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Lower for longer under endogenous technology growth

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Abstract

This paper studies monetary policy strategies under endogenous technology dynamics and low r^*. Endogenous growth strengthens the gains from make-up strategies relative to inflation targeting, especially if policy space is reduced. This result is due to the long-run non-neutrality of money and the hysteresis effects in TFP through which ELB episodes generate permanent scars on long-run aggregate supply. Make-up strategies not only foster the alignment of inflation with target but also support productivity-improving investment in R&D and technology adoption and hence the long-run trend path, provided that the inherent make-up element is sufficiently pronounced. Inflation is less responsive to monetary policy due to the interaction with productivity dynamics. As a result, additional stimulus is required at the ELB and the degree of subsequent overshooting is alleviated. Endogenous growth also generates novel monetary policy trade-offs, most notably credibility challenges, which can be mitigated by confining make-up elements to ELB episodes.

JEL Classification: E24, E31, E32, E52, O30
Keywords: Make-up Strategies, ZLB, Endogenous TFP, Hysteresis, Cycle-Trend Interaction

Non-technical summary

As long-run interest rates have trended down over the past decades, the scope of monetary policy to fight future recessions by cutting interest rates became increasingly narrow, exacerbating the potential challenges posed in the form of the downward constraint on policy rates due to the effective lower bound (ELB). To address these challenges the previous literature has studied policies which make up for past inflation shortfalls during expansions by keeping interest rates lower for longer (make-up strategies). The contribution of this paper to this strand of the literature is to study make-up strategies in an environment featuring endogenous technology dynamics. In such an environment, the stock of technology evolves endogenously as the result of productivity-improving investments in both research and development and in the adoption of new technologies. A special emphasis was made to consider the role of the ELB in this setting. We study a range of different make-up strategies, such as price level targeting (PLT), average inflation targeting (AIT) of various averaging horizons, temporary price level targeting (TPLT) and a hysteresis rule targeting the technology stock. We analyse their respective mechanisms and performance with respect to inflation and output stabilisation and, crucially and novel to the literature, their effect on the technology stock and the long-run output path. Moreover, we characterise the changed operating environment of monetary policy under endogenous growth and the corresponding implications for monetary policy design. A further focus of this paper is the analysis of the policy trade-offs for monetary policy arising under endogenous technology dynamics.

Our main results can be summarized in three sets: The first set of results describes how the operating environment of monetary policy changes when considering endogenous growth. Specifically, the interaction between cycle and trend generates hysteresis effects in TFP and permanent scars to the long-term output path and therefore the costs of the ELB are both amplified and no longer only transitory. In addition, the interaction of inflation and productivity dynamics reduces the responsiveness of inflation to monetary stimulus, requiring relatively more support to realign inflation with target at the ELB, while simultaneously reducing the costs of subsequent overshooting. Concerning the role of monetary policy space, we demonstrate that while inflation targeting performs relatively well when monetary policy space is large, both the stabilization and trend losses are strongly amplified in an environment of low long-run real interest rates.

Our second set of results analyses the relative performance and effectiveness of the various make-up strategies by considering both demand and supply-side shocks. We show that most make-up strategies improve the stabilization of inflation and output and reduce the long-run losses in output due to technology shortfalls. We show that the respective gains vary across make-up strategies and are increasing in the strength of the make-up element. Crucially, the relative gains from make-up strategies become substantially more pronounced when the long-run real interest rate is low, strengthening the cause for make-up strategies in proximity to the ELB.

The third set of results discusses the policy trade-offs arising under make-up strategies as communication is essential for their effectiveness which requires the strategies to be well-understood by economic agents. Communicating the averaging horizon may in the cases of AIT and PLT pose challenges. Similar concerns apply to the hysteresis rule given the complexity of the terminology of underutilization in the technology stock, compared with conventional slack measures. The latter challenges are intensified by measurement issues as to the technology gap, further exacerbating prevailing issues of potential output measurement. Lastly, we show that some make-up strategies are subject to credibility issues under endogenous growth which are rooted in their implied response to inflationary demand and supply shocks.

1 Introduction

Over the past decades interest rates have persistently trended downwards and the associated decline of monetary policy space rendered the effective lower bound (ELB) a relevant concern for monetary policy in advanced economies, where policy rates have ranged close to or at the ELB since the Great Recession.[1] In an environment of low monetary policy space, ELB episodes occur more frequently, with correspondingly adverse effects for inflation and output stabilization. Against this background, discussions emerged on the adequacy of prevailing monetary policy frameworks designed for an environment of higher long-run interest rates and several central banks, such as the the Federal Reserve and the European Central Bank, prompted reviews of their monetary policy strategies. Among the proposals to address the challenges posed by the ELB, a shift from inflation targeting frameworks, as implied by the Taylor rule which treats bygones in terms of past inflation shortfalls as bygones, to make-up strategies was proposed given their potentially improved performance in the presence of the ELB (see Bernanke, Kiley and Roberts (2019) and Mertens and Williams (2019)). Make-up strategies entail a commitment to compensate for past shortfalls from target by means of a subsequent overshooting episode, thus improving the performance of monetary policy.

In this paper, we show that endogenous growth alters the operating environment of monetary policy and raises the gains from make-up strategies over inflation targeting relative to standard frameworks with constant trend growth. While there is a growing literature on make-up strategies, previous evidence is, however, confined to models which abstract from technology growth. The underlying assumption of strictly exogenous technology, driven by technology shocks only, constitutes a simplifying assumption, imposed for tractability purposes. It is well-established in the endogenous growth literature, however, that productivity-improving investment constitutes the key driver of technology growth (Aghion and Howitt (1992), Grossman and Helpman (1991), Romer (1990)). From this perspective, the mechanisms and performance of make-up strategies under endogenous technology dynamics are hence not yet understood by the literature. This paper bridges this gap by studying make-up strategies under endogenous technology growth, thus providing a synthesis of the literature on make-up strategies on the one hand and the literature on endogenous growth in New Keynesian DSGE models on the other hand. A central insight from the latter is that modeling TFP dynamics endogenously holds crucial implications as to the drivers of deep recession episodes and sources of hysteresis effects, for the interaction between short- and long-run dynamics and, crucially, the role of aggregate demand in this context (Moran and Queralto (2018), Anzoategui, Comin, Gertler and Martinez (2019), Bianchi, Kung and Morales (2019), Ikeda and Koruzumi (2019), Elfsbacka-Schmöller and Spitzer (2021)). Against this backdrop, it is central to evaluate the underlying mechanisms, performance and relative effectiveness of make-up strategies and related policy trade-offs when the response of the technology stock is endogenously accounted for. These goals are at the core of this paper which, to the best of our knowledge, is the first to study make-up strategies under endogenous growth.

[1] The downward trend in equilibrium real interest rates is also reflected in estimates of the natural rate of interest (see, for instance, Holston, Laubach and Williams (2017)).

Technically, we study make-up strategies in an environment of low r^* in a medium-scale New Keynesian DSGE model with rich endogenous technology dynamics and under the nonlinearity of the effective lower bound. The technology stock evolves endogenously as the result of productivity-improving investment in R&D and technology adoption (Comin and Gertler (2006)). The main model backbone is hence based on the approach by the previous literature on endogenous growth in the DSGE context (Moran and Queralto (2018); Anzoategui et al. (2019)). We introduce and model make-up monetary policy strategies in this setting. Concretely, we study price level targeting (PLT), average inflation targeting (AIT) of various averaging horizons, temporary price level targeting (TPLT) and a hysteresis rule targeting the technology stock and thus the long-run trend. We study their mechanisms and performance with respect to inflation and output stabilization and, crucially and novel to the literature, their effect on the technology stock and the long-run output path. Moreover, we characterize the changed operating environment of monetary policy under endogenous growth and the corresponding implications for monetary policy design. This paper further derives the policy trade-offs for monetary policy arising under endogenous technology dynamics.

Our main findings can be summarized as follows. The first set of results derives the altered operating environment of monetary policy under endogenous growth and analyzes the performance of inflation targeting as implied by the Taylor rule in this context. Specifically, macroeconomic dynamics differ in four central aspects which constitute additional and not yet accounted for motives for the conduct of make-up strategies under low r^*. Firstly, recessions are particularly costly due to the inherent interaction between cycle and trend, thus generating hysteresis effects in TFP and permanent scars to the long-term output path. Secondly, the costs of the ELB are both amplified and no longer only transitory but permanent due to the adverse spillovers to the technology stock. Moreover, both the role and scope of monetary policy are increased due to its influence on productivity-improving investment and hence the technology stock and the long-run trend, thus inducing long-run non-neutrality of monetary policy. Fourth, the interaction of inflation and productivity dynamics reduces the responsiveness of inflation to monetary policy, requiring relatively more stimulus to realign inflation with target at the ELB, while simultaneously reducing the costs of running the economy hot in this context as the degree of overshooting is reduced.

We study the performance of the Taylor rule in this setting and under different levels of monetary policy space. In the baseline scenario, ELB frequency amounts to roughly 20% and the Taylor rule is subject to pronounced stabilization losses on the inflation and output target margin. Crucially, and not yet accounted for by the previous literature, shortfalls occur also on the technology margin, thus generating permanent losses in terms of the long-run trend. Concerning the role of monetary policy space, we demonstrate that while inflation targeting as implied by the Taylor rule performs relatively well when monetary policy space is high, both the stabilization and trend losses are strongly amplified in an environment of low r^*.

Our second set of results addresses the operating mechanisms underlying make-up strategies and their relative performance and effectiveness. The transmission mechanism of make-up strategies under endogenous technology growth differs in two central aspects. Firstly, the real interest rate channel is stronger than under exogenous technology as it stimulates in addition to the alignment of inflation and the output measure with target also technology-improving investment and hence the technology stock and long-run output path. Moreover, make-up strategies operate in addition via an innovation payoff channel. Under the latter, the implied commitment to hold interest rates lower for longer raises expectations about the future output trajectory and hence the expected payoff from new innovations, thus stimulating investment in R&D and technology adoption. Via these channels make-up strategies can boost technology growth and the long-run output path, thus alleviating the permanent output costs of the ELB. As a consequence, make-up strategies with a sufficiently strong make-up element are subject to improved performance at the ELB compared with Taylor-type rules as they are capable of reducing both the stabilization loss as to inflation and the output target, as well as the long-run scars in the technology stock.

We next study the performance of make-up strategies over the cycle, i.e. under both recessionary and expansionary shocks emerging from the demand as well as the supply side, and show that most make-up strategies reduce the stabilization loss as to inflation and the output target as well as the trend loss compared with the Taylor rule. We show that the respective gains vary across make-up strategies and is increasing in the strength of the make-up element. The effectiveness of AIT is increasing in the length of the averaging window. However, inflation targeting in the form of the Taylor rule with inertia, outperforms AIT of all averaging horizons both in terms of inflation and output stabilization and with respect to realized technology growth. Strategies with a strong make-up element (PLT, hysteresis rule, TPLT) perform substantially better than inflation targeting in terms of both the stabilization loss and as to the shortfall in technology growth. Their overall performance is comparable but varies as to subcategory. PLT minimizes the losses as to inflation stabilization, while also substantially reducing the losses in terms of the output target and nearly fully offsetting the losses in terms of technology growth. The hysteresis rule targets in addition to a standard output target also the shortfall of the technology stock. Under the hysteresis rule, the losses in terms of output target stabilization are minimized and the trend loss returns close to zero, while also significantly reducing the shortfall in terms of inflation stabilization. Lastly, TPLT substantially reduces the stabilization losses both as to the output and inflation target. Despite not directly targeting the technology stock, TPLT realizes the highest average rate of technology growth, due to treating bygones outside the ELB as bygones, thus intensifying the technology-improving effects of expansions. We show that the described relative ranking as to both the stabilization and trend losses prevail also for varying assumptions on the monetary policy space. Crucially, the relative gains from make-up strategies become substantially more pronounced in regions of low r^*, strengthening the cause for make-up strategies in proximity to the ELB.

The third set of results derives the policy trade-offs arising under make-up strategies. Communication is essential for their effectiveness which requires the strategies to be well-understood by economic agents. The make-up element under TPLT is confined to ELB episodes and hence constitutes a less pronounced change in the monetary policy framework relatively to inflation targeting, which facilitates communication. Communicating the averaging horizon may, in turn, pose challenges under AIT and PLT. Similar concerns apply to the hysteresis rule given the complexity of the notion of underutilization on the technology margin compared with conventional slack measures. These challenges are intensified by measurement issues as to the technology gap, further exacerbating prevailing issues of potential output measurement. Lastly, we show that some make-up strategies are subject to credibility issues under endogenous growth which are due to their implied response to inflationary demand and supply shocks. Specifically, agents may not fully believe that monetary policy would lean sufficiently forcefully against a demand-riven expansion and hence forego permanent technology gains. In the case of supply shocks, in turn, weakened credibility is owed to the monetary policy response further intensifying the downturn and hence amplifying the permanent output losses emerging from decelerating technology-improving investment.

Previous literature

As discussed earlier, this paper predominantly contributes to both the literature on New Keynesian models with endogenous technology growth and to the literature on monetary policy strategies in a low interest rate environment. As to the former, this literature focuses in particular on the effect of aggregate demand and monetary policy on productivity-improving investment and thus the long-run (Benigno and Fornaro (2018), Moran and Queralto (2018), Anzoategui et al. (2019), Bianchi, Kung and Morales (2019), Ikeda and Koruzumi (2019), Garga and Singh (2021), Elfsbacka-Schmöller and Spitzer (2021)), as recently also reviewed by Cerra, Fatás and Saxena (2022). This literature has, however, not yet studied the performance of monetary policy strategies in a low r^* environment under the non-linearity of the ELB, which is at the core of this paper. Our paper follows the approach taken by the previously literature in modeling technology growth through horizontal innovation (Romer (1990)) evolving as a two-stage process of R&D and technology adoption (Comin and Gertler (2006)), where the backbone of our model builds closely on Moran and Queralto (2018).[2] Differently to their work, we study the non-linearity of the ELB and its implications for the effectiveness of monetary policy strategies in terms of inflation and output stabilization over both the short- and long-run. A further key contribution of ours is to study make-up strategies, in particular price level targeting, average inflation targeting of various averaging windows, temporary price level targeting, and a novel hysteresis rule which have at this point not yet been studied under endogenous growth. Moreover, this paper is linked to the empirical work on the interconnection between aggregate demand and monetary policy on total factor productivity and thus the long-run (see Jordà, Singh and Taylor (2021), Furlanetto et al. (2021), Ilzetzki (2021), Bertolotti, Gavazza and Lanteri (2022)).

This paper further adds to the literature which studies the performance of monetary policy strategies under the zero lower bound constraint. The most central contribution relatively to this line of the literature is the study of the operating channels, transmission mechanisms and performance of monetary policy frameworks under endogenous technology growth. The existing literature

[2] See section 2.10 for a detailed discussion on the technical differences relative to the previous literature.

demonstrated that monetary policy should use rules which imply a commitment to temporary inflation overshooting in proximity to the ELB (Eggertsson and Woodford (2003) and Adam and Billi (2006)). Earlier work studied price level targeting and average inflation targeting in the absence of the ELB (Svensson (1999); Vestin (2006); Nessén and Vestin (2015)). More recently, an increasing strand of the literature focused on the analysis of PLT and AIT under the ELB constraint (Budianto, Nakata and Schmidt (2020); Hebden et al. (2020); Honkapohja and Mitra (2020); Andrade, Galí, Le Bihan and Matheron (2021); Coenen, Montes-Galdón and Schmidt (2021); Honkapohja and McClung and (2021)). Temporary price level targeting was proposed earlier by Evans (2012) and Bernanke (2017). The hysteresis rule studied in this paper is novel to the literature. It is to some extent related to the concept of nominal GDP targeting (see Taylor (1985) and Billi (2020) for reference), with the hysteresis rule targeting the underutilization of the technology stock and hence in the trend itself constituting the central difference relatively to nominal GDP targeting. Work most closely related to this paper comparatively studies a set of make-up strategies in the presence of the ELB constraint and under various assumptions on r^* (Bernanke et al. (2019), Mertens and Williams (2019), Arias et al. (2020)).

