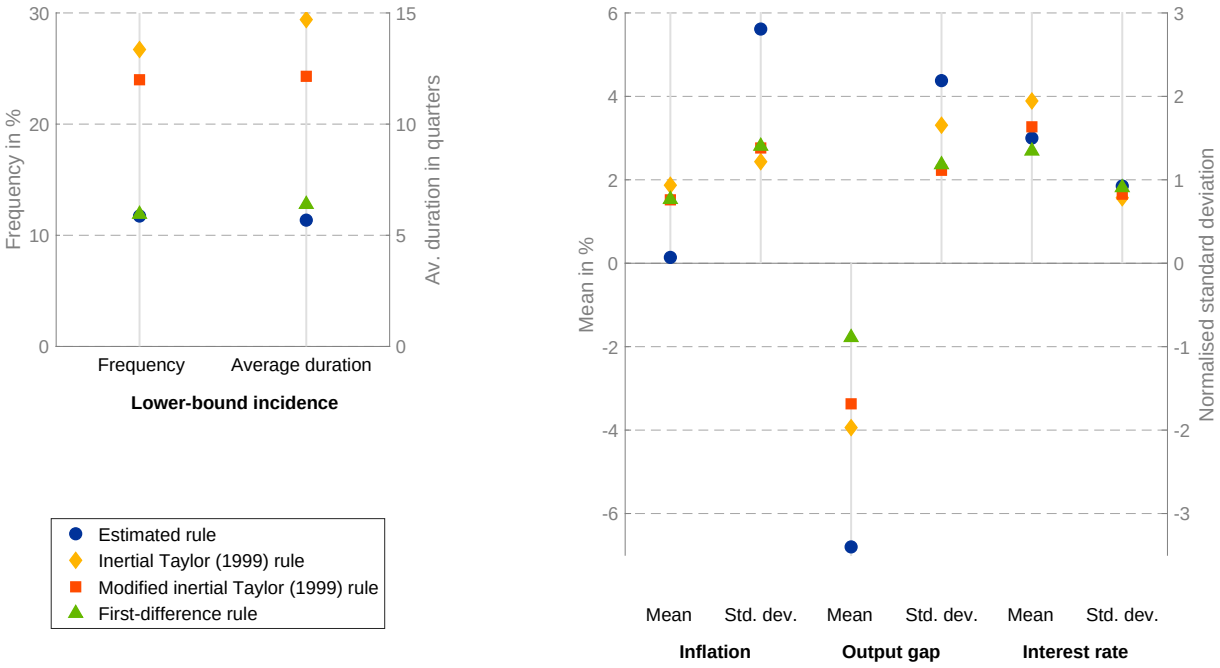
Notes: r^* denotes the annualised long-run equilibrium real rate, R_t is the annualised short-term nominal interest rate, $\bar{\pi}^{(4)}_t$ is the annual consumer price inflation rate, π^* is the inflation target, and y^{gap}_t is the output gap. In the estimated rule, $\hat{r}_t$ denotes the logarithmic deviation of the gross short-term nominal interest rate from its deterministic steady-state value, and $\hat{\pi}_t$ is the logarithmic deviation of (gross) consumer price inflation from the steady-state inflation rate. Throughout, $\hat{y}_t = y^{gap}_t$ 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. $\hat{r}^r_{t|t}$ 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.

Table 2: Make-up rules

Average inflation targeting (4-year window)	$R_t = 0.85R_{t-1} + 0.15\left(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + 4.0\left(\bar{\pi}_t^{(16)} - \pi^*\right)\right)$
Average inflation targeting (8-year window)	$R_t = 0.85R_{t-1} + 0.15\left(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + 8.0\left(\bar{\pi}_t^{(32)} - \pi^*\right)\right)$
Asymmetric average inflation targeting (4-year window)	$R_t = 0.85R_{t-1} + 0.15\Big(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + I_{[\bar{\pi}_t^{(16)} \geq \pi^*]} 2.0\left(\bar{\pi}_t^{(4)} - \pi^*\right) + I_{[\bar{\pi}_t^{(16)} < \pi^*]} 3.0\left(\bar{\pi}_t^{(16)} - \pi^*\right)\Big)$
Price-level targeting	$R_t = 0.85R_{t-1} + 0.15\left(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + (p_t - p_t^*)\right)$
Temporary price-level targeting	$R_t = 0.85R_{t-1} + 0.15\Big(r^* + \bar{\pi}_t^{(4)} + y_t^{gap} + 2.0\left(\bar{\pi}_t^{(4)} - \pi^*\right) + 0.1p_{t-1}^{[-]}\Big)$ $p_t^{[-]} = \min\left(I_{[R_t = ELB \mid p_{t-1}^{[-]} < 0]}(p_{t-1}^{[-]} + \pi_t), 0\right)$

