**Navarra Center for International Development**

# Working Paper nº 01/2023

# Monetary policy invariance, hysteresis, and optimal inflation

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# Monetary policy invariance, hysteresis, and optimal inflation[*]

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This Version: December 19, 2022

## Abstract

Standard New Keynesian (NK) models feature an optimal inflation target well below 2 percent, limited welfare losses from business cycle fluctuations and long-term monetary neutrality. We develop a NK framework with endogenous productivity and downward wage rigidity (DWR) which challenges these results. The interaction between endogenous growth and DWR generates asymmetric hysteresis effects on unemployment and R&D. As a consequence, the model features a non-vertical long-run Phillips curve and a trade-off between price distortions and output hysteresis that changes the welfare-maximizing inflation rate to above 2 percent. Deviations from the optimal target carry welfare costs multiple times those in traditional NK models. Taylor rules responding to labor market developments handle better the asymmetric hysteresis effects in our model. Results are robust to the inclusion of the effective lower bound on interest rates.

*Keywords:* Endogenous Growth, Monetary Policy, Optimal Inflation Target, Downward Wage Rigidity, Monetary Policy Invariance, Zero Lower Bound.

*JEL Classification: E24, E3, E5, O41, J64*

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[*] A previous version of this paper was circulated under the title "Endogenous growth, downward wage rigidity and optimal inflation". We thank for helpful comments Robert Amano, Robert Anderton, Guido Ascari, Paolo Bonomolo, Ignacio Campomanes, Stephane Dupraz, Philip Lane, Michele Lenza, Wolfgang Modery, Antonio Moreno, Roberto Motto, Fabio Panetta, Giorgio Primiceri, Frank Smets, William Tayler, Oreste Tristani and seminar participants at the ECB, IMF, University of Navarra and at the 2021 ECB-Cleveland Fed Inflation Conference. We are especially grateful to Tom Holden for his help with the DynareOBC toolkit and to Stephan Fahr for fruitful discussions over the years. The views expressed in this paper are those of the authors and do not necessarily represent those of the ECB or the IMF.

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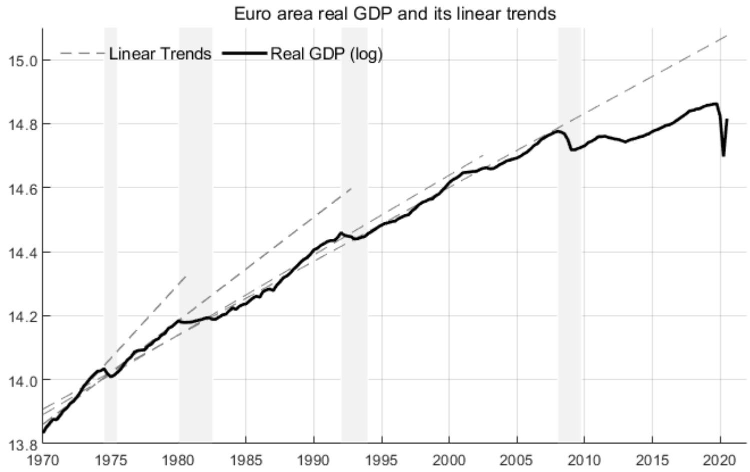
# 1 Introduction

The monetary policy framework and the definition of price stability prevailing in modern central banking hinge on the seminal contribution from Friedman (1968) that crystallized two main propositions: *(i) there is a natural level of the unemployment rate that is invariant to inflation* and *(ii) monetary policy has no long-run effects on the real economy* (Blanchard, 2018). This view, described by Hall and Sargent (2018) as the *monetary policy invariance hypothesis*, has been challenged by the events following the Global Financial Crisis: In most advanced economies, output and TFP had shifted permanently to a lower level, leading researchers to revisit the issue of hysteresis. An insufficient reaction of monetary policy – due in part to the zero lower bound – is considered one of the amplifiers of the initial recession, and has spurred calls for more aggressive policy reaction (Yellen, 2016) and a higher inflation target (Ball, 2014).[1] In the euro area the hysteresis effect of the 2008 crisis has been particular harsh, as the Great Recession seems to have affected not only the long run level of output, but also the growth rate of output (see Figure 1).