This paper is structured as follows. Section 2 presents the model framework. Section 3 studies the performance of inflation targeting in this framework under various assumptions as to monetary policy space. Section 4 derives the changed operating environment of monetary policy under endogenous technology growth. Section 5 studies the mechanisms of make-up strategies under endogenous growth and section 6 their relative performance and effectiveness as well as the underlying policy trade-offs. Section 7 concludes.

2 Model

This section presents the model framework. The main model structure follows a medium-scale New Keynesian DSGE model in the spirit of Christiano et al. (2005) and Smets and Wouters (2007) augmented by an endogenous total factor productivity mechanism. Specifically, technology growth evolves endogenously as the result of innovation through R&D and technology adoption (Comin and Gertler (2006)). We present first the elements of the framework that are related to monetary policy as they both constitute the main focus of this paper and a central departure from related frameworks in this literature.

2.1 Effective lower bound

The central bank conducts monetary policy by setting the nominal interest rate R_t. Monetary policy may be constrained by the effective lower bound on nominal interest rates[3]:

$$R_t \geq \bar{R}. \tag{1}$$

We incorporate the effective lower bound (ELB) by means of the piecewise-linear method, as implemented in the OccBin toolbox (Guerrieri and Iacoviello (2015)). In doing so we assess the implications from the non-linearity induced by the ELB under endogenous technology growth and the performance of different monetary policy frameworks in this context. The respective monetary policy frameworks are presented in the next section.

2.2 Monetary policy strategies

Monetary policy is typically modeled in the form of a Taylor rule which constitutes the baseline in this analysis. As an alternative to the Taylor rule, we study further make-up monetary policy strategies which entail a commitment to hold interest rates *lower for longer* as they - in contrast to inflation targeting implied by the Taylor rule - entail make-up elements and thus take bygones in terms of past misses in inflation and output stabilization no longer as bygones. Specifically, we study price level targeting, average inflation targeting of various horizons, a hysteresis rule, as well as the asymmetric strategy temporary price level targeting which we describe in what follows.

2.2.1 Inflation targeting

In the baseline scenario, monetary policy sets the policy rate R_t by means of a standard Taylor rule representing an inflation targeting approach

$$R_t = \left(\left(\frac{\pi_t}{\pi^*} \right)^{\gamma_\pi} \left(\frac{y_t}{y_t^{pot}} \right)^{\gamma_y} R_n \right)^{1-\rho_r} (R_{t-1})^{\rho_r} \, r_t^m. \tag{2}$$

The policy rate is hence set based on the deviation of inflation π_t from target π^* which we set to 2% annually. In addition, the central bank targets an output measure with relatively lower policy weight ($\gamma_\pi > \gamma_y$).[4] Targeted output constitutes the deviation of detrended output y_t from respective potential output y_t^{pot}, i.e. the allocation prevailing under perfectly flexible prices and wages.[5] We study both non-inertial ($\rho_r = 0$) and inertial versions of the Taylor rule ($\rho_r > 0$). R^n denotes the steady state gross nominal interest rate. In the baseline scenario the steady state

[3]We assume in our analysis an effective lower bound of zero ($\bar{R} = 1$).

[4]We set $\gamma_\pi = 1.5$ and $\gamma_y = 0.5$, reflecting the parameterization in Taylor (1993).

[5]Detrended output, as described in later sections, corresponds to $\frac{Y_t}{A_t}$, where A_t denotes the technology stock which is subject to endogenous growth. We further explore alternative measures for the output margin in this setting. A possible candidate is to formulate the output measure in terms of employment $\frac{L_t}{L^{ss}}$ for which we find robust results (section 6.2).

nominal interest rate is set to 3% annually, reflecting a long-run real interest rate of 1% annually. The latter is based on empirical estimates for the long-term natural rate for the United States (Holston, Laubach, Williams (2017)) and also represents a value imposed by the recent literature on make-up strategies (see for instance Bernanke, Kiley and Roberts (2019)). The monetary policy shock r_t^m follows an AR(1)-process ($r_t^m = \rho^m r_{t-1}^m + \epsilon_t^m$).

2.2.2 Price level targeting

We study a flexible price level targeting strategy under which monetary policy targets in addition to the price level P_t also inflation and an output measure.[6] Hence, $\frac{P_t}{P^*}$ denotes the deviation of the price level from the targeted level at which inflation grows constantly at 2% annually and γ_P constitutes the weight on the price level.[7]

$$R_t = \left(\left(\frac{\pi_t}{\pi^*}\right)^{\gamma_\pi} \left(\frac{y_t}{y_t^{pot}}\right)^{\gamma_y} \left(\frac{P_t}{P^*}\right)^{\gamma_P} R_n \right) r_t^m. \tag{3}$$

Under price level targeting (PLT), the central bank hence fully keeps track of past deviations of inflation from target as it seeks to stabilize the price level with full lookback horizon. Thus, any shortfall of inflation from target realized during an ELB episode fully accumulates and is to be made up in full during a subsequent phase of overshooting.

2.2.3 Average inflation targeting

The assumption of a full lookback horizon with respect to past shortfalls of inflation from target prevalent under PLT is relaxed under average inflation targeting (AIT). Under this strategy the central bank aims at an average inflation rate of 2% over a specified averaging horizon. Hence, also under AIT past shortfalls of inflation from target have to be made up in the form of subsequent overshooting of inflation from targeted inflation. The lookback horizon up until which inflation shortfalls accumulate are, however, restricted to the respective average horizon. AIT thus approaches PLT as the averaging horizon goes to infinity. AIT is modeled otherwise as described for the case of PLT, but instead of the deviation from the price level the deviation of average inflation from targeted inflation enters the policy rule[8]

$$R_t = \left(\left(\frac{\pi_t}{\pi^*}\right)^{\gamma_\pi} \left(\frac{y_t}{y_t^{pot}}\right)^{\gamma_y} \left(\frac{\pi_{t,j}^{AI}}{\pi_{t,j}^*}\right)^{\gamma_{AI}} R_n \right) r_t^m, \tag{4}$$

[6] Except for the make-up element, the make-up strategies described in this section otherwise follow the specification as described in section 2.2.1.

[7] In our simulations we set $\gamma_y = \gamma_P$, in line with the previous literature (see Bernanke, Kiley and Roberts (2019). Since under this parameterization deviations in both the output measure and in the price level are weighed equally it permits also the interpretation of a trend-adjusted nominal income target.

[8] As to parameterization, we set $\gamma_{AI} = \gamma_P$.

where j denotes the averaging horizon and $\frac{\pi^{AI}_{t,j}}{\pi^{*}_{t,j}}$ denotes the deviation of average inflation from target inflation over the respective averaging horizon. More specifically, $\pi^{AI}_{t,j} = \prod_{i=0}^{j} \pi_{t+i}$ and $\pi^{*}_{t,j} = (\pi^{*})^{j}$. In our simulations we study a rich set of lookback periods in order to give insights on the relationship between the length of the averaging horizon and the underlying medium to long-run orientation on the performance of AIT.

2.2.4 Temporary price level targeting

Temporary price level targeting (TPLT) is studied as initially proposed by Bernanke (2017). Differently to PLT, which applies both at and outside the effective lower bound, TPLT is confined to ELB episodes and otherwise the monetary policy follows a standard Taylor rule. Technically, TPLT can be described as follows

$$R_t = \left(\left(\frac{\pi_t}{\pi^*} \right)^{\gamma_\pi} \left(\frac{y_t}{y_t^{pot}} \right)^{\gamma_y} \left(\frac{P_t}{P^*} \right)^{\gamma_{TP}} R_n \right) r_t^m \tag{5}$$

and hence resembles the symmetric PLT strategy (section 2.2.2). The central difference is that $\gamma_{TP} = \gamma_P$ applies only during ELB episodes in the sense that shortfalls in inflation only accumulate at the ELB and are made up in the course of subsequent overshooting episodes. By contrast, outside the ELB and in the absence of a preceding ELB episode interest rates are set based on a standard Taylor rule, as described in section 2.2.1, and past deviations of inflation from target are treated as bygones ($\gamma_{TP} = 0$). TPLT can thus be considered an asymmetric monetary policy strategy in the sense that its make-up element is restricted to ELB episodes.[9]

2.2.5 Hysteresis rule

We next present the hysteresis rule under which the central bank targets the technology gap and hence the long-run trend of aggregate output. While in the standard DSGE model setup technology growth is determined by structural, long-run factors only, total factor productivity dynamics are endogenous in this framework and, as discussed in subsequent sections of the paper, are affected by cyclical fluctuations in the economy and influenced by monetary policy, thus breaking long-run non-neutrality of monetary policy.[10] The hysteresis rule hence does not only target the standard output gap measure y_t/y_t^{pot} capturing the degree of economic slack in terms of standard production factors and as typically employed in the DSGE model context and at central banks, but in addition

[9] More specifically, shortfalls accumulated at the ELB can generally also carry over to phases outside the ELB. To be thus more precise, monetary policy is conducted by means of a standard Taylor rule outside the ELB and to the extent that past inflation shortfalls at the ELB have been made up in full. We implement TPLT in the form of a shadow rate approach, as also discussed in Bernanke et al. (2019).

[10] We postpone a more detailed analysis of the role of cyclical fluctuations and monetary policy on the evolution of the technology stock to latter parts of this paper.

also a measure of the technology stock and thus the trend component itself. Specifically, under the hysteresis rule the policy rate is set based on

$$R_t = \left(\left(\frac{\pi_t}{\pi^*} \right)^{\gamma_\pi} \left(\frac{y_t}{y_t^{pot}} \right)^{\gamma_y} \left(\frac{A_t}{A_t^{pot}} \right)^{\gamma_A} R_n \right) r_t^m, \tag{6}$$

where $\frac{A_t}{A_t^{pot}}$ denotes the deviation of the technology stock A_t from potential, where potential output is defined as the allocation realized under perfectly flexible prices and wages.[11]

2.3 Endogenous Technology Growth

As a key difference to the previous literature on monetary policy strategies at the ELB, we depart from the strictly exogenous technology, driven by technology shocks only and instead model technology growth endogenously. Endogenous technology dynamics are modeled as in Comin and Gertler (2006), in line with the previous literature (Moran and Queralto (2018), Anzoategui et al. (2019), Ikeda and Koruzumi (2019)).[12] Technology growth is modeled in the form of expanding varieties (Romer (1990)) and occurs on two margins, specifically via research and development and technology adoption. New technologies are created through R&D adding to the total stock of technologies Z_t, while technology adoption renders new technologies usable in production, where the stock of adopted technologies is denoted by A_t. Aggregate output thus follows

$$Y_t = \theta_t A_t^{\frac{1}{\vartheta - 1}} K_t^{\alpha} L_t^{1-\alpha}, \tag{7}$$

where θ_t denotes a standard technology shock[13] and $A_t^{\frac{1}{\vartheta-1}}$ refers to technology stock which evolves endogenously as the result of productivity-improving investment in R&D and technology adoption.

2.3.1 R&D sector

Innovation is modeled in the form of horizontal innovation through expanding varieties (Romer (1990)). New varieties of intermediate goods are created by the R&D sector in which competitive innovators invest in R&D to invent new technologies. They sell the rights to use the newly invented technologies to the adopters (see section 2.3.2). The stock of technologies Z_t corresponds to the technological frontier at time t. Technologies can become obsolete with exogenous probability $1-\phi$.

[11] We assume $\gamma_A = \gamma_y$ in our simulations which can be interpreted as the central bank targeting the trend path of potential output. Since under the exogenous technology assumption imposed in standard DSGE models, the trend component A_t^{pot} is unaffected by cyclical movements and strictly determined by long-run, structural factors only, setting the policy rate based on the Taylor rule or the hysteresis rule would be congruent as $A_t = A_t^{pot}$ at all times, this does not apply under the endogenous technology growth mechanism and monetary policy may fall short of its initial trend path following a recession.

[12] Our model builds on earlier work by Moran and Queralto (2018). See section 2.10 for a discussion on the relationship to earlier frameworks.

[13] θ_t denotes a standard technology shock, modeled in the form of an AR(1)-process: $(\theta_t = \rho^\theta \theta_{t-1} + \epsilon_t^\theta)$

The law of motion of the technology stock states as

$$Z_{t+1} = \phi Z_t + \varphi_t X_t. \tag{8}$$

Hence, the technology stock at $t+1$ is the sum of the technologies surviving from the previous period (ϕZ_t) and the newly invented technologies ($\varphi_t X_t$) in t. Innovator i generates new technologies as described by the process

$$\varphi_t X_t^i, \tag{9}$$

where X_t^i denotes i's investment in R&D, measured in units of final output. Aggregated R&D investment equals to $X_t = \int_i X_t^i di$. φ_t in the R&D production technology follows

$$\varphi_t = \frac{\chi Z_t}{Z_t^{\zeta} X_t^{1-\zeta}}. \tag{10}$$

Hence, the innovation process is subject to a positive spillover from the aggregate stock of technologies Z_t to the productivity of an individual innovator (Romer (1990)). In addition, the R&D process features an externality from aggregate R&D efforts $\frac{1}{Z_t^{\zeta} X_t^{1-\zeta}}$, where $0 < \zeta < 1$ denotes the R&D elasticity of the aggregate creation of new technologies. The externality is increasing in Z_t which implies that R&D productivity decreases with the aggregate technology stock becoming more advanced and ensures also the stationarity of the innovation process. At the same time, higher aggregate innovation activity X_t decreases the probability of successful innovation on the level of an individual innovator. χ constitutes a scaling term reflecting the efficiency of R&D investment and is set to match the long-run growth rate at the balanced growth path.

Innovator's problem: We now turn to innovator i's problem. J_t refers to the value of an unadopted technology, i. e. a technology which has been invented but not yet incorporated in production (see section 2.3.2). Technologies invented at t are available as of the following period. The innovator's problem can then be stated as follows:

$$\max_{\{X_{i,t+j}\}_{j=0}^{\infty}} \mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \Lambda_{t,t+1+j} \left\{ \left[J_{t+1+j} \varphi_{t+j} X_{i,t+j} - \left(1 + f^x \left(\frac{X_{i,t+j}}{X_{i,t+j-1}} \right) \right) X_{i,t+j} \right] \right\} \right\} \tag{11}$$

where $\Lambda_{t,t+1+j}$ denotes the stochastic discount factor of the household. R&D is subject to adjustment costs, captured by the convex function $f^x(\cdot)$ with the property that on the balanced growth path $f^x(g) = f^{x'}(g) = 0$ applies, where g denotes the growth rate of R&D, of the technology stock and of aggregate output on the balanced growth path.