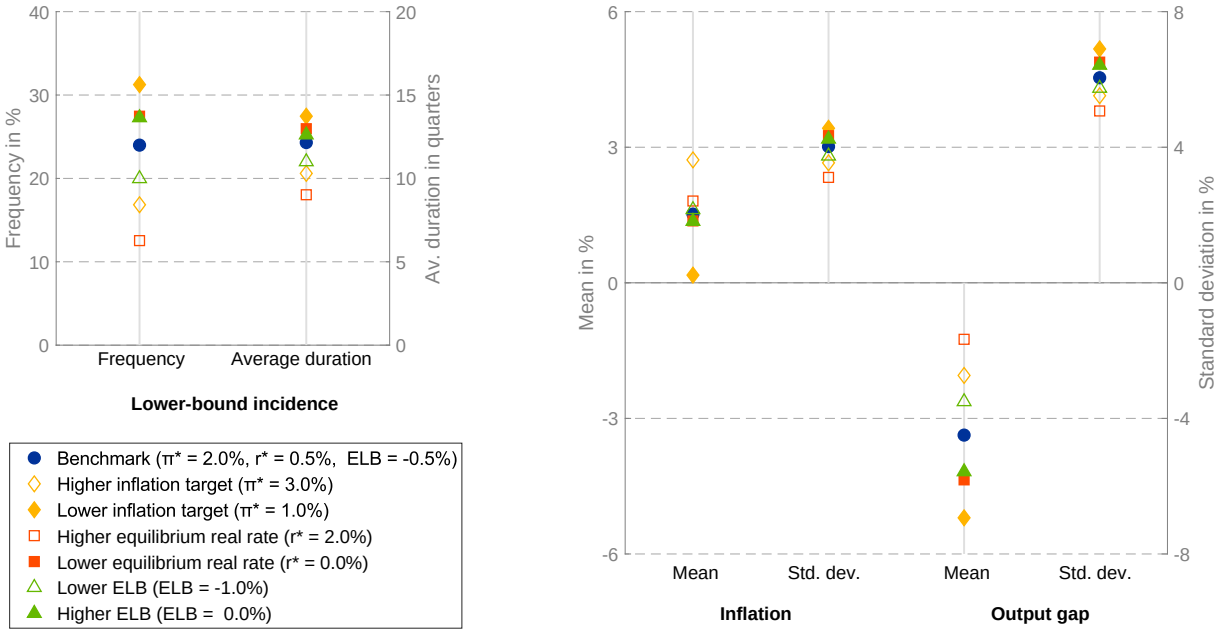
Notes: r^* denotes the annualised long-run equilibrium real rate, R_t is the annualised short-term nominal interest rate, $\bar{\pi}_t^{(4T)}$ is the annualised average consumer price inflation rate over the past T years, π^* is the inflation target, and y_t^{gap} is the output gap. In the asymmetric average inflation targeting rule, $I_{[\bar{\pi}_t^{(16)} \geq \pi^*]}$ is an indicator variable that takes on a value of one if the 4-year average inflation rate is larger than or equal to the inflation target, and equals zero otherwise. In the price-level targeting rule, p_t is the consumer price level, and $p_t^* = p_{t-1}^* + \pi^*$ is the price-level target. In the temporary price-level targeting rule, $p_t^{[-]}$ is a price-level gap variable that represents the cumulated shortfalls of the inflation rate from the inflation target during ELB episodes and thereafter, until the price-level gap is closed. The indicator variable $I_{[R_t = ELB \mid p_{t-1}^{[-]} < 0]}$ equals one if the ELB constraint is contemporaneously binding or if the previous period's price level gap is negative, and it equals zero otherwise.