Figure 1: **Hysteresis in output in the euro area**



*Data are in logs. Shaded areas are euro area recessions as identified by the CEPR business cycle dating committee. Dashed lines refer to linear trends prevailing before each respective recession.*
*Source: Eurostat, CEPR and ECB Area Wide database*

Against this backdrop, we propose a new framework to study monetary policy when economic fluctuations interact with long-term productivity trends. We incorporate two features into an otherwise standard New Keynesian (NK) model with unemployment: endogenous productivity growth via an R&D innovation channel and downward wage rigidity (DWR).

The interaction between DWR and endogenous productivity generates three key

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[1] Recent papers present cross-country evidence indicating that deep and persistent recessions are often followed by lower output relative to the pre-recession trend even after the economy has recovered (see e.g. Blanchard et al. (2015); Cerra and Saxena (2008)).

findings that are of relevance for the conduct of monetary policy, not captured by traditional models with exogenous growth. *First*, the model implies what could be labeled "super non-neutrality" of monetary policy, that is a long-run trade-off between output *growth* and the inflation target.[2] *Second*, consumption-equivalent welfare losses are a multiple of those associated with traditional models, because the interaction between endogenous growth and DWR magnify the trade-off between the costs of price distortions and the ones of output hysteresis. *Third*, the optimal inflation rate is consistently above the inflation target commonly used across central banks, and the welfare costs of adopting a sub-optimally low inflation target are an order of magnitude larger than in workhorse New Keynesian models. To the best of our knowledge, we are the first studying the implications of endogenous growth *and* DWR for the optimal inflation target.

The endogenous productivity channel enriches a standard NK model with supply-side features that create path dependence and affect the determinants of long-run growth. We follow Anzoategui et al. (2019), Kung and Schmid (2015) and introduce endogenous growth in the model via an innovation sector that conducts R&D expenditure to expand the stock of intangibles and the variety of patented goods in the economy. In this setting, negative demand shocks (e.g. risk premium shocks) reduce firms' profits and R&D investment, which in turn reduce the process of intangible capital accumulation, which is ultimately the engine of growth. Through this channel, temporary shocks have the potential to generate *hysteresis effects* on TFP and output that resemble those of the Global Financial Crisis (Benigno and Fornaro, 2018; Abbritti and Weber, 2019).

The inclusion of DWR in a frictional labour market generates *asymmetric responses* in unemployment and output. Following Schmitt-Grohé and Uribe (2013, 2016), we model DWR as an occasionally binding constraint on nominal wage adjustment.[3] The presence of DWR constrains the adjustment of nominal wages following a large negative demand shock. As prices decrease relatively faster, real wages increase

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[2] There are two important differences with the work of Benigno and Ricci (2011) and Dupraz et al. (2022), which also derive a non-vertical Phillips curve. First, our model features endogenous productivity, giving rise to hysteresis effects that are absent in standard setups with exogenous growth. Second, our model features DWR as well as price and wage adjustment costs, while they do not account for price and wage distortions. Therefore, in their models, there is no long-run trade-off between the costs from output hysteresis (and DWR) and the costs of price and wage distortions. As such, their long-run non-vertical Phillips curve only captures the "greasing the wheels" effect of DWR. In our setting, the interaction between DWR and endogenous growth implies that the inflation target affects both the level of output and its long-term growth rate. While the growth effect is quantitatively small on average, it has large welfare consequences.

[3] While our findings only require that increasing wages is easier than cutting them, the introduction of DWR is underpinned by ample microeconometric evidence on the importance of downward nominal and real wage rigidity both in the US and in the euro area (see e.g. Gertler et al. (2020); Dickens et al. (2007); Daly and Hobijn (2014); Barattieri et al. (2014) ). More recently, Grigsby et al. (2021) find strong evidence of DWR in administrative payroll data, and Hazell and Taska (2020) show that also the wage for new hires is rigid downward, but flexible upward using firm wage posting data.

during the downturn and strongly amplify the negative effects on employment, investment and output. In a search and matching framework, this leads to higher unemployment duration. The opposite is *not* true with large positive demand shocks as the increase in nominal wages limits hiring and job creation. DWR thus generates asymmetric business cycle fluctuations that resemble those of the plucking theory in which the unemployment rate jumps at the start of a recession and slowly declines during a recovery (Friedman, 1993).