Dropping subscript i given a symmetric equilibrium, the corresponding optimality condition states that the marginal gains from R&D investment equal the respective marginal costs:

$$\mathbb{E}_t \left(\Lambda_{t,t+1} J_{t+1} \right) \varphi_t = 1 + f^{x'} \left(\frac{X_t}{X_{t-1}} \right) \frac{X_t}{X_{t-1}} + f^x \left(\frac{X_t}{X_{t-1}} \right) - \mathbb{E}_t \left[\Lambda_{t,t+1} f^{x'} \left(\frac{X_t}{X_{t-1}} \right) \left(\frac{X_t}{X_{t-1}} \right)^2 \right]. \tag{12}$$

The creation of new technologies in time t can be stated as $V_t = \int_i V_t^i di = \chi Z_t^{1-\zeta} X_t^{\zeta}$.

2.3.2 Technology adoption

Newly created technologies do not instantaneously result in productivity gains as they first have to be adopted. This section describes the technology adoption process which converts invented technologies into technologies usable in production, performed by competitive adopters.[14] Let λ_t denote an individual adopter's probability of being able to successfully render an invented technology usable in the production process at time t. Adoption activity is subject to adjustment costs[15]. Specifically, we assume that technology adoption requires specialized input E_t, i.e. equipment, which is generated using final output and is bought at price Q_t^a. The probability of a successful adoption is an increasing function in the equipment used by the respective adopter E_t^i and follows

$$\lambda_t \left(E_t^i\right) = \kappa_\lambda \left(\frac{X_t}{A_t}\right)^{\eta} \left(E_t^i\right)^{\rho_\lambda}, \tag{13}$$

where $\kappa_\lambda > 0$, $0 < \eta < 1$ and $0 < \rho_\lambda < 1$ applies. The probability of successful adoption is thus increasing and concave in the adoption effort E_t^i. The adoption rate is in addition also influenced by a spillover term from aggregate R&D expenditure Z_t - formulated in relationship to A_t to ensure stationarity and governed by the spillover η. This assumption captures the notion that R&D may exert a positive effect on the probability of adopting innovation, for instance due to adopters learning from aggregate efforts in research and development.[16]

Adopters buy the rights to use an unadopted technology from the innovators at the competitive price J_t. The adopter employs equipment E_t^i in order to render a technology usable in production which is successful with probability λ_t. In case of successful adoption, the adopter sells the technology at price H_t which is defined as

$$H_t = \Pi_t + \phi \mathbb{E}_t \left(\Lambda_{t,t+1} H_{t+1}\right), \tag{14}$$

where Π_t denotes the firm profits generated in this technology. The adopters' problem can then be stated as

$$J_t = \max_{E_t^i} -Q_t^a E_t^i + \phi \mathbb{E}_t \left\{\Lambda_{t,t+1} \left[\lambda_t \left(E_t^i\right) H_{t+1} + \left(1 - \lambda_t \left(E_t^i\right)\right) J_{t+1}\right]\right\}. \tag{15}$$

Adopters thus weigh the costs of adoption against its expected gains which corresponds to the probability weighted sum of the value of adopted and unadopted technologies respectively. Note that adoption effort will be identical across technologies ($E_t^i = E_t$). Dropping the subscript i the

[14] Modeling technology adoption by means of an adoption sector permits the endogenous evolution of the diffusion of technologies to the economy, while at the same time simplifying aggregation. Specifically, the probability of successful adoption will be equal across technologies which allows for aggregation without the need to track the share of firms which have adopted the respective technologies.

[15] The adjustment cost function is analogous to adjustment costs for capital producers (see section 2.6 for details.)

[16] As discussed in more detail in section 2.10, the framework follows closely Moran and Queralto (2018) who introduce the spillover from R&D to technology adoption, thus departing from Comin and Gertler (2006), to increase realism with respect to the interaction between shifts in R&D and adoption respectively.

optimality condition for adoption can be stated as

$$\rho_\lambda \kappa_\lambda \phi \left(\frac{X_t}{A_t}\right)^\eta \mathbb{E}_t \left[\Lambda_{t,t+1} \left(H_{t+1} - J_{t+1}\right)\right] = Q_t^a E_t^{1-\rho_\lambda}. \tag{16}$$

Aggregate adoption effort can then be derived as the product of the effort of a respective adopter E_t and the stock of unadopted technologies $(Z_t - A_t)$ and thus equals to $(Z_t - A_t) E_t$. Investment in adoption equipment E_t is thus increasing in the expected, discounted value of the difference between the value of an adopted and unadopted technology $H_{t+1} - J_{t+1}$. This condition moreover demonstrates the role of the R&D externality as increases in R&D will also raise technology adoption activity.

Lastly, the law of motion for adopted technologies can be stated as follows:

$$A_{t+1} = \phi \left[A_t + \lambda_t \left(Z_t - A_t\right)\right]. \tag{17}$$

Endogenous technology growth is hence driven by two margins, i.e. the technology adoption rate λ_t and the ratio of total technologies over the stock of adopted technologies.[17]

2.4 Final good production

There is a continuum of measure one of final goods producers which are monopolistically competitive. Each final good firm i produces differentiated output Y_t^i. The corresponding final good composite is a CES aggregate of the differentiated final goods

$$Y_t = \left[\int_0^1 \left(Y_t^i\right)^{\frac{\mu-1}{\mu}} di\right]^{\frac{\mu}{\mu-1}}. \tag{18}$$

The price set by final good producer i is P_t^i and the price level of final output can be derived as $P_t = \left[\int_0^1 P_t^{i\,1-\mu} di\right]^{\frac{1}{1-\mu}}$. Final goods producer i's output follows from cost minimization and equals to

$$Y_t^i = \left(\frac{P_t^i}{P_t}\right)^{-\mu} Y_t. \tag{19}$$

Prices are sticky and each final good firm can adjust its price with probability $1 - \theta^p$. Firms which cannot adjust their price set it according to the indexation rule

$$P_t^i = P_{t-1}^i \pi_{t-1}^{\iota_p} \left(\pi^*\right)^{1-\iota_p}, \tag{20}$$

where ι_p is the price indexation parameter and $\pi_t = \frac{P_t}{P_{t-1}}$ denotes time t inflation and π^* inflation in the steady state. Final good firms face nominal marginal costs in the form of intermediate good input price P_t^m. The final good producer's problem can be stated as choosing the optimal reset price P_t^* as follows

[17] To see this, divide equ. 17 by A_t to obtain $\frac{A_{t+1}}{A_t} = \phi \left[1 + \lambda_t \left(\frac{Z_t}{A_t} - 1\right)\right]$.

$$\max_{P_t^*} \mathbb{E}_t \sum_{j=0}^{\infty} \theta_p^j \Lambda_{t,t+j} \left(\frac{P_t^* \prod_{k=1}^{j} \pi_{t+k-1}^{\iota_p} \left(\pi^*\right)^{1-\iota_p}}{P_{t+j}} - \frac{P_{t+j}^m}{P_{t+j}} \right) Y_{t+j}^i \tag{21}$$

subject to final good demand (19).

2.5 Intermediate goods production

Total factor productivity growth occurs in the form of expanding varieties A_t of intermediate goods generated through both R&D and technology adoption. Importantly, as the preceding sections demonstrated, the profits resulting from the production of new intermediate goods is the central driver behind both margins of productivity-improving investment. Intermediate products of A_t varieties are produced by monopolistically competitive producers. Y_t^{im} is output produced by intermediate good producer i and the composite of intermediate goods Y_t^m used as input by final good firms (section 2.4) can be stated as follows:

$$Y_t^m = \left[\int_0^{A_t} \left(Y_t^{im} \right)^{\frac{\vartheta-1}{\vartheta}} di \right]^{\frac{\vartheta}{\vartheta-1}}. \tag{22}$$

P_t^{im} refers to the nominal price set by producer i and the price level of the intermediate good composite equals to $P_t^m = \left[\int_0^{A_t} \left(P_t^{im} \right)^{1-\vartheta} di \right]^{\frac{1}{1-\vartheta}}$. Intermediate good firms produce using capital and labor by means of a Cobb-Douglas production technology:

$$Y_t^{im} = \theta_t \left(K_t^i \right)^{\alpha} \left(L_t^i \right)^{1-\alpha}. \tag{23}$$

Let R_t^k denote the rental rate of capital and W_t the nominal wage rate. Intermediate goods producers' cost minimization delivers the following first order conditions

$$\alpha \frac{\vartheta - 1}{\vartheta} \frac{P_t^m}{P_t} \frac{Y_t^m}{K_t} = R_t^k \tag{24}$$

$$(1-\alpha) \frac{\vartheta - 1}{\vartheta} P_t^m \frac{Y_t^m}{L_t} = W_t, \tag{25}$$

where $\frac{\vartheta}{\vartheta-1}$ denotes the markup resulting from imperfect competition in the intermediate goods sector. $\frac{P_t}{P_t^m}$, in turn, denotes the markup of the price level of final output P_t over the price level of the intermediate good composite P_t^m.[18]

Profits from intermediate good production are a central determinant of R&D investment (section 2.3.1) and technology adoption (section 2.3.2). Intermediate goods profits are identical across firms

[18] P_t is described in more detail in section (2.4).

($\Pi_t^i = \Pi_t$) and can be derived as

$$\Pi_t = \frac{1}{\vartheta}\frac{\vartheta - 1}{\vartheta}\frac{Y_t^m}{A_t}. \tag{26}$$

Market clearing in factor markets requires $K_t = \int_0^{A_t} K_t^i di$ and $L_t = \int_0^{A_t} L_t^i di$. Aggregate intermediate good output can be derived combining these conditions with equations (23) to (25):

$$Y_t^m = \theta_t A_t^{\frac{1}{\vartheta-1}} K_t^{\alpha} L_t^{1-\alpha}. \tag{27}$$

2.6 Capital producers

Capital producers turn final output into capital which they sell to households at price Q_t. Capital is subject to adjustment costs. The representative capital producer's problem consists of choosing the sequence $\{I_{t+j}\}_{j=0}^{\infty}$ to maximize expected discounted profits

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left[Q_{t+j} I_{t+j} - \left(1 + f_I \left(\frac{I_{t+j}}{I_{t+j-1}} \right) \right) I_{t+j} \right] \right\}. \tag{28}$$

The properties of the adjustment cost function are analogous to the properties of f_x. Profit maximization implies that the marginal costs of generating investment goods equals their price:

$$Q_t = 1 + f_I \left(\frac{I_t}{I_{t-1}} \right) + \frac{I_t}{I_{t-1}} f_I' \left(\frac{I_t}{I_{t-1}} \right) - \mathbb{E}_t \left[\Lambda_{t+1} \left(\frac{I_t}{I_{t-1}} \right)^2 f_I' \left(\frac{I_t}{I_{t-1}} \right) \right]. \tag{29}$$

The law of motion for capital can be stated as follows

$$K_{t+1} = (1 - \delta) K_t + I_t. \tag{30}$$

Producers of adoption equipment are subject to an analogous problem, subject to adjustment cost function f_a. Market clearing for equipment goods requires $I_t^a = (Z_t - A_t) E_t$.

2.7 Labor market

A continuum of households $i \in [0, 1]$ monopolistically supplies specialized labor L_t^i.[19] There is a large number of competitive employment agencies which generate homogeneous labor input L_t to be used in intermediate goods production by combining specialized labor based on

$$L_t = \left[\int_0^1 L_t^{i\,\frac{\omega-1}{\omega}} di \right]^{\frac{\omega}{\omega-1}}. \tag{31}$$

[19] This approach follows Erceg et al. (2000).

Labor demand for type i can be derived from the cost minimization problem of the employment agencies and equals to

$$L_t^i = \left(\frac{W_t^i}{W_t}\right)^{-\omega} L_t. \tag{32}$$

W_t^i denotes the nominal wage of labor variety i. The wage rate at which the intermediate goods producers buy the labor composite corresponds to

$$W_t = \left[\int_0^1 W_t^{i\,1-\omega} di\right]^{\frac{1}{1-\omega}}. \tag{33}$$

2.8 Household problem

We now turn to the households' problem. Household i maximizes utility

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \beta^j \left[log\left(C_{t+j} - hC_{t+j-1}\right) + \varrho B_{t+1} - \frac{\psi}{1+\nu} L_{i,t+j}^{1+\nu} \right] \right\} \tag{34}$$

subject to the budget constraint

$$\frac{W_t^i}{P_t} L_t^i + R_t \frac{B_t}{P_t} + \left(R_t^k + (1-\delta) Q_t\right) K_t + \Pi_t \geq C_t + \frac{B_{t+1}}{P_t} + Q_t K_{t+1}, \tag{35}$$

where C_t denotes consumption and h the habit formation parameter $(0 < b < 1)$. B_t are holdings of riskless bonds in nominal terms, Q_t the real price of capital and Π_t firm profits. ϱ denotes a liquidity demand shock which favors safe asset holdings at the expense of consumption. Only a fraction $1 - \theta^w$ of households can adjust their wage in period t. They set the optimal wage by

$$\max_{W_t^*} \mathbb{E}_t \sum_{j=0}^{\infty} \left\{ (\theta^w \beta)^j \left[\frac{U_{c,t+j}}{P_{t+j}} L_{t+j}^i W_t^* \prod_{k=1}^{j} (1+g)\, \pi_{t+k-1}^{\iota_w} \bar{\pi}^{1-\iota_w} - \frac{\psi}{1+\nu} \left(L_t^i\right)^{1+\nu} \right] \right\} \tag{36}$$

subject to labor demand (32). Households which cannot adjust their wage set it according to the following indexation rule

$$W_t^i = W_{t-1}^i (1+g)\, \pi_{t-1}^{\iota_w} \pi^{*\,1-\iota_w}. \tag{37}$$

2.9 Aggregation

The economy is subject to the aggregate resource constraint

$$Y_t = C_t + \left[1 + f_I\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + \left[1 + f_a\left(\frac{I_t^a}{I_{t-1}^a}\right)\right] I_t^a + \left[1 + f_x\left(\frac{X_t}{X_{t-1}}\right)\right] X_t, \tag{38}$$

which states that final output is consumed, used for physical capital investment, for expenditure on technology adoption and innovation, as well as for the respective investment adjustment costs. Aggregate output corresponds to a first order to the intermediate good composite and can be derived as $Y_t = Y_t^m = \theta_t A_t^{\frac{1}{\vartheta-1}} K_t^{\alpha} L_t^{1-\alpha}$ (see equ. 7). We list the full set of equations characterizing the model in the online appendix.

2.10 Connection to previous literature

We next discuss how the presented model framework relates to the previous literature on New Keynesian DSGE models with endogenous total factor productivity dynamics.[20] TFP growth in this context is typically modeled as a two-stage process where one margin captures the evolution of the technological frontier and the second margin maps the diffusion process of new technologies to the wider economy. Bianchi et al. (2019) model technology growth in the form of within-firm vertical innovation generated by knowledge accumulation through R&D as well as by the degree of technology utilization. Further frameworks (Moran and Queralto (2018), Anzoategui et al. (2019), Ikeda and Kurozumi (2019)) model technology growth via horizontal innovation (Romer (1990)), specifically in the form of the endogenous growth mechanism proposed by Comin and Gertler (2006). In this setting, technology growth is driven by entrepreneurs' R&D investment expanding the technological frontier and by technology adoption. Our framework builds on earlier work by Moran and Queralto (2018). In addition to the different research agenda we pursue by means of this model, our framework differs technically in several central aspects. Our model imposes the effective lower bound, thus enabling us to study the implications arising from this non-linearity for the effectiveness of monetary policy in terms of inflation and output stabilization over both the short- and long-run. A further central technical contribution novel to our model is the departure from the Taylor rule approach as we introduce novel type of monetary frameworks, thus linking the literature on New Keynesian DSGE models with endogenous growth with the recent literature on make-up monetary policy strategies. Specifically, we model monetary policy in addition to a Taylor rule also monetary policy strategies in the form of price level targeting, average inflation targeting of various horizons, an hysteresis rule, as well as the asymmetric strategy of temporary price level targeting.