Figure 1: ELB incidence and macroeconomic stabilisation



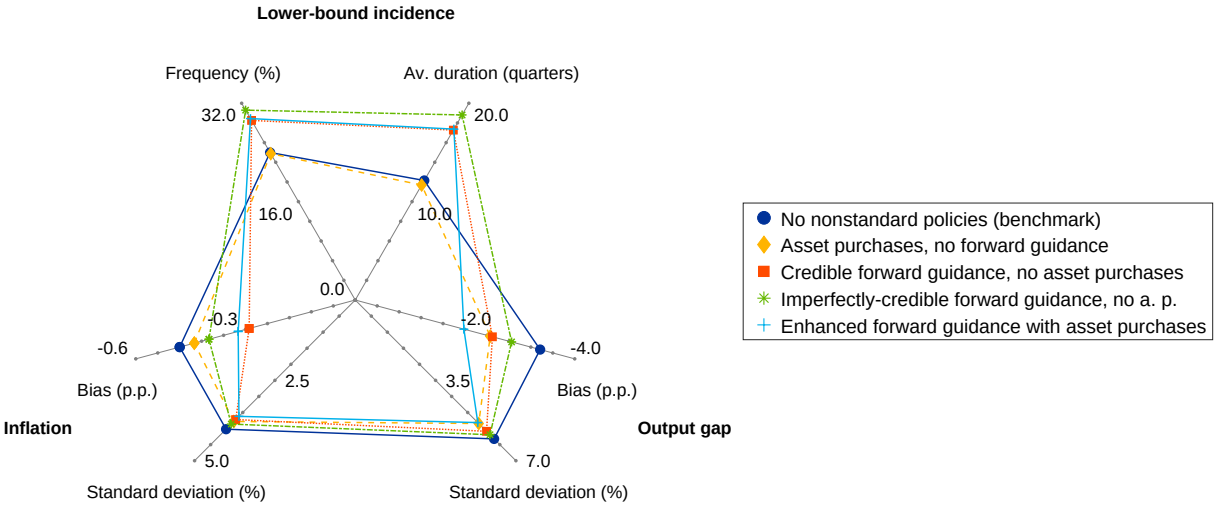
Notes: This chart presents summary statistics of the steady-state probability distributions for the short-term nominal interest rate, annual consumer price inflation, and the output gap. These statistics include the incidence of the ELB constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the (average) duration of an ELB event, in quarters); and the mean and standard deviation of consumer price inflation, the output gap and the annualised short-term nominal interest rate. The means are expressed in percent, and the standard deviations are normalised by the respective standard deviation in the absence of the ELB constraint. The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation target equal to 2% and an equilibrium real interest rate set equal to 0.5%. They are carried out for alternative specifications of the interest-rate rule taking into account an ELB constraint set equal to -0.5%. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator. Table A in the Appendix provides a tabular presentation of the results.

Figure 2: The roles of the inflation target, the equilibrium real rate, and the level of the ELB



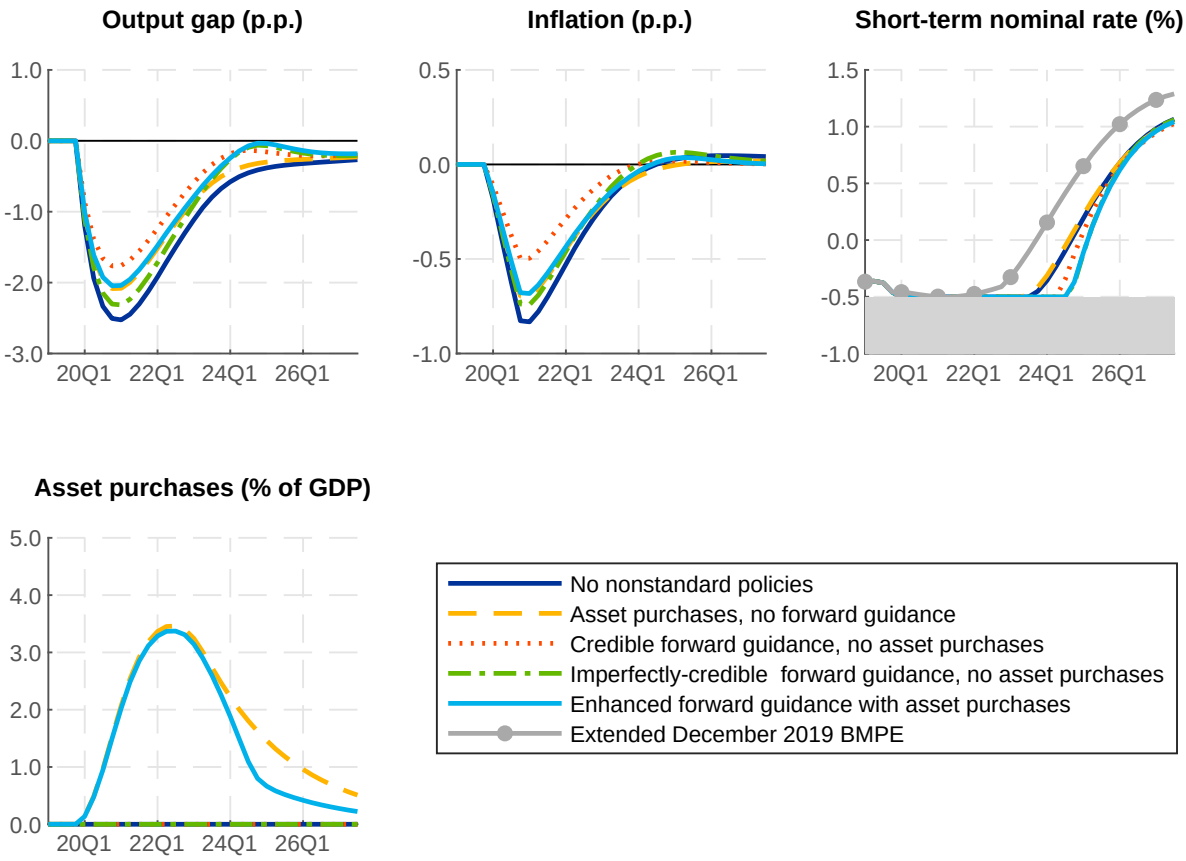
Notes: This chart presents summary statistics of the steady-state probability distributions for the short-term nominal interest rate, annual consumer price inflation, and the output gap. These statistics include the incidence of the ELB constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the (average) duration of an ELB event, in quarters); and the mean and standard deviation of consumer price inflation and the output gap (all in percent). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state. They are carried out for alternative combinations of steady-state inflation (as pinned down by the inflation target), the steady-state real interest rate and the ELB constraint. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator. Table B in the Appendix provides a tabular presentation of the results.