When endogenous productivity and DWR are combined, large temporary shocks have *asymmetric hysteresis effects* on the real economy. Because of DWR, the hysteresis effects of negative shocks are larger than those of equal-sized, positive shocks, therefore affecting the trajectories of output and TFP. The monetary policy framework or the inflation target adopted by the central bank may influence the degree of asymmetric hysteresis and the long-run effects on output. Hence, the monetary policy invariance hypothesis does not hold.

We find that the optimal inflation target is above 2 percent - a value commonly targeted by central banks across advanced economies - and deviations from the optimal inflation target carry non-trivial welfare costs. In our model, increasing the inflation target has two main effects. First, it *increases* the distortions related to price and wage rigidity. Second, it *reduces* the probability of hitting the occasionally binding wage constraint, and therefore reduces the costs related to DWR. From a welfare perspective, the optimal rate of inflation in our model balances the costs of price distortions on one side and the ones from DWR on the other. Asymmetric hysteresis enriches this trade-off along two important dimensions: (i) recessions have long-term effects on output, and (ii) the costs associated with the lower bound on wages are no longer paid infrequently, but they persist in the future. These findings go beyond Tobin (1972) results based on the role of DWR. In a model with asymmetric hysteresis, the lack of short-term adjustment in wages has permanent effects on productivity, output and welfare, hence amplifying the original "greasing the wheels" effect in the labour market.

We verify the robustness of our results to several changes in the assumptions underlying the calibration of key parameters of the economy such as the volatility of the shock processes, the pricing scheme (Rotemberg vs. Calvo), the tightness of the wage floor, the endogenous TFP process and the hiring and investment adjustment costs. We consistently find large welfare costs associated with deviating from the optimal inflation target, which remains throughout above 2 percent.

Finally, we complement our analysis with two extensions. In the first extension we analyse the effects of adding the zero lower bound (ZLB) on the monetary policy rate. We find that the introduction of the effective lower bound on the nominal interest rate (Bernanke, 2017; Eggertsson and Woodford, 2003) leaves our main results unaffected. In the second extension, we compare the performances of alternative monetary policy strategies. We find that a price-level targeting or a simple monetary policy rule that responds to the unemployment rate are better suited than a standard Taylor rule for a model economy which features asymmetric hysteresis. Shifting to such strategies would lead to significant welfare gains and, in our framework, is superior to an average inflation targeting regime.

Our model and findings are related to three broad strands of the literature studying endogenous growth, DWR, and optimal inflation targeting in NK models. The endogenous productivity channel has been used to explain the persistence of the propagation mechanism from the Global Financial Crisis, which has led to long slumps (Hall, 2011) and has further exacerbated the secular trend in economic growth (Bianchi et al., 2019) as well as the scarring effects from global supply disruptions (Fornaro and Wolf, 2022). More specifically, Anzoategui et al. (2019) provide evidence for the US economy that productivity-enhancing investment such as R&D is highly procyclical and find that part of the long-term productivity slowdown following the Great Recession has been driven by a reduction in R&D investment and a lower adoption rate of new technologies. For European companies, Ferrando and Preuss (2018) find that investment in intangible assets is also highly procyclical as it depends on firms' internal finance and firms' size.[4] Moran and Queralto (2018) study the link between monetary policy and endogenous TFP dynamics in a NK model, showing that the ZLB on interest rates can lead to large permanent TFP losses. Garga and Singh (2021) analyse optimal monetary policy in a NK model featuring endogenous growth and the ZLB on interest rates, and find that at the ZLB a strict inflation targeting rule is suboptimal, leading to output hysteresis, defined as a permanent loss in potential output. The literature featuring endogenous growth has not focused on DWR and optimal inflation.