2.11 Parameterization

We discuss next the parameterization of the model. Specifically, we calibrate the structural parameters based on recent estimated DSGE models with endogenous technology growth through R&D and technology adoption (see Moran and Queralto (2018), Anzoategui et al. (2019), Elfsbacka-Schmöller and Spitzer (2021)). We estimate the structural shock processes underlying the simulations by means of Bayesian methods (see Appendix A.1).

Preferences: We set the discount factor β following Moran and Queralto (2018) which generates, in combination with the long-run growth rate of TFP, an annualized real interest rate of 1% on

[20] We focus in this section on the technical differences relatively to earlier models. We discuss the general contribution of this paper relative to the previous literature in detail in section 1 and 7.

the balanced growth path. This value of the real interest rate corresponds to the estimates of the natural rate of interest for the United States (Holston, Laubach and Williams (2017)) and is commonly assumed in other recent studies on the performance of make-up strategies in a low interest rate environment (see, for example, Bernanke et al. (2019) and Mertens and Williams (2019)). The inverse Frisch elasticity equals to 0.5 and habit persistence h to 0.6.

Production: We calibrate the parameters characterizing the production process following Moran and Queralto (2018) and Anzoategui et al. (2019). The capital share is set to 0.33 and the rate of capital depreciation to 0.02. The elasticity of final output to intermediate goods ϑ and thus growth in endogenous total factor productivity A_t is calibrated for growth to be purely labor-augmenting.[21] The corresponding markup for intermediate goods ($\vartheta/(\vartheta-1)=1.67$) is very similar to the choice in Comin and Gertler (2006). We set the adjustment cost parameter of physical capital $f_k^{''}$ to 5.5, consistent with the estimate in Anzoategui et al. (2019) and the adjustment costs for investment in R&D ($f_{R\&D}^{''}$) and technology adoption ($f_{ta}^{''}$) to 6, preventing excess volatility of productivity-improving investment, in line with the data[22].

Research and development and technology adoption: The survival rate of existing technologies ϕ is set to 0.974 and is based on the annual survival rate employed in Moran and Queralto (2018).[23] We set the steady state adoption rate to 0.925, following Moran and Queralto and as derived in Anzoategui et al. (2019) who obtain this value from panel data on the proclicality of adoption and show that this value generates a R&D to GDP ratio consistent with the United States. We set the steady state adoption rate of 0.05, as derived in Comin and Gertler (2006) and Anzoategui et al. (2019) based on empirically observable adoption lags.[24] This parameterization implies an average adoption lag of five years. We assume an R&D elasticity to 0.30 and set the strength of the spillover from R&D to technology adoption to 0.29, based on the estimation results provided in Moran and Queralto (2018). Steady state employment is normalized to unity and we calibrate the remaining model parameters to be consistent with the steady state adoption lag and the respective total factor productivity growth rate, as implemented in Moran and Queralto (2018).

We set disutility of labor ψ, R&D efficiency χ and the adoption process constant κ_λ to match the targeted characteristics of the balanced growth path. Specifically, we target the respective balanced growth path growth rate, employment of unity and a quarterly adoption rate of 0.05, consistent with an average technology adoption lag of 5 years, as used in the previous literature. The parameters governing the adjustment costs for R&D and adoption are set to 6 and thus range

[21] Technically, we set $(1-\alpha)(\vartheta-1)=1$, permitting for simplification of the balanced growth path.

[22] Moran and Queralto (2018) introduce adjustment costs to R&D and technology adoption to prevent too volatile productivity-improving investment in the model vis-à-vis the data and to generate realistic responses in R&D after monetary policy shocks

[23] The obsolescence rate $\phi=0.026$ is thus also very close to the value employed in Anzoategui et al. (2019) which is, in turn, based on patent-based estimates provided by Caballero and Jaffe (1993) and Bosworth (1978).

[24] Moran and Queralto (2018) use the same assumption on the adoption rate, i.e. corresponding to an annual adoption rate of 0.2.

somewhat above the respective value for physical capital, capturing the relatively lower volatility in productivity-enhancing investment.

Prices, wages and monetary policy: We set the Calvo parameters θ_p and θ_w to 0.85 and 0.8 respectively and indexation to 0.25 and hence consistent with the nominal rigidity parameters in previous estimated DSGE models with endogenous technology growth through R&D and technology adoption.[25] The elasticity of substitution across final goods producers as well as across different types of labor is set, following Moran and Queralto (2018), to 6, generating markups of 20% in steady state. We assume an inflation target and thus a steady state inflation rate of 2% annually. The weight of inflation and output in the monetary policy rule, are set based on the standard Taylor rule (Taylor 1993), i.e. to 1.5 and 0.5 respectively.

Shock processes: We estimate the parameters governing the shocks used in our simulations using Bayesian methods and data for the United States. The details of the estimation approach and Data used are described in Appendix A.1.

3 Monetary policy space and performance of inflation targeting

A decline in steady state interest rates implies decreased monetary policy space given the closer proximity to the ELB, thus constraining monetary policy in economic stabilization. We study the performance of inflation targeting, in the form of the baseline, inertial Taylor rule, under different assumptions on the monetary policy space, as presented in Table 2.[26] The simulations show that the frequency and average duration of ELB events substantially increases when monetary policy space is low. In the baseline scenario ($r^* = 1$) the ELB frequency equals to 22% and the ELB binds for roughly 11 quarters on average, emphasizing the importance of ELB events in this context. Moreover, relatively small reductions in policy space generate significant shifts in terms of the probability and duration of ELB events.

We derive the mean realizations of inflation and the output target[27] respectively, as well as the corresponding losses measured in terms of root mean squared deviation (RMSD). We derive the

[25]Estimated price and wage rigidities in this class of models generally range above the parameters typically underlying DSGE models with exogenous technology (see, for instance, Smets and Wouters (2007)). The estimation results are, however, consistent with more recent studies (see, for instance Del Negro, Giannoni and Schorfheide (2015)). We calibrate the Calvo parameters at the lower end of Anzoategui et al. (2019) and Elfsbacka-Schmöller and Spitzer (2021).

[26]Simulation results are based on the baseline, inertial Taylor rule (see section 2.2) and under technology shocks, liquidity demand shocks and monetary policy shocks. Given an annualized inflation target of 2%, the corresponding annualized long-run real interest rate can then be derived as $r^* = i^* - \pi^*$, where $\pi^* = 2$. Relatively higher (lower) long-run real rates r^* are imposed through relatively higher (lower) balanced growth path rates of technology growth $\bar{g}$. Long-run growth occurring on the balanced growth path is thus taken as given and driven by structural factors outside the model.

[27]The mean realization in the output target is denoted in percentage deviations from steady state.

Parameter	Description	Value
α	Capital share	0.33
β	Discount factor	0.999
h	Habit persistence	0.60
ν	Inverse Frisch elasticity	0.50
δ	Capital depreciation	0.02
f_k''	Capital adjustment costs	5.5
$\bar{L}$	Steady state employment	1
θ_p	Calvo prices	0.85
θ_w	Calvo wages	0.8
ι_p	Price indexation	0.25
ι_w	Wage indexation	0.25
μ	Elasticity of substitution (final goods)	6
ω	Elasticity of substitution (labor)	6
γ_π	Inflation weight	1.5
γ_y	Output weight	0.5
π^*	Inflation target	0.005
ϑ	Elasticity of substitution (intermediates)	2.493
ζ	R&D elasticity	0.304
ρ^λ	Adoption elasticity	0.925
$\bar{\lambda}$	Steady state adoption rate	0.05
η	R&D-adoption spillover	0.294
$1-\phi$	Obsolescence rate	0.026
$f_{R\&D}''$	Adjustment costs R&D	6
f_{ta}''	Adjustment costs adoption	6
$\bar{g}$	Steady state technology growth (*100)	0.2

Table 1: Calibrated parameters

stabilization loss as the combined loss from the stabilization of inflation and the output target.[28] In addition, we compute the trend loss, which is novel to the endogenous growth setup and is not accounted for by DSGE models which abstract from modelling the evolution of the technology stock endogenously in general equilibrium, and denotes the average shortfall of technology growth from its balanced growth path rate. Crucially, while stabilization losses are transitory, losses on the technology margin accumulate over time and lead to permanent losses in terms of the long-run path of aggregate output which emphasizes their increased importance relative to the transitory stabilization loss. This also demonstrates the long-run adverse effects of the ELB constraint due to the scars inflicted on long-run aggregate supply and illustrates the role of the implications of the conduct of different monetary policy strategies in this setting, in contrast to standard DSGE models with exogenous technology shocks only. We present a detailed analysis of the underlying mechanisms and causes of these effects in the subsequent sections.

[28] The stabilization loss is hence defined as $(RMSD_{infl.})^2 + (RMSD_{outp.})^2$

While the Taylor rule performs rather well when policy space is high, its performance is substantially weakened when monetary policy space is reduced. The Taylor rule performs increasingly subpar and the respective losses on the inflation and output target are significantly amplified under reduced monetary policy space, thus substantially raising the stabilization loss. Importantly, the loss on the technology margin is increased under lower long-run real interest rates, thus accumulating to marked long-run output losses over time when r^* is low. Moreover, both stabilization and long-run losses are significantly higher when inflation targeting is modeled in the form of a non-inertial Taylor rule (see section 6.1).

Policy space	ELB freq.	ELB dur.	Inflation		Output target		Stabilization	Trend loss
			Mean	RMSD	Mean	RMSD	loss	(tech. growth)
$r^* = 0$ [29]	0.30	13.84	1.75	2.20	-1.20	5.59	36.09	-0.18
$r^* = 1$ (baseline)	**0.22**	**11.4**	**1.89**	**1.64**	**-0.56**	**3.79**	**17.05**	**-0.09**
$r^* = 2$	0.13	9.10	1.96	1.35	-0.21	2.61	8.64	-0.04
$r^* = 3$	0.07	7.59	1.99	1.27	-0.07	2.15	6.23	-0.01

Table 2: ELB frequency and losses by monetary policy space under the baseline Taylor rule (simulation results (100 000 draws); ELB nonlinearity accounted for using Occbin)

In sum, under reduced monetary policy space and increased proximity to the ELB, the Taylor rule performs increasingly subpar. The subsequent sections show that make-up strategies can substantially reduce these losses. Moreover and crucially, the cause for the conduct of make-up strategies is substantially strengthened under endogenous growth, as discussed in the subsequent section.

4 Operating environment of monetary policy under endogenous technology growth

Modeling total factor productivity dynamics endogenously in an otherwise standard DSGE model setup significantly changes macroeconomic dynamics and the operating environment of monetary policy. This has also crucial implications for the effectiveness and design of monetary policy strategies in proximity to the effective lower bound. This section derives the most notable differences relative to models which abstract from modeling technology growth endogenously. These include the interaction between the cycle and the long-run trend and resulting permanent output costs of recessions (section 4.1), the long-run non-neutrality of monetary policy (section 4.2), the increased costs of the effective lower bound (section 4.3), as well as the diminished responsiveness of inflation to monetary stimulus and the related increased gains from and reduced costs of running the economy hot (section 4.4).

4.1 Cycle-trend interaction and permanent scars of recessions

When the dynamics of total factor productivity are modeled endogenously in general equilibrium, the evolution of the technology stock and hence the long-term trend path are no longer independent of cyclical fluctuations in the economy and recessions can induce permanent losses in aggregate output. Figure 1 illustrates this property by means of the macroeconomic response in a recession, as generated by a contractionary liquidity demand shock, under endogenous technology (black line) and exogenous technology (blue line) respectively.[30] In the endogenous TFP model the recession generates permanent output losses, while the economy reverts by construction to its initial trend path under exogenous technology. The underlying source of the business cycle amplification and the long-term output losses is the endogenous deceleration in total factor productivity in the course of the recession, as opposed to the standard DSGE model setup in which technology growth evolves strictly exogenously and hence does not respond to cyclical fluctuations in the economy.

TFP decelerates as its two main drivers, R&D investment and investment in technology adoption, decline in the context of the recession. Investment in research and development decreases since entrepreneurs' incentive for R&D, as captured by the value of a new, unadopted technology J_t (equ. 15), drops in the recession as the latter decreases the profits from selling a new innovation Π_t owed to the decline in intermediate goods production (see equ. 26). The recession-induced reduction in profits from a new technology translates via equ. 14 also into a lower value of an adopted technology H_t and thus lower investment in technology adoption (see equ. 16).[31] The fall in productivity-improving investment in both R&D and technology adoption generates an endogenous, procyclical deceleration in total factor productivity with permanent output losses as the technology stock falls short of its initial trend path.

The deceleration in total factor productivity thus operates as an amplification mechanism capable of generating deep and persistent recessions via the spillover from cyclical fluctuations in the economy to the path of total factor productivity. Under a standard Taylor rule, recessions may be thus associated with significant output losses.[32] and thus permanent effects on the technology stock. The recession illustrated in Figure 1 generates a permanent shortfall in total factor productivity and thus in aggregate output from the initial trend path of about 0.3%. These hysteresis effects in the technology stock induced by the recession generate permanent output losses since,

[30] We generate the recession by means of a contractionary liquidity demand shock as the latter induces the typical comovement in key economic variables over the business cycle and is empirically documented as the most important driver of both business cycle fluctuations and endogenous TFP under endogenous technology growth (Anzoategui et al. (2019); Elfsbacka-Schmöller and Spitzer (2021)).

[31] The drop in the investment in technology adoption follows from equ. 16. Equ. 15 shows that R&D falls in a less procyclical manner relatively to adoption, in line with empirical observations. Technically, the value of an unadopted technology, which drives the incentive to invest in R&D, is a function of both the expected continuation value of an unadopted technology J_{t+1} and the expected value of an adopted technology H_{t+1} and hence discounts the positive procyclical effect originating through the stochastic discount factor and firm profits more strongly than in the case of adoption.

[32] Under the standard Taylor rule, monetary policy does not target underutilization in terms of the technology stock. In section 2.2.5, we consider an alternative monetary policy strategies which directly targets the long-run output gap and monetary policy strategies which do not fully offset hysteresis effects in TFP, but are capable of returning the technology stock close to its initial, pre-recession trend level.