Figure 3: Effects of nonstandard policies on ELB incidence and macroeconomic stabilisation



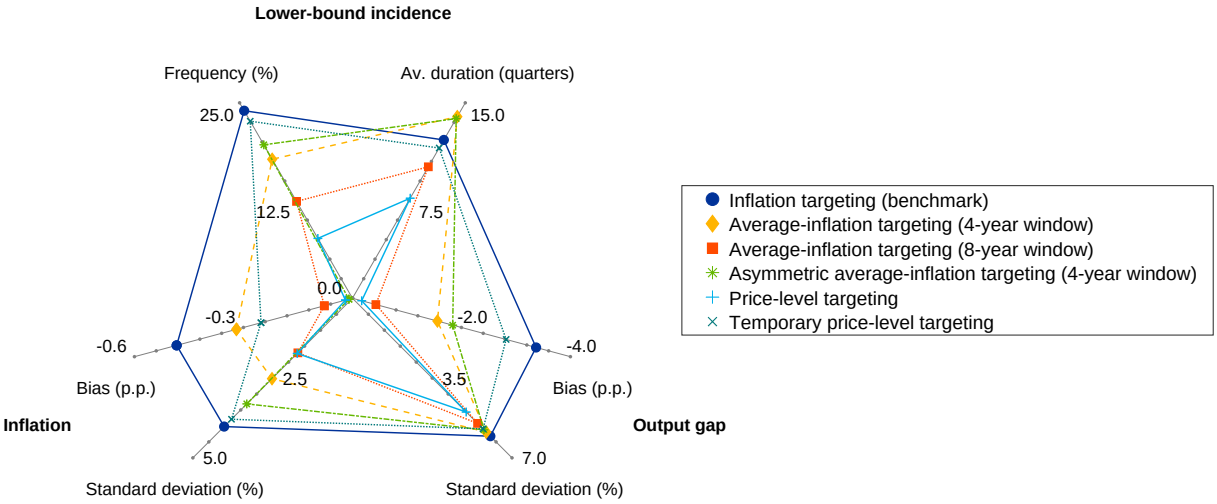
Notes: This chart presents summary statistics of the steady-state probability distributions for the short-term nominal interest rate, annual consumer price inflation, and the output gap. These statistics include the incidence of the ELB constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the (average) duration of an ELB event, in quarters); and the bias (in percentage points) and standard deviation (in percent) of consumer price inflation and the output gap. The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation target equal to 2% and an equilibrium real interest rate set equal to 0.5%. They are carried out for alternative combinations of state-dependent asset purchases and state-dependent forward guidance on short-term nominal interest rates taking into account an ELB constraint set equal to -0.5%. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator. Table C in the Appendix provides a tabular presentation of the results.