Starting with Tobin (1972), the presence of DWR provides a rationale for a positive inflation buffer, which can support relative wage adjustment without incurring significant social costs in terms of unemployment and discouraging workers. Downward wage stickiness can generate large business cycle asymmetries (Akerlof et al., 1996) and lack of wage adjustment has contributed to the severity and persistence of the Great Depression in the United States (Erceg et al., 2000). Benigno and Ricci (2011) provide a theoretical foundation for a highly nonlinear relationship of the long-run trade-off between average wage inflation and output gap: the trade-off is virtually inexistent at high inflation rates, while it becomes relevant in a low inflation environment because of DWR. Abbritti and Fahr (2013) demonstrate that the presence of DWR strongly improves the fit of a NK model with labour market frictions to the observed pattern of asymmetries of a number of OECD countries. Dupraz et al. (2022) embed DWR in a search model of the labour market to develop a microfounded plucking model of the business cycle, whereby economic contractions are

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[4] Over the business cycle, larger firms substitute internal and external finance depending on pricing conditions - as they are less affected by financial constraints and collateral requirements - while smaller firms use external equity and debt financing in a procyclical manner (Begenau and Salomao, 2018). Given the prevalence of small- and medium-size firms in the euro area, financial constraints play an important role on the procyclicality of R&D investment and on the long-term consequences for productivity growth.

followed by expansions of a similar amplitude, while the amplitude of contractions are not related to the previous expansion. Most of this literature has focused on DWR in models with *exogenous* trend growth. Therefore, the asymmetric feature of DWR had limited propagation mechanisms for long-term output. In our model the endogenous growth channel is critical for the determination of the long run Phillips curve and the welfare implications.

Finally, our work is related to the extensive literature on the optimal rate of inflation in NK models (see e.g. Schmitt-Grohé and Uribe (2010), Kim and Ruge-Murcia (2009), Coibion et al. (2012), Ascari and Sbordone (2014); Ascari et al. (2018), Amano and Gnocchi (2022)). Most of these studies show that even in the presence of the ZLB, the optimal inflation target is relatively low, typically below 2 percent.[5] The reason is that ZLB episodes are infrequent and welfare-related costs are large but short lived in models with exogenous growth dynamics. Price and wage distortions created by higher inflation targets, instead, are small but paid in each period.[6]

The remainder of the paper is structured as follows: Section 2 lays out the New Keynesian model with endogenous growth and downward wage rigidity. Section 3 describes the calibration strategy and solution method for the endogenous growth model with DWR and for the benchmark models with exogenous growth and no DWR. Section 4 analyzes how the introduction of endogenous growth (i) allows for persistent and even permanent effects in response to temporary shocks, and (ii) affects the slope of the long run Phillips curve and monetary policy effectiveness. Section 5 describes a welfare metric that accounts for long-term growth, which is then used to derive the optimal inflation target, and to analyze the implied welfare losses under different scenarios. Section 6 discusses two extensions of our model. Section 7 concludes.

## 2 The Model

In this section we set up a New Keynesian (NK) model which combines nominal price stickiness á la Rotemberg (1982) with three additional ingredients: (1) search and matching frictions in the labour market, which give rise to involuntary unemployment; (2) endogenous TFP growth through R&D investment and innovation; and (3) downward wage rigidity in the form of an occasionally binding constraint on

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[5] There are a few exceptions. For instance, Adam and Weber (2019) find that the optimal inflation rate ranges between 1 and 3 percent in a model with firm heterogeneity. A higher firm turnover would call for a higher optimal inflation rate to *grease* relative productivity adjustments among new and old firms. Blanco (2021) studies optimal inflation in a quantitative menu cost model with a zero lower bound on interest rates and find that the optimal inflation target is larger than what is typically found in models with time-dependent pricing. Ball (2014) argues that a higher inflation target, around four percent, has more benefits as economic downturns would be less severe and costs from higher average inflation would be minimal.

[6] As shown by Andrade et al. (2019, 2021), the case for a higher inflation target gets stronger when the decline in the natural rate of interest is taken into account.

wage inflation.

## 2.1 The labour market

The labour market is characterized by search frictions. Let $m_t$ denote the newly formed firm–worker matches in the labour market. Their number depends on the measure of vacancies, $v_t$, and job seekers, $u_t$, following a constant return to scale matching technology:

$$m_t = \bar{m} u_t^{\zeta} v_t^{1-\zeta},$$

where $\bar{m} > 0$, $\zeta \epsilon (0, 1)$ and $u_t = 1 - (1 - \rho) N_{t-1}$ is the number of *searching workers* at the beginning of period $t$. $N_t$ denotes aggregate employment and $\rho$ is the fraction of employment relationships that is destroyed in each period. The probability for the firm to fill an open vacancy is