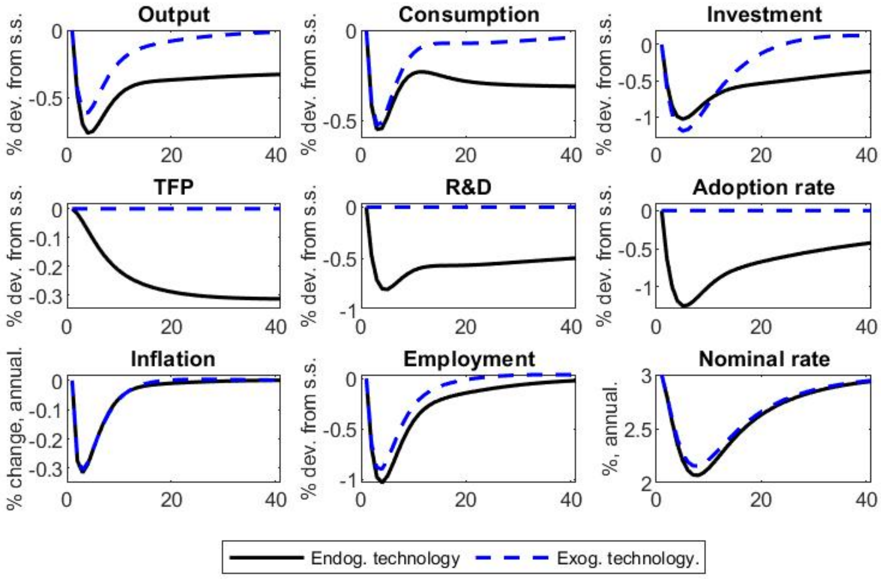

Figure 1: Impulse response to an expansionary liquidity demand shock.

as discussed, total factor productivity does not revert to its initial trend path and settles at a permanently lower level.[33]

The costs of recessions are thus fundamentally higher under endogenous technology as short-run fluctuations under endogenous technology dynamics can exert permanent effects on the technology stock and thus the long-term trend in the economy - in sharp contrast to the standard view in the DSGE literature where typically even deep and highly persistent recessions leave the long-term trend unchanged. This example crucially highlights also the substantially increased costs of recessions under endogenous technology given their possible long-term effects on total factor productivity and emphasizes the importance of stabilization policies in this context. Conversely, this property emphasizes also the costs of constraints to economic stabilization during recessions, such as the effective lower bound constraint - above all given the changed role of monetary policy and its long-run non-neutrality which will be discussed in detail in the next section.

4.2 Long-run non-neutrality of monetary policy

As discussed in the previous section, in the model with endogenous total factor productivity dynamics cyclical fluctuations spill over to TFP and hence the long-run trend path. A further and related implication is that demand-side shocks can influence, in contrast to the conventional assumption, productivity-enhancing investment and thus total factor productivity.[34] In particular

[33]Note that the system reverts over time to its initial long-run growth rate of technology growth. The shift thus constitutes a level shift in terms of output, but not with respect to the long-run growth rate.

[34]This property is also shown in Figure 1 by example of the response to the shock to liquidity demand.

monetary policy can influence the evolution of the technology stock and thus long-run aggregate supply. Monetary policy is hence non-neutral also over the long run, with important consequences for both the role and the conduct of monetary policy in economic stabilization.

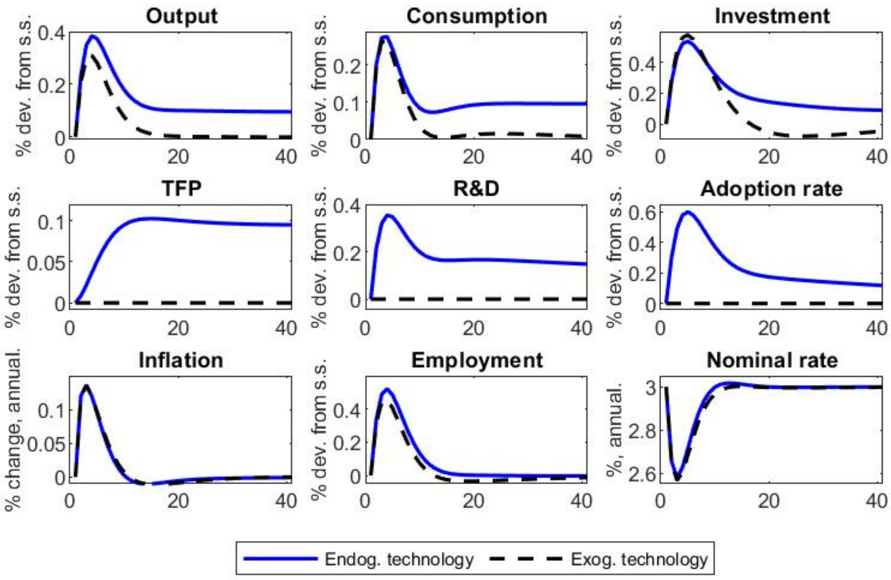

Figure 2: Impulse responses to an expansionary monetary policy shock.

Figure 2 illustrates these properties by means of the impulse responses to an accommodative monetary policy shock under endogenous and exogenous technology respectively. The decline in the nominal interest rate translates in a decrease in the real interest rate which stimulates consumption, investment in physical capital and aggregate output. Crucially and in contrast to the model with exogenous TFP (grey dashed line), the aggregate output effects of monetary stimulus are permanent as monetary policy also raises productivity-improving investment in R&D and technology adoption and thus TFP via two major channels. The first operates via the decline in the real interest rate and raises $\Lambda_{t,t+1}$ thereby also raising the discounted values of both a newly invented technology, J_t, and an adopted technology, H_t. The second mechanism operates through the upswing generated by monetary policy which raises the profits from a new innovation Π_t (equ. 26). Consequently, the value of an adopted technology (H_t, equ. 14) and an unadopted technology (J_t, equ. 14) increases. As a result, both investment in research and development (equ. 12) and investment in technology adoption (equ. 16) increase, thus generating a permanent improvement in total factor productivity. This stands in sharp contrast to macroeconomic dynamics underlying standard DSGE models (black dashed line), in which the technology stock is assumed to evolve strictly exogenously and to be determined only by structural factors outside the model.

In sum, monetary policy has an increased role under endogenous technology growth due its influence on the evolution of total factor productivity, which alters the impact of monetary policy along two major dimensions. Firstly, its effect on aggregate output is substantially increased in terms of magnitude as monetary stimulus induces an expansion in productivity-improving investment and thus also TFP. The second dimension concerns the permanency of this effect: while the system reverts back to its initial trend path in models with exogenous technology, the output effects of monetary stimulus are permanent in this framework as it raises the technology stock and hence induces a shift of the long-run path of aggregate output. Monetary policy thus accrues an additional, increased role in economic stabilization owed to its influence on total factor productivity dynamics and thus the evolution of the supply-side and long-term output path.

4.3 Increased costs of the effective lower bound

Long-run non-neutrality of monetary policy under endogenous technology growth also raises the costs of the effective lower bound. Figure 3 shows the effect of the ELB under endogenous technology dynamics. As is well-established in the literature, the effective lower bound amplifies the fall of aggregate output and intensifies the deceleration in inflation subject to a prolonged period of inflation undershooting. Crucially, the ELB also amplifies the spillovers from deficient aggregate demand to TFP, intensifying the procyclical deceleration in total factor proudctivity and the depth of the recession. The effective lower bound considerably increases the long-term losses in terms of the technology stock and with it the downward shift in long-run aggregate output. The simulations show that the simulated ELB episode (Figure 3), which persists for about four years, is associated with a permanent drop in total factor productivity and hence aggregate output relative to trend by roughly 2.5%, while the same magnitude recession in the absence of the ELB induces a shortfall in terms of TFP of 1.1%.

Against this backdrop, the true output losses attributable to the ELB are larger than conventionally assessed by models with exogenous technology stock, as they do not factor in the output losses inflicted on the total factor productivity margin. As the shortfall in terms of the technology stock is permanent, the ELB also exerts permanent effects on aggregate output, highlighting the severity of this constraint for the conduct of monetary policy. Measures to alleviate the effective lower bound problem can thus be considered of crucial importance also in terms of the long-run output path. The adoption of make-up monetary policy strategies has frequently been proposed as a policy option to alleviate the adverse consequences of the effective lower bound on inflation and with respect to the output gap. The adverse spillovers from deficient aggregate demand to technology growth and hence the long-run output path which are substantially intensified at the ELB, constitute an additional motive for the pursuit of make-up monetary policy strategies, which has not yet been accounted for by the previous literature and which will be discussed in more detail in section 6.

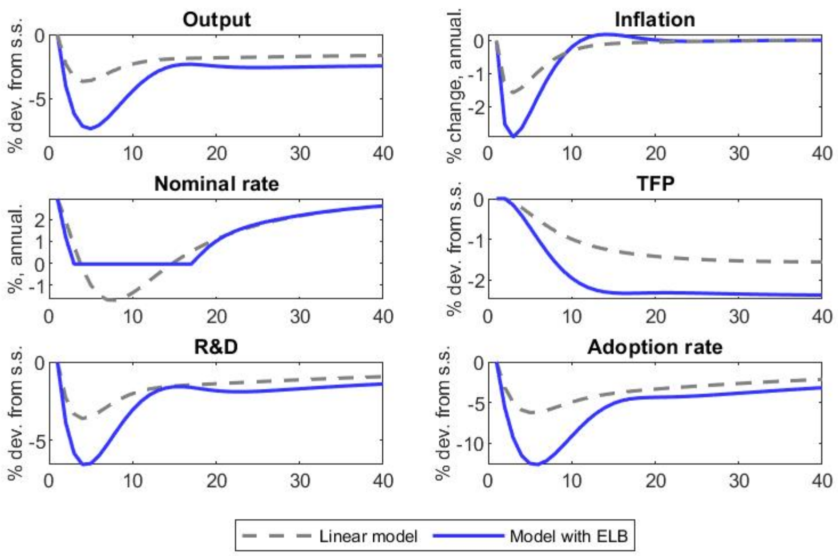

Figure 3: Dynamics at the ELB (induced by a 5 std. liquidity demand shock).

4.4 Less responsive inflation and reduced costs of running the economy hot

Inflation responds less strongly when TFP is modeled endogenously due to the interaction between inflation and productivity dynamics. Under endogenous growth, the inflation response over the business cycle is dampened since inflationary pressures in an expansion are alleviated by simultaneous, procyclical productivity gains, while disinflationary pressures in recessions are counteracted by a simultaneous deceleration in TFP (see also Elfsbacka-Schmöller and Spitzer (2021)). The interaction between productivity and inflation dynamics has also important implications for the responsiveness of inflation to monetary stimulus. Specifically, liftoff from the ELB may be more challenging than conventionally assessed as inflation reacts less to monetary policy interventions. This property is shown in Figure 2, which, as also discussed in context of the analysis of long-run non-neutrality (section 4.2), shows the response to an accommodative monetary policy shock under endogenous TFP growth (blue solid line) and strictly exogenous technology (black dashed line) respectively. Via the earlier discussed mechanism, the monetary expansion reduces the real interest rate and, in addition, the value of both an adopted and unadopted technology, thus generating an expansion of investment in both R&D and technology adoption. Total factor productivity thus expands under endogenous growth, while it is unaffected by monetary policy in the exogenous TFP model. The endogenous TFP increase generates a more pronounced employment response in the model with endogenous technology. Despite the stronger reaction of employment, the response of inflation is less pronounced. While the initial inflation response is of similar range in both models, the monetary expansion generates under endogenous TFP increases in total factor productivity over time and the related reduction of firms' marginal cost counteracts the inflationary pressures from relatively lower economic slack. A tighter labor market is thus also associated with relatively lower inflationary pressure under endogenous technology growth.

The alleviated response of inflation has important implications for the impact and effectiveness of monetary policy stimulus in the endogenous technology model. Monetary policy is more effective in stimulating aggregate output under endogenous versus exogenous technology owed to the amplification of monetary stimulus on total factor productivity and, in addition, employment. Monetary policy is, however, less effective in stimulating inflation which may render stimulating inflation at the effective lower bound particularly challenging. The reduced responsiveness of inflation to monetary stimulus under endogenous TFP thus constitutes an additional motive for the departure from Taylor-type rules and inflation targeting and for the conduct of make-up strategies in proximity to the effective lower bound. At the same time, the muted response of inflation alleviates the risk of inflation overshooting post-ELB and thus weakens a central argument against the conduct of make-up strategies.

5 Mechanisms of make-up strategies under endogenous growth

We study next the general channels through which make-up strategies operate under endogenous growth (section 5.1). Subsequent sections (5.2) to (5.5) describe the concrete mechanisms underlying the respective make-up strategies under consideration.

5.1 Real interest rate and innovation-payoff channel

The main operating channels underlying make-up strategies under endogenous TFP growth can be summarized as follows. The first, traditional channel operates directly through the real interest rate. The commitment to hold interest rates lower for longer until the shortfall in terms of the metric under consideration is made up in full, lowers real interest rates both directly and indirectly. Straightforwardly, given the make-up element in the monetary policy rule, interest rates would be on average held at relatively lower levels compared to the standard inflation targeting approach underlying the Taylor rule which sets policy rates based on current realizations of inflation and output. In addition, the make-up element affects not only future interest rates but reduces real interest rates also via an increase in inflation expectations, thus lowering real interest rates and providing additional stimulus already during the ELB episode. While this constitutes a conventional channel underlying make-up strategies also under exogenous technology, the real interest channel exerts more powerful effects under endogenous technology growth. This holds true, as in the standard DSGE model setting the technology stock is exogenous and thus unaffected by temporary changes in the real interest rate while under endogenous technology dynamics a decrease in the real interest rate raises the value of an unadopted technology J_t and of an adopted technology H_t (see equ. 14 and equ. 15). This stimulates productivity-improving investment in R&D and technology adoption.

Crucially though, make-up strategies operate also through an additional channel which we refer to as the *innovation-payoff channel* taking effect both at the research and development and the technology adoption margin. Specifically, the implied commitment to hold rates lower for longer raises expectations about the future output trajectory, thus increasing expected firm profits Π_t. The latter constituting a key determinant of both the value of an adopted technology (equ. 14) and, by extension, the value of an unadopted technology (equ. 15). Hence, this shift raises both the payoff from R&D investment and from investment in technology adoption, thus providing an additional channel for stimulating productivity-improving investments on both margins of technology growth (see equ. 12 and equ. 16). Via the combined effect of the real interest rate channel and the innovation-payoff channel, make-up strategies can therefore not only reduce the shortfall of inflation from target and the output drop but in addition also render the adverse spillovers to technology growth less severe, thus reducing the hysteresis effects on the technology stock and hence the permanent output losses inflicted during ELB episodes.

In what follows we analyze the specific mechanisms and dynamics during ELB episodes under price level targeting (section 5.2), average inflation targeting (section 5.3), temporary price level targeting (section 5.4) and the hysteresis rule (section 5.5).

5.2 Price level targeting

Under price level targeting (PLT, see equ. 3), monetary policy targets a fixed path for the price level at which prices increase at a constant target rate which we assume to equal to 2 percent annually. A central difference compared to conventional inflation targeting under the Taylor rule approach is thus the treatment of past deviations of inflation from target. Under the Taylor rule, monetary policy aligns inflation with target but does not feature an element of making up for past phases of subdued or excess inflation. Price level targeting, by contrast, implies that bygones regarding misses in terms of past inflation are no longer bygones as it involves the commitment to offset episodes of too low (too high) inflation by temporarily higher (lower) inflation to align the price path with the target price level. While under a standard inflation targeting framework an ELB-induced downward bias in inflation emerges (see section 3 and 6), price level targeting aims to make up for past shortfalls of inflation from target by allowing for temporary overshooting following an ELB episode.

Figure 4 illustrates the macroeconomic response in a contraction during which the ELB binds under price level targeting (red line) and the baseline Taylor rule approach (blue line).[35] Under price level targeting, the drop in terms of the output target measure is both less pronounced and less long-lived. In addition, price level targeting substantially reduces both the fall in inflation relatively to the standard Taylor rule approach and the time period in which inflation undershoots during ELB periods. Contrary to not making up past shortfalls in inflation under the Taylor rule,

[35] As in the previous and subsequent sections, the recession is triggered by a large contractionary liquidity demand shock which induces the effective lower bound to bind. We use the identical shock size for all monetary policy strategies under consideration in this section.