Figure 4: Nonstandard policies in a recession scenario with low interest rates



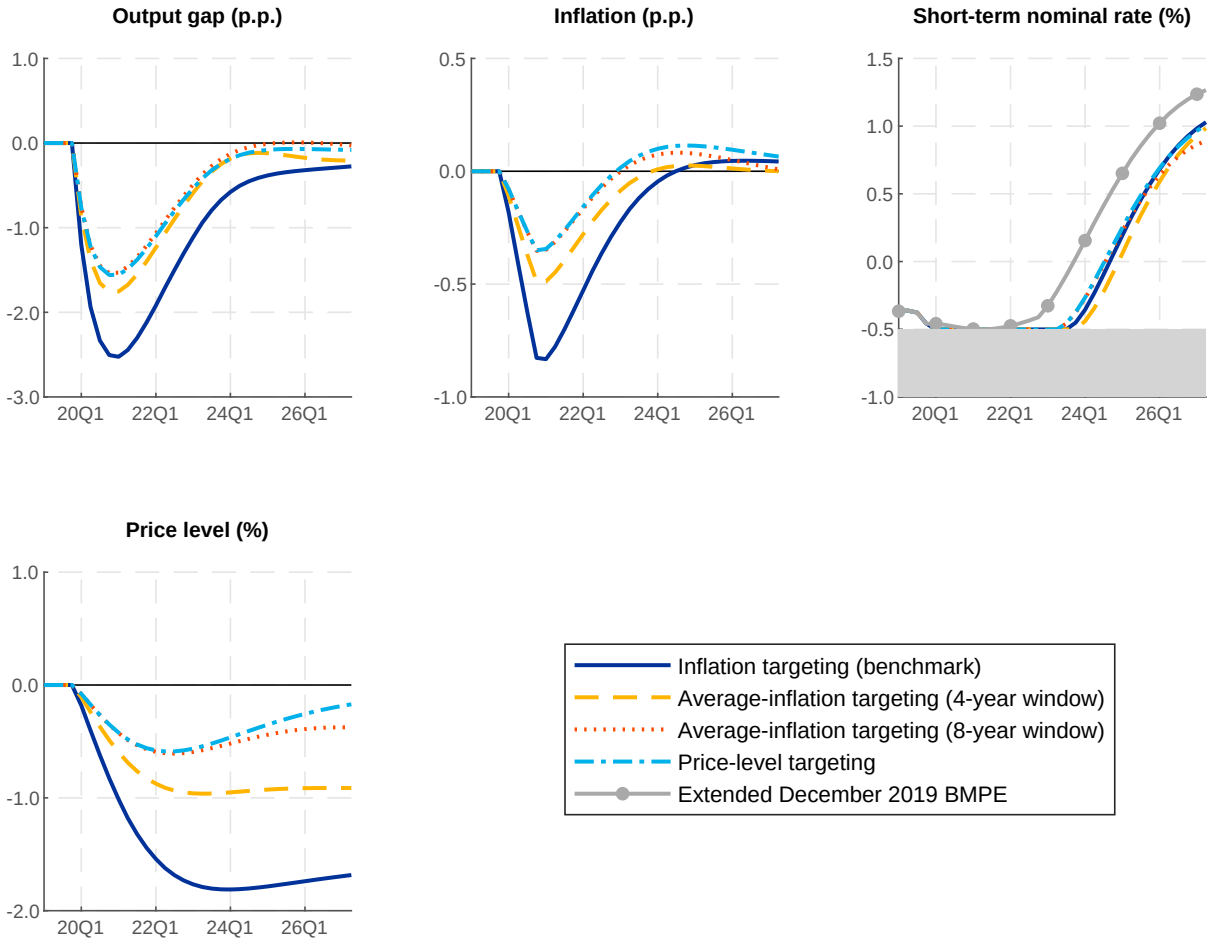
Notes: This chart shows the evolution of the output gap, annual consumer price inflation, the annualised short-term nominal interest rate and central bank large-scale asset purchases in a counterfactual simulation of a recession scenario. The simulation is conducted around a model-based extension of the December 2019 BMPE, and the recession is induced by a 1.5 standard deviation risk premium (demand) shock. The output gap and inflation are depicted in percentage-point deviation from their respective baseline path, the short-term nominal interest rate is displayed in levels and expressed in percent, and asset purchases are depicted as a percent of GDP. The short-term nominal interest rate corresponds to the 3-month EONIA, and consumer price inflation is measured in terms of the private consumption deflator. In the simulation, the inflation target is set to 2.0%, the steady-state real interest rate equals 0.5% and the ELB is set to -0.5%.