PLT results in a subsequent overshooting in inflation and output, returning the price level to its initial, targeted path. In addition to the described gains in terms of stabilizing the output target and aligning inflation, PLT also significantly alleviates the downward adjustment on the technology margin via both the real interest rate channel and the innovation-payoff channel.

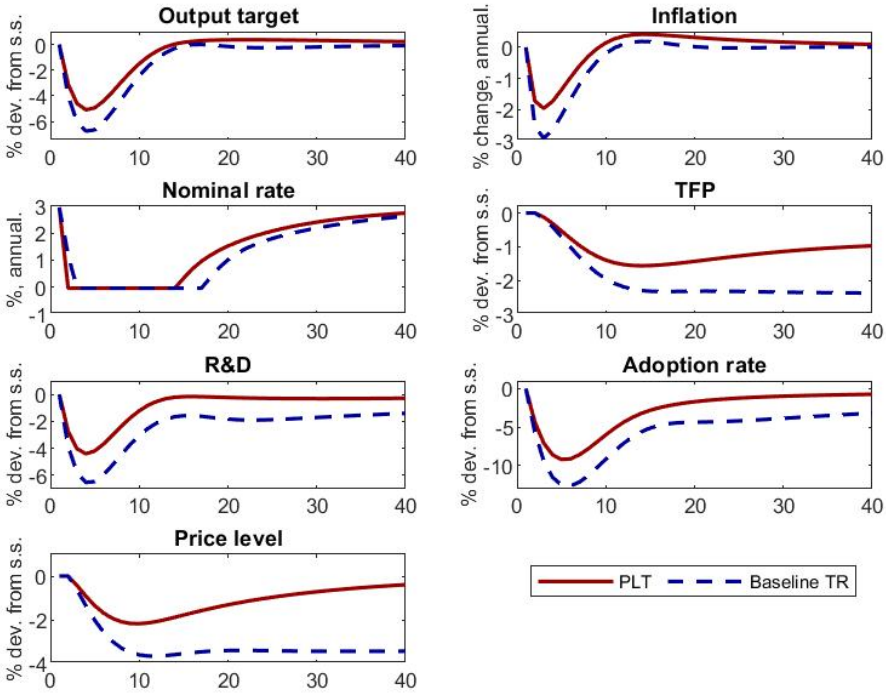

Figure 4: Dynamics at the ELB under price level targeting.

As a result, R&D and technology adoption fall relatively less rendering the deceleration in total factor productivity less severe. Importantly, while the price level targeting strategy does not fully close the technology gap, i.e. the shortfall on the technology margin, the long-run output losses are considerably reduced compared with the baseline Taylor rule. Concretely, for the specific simulated ELB episode, PLT reduces the long-term output gap to roughly 1%, compared with about 2.5% under the baseline Taylor rule.[36]

[36]Note that the permanent shortfall in total factor productivity is increasing in the severity and duration of the ELB episode and that the simulated ELB phase is only of moderate length. The respective long-run gains from the conduct of PLT relatively to inflation targeting are the larger the more prolonged the ELB event and can be considerably more pronounced than suggested by this specific example.

5.3 Average inflation targeting

We next study average inflation targeting (AIT) under which the central bank targets the average inflation rate over a predefined time horizon.[37] If the economy experiences, for instance, a transitory shortfall of inflation from target, the central bank would aim for temporarily higher inflation until average inflation over a given horizon is again aligned with the respective target inflation which we assume to equal to 2% annually. As in the case of PLT, monetary policy keeps track of past deviations from target inflation but limits the time period over which inflation shortfalls are to be made up for to a specific averaging horizon. Hence, in the limits, i.e. for infinitely large averaging horizons, AIT approaches PLT. Generally, a central motive for limiting the averaging horizon is the possibility of long ELB episodes with correspondingly large cumulative inflation shortfalls and thus the related sizeable and sustained required overshooting period upon ELB exit under PLT. Under AIT the lookback period is, by contrast restricted, thus reducing the length and intensity of the subsequent overshooting episode.

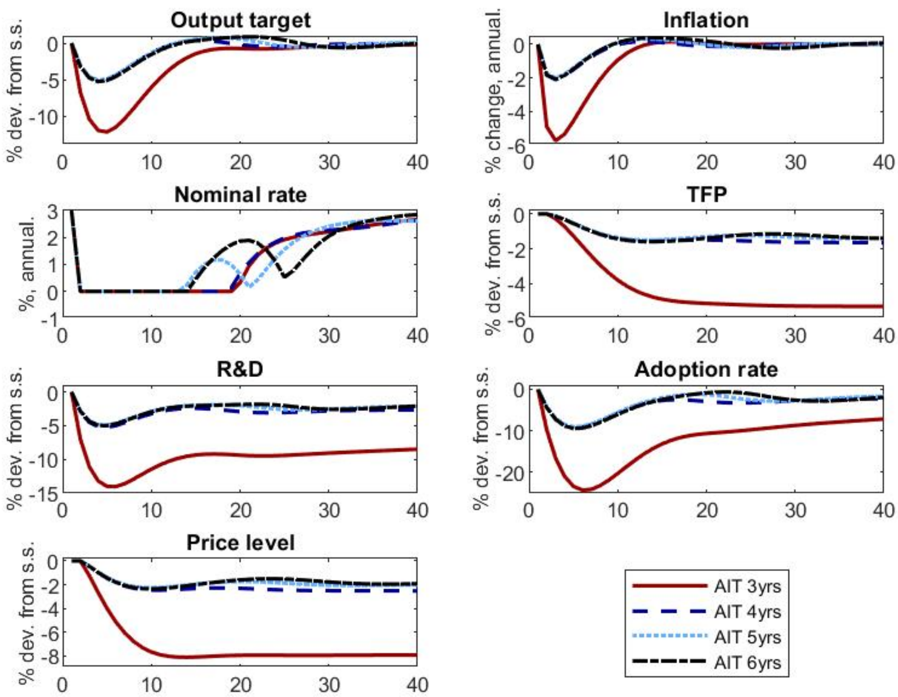

Figure 5: Dynamics at the ELB under average inflation targeting.

Figure 5 illustrates the macroeconomic response in a contraction under AIT with averaging horizons of three, four, five and six years respectively. The simulations show that AIT of all horizons under consideration performs substantially worse than PLT (see Figure 4) at the ELB.

[37]Note that to keep Figure 5 tractable, we abstract from including the baseline Taylor rule in the same chart. Please consult, for instance, Figure 4 for the respective impulse responses under inflation targeting.

Moreover, the performance of the AIT strategies depends on the averaging horizon. Specifically, AIT with a lookback period of three years delivers subpar results compared with both the baseline Taylor rule and AIT strategies with averaging horizon of four years and longer. The performance of the latter are in a similar range and they all generate improvements in terms of the stabilization of inflation and the output target measure as well as with respect to reducing the losses on the technology margin, albeit to a less extent than for the case of PLT. Importantly, our results of AIT strategies versus inflation targeting are based on an inertial version of the Taylor rule. As to the dynamics of the nominal interest rate, AIT of three and four year horizons extend the respective ELB duration compared with the baseline Taylor rule. Longer-term orientated AIT strategies (five and six years) generate a respectively earlier exit from the ELB but are subject to an additional temporary drop in nominal interest rate following lift-off. Section 6 discusses in detail the performance of a non-inertial Taylor rule without path dependence in the nominal interest rate which is subject to substantially more pronounced stabilization and trend losses.

5.4 Temporary price level targeting

Price level targeting and average inflation targeting strategies constitute symmetric strategies as they entail an equally pronounced response to both inflation under- and overshooting. The ELB problem, however, is an inherently asymmetric as the ELB constrains the downward adjustment of the policy rate and thus renders undershooting of inflation the predominant concern. Temporary price level (TPLT) targeting was proposed (see Bernanke (2017)) to take this asymmetry into account by utilizing the positive gains from TPLT in ELB episodes, while otherwise pursuing a standard inflation targeting strategy. Specifically, under TPLT, the policy maker commits to a deferral of the exit from the ELB until past shortfalls in inflation realized over the ELB episodes are made up for. Differently to AIT and PLT, TPLT thus restricts the make-up approach to the inflation shortfall accumulated at the ELB and thus does not target the price level in normal times. As shown in Figure 6, TPLT preserves the positive aspects attributed to PLT at the ELB. Specifically, under TPLT, inflation returns to target substantially more rapidly than under the standard Taylor rule approach and the policy maker allows for some degree of overshooting following the ELB episode. Similarly, the output target is stabilized faster and the drop in output is alleviated. The permanent output losses in terms of the technology stock are reduced. While the dynamics under TPLT are very similar to PLT in the context of ELB episodes and their direct aftermaths, they are fundamentally different when policy rates are not constrained, above all in the response to inflationary shocks, as discussed in detail in section 6.

5.5 Hysteresis rule

The monetary policy strategies discussed in the previous sections employed traditional output gap measures, reflecting the underutilization on the margin of production factors only - in line with the output gap measures typically employed in the DSGE model context and with slack

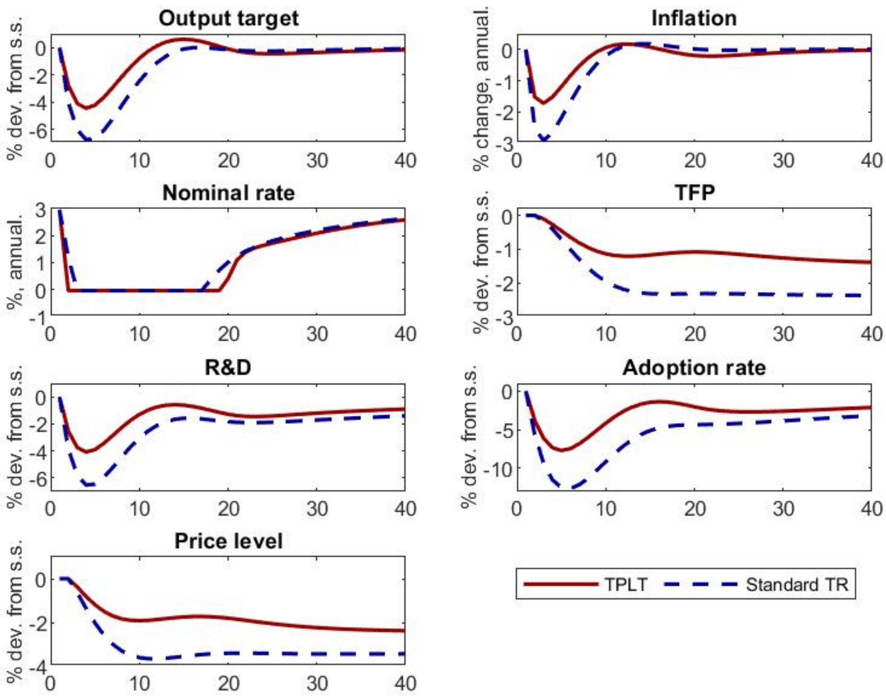

Figure 6: Dynamics at the ELB under temporary price level targeting.

measures commonly used by central banks. Crucially, these measures do not include the shortfall of the technology stock from potential. The underlying assumption that total factor productivity is driven by long-run structural factors outside the model only and that technology shocks are the only drivers of short-run fluctuations in TFP, thus ruling out the possibility of underutilization on the technology stock. However, as shown earlier and in line also with the recent literature, when modeling the evolution TFP endogenously in a general equilibrium setup, cyclical fluctuations and demand-side movements affect total factor productivity and monetary policy influences the long-run output path. Based on these insights, we study next the macroeconomic dynamics at the ELB underlying a monetary policy rule which targets also the underutilization on the technology margin. We refer to this monetary policy strategy as the "hysteresis rule" as it captures the notion of targeting the long-run output gap, i.e. the output gap measure which takes into account in addition to the conventional short-run output gap measure also the shortfall in terms of the technology stock. Figure 7 contrasts the dynamics at the ELB under the baseline Taylor rule and the hysteresis rule respectively (equ. 6).

Under the hysteresis rule monetary policy commits to reverting output fully to its initial potential output path. This has crucial implications for the trajectory of total factor productivity as the technology gap is made up in full over time, whereas the baseline Taylor rule admits a permanent shortfall in terms of the technology stock and hence long-run output losses. Importantly,

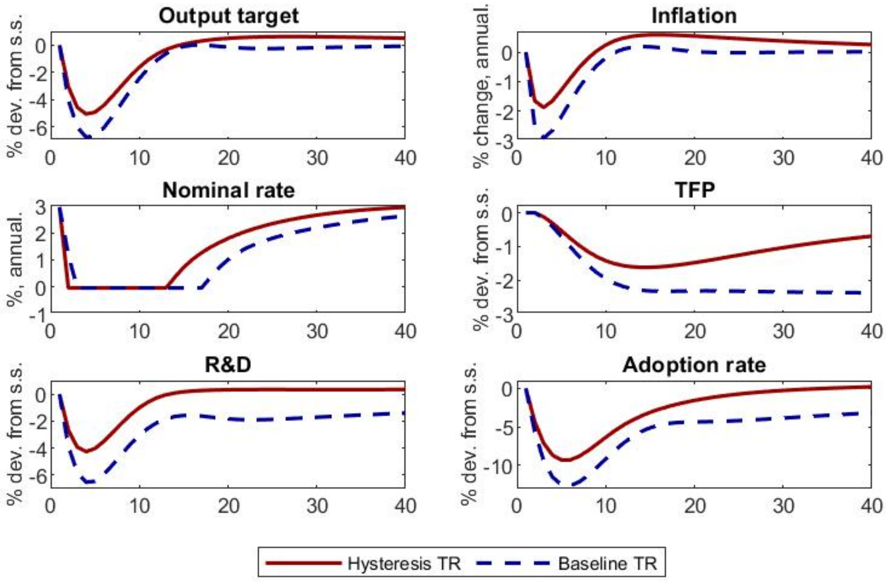

Figure 7: Dynamics at the ELB under the hysteresis rule.

the implied commitment to hold interest rates lower for longer not only offsets the output losses over the long run but instead also considerably alleviates the initial output drop, thus significantly cushioning the effect of the recession already on impact. Moreover, the commitment to realign output with trend and hence to the closure of the technology gap substantially reduces the downward adjustment in inflation. As total factor productivity constitutes a slowly-moving factor as it takes time until research and development and technology adoption rebound and help reverting TFP to its trend path, inflation experiences a temporary sustained phase of overshooting. Due to these described dynamics, exit from the ELB is attained relatively earlier under the hysteresis rule relatively to the baseline Taylor rule.

6 Performance of make-up strategies under endogenous growth

This section presents the results regarding the performance and effectiveness of make-up strategies under endogenous technology growth. Section 6.1 shows the simulation results with respect to stabilization and trend loss in the baseline model specification. Section 6.2 demonstrates the corresponding results under alternative model specifications, in particular for different levels of r^* and for an alternative measure of the output target.

6.1 Stabilization and trend losses: baseline scenario

The previous section showed that make-up strategies with a sufficiently strong make-up element perform better than inflation targeting as implied by the Taylor rule at the ELB with respect to the stabilization of inflation and the output target, as well as regarding the technology stock. We next depart from the study of disinflationary demand shocks at the ELB and extend our analysis to shocks moving nominal and real variables in either direction and emerging from both the demand and supply side.[38] Table 3 presents the simulation results for the mean realizations of annualized inflation and the output target[39] and the respective losses, measured in terms of root mean-squared deviation (RMSD). Based on the latter we calculate the stabilization loss as the combined losses from inflation and output target stabilization.[40] We further compute the loss in terms of the long-run trend path, defined as the mean shortfall of technology growth from the growth rate on the balanced growth path.[41]

	ELB freq.	ELB dur.	Inflation		Target output		Stabilization	Mean trend loss
			Mean	RMSD	Mean	RMSD	loss	(tech. growth)
Taylor rule (inertial)	0.22	11.4	1.89	1.64	-0.56	3.79	17.05	-0.09
Taylor rule (non-inertial)	0.29	8.20	1.18	5.40	-3.53	14.43	237.39	-0.63
AIT (3yrs.)	0.29	8.16	0.99	7.28	-4.24	19.43	430.52	-0.75
AIT (4yrs.)	0.28	8.02	1.26	5.30	-3.15	14.19	229.45	-0.56
AIT (5yrs.)	0.28	7.87	1.46	3.61	-2.34	9.66	106.35	-0.41
AIT (6yrs.)	0.28	7.83	1.51	3.19	-2.16	8.46	81.75	-0.38
PLT	0.23	7.00	2.00	0.93	-0.23	2.60	7.63	-0.03
TPLT	0.32	9.63	2.08	1.25	0.15	1.96	5.40	0.04
Hysteresis rule	0.23	5.67	2.06	1.32	-0.07	1.99	5.70	0.00

Table 3: Mean biases and losses under various monetary policy strategies (simulation results (100 000 draws); ELB nonlinearity accounted for using Occbin)

Under the baseline Taylor rule the ELB binds in 22% of the time, with an average ELB duration of 11.4 quarters. Mean inflation is biased below (1.89) and the inflation stabilization loss equals to 2.69. The baseline TR is subject to a mean downward bias in the output target and generates significant losses in terms of the stabilization of the output target (14.36). In combination, the baseline TR is subject to considerable stabilization losses (17.05). Crucially, and differently to models with exogenous technology, the conduct of monetary policy also matters for the stabilization of technology growth and thus the trend path. We document a trend loss, i.e. the shortfall of

[38] We simulate the model under the liquidity demand shock, the technology shock and the monetary policy shock. The simulations account for the ELB ($\bar{R} = 1$) by means of the piecewise-linear method underlying the Occbin toolbox (Guerrieri and Iacoviello (2015)).

[39] The mean output target is stated in terms of percentage deviations from the steady state.

[40] The stabilization loss is defined as $(RMSD_{infl.})^2 + (RMSD_{outp.})^2$, as specified, for instance, in Bernanke et al. (2019).

[41] Trend losses are defined as the mean difference between annualized mean technology growth and the rate of technology growth on the balanced growth path. Note that shortfalls on the technology margin induce permanent harm to long-run aggregate output and hence generate substantial output losses over time due to their cumulative effect.

average technology growth from the balanced growth path rate, of about 0.1 percentage point annualized growth. Crucially, shortfalls on the technology margin are permanent and cumulative, thus accumulating to substantial losses of aggregate output in the long run. Moreover, as shown in section 5, the trend loss stated in Table 3 denotes the mean loss, while the shortfalls from trend after deep recessions, above all post-ELB, may be substantially higher, thus generating marked losses with respect to long-run aggregate output.[42] As will be discussed in section 6.2, the trend losses are substantially amplified when monetary policy space is decreased.

The baseline Taylor rule is subject to inertia. Thus, while it does not feature a make-up element, the backward-looking element implies that abrupt fluctuations in the policy rate are avoided and interest rates held lower for longer at the ELB. We study next the performance of a non-inertial Taylor rule to demonstrate the costs of a more volatile monetary policy strategy and the related implications of raising interest rates relatively earlier at the ELB. The results show that the non-inertial Taylor rule generates markedly higher losses on all three margins under consideration. The non-inertial TR holds rates at the ELB for the shortest time period (8.2 quarters on average) and is subject to a high frequency of ELB events (29%). Mean annualized inflation is substantially downward-biased and equals to 1.18 and the inflation losses are sizeable. Both the mean gap and the losses in the output target are strongly amplified. The non-inertial TR thus generates large stabilization losses emerging from both inflation and output stabilization. Crucially, it is subject to extensive trend losses, with annualized mean technology growth ranging -0.63 percentage points below the balanced growth path rate.

Make-up strategies can provide additional stimulus operating through the real interest rate channel and innovation-payoff channel, thus capable of generating a considerably improved performance at the ELB, as discussed in section 5. We study next their overall performance to the extended set of shocks and show that make-up strategies can generate substantial improvements compared with Taylor-type strategies, where the relative performance varies across the respective type of make-up strategies under consideration. As a central result emerges that the make-up element has to be sufficiently pronounced for make-up strategies to improve performance relative to inflation targeting, in particularly compared with the baseline Taylor rule subject to inertia.

AIT and PLT are symmetric as to the price level-specific make-up elements since the latter are not confined to ELB episodes but instead apply symmetrically to up- and downward deviations from target. The performance of AIT is increasing in the averaging window. Only with an averaging window of four years and longer AIT reduces the losses as to inflation and the output target as well as regarding the trend loss relatively to the non-inertial Taylor rule. Compared with the inertial Taylor rule all versions of AIT perform subpar as the underlying inertia in policy rates is more effective than the comparatively weakly pronounced make-up elements under AIT. Recall, however, that AIT strategies of sufficiently long averaging horizons, i.e. of four years and longer,

[42] Note in addition that the baseline scenario is in an environment of a reduced natural rate of interest rate with a balanced growth path rate of about 0.80 % p.a. , demonstrating that the average loss in terms of technology growth corresponds to more than 12 per cent of the balanced growth path rate, thus demonstrating the substantial shortfalls with respect to technology growth.

reduce hysteresis on the technology margin at the ELB (section 5).

We analyze next PLT which represents, as discussed, AIT with infinite lookback horizon, requiring that any deviations of inflation from target be made up in full. This implies significantly strengthened stimulus at the ELB and overshooting post-ELB may be persistent, above all after long-lived ELB episodes. PLT fully offsets the downward bias in inflation, aligning mean inflation with target. Moreover, PLT constitutes the strategy which minimizes the losses in inflation stabilization. Additionally, PLT generates substantial gains on the output margin by significantly decreasing the mean downward bias of the output target and reducing the corresponding losses. The resulting stabilization losses range distinctly below the ones obtained under both the inertial and baseline TR rule and AIT of all horizons under consideration. Crucially, PLT nearly fully offsets the average shortfall of technology growth, demonstrating its effectiveness in improving and stabilizing trend growth despite not directly targeting it. Given the strongly pronounced make-up element, PLT is also subject to a reduced mean duration of ELB episodes.

The hysteresis rule constitutes a further symmetric strategy as it aims at offsetting both upward and downward deviations from the output path. We show that it minimizes the average duration of ELB events. This finding can be attributed to the strong stimulus at the ELB which is most pronounced under the hysteresis rule and rooted in the sluggishness of the technology stock.[43] Moreover, the hysteresis rule strongly improves the performance in terms of output stabilization as the mean bias in the output target is close to zero and the losses with respect to output stabilization are alleviated relative to the baseline Taylor rule. The hysteresis rule realizes mean inflation slightly above target (2.06) and generates a strong reduction of the stabilization losses of inflation. In sum, the hysteresis rule strongly reduces the stabilization loss, ranking second after TPLT. Crucially, the hysteresis rule also performs well regarding the stabilization of the trend loss, aligning average technology growth rates with balanced growth path trend growth.

In contrast to the previously discussed strategies, TPLT is asymmetric as its response during ELB episodes and in their immediate aftermath differs from the one in normal times. TPLT performs well in reducing the loss in terms of inflation stabilization, where only PLT performs better. Mean inflation under TPLT ranges slightly above target (2.08). The underlying cause for the differences of the results compared with PLT is a relatively more accommodative stance at the ELB and a less restrictive response to inflationary shocks due to the pursuit of standard inflation targeting in normal times. Importantly, as a further consequence of treating bygones as bygones outside the ELB, TPLT allows for relatively more expansionary upswings, inducing the highest and slightly positive mean realization of the output target. TPLT minimizes the output target loss. In sum, TPLT thus minimizes the stabilization loss, closely followed by the hysteresis rule. Crucially, albeit not directly targeting the technology stock, TPLT performs very well in terms of supporting technology growth, leading to slightly above-balanced growth path technology growth rate (0.04) attributable to its relatively more expansionary stance in upswings which permits a more pronounced expansion as to the long-run trend.

[43] See section 5 for a detailed discussion of the respective mechanisms.

6.2 Alternative model specifications

We next present additional simulation results under alternative model assumptions. Specifically, we discuss the role of monetary policy space by changing the long-run real rate and demonstrate the findings under an alternative output target specification.

Change in the monetary policy space:

Section 6.1 showed the results for the baseline scenario under an equilibrium real interest rate of 1%. We discuss next how changes in the underlying long-run real interest rate and hence the monetary policy space affect the performance and effectiveness of the monetary policy strategies under consideration as well as their relative ranking. The detailed simulation results are presented in Appendix B, where Table 5 and Table 6 show the simulations under a respectively higher and lower equilibrium real interest rate. The results can be summarized as follows. Firstly, the main results for the baseline scenario presented in section 6.1 are preserved also under alternative assumptions on the long-run real rate. Secondly, we find that the gap in terms of performance between low-performing and high-performing monetary policy strategies widens under the low rate scenario (Table 6), while the gap is relatively narrower in the high rate scenario (Table 5). This is the case as both the stabilization losses and the trend losses are amplified under inflation targeting and AIT strategies under reduced monetary policy space, while strategies with pronounced make-up elements maintain low losses also under lower r^*. Thus, firstly, while the relative gains from strategies with pronounced make-up mechanisms are also relevant in normal times, as captured by the high rate scenario (long-run real rate of 2%), the relative gains from the conduct of make-up strategies is less pronounced. Given the policy trade-offs associated with make-up strategies (see section 6.4), the gains from a change in the monetary policy framework may thus not be sufficiently large vis-à-vis the related costs. However, and crucially, when monetary policy space becomes reduced as the result of structural factors exerting downward pressure on the long-run real rate, the cause for the make-up approach is significantly strengthened.

Alternative output target measure:

Finally, the baseline simulations were based on the output target measure in the monetary policy rule as defined by $\frac{y_t}{y_t^{pot}}$, as used, for instance, in Moran and Queralto (2018). We study in addition an alternative output gap measure, specifically the unemployment gap ($\frac{L_t}{L}$) following, among others Anzoategui et al. (2019). The detailed simulation results are presented in Table 7 in Appendix C. In sum, our results with respect to the performance and relative ranking of monetary policy strategies also prevail under the alternative output measure and the respective mean biases and losses are in similar range.

6.3 Dynamics under inflationary shocks

We study next the dynamics under inflationary shocks emerging from both the demand- and the supply-side. Figure 8 shows the response to an expansionary liquidity demand shock which simultaneously raises inflation and output.

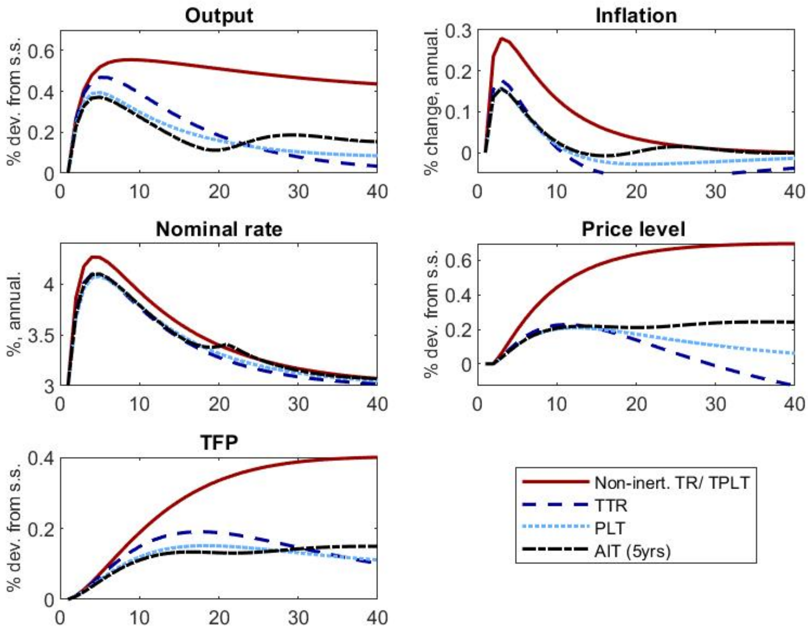

Figure 8: Impulse responses to inflationary liquidity demand shock.

We find that TPLT permits the strongest expansion in aggregate output since it behaves outside ELB episodes as a conventional Taylor rule and does not feature a make-up element. Crucially, this enables also the strongest expansion in total factor productivity and the long-run trend path. TPLT, however, also implies the most intense inflation increase, reflected in the most pronounced rise of the price level. Other monetary policy strategies under consideration feature path-dependent elements also in normal times, thus changing their response compared with the standard Taylor rule also significantly outside the ELB. Specifically, these expansions in aggregate output are more moderate under AIT, PLT and the hysteresis rule and generate also a weaker increase in technology stock. Moreover, inflation responds less strongly. Under AIT and PLT this is due to the commitment of partially (AIT) or fully (PLT) offsetting past overshootings in inflation by means of subsequent episodes of below-target inflation, subject to a correspondingly dampening effect on the boom and on the corresponding boost to long-run growth. Under the hysteresis rule (or technology Taylor rule (TTR)), in turn, the commitment to realign long-run aggregate output implies that the central bank will to some extent lean against the expansion, thus foregoing parts of the productivity gains. This is also accompanied by lower inflation and the most sustained phase of inflation undershooting among the considered strategies as the reversal of the aggregate output path and re-alignment with trend is slowly-moving. The described dynamics under AIT, PLT and the hysteresis rule may give rise to credibility issues, as discussed in more detail in section 6.4.

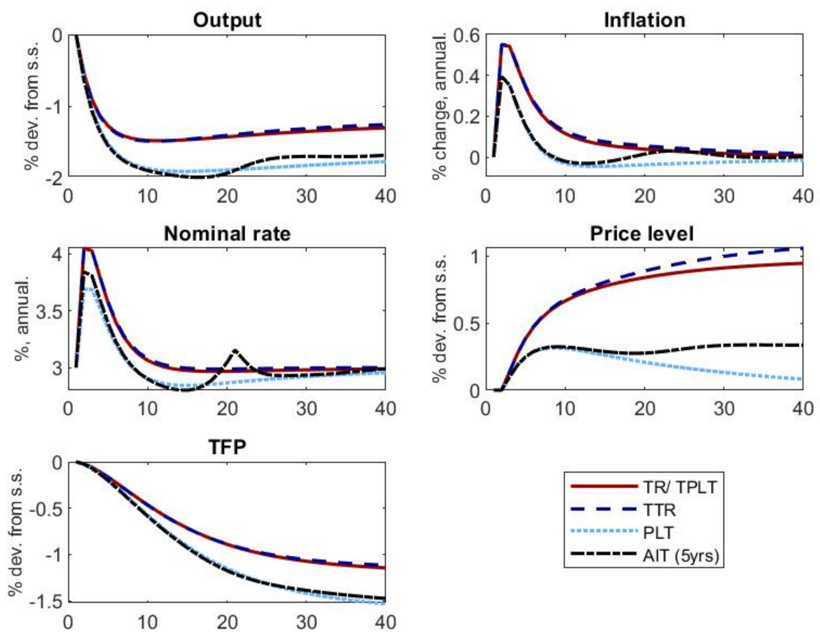

Figure 9: Impulse responses to inflationary supply shock.