Figure 5: Effects of make-up strategies on ELB incidence and macroeconomic stabilisation



Notes: This chart presents summary statistics of the steady-state probability distributions for the short-term nominal interest rate, annual consumer price inflation, and the output gap. These statistics include the incidence of the ELB constraint (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the (average) duration of an ELB event, in quarters); and the bias (in percentage points) and standard deviation (in percent) of consumer price inflation and the output gap. The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation target equal to 2% and an equilibrium real interest rate set equal to 0.5%. They are carried out for alternative make-up rules, taking into account an ELB constraint set equal to -0.5%. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator. Table D in the Appendix provides a tabular presentation of the results.

Figure 6: Make-up strategies in a recession scenario with low interest rates



Notes: This chart shows the evolution of the output gap, annual consumer price inflation, the annualised short-term nominal interest rate and the consumer price level in a counterfactual simulation of a recession scenario. The simulation is conducted around a model-based extension of the December 2019 BMPE, and the recession is induced by a 1.5 standard deviation risk premium (demand) shock. The output gap and inflation are depicted in percentage-point deviation from their respective baseline path, the short-term nominal interest rate is displayed in levels and expressed in percent, and the price level is depicted in percentage deviation from its baseline path. The short-term nominal interest rate corresponds to the 3-month EONIA, and consumer price inflation is measured in terms of the private consumption deflator. In the simulation, the inflation target is set to 2.0%, the steady-state real interest rate equals 0.5% and the ELB is set to -0.5%.

Appendix A: The New Area-Wide Model

The original NAWM is an open-economy DSGE model of the euro area designed for use in the (Broad) Macroeconomic Projection Exercises regularly undertaken by ECB/Eurosystem staff and for analysis of topical policy issues; see Christoffel et al. (2008) for a detailed description of the model's structure. Its development has been guided by the principal consideration of covering 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.

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 domestic 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 already exist some stylised financial frictions which however enter the model only in the form of exogenous risk premia.

The fiscal authority purchases the public consumption good, issues domestic bonds, and levies different types of distortionary taxes, albeit 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 a Taylor (1993)-type interest-rate rule, stabilising inflation in line with the ECB's definition of price stability.

The extended version of the NAWM—called NAWM II—includes a rich financial sector which is centered around two distinct types of financial intermediaries that are exposed to sector-specific shocks: (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 govern the holdings of domestic and foreign long-term government bonds by the financial and the non-financial private sector, respectively, building on Gertler and Karadi (2013).

The incorporation of these financial extensions into the original model reflects the threefold 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 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 long-term government bonds ease wholesale banks' funding constraint and create (excess) balance sheet capacity that banks can use to extend new credit to the non-financial private sector. As a consequence, lending conditions improve and stimulate private investment. Concomitantly, the lending rate spread and the expected excess return, or *premium*, on long-term government bonds relative to the short-term government bond yield fall and asset valuations rise. This generates windfall gains for the wholesale banks, raising their net worth, and allows them to loosen credit conditions further in a positive feedback loop. The ensuing increase in domestic demand puts upward pressure on firms' marginal cost of production and leads to a rise in domestic prices. The 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 increasing import prices.

In estimating NAWM II, the standard Bayesian approach outlined in An and Schorfheide (2007) was followed, which was likewise adopted by Christoffel et al. (2008) for estimating the original version of the NAWM. In doing so, the 18 macro variables that were used as observed variables for estimating the original model were retained, albeit with two important changes: all real variables were transformed into per-capita units, and the estimation sample was extended until 2014Q4, resulting in somewhat larger variances of the model's structural shock processes. In addition, six variables were added to the original set of observables, partly in order to provide useful measurements for identifying the model's financial-sector parameters and shocks.

Appendix B: Solution and simulation methods

We solved NAWM II for its reduced form using the AIM implementation (Anderson and Moore, 1985; 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 computed at the model's deterministic 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 deterministic steady state of the model, while imposing the lower bound constraint and taking into account the threshold conditions of the state-dependent policy rules. 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 50 realisations of each of the simulated variable paths and retained only the 100 final realisations.

We simulated the non-linear model with the lower-bound constraint and policy thresholds using a computationally efficient and robust algorithm which is implemented in TROLL and based on work by Laffargue (1990), Juillard (1996) and Boucekkine (1995).[31] It is related to the Fair and Taylor (1983) extended-path algorithm. In the simulations, the lower-bound constraint also applies to the expectations of future interest rates. 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 path 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 effective 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, importantly, interest rates. To be clear, we should emphasise that the variance of shocks has both a direct and an indirect effect on the 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. The simulation algorithm captures the direct effect but not the indirect one.

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 ELB 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

[31] TROLL is an integrated econometric modelling and time-series management tool used by many central banks and international organisations.

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.

There are other solution algorithms for non-linear rational expectations models that do not impose certainty equivalence. 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.

Table A: Incidence of effective lower-bound events and macroeconomic stabilisation performance under alternative interest-rate rules

	Lower-bound incidence		Inflation		Output gap		Short and long-term interest rates			
Interest-rate rule	Frequency	Duration	Mean	Std	Mean	Std	Mean		Std	
Modified inertial Taylor (1999) rule (benchmark)										
with ELB constraint	23.99	12.15	1.52	4.02	-3.37	6.05	3.27	4.63	2.69	1.98
w/o ELB constraint	—	—	2.00	2.91	0.00	5.43	2.50	4.14	3.25	2.17
Inertial Taylor (1999) rule										
with ELB constraint	26.71	14.70	1.87	6.00	-3.94	5.84	3.89	5.03	3.24	2.76
w/o ELB constraint	—	—	2.00	4.93	0.00	3.53	2.50	4.14	4.13	3.22
First-difference rule										
with ELB constraint	11.89	6.39	1.53	1.74	-1.78	7.36	2.69	4.23	1.94	0.90
w/o ELB constraint	—	—	2.00	1.24	0.00	6.23	2.50	4.14	2.14	0.90
Estimated rule										
with ELB constraint	11.73	5.68	0.14	4.94	-6.80	12.76	3.00	4.45	2.11	0.93
w/o ELB constraint	—	—	2.00	1.76	0.00	5.83	2.50	4.14	2.28	0.88

Note: This table reports summary statistics of the steady-state probability distributions for annual consumer price inflation, the output gap and short and long-term nominal interest rates based on the New Area-Wide Model II. These statistics include the incidence of effective lower-bound (ELB) events (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the average duration of an ELB event, in quarters), and the means and standard deviations (std) of consumer price inflation, the output gap and the short and long-term interest rates (all in percent). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation rate set equal to 2% and an equilibrium real interest rate equal to 0.5%. The simulations cover 2,500 simulated paths with an effective length of 100 quarters. They are carried out for alternative interest-rate rules both with and without taking into account an ELB constraint set equal to -0.5%. The numerical specifications of the alternative rules are presented in Table 1 of the paper. The modified inertial Taylor (1999) rule features a higher weight of 2 on the inflation gap, instead of a weight of 0.5 in the original rule, and serves as the benchmark interest-rate rule for conducting all further analysis. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator.

Table B: Incidence of effective lower-bound events and macroeconomic stabilisation performance under alternative steady-state calibrations of the monetary policy space

Modified inertial Taylor (1999) rule	Lower-bound incidence		Inflation		Output gap		Short and long-term interest rates			
	Frequency	Duration	Mean	Std	Mean	Std	Mean		Std	
Benchmark values										
$\pi^* = 2.0\%$, $r^* = 0.5\%$, ELB = -0.5%	23.99	12.15	1.52	4.02	-3.37	6.05	3.27	4.63	2.69	1.98
Sensitivity wrt π^*										
$\pi^* = 3.0\%$	16.84	10.30	2.72	3.54	-2.05	5.52	3.99	5.45	2.73	1.99
$\pi^* = 1.0\%$	31.25	13.73	0.17	4.56	-5.20	6.90	2.54	3.84	2.43	1.89
Sensitivity wrt r^*										
$r^* = 2.0\%$	12.54	9.02	1.81	3.11	-1.25	5.07	4.32	5.83	2.72	1.91
$r^* = 0.0\%$	27.46	12.98	1.37	4.34	-4.36	6.51	2.93	4.26	2.54	1.96
Sensitivity wrt ELB										
ELB = -1.0%	19.97	11.00	1.62	3.74	-2.63	5.74	3.10	4.53	2.66	1.97
ELB = 0.0%	27.28	12.61	1.36	4.24	-4.18	6.42	3.37	4.72	2.51	1.92

Note: This table reports summary statistics of the steady-state probability distributions for annual consumer price inflation, the output gap and short and long-term nominal interest rates based on the New Area-Wide Model II. These statistics include the incidence of effective lower-bound (ELB) events (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the average duration of an ELB event, in quarters), and the means and standard deviations (std) of consumer price inflation, the output gap and the short and long-term interest rates (all in percent). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state. They are carried out for alternative combinations of steady-state inflation (π^*), the steady-state real interest rate (r^*) and the ELB constraint. The modified version of the inertial Taylor (1999) rule is used as the benchmark interest-rate rule, and the benchmark calibration of the monetary policy space is given by $\pi^* = 2.0\%$, $r^* = 0.5\%$ and ELB = -0.5%. For the sensitivity analysis, the simulations are limited to 500 simulated paths with an effective length of 100 quarters. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator.