Figure 8 showed the case of an inflationary demand shock which moved inflation and output in the same direction. The response to inflationary supply shocks which raise inflation but decrease aggregate output, as shown in Figure 9 by means of a technology shock, is, however of crucial relevancy when evaluating the performance of monetary policy strategies. This applies above all because of the potentially emerging risk of an excess increase in inflation and correspondingly, in inflation expectations. Our results are as follows. TPLT and the Taylor rule, which as stated earlier coincide outside the ELB, as well as the hysteresis rule lead to substantially more pronounced inflation responses translating into a larger increase of the price level. The drop in aggregate output, in turn, is relatively less pronounced under TPLT and the hysteresis rule. As a result, the corresponding shortfall on the technology margin is relatively less severe. The hysteresis rule, moreover, requires the full reversal of the latter and full realignment of the output path, thus requiring additional accommodation and hence leading to the strongest and most persistent increase in inflation.[44] AIT and PLT, in turn, induce a significantly less pronounced inflation increase. The initial overshooting is followed by a persistent phase of inflation undershooting which is more pronounced under PLT since it aims at fully realigning the price level. Under AIT and PLT, however, the fall in aggregate output is substantially amplified and the hysteresis effects to total

[44] For clarification, note that TFP in the impulse response charts refers to the endogenous component of TFP only and hence does not include the strictly exogenous part driven by the technology shock.

factor productivity and the long-run trend path emerging from the supply shock substantially higher.

6.4 Trade-offs for monetary policy

We discuss next potential trade-offs for monetary policy underlying the respective make-up strategies. More specifically, we demonstrate issues with respect to credibility, communication and measurement underlying some strategies under consideration.

Credibility

An essential requirement for the effectiveness of a monetary policy strategy in practice is its credibility. Besides the usual issues emerging in this respect, we demonstrate a new challenge as to credibility which is novel to the endogenous growth context, rooted in the response to inflationary shocks underlying some strategies, as discussed in detail in section 6.3. As a key result emerged that under symmetric strategies, i.e. AIT, PLT and the hysteresis rule, the departure from the "bygones are bygones" approach prevalent under the Taylor rule also implies that monetary policy cannot "look through" temporary increases in inflation (AIT, PLT) or respectively upward deviations from the long-run output path (hysteresis rule). This property may lead to reduced credibility of AIT, PLT and the hysteresis rule as economic agents may not fully believe that in the event of an expansionary demand shock the central bank will offset the expansion in a similarly forceful manner as in a recession, thus limiting the expansion in aggregate output and the boost to the technology stock. Or, in the case of inflationary supply shocks, AIT and PLT imply that the central bank would further reinforce the output drop, including an intensification of the long-run hysteresis of the technology stock. Crucially, while this constitutes a general concern as to the credibility of symmetrically designed make-up strategies, it is strengthened under the endogenous TFP model given the implications for TFP and hence the long-run. By contrast under TPLT, the implied "bygones" approach outside the ELB accommodates more the expansion induced by the demand shock and reinforces less the downturn caused by the supply shock, thus in both cases admitting considerably more pronounced gains in total factor productivity and thus the long-run output path. Consequently, symmetric strategies may be subject to more pronounced credibility issues than suggested by the previous literature given their implied tightening policy stance to inflationary shocks and the corresponding adverse output effect in not just a transitory manner, but via the impact on the technology stock also in a permanent manner. The corresponding long-run output costs inflicted under symmetric strategies may thus reduce their credibility as agents may doubt the central bank would be willing to admit these losses in the event of inflationary shocks.

Communication

A prerequisite for the effectiveness of make-up strategies is that they are well understood by economic agents which may not necessarily be given in practice. Depending on the respective make-up strategy different challenges may arise in this respect. As to the hysteresis rule, the concept of underutilization on the technology margin constitutes a central challenge given the increased complexity underlying the technology gap compared with conventionally used measures of slack, such as the unemployment rate. Regarding versions of AIT and PLT, understanding the averaging horizon over which inflation is to equal target inflation may pose a challenge. Asymmetric strategies, such as TPLT which feature an ELB-specific element may be easier to communicate as their make-up element is confined to ELB episodes and their direct aftermaths, thus implying a relatively minor shift in terms of monetary policy framework since inflation targeting is further on pursued outside the ELB. With larger deviations of inflation from target confined to the ELB context, TPLT may also be subject to a lower risk of misinterpreting temporarily higher (lower) inflation as a shift towards a permanently higher (lower) inflation target, especially relatively to frameworks with long memory.

Measurement

In order for any of the considered make-up strategies to be effective, the strategy also has to be implementable by the central bank in practice. This requires sufficiently reliable identification and tracking of the variables entering the monetary policy rule. Make-up strategies predominantly focused on inflation, such as PLT, TPLT and AIT face relatively less difficulties in this respect as inflation is generally easier to measure and the respective inclusion of inflation-based make-up elements only require tracking inflation over a more prolonged time period. Moreover, inflation measurement is part of the established tool set of central banks. Measurement is, by contrast, substantially more challenging in the case of the hysteresis rule. Specifically, the empirical measurement of the full output gap, i.e. including the underutilization on the technology margin, poses a key challenge. Measuring potential output - a purely theoretical concept - has always been subject to difficulties and high uncertainty and distinguishing between shifts in TFP which may be reverted by means of monetary stimulus vis-à-vis structural shifts may prove substantially challenging, above all in real time. Related concerns have been raised by Coibion, Gorodnichenko and Ulate (2018) in the context of the Great Recession, demonstrating that declines in aggregate output following pronounced recessions may be falsely interpreted as permanent and thus outside the scope of monetary policy. These practical issues related to measurement and related implementability can be considered thus a substantial drawback underlying the hysteresis rule and an argument in favor of the conduct of inflation-specific make-up strategies, above all of the strategies which perform well in correcting the downward bias in long-run growth, i.e. PLT and TPLT (see section 6). Hence, even if a central bank were to target the long-run GDP path, it may be desirable to conduct a form of price level targeting, above all TPLT, in the absence of adequate output gap measures as some of the inflation-specific make-up strategies with sufficiently long memory perform well in terms of the technology stock and hence the long-run output path.

7 Conclusions

This paper studies make-up strategies in a medium-scale New Keynesian DSGE model with endogenous technology growth through R&D and technology adoption (Comin and Gertler (2006)) under the non-linearity of the effective lower bound (ELB). Due to the inherent cycle-trend interaction, the operating environment, transmission mechanism, and scope of monetary policy are altered under endogenous growth, strengthening the gains from make-up strategies relatively to inflation targeting as implied by Taylor-type rules. Hysteresis effects in TFP induce permanent scars to the long-run trend, raising the costs of recessions. Moreover, the ELB induces both amplified and permanent costs under endogenous growth. Monetary policy influences productivity-improving investment and is thus non-neutral over the long-run. Moreover, due to the interaction between inflation and technology dynamics, inflation is less responsive to monetary stimulus, hence requiring a relatively more aggressive stance at the ELB, while simultaneously lowering the costs of running the economy hot. Inflation targeting as implied by the Taylor rule performs subpar in this environment, in particular under low r^*, subject to pronounced stabilization losses as to the inflation and the output target. Crucially, and novel to the literature, the Taylor rule induces significant shortfalls in technology growth and the long-run trend.

We show that make-up strategies with sufficiently strong make-up element can significantly reduce the losses as to inflation and output gap stabilization as well as the long-run trend losses during ELB episodes. The strengths of make-up strategies is amplified under endogenous growth as the real interest rate channel supports also productivity-improving investment and reduces long-run hysteresis in the technology stock. In addition, make-up strategies transmit via a novel innovation payoff channel through which the commitment to hold interest rates lower for longer raises the expected payoff from new innovations, hence boosting investment in R&D and technology adoption. As to the performance under both demand and supply shocks, most make-up strategies outperform inflation targeting as implied by the Taylor rule, where gains differ across strategies and are increasing in the strength of the make-up element. While the performance of average inflation targeting is increasing in the averaging window, all horizons studied deliver subpar performance relative to inflation targeting under the inertial Taylor rule. Strategies with a strong make-up element, in turn, i.e. price level targeting, temporary price level targeting as well as a hysteresis rule, deliver markedly improved results on all margins, including the shortfall in the technology stock.

The make-up approach is subject to novel challenges under endogenous growth in the areas of communication, measurement and, most notably, credibility. Strategies are prone to these pitfalls by varying degrees, where temporary price level targeting, by treating bygones as bygones outside the ELB, is most robust. Weakened credibility of some frameworks is founded in the underlying response to inflationary shocks, implying that the central bank would either jeopardize procyclical technology gains in demand-driven expansions, or in the case of supply shocks intensify the downturn and permanent scars to the long-run trend.

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A Appendix

A.1 Estimation of shock processes

Data sources used in the estimation of the shock process parameters are available at the FRED database. We use data from 1984:Q1 to 2008:Q3 in order to avoid distortions due to the Great Recession and subsequent lower bound period. We estimate the underlying parameters of the monetary policy shock, liquidity demand shock and technology shock. We use quarterly time series on real GDP (*GDPC1*) and the GDP deflator (*GDPDEF*). We use the effective federal funds rate (*DFF*) of which we compute quarterly averages of the annualized, daily series. We divide the series by four to align them with the quarterly frequency of the model. By means of this data we estimate the persistence parameters and standard deviations of the shocks under consideration, specifically the monetary policy shock, the liquidity demand shock and the technology shock. The series on output, inflation and the federal funds rate are computed based on the data described in the beginning of the section and are generated in what follows.

- Output growth= $\Delta ln\left(\frac{GDPC1}{CNP16OV}\right)$
- Inflation $= \Delta ln\,(GDPDEF)$
- Federal funds rate $= \frac{1}{4} * DFF$

Table 4 presents the prior and posterior distributions of the estimated shocks.[45]

Parameter	Description	Prior			Posterior	
		Distrib.	Mean	Std.	Mean	Std.
Persistence						
ρ_m	Monetary policy	Beta	0.5	0.2	0.5806	0.0694
ρ_b	Liquidity demand	Beta	0.5	0.2	0.9211	0.0362
ρ_θ	Technology	Beta	0.5	0.2	0.9407	0.0429
Std. deviations						
σ_m	Monetary policy	Inv. gamma	0.001	2.00	0.0011	0.0001
σ_b	Liquidity demand	Inv. gamma	0.001	2.00	0.0038	0.0009
σ_θ	Technology	Inv. gamma	0.001	2.00	0.0120	0.0015

Table 4: Shock processes: prior and posterior distributions

B Simulation scenarios: long-run real rates

We present additional simulation results for different assumptions on the long-run equilibrium real interest rate, i.e. the real interest rate prevailing on the balanced growth path. This section thus

[45] Note that the data series are log differences, which is reflected in the shock size.

also demonstrates the role of monetary policy space for the realized losses occurred under and the relative ranking of monetary policy strategies. Table 5 presents the simulation results for a higher long-run real interest rate of 2 % and thus a long-run nominal interest rate of 4%.

	ELB freq.	ELB dur.	Inflation		Output target		Stabilization	Mean trend loss
			Mean	RMSD	Mean	RMSD	loss	(tech. growth)
Taylor rule (inertial)	0.13	9.10	1.96	1.35	-0.21	2.61	8.64	-0.04
Taylor rule (non-inertial)	0.21	6.66	1.70	2.93	-1.40	7.58	66.04	-0.27
AIT (3yrs.)	0.20	6.65	1.67	3.36	-1.46	8.94	91.21	-0.28
AIT (4yrs.)	0.20	6.57	1.75	2.62	-1.14	6.78	52.83	-0.22
AIT (5yrs.)	0.20	6.50	1.79	2.13	-0.96	5.28	32.42	-0.18
AIT (6yrs.)	0.20	6.50	1.80	2.06	-0.94	5.05	29.75	-0.18
PLT	0.15	5.89	2.00	0.81	-0.11	2.21	5.54	-0.02
TPLT	0.23	7.93	2.05	1.26	0.11	1.71	4.52	0.03
Hysteresis rule	0.15	4.72	2.03	1.27	-0.04	1.56	4.05	0.00

Table 5: Mean biases and losses under various monetary policy strategies (high real rate scenario)

Table 6 shows the corresponding simulations for a lower long-run real interest rate of approximately 1%. We discuss the presented results in more detail in section 6.2.

	ELB freq.	ELB dur.	Inflation		Output target		Stabilization	Mean trend loss
			Mean	RMSD	Mean	RMSD	loss	(tech. growth)
Taylor rule (inertial)	0.30	13.84	1.75	2.20	-1.20	5.59	36.09	-0.18
Taylor rule (non-inertial)	0.36	9.67	0.34	8.67	-6.84	22.95	601.87	-1.12
AIT (3yrs.)	0.35	9.72	-0.25	12.73	-9.03	33.31	1270.85	-1.48
AIT (4yrs.)	0.36	9.54	0.35	9.23	-6.69	24.38	679.58	-1.09
AIT (5yrs.)	0.36	9.34	0.88	5.90	-4.61	15.83	285.40	-0.75
AIT (6yrs.)	0.36	9.34	1.06	4.65	-3.95	12.56	179.38	-0.64
PLT	0.30	8.20	2.00	1.09	-0.39	3.09	10.74	-0.05
TPLT	0.40	11.46	2.12	1.28	0.18	2.28	6.84	0.05
Hysteresis rule	0.29	6.56	2.12	1.42	-0.12	2.48	8.17	0.00

Table 6: Mean biases and losses under various monetary policy strategies (low real rate scenario)

C Simulation scenarios: alternative output target

We in addition verify the robustness of our findings to the choice of output measure by using instead of the baseline output target measure employment in the monetary policy rules, as used for instance by Anzoategui et al. (2019). Table 7 shows the simulation results for the described versions of the Taylor rule and make-up strategies as described earlier, with the only difference constituting that the central bank targets as an output measure $\frac{L_t}{L^{ss}}$. We present a more detailed discussion of these results in section 6.2.

	ELB freq.	**ELB dur.**	**Inflation**		**Output target**		**Stabilization**	**Mean trend loss**
			Mean	RMSD	Mean	RMSD	**loss**	**(tech. growth)**
Taylor rule (inertial)	0.24	10.77	1.87	1.92	-0.61	3.60	16.64	-0.10
Taylor rule (non-inertial)	0.36	5.35	1.29	4.39	-2.93	11.18	144.27	-0.52
AIT (3yrs.)	0.35	5.06	1.30	4.57	-2.81	11.86	161.55	-0.49
AIT (4yrs.)	0.35	5.02	1.39	4.13	-2.48	10.57	128.78	-0.44
AIT (5yrs.)	0.34	5.00	1.48	3.47	-2.14	8.68	87.38	-0.37
AIT (6yrs.)	0.34	4.99	1.52	3.18	-2.02	7.79	70.80	-0.35
PLT	0.29	4.28	2.00	1.15	-0.31	2.40	7.08	-0.04
TPLT	0.38	6.35	2.07	1.57	0.13	1.77	5.60	0.04
Hysteresis rule	0.30	3.94	2.13	1.54	-0.08	2.13	6.91	0.00

Table 7: Mean biases and losses under various monetary policy strategies (alternative output target scenario)

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