Table C: Effects of state-dependent asset purchases and forward guidance on the incidence of effective lower-bound events and on macroeconomic stabilisation performance

Modified inertial Taylor (1999) rule	Lower-bound incidence		Inflation		Output gap		Short and long-term interest rates				Asset purchases
	Frequency	Duration	Mean	Std	Mean	Std	Mean		Std		95th perc.
No state-dependent policies (benchmark)	23.99	12.15	1.52	4.02	-3.37	6.05	3.27	4.63	2.69	1.98	—
Asset purchases, no forward guidance	23.80	11.69	1.56	3.78	-2.46	5.38	3.24	4.46	2.66	2.06	41.59
Strong forward guidance, no asset purchases	29.21	17.27	1.71	3.72	-2.50	5.72	3.15	4.55	2.68	1.98	—
Weak forward guidance, no asset purchases	30.88	18.81	1.60	3.86	-2.85	5.87	3.12	4.56	2.69	1.97	—
Enhanced forward guidance with asset purchases	29.51	17.37	1.68	3.62	-1.98	5.34	3.12	4.42	2.66	2.04	35.45

Note: This table reports summary statistics of the steady-state probability distributions for annual consumer price inflation, the output gap, short and long-term nominal interest rates and central bank asset purchases based on the New Area-Wide Model II. These statistics include the incidence of effective lower-bound (ELB) events (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the average duration of an ELB event, in quarters), the means and standard deviations (std) of consumer price inflation, the output gap and the short and long-term interest rates (all in percent), and the 95th percentile of the stock of purchased assets (as a share of GDP, in percent). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation rate set equal to 2% and an equilibrium real interest rate equal to 0.5%. The simulations cover 2,500 simulated paths with an effective length of 100 quarters. They are carried out for alternative combinations of state-dependent asset purchases and state-dependent forward guidance on short-term nominal interest rates taking into account an ELB constraint set equal to -0.5%. The modified inertial Taylor (1999) rule serves as the benchmark interest-rate rule. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator.

Table D: Effects of alternative monetary policy strategies on the incidence of effective lower-bound events and on macroeconomic stabilisation performance

	Lower-bound incidence		Inflation		Output gap		Short and long-term interest rates			
Monetary policy strategy	Frequency	Duration	Mean	Std	Mean	Std	Mean		Std	
Inflation targeting (benchmark)										
Modified inertial Taylor (1999) rule	23.99	12.15	1.52	4.02	-3.37	6.05	3.27	4.63	2.69	1.98
Average-inflation targeting										
$T = 4$ years, weight equal to T	17.78	13.94	1.69	2.52	-1.56	5.87	2.75	4.30	2.00	1.33
$T = 8$ years, weight equal to T	12.39	10.09	1.94	1.71	-0.43	5.49	2.62	4.20	1.80	1.00
Asymmetric average-inflation targeting										
$T = 4$ years, weight equal to T	18.31	13.19	2.16	3.07	-1.45	5.79	3.29	4.61	2.46	1.70
$T = 4$ years, weight equal to $3/4\ T$	19.63	13.79	2.01	3.31	-1.84	5.77	3.25	4.59	2.49	1.78
Price-level targeting										
indefinite, weight equal to 1	7.66	7.68	2.00	1.73	-0.17	4.99	2.59	4.18	1.62	0.84
temporary, weight equal to 0.1	22.65	11.53	1.76	3.79	-2.82	5.73	3.33	4.72	2.70	1.96

Note: This table reports summary statistics of the steady-state probability distributions for annual consumer price inflation, the output gap and short and long-term nominal interest rates based on the New Area-Wide Model II. These statistics include the incidence of effective lower-bound (ELB) events (measured by the frequency, i.e. the number of times, the short-term nominal interest rate is at the ELB, in percent, and the average duration of an ELB event, in quarters), and the means and standard deviations (std) of consumer price inflation, the output gap and the short and long-term interest rates (all in percent). The steady-state distributions are derived from stochastic simulations around the model's non-stochastic steady state with an inflation rate set equal to 2% and an equilibrium real interest rate equal to 0.5%. The simulations cover 2,500 simulated paths with an effective length of 100 quarters. They are carried out for alternative make-up strategies, taking into account an ELB constraint set equal to -0.5%. The modified inertial Taylor (1999) rule serves as the benchmark interest-rate rule for formulating and assessing the alternative monetary policy strategies, the numerical specifications of which are presented in Table 2 of the paper. The short-term nominal interest rate corresponds to the 3-month EURIBOR, and consumer price inflation is measured in terms of the private consumption deflator.

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