$$q_t = \frac{m_t}{v_t} = \bar{m} \theta_t^{-\zeta}$$

where $\theta_t = \frac{v_t}{u_t}$ denotes labour market tightness. The probability that a worker looking for a job is matched with an open vacancy is

$$f_t = \frac{m_t}{u_t} = \theta_t q_t.$$

For future reference, let us also define *(after-hiring) unemployment* as the fraction of searching workers that remain unemployed after hiring takes place:

$$ur_t = 1 - N_t \tag{1}$$

## 2.2 Households

Each household is made up of a continuum of members represented by the unit interval. The representative household maximizes a standard lifetime utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \log C_t$$

where $C_t$ is a Dixit-Stiglitz consumption bundle with elasticity of substitution $\epsilon$ and $\beta$ is the subjective discount factor. Households own all firms in the economy and face the following per period budget constraint:

$$C_t + I_t + \frac{B_t}{P_t} = w_t N_t + r_{Kt} z_t k_t + b_t (1 - N_t) + \frac{R_{t-1} \varrho_{t-1} B_{t-1}}{P_t} + D_t$$

where $I_t$ denotes investment in the physical capital stock, $P_t$ is the aggregate price level and $R_t$ is the gross nominal interest rate of the nominal bond $B_t$. $z_t$ denotes the utilization rate of capital.[7] Total household income is the sum of the real wage income earned by employed family members $w_t N_t$, the benefits earned by the unemployed $b_t(1-N_t)$, the return on capital $r_{Kt} z_t k_t$ and the family share of aggregate profits from retailers and matched firms net of taxes, $D_t$.[8] $\varrho_t$ is a risk premium á la Smets and Wouters (2007), which will allow us to gauge the implications of financial shocks without explicitly modelling financial frictions.

The number of employed family members is given by the number of continuing relationships, $(1-\rho) N_{t-1}$, plus the number of new hires, $m_t = f_t u_t$, which are immediately operative:

$$N_t = (1-\rho) N_{t-1} + f_t u_t$$

The law of motion of physical capital is:

$$k_{t+1} = (1-\delta_K(z_t)) k_t + \left[1 - \frac{\Theta_I}{2}\left(\frac{I_t}{I_{t-1}} - g\right)^2\right] I_t$$

where $\frac{\Theta_I}{2}\left(\frac{I_t}{I_{t-1}} - g\right)^2$ captures convex costs in physical investment, $\Theta_I > 0$ is a scale parameter and $g$ is the steady state gross growth rate of the economy. The depreciation rate is convex in the capital utilization rate: $\delta_K(z_t) = \delta z_t^{\phi_k}$.

Let us denote by $\lambda_t$ the multiplier associated with the budget constraint and by $\pi_t = \frac{P_t}{P_{t-1}}$ the gross inflation rate. The solution to the maximization problem of the household leads to the following first order conditions:

$$\begin{aligned}
\lambda_t &= \frac{1}{C_t} \\
1 &= \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} \frac{R_t}{\pi_{t+1}} \varrho_t \\
1 &= Q_{Kt}\left\{\left(1 - \frac{\Theta_I}{2}\left(\frac{I_t}{I_{t-1}} - g\right)^2\right) - \Theta_I\left(\frac{I_t}{I_{t-1}} - g\right)\frac{I_t}{I_{t-1}}\right\} \\
&\quad + \mathbb{E}_t \beta \frac{\lambda_{t+1}}{\lambda_t} Q_{Kt+1}\left\{\left[\Theta_I\left(\frac{I_{t+1}}{I_t} - g\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right]\right\} \\
Q_{Kt} &= \mathbb{E}_t \beta \frac{\lambda_{t+1}}{\lambda_t}\left\{r_{Kt+1} z_{t+1} + Q_{Kt+1}(1 - \delta_K(z_{t+1}))\right\} \\
r_{Kt} &= Q_{Kt} \delta_K'(z_t)
\end{aligned}$$

where $Q_{Kt}$ is the Tobin's Q. For future reference, let us also define the value of employment for the family, $V_t^E$, as

$$V_t^E = w_t - b_t + \beta(1-\rho)\mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t}\left\{(1 - f_{t+1}) V_{t+1}^E\right\} \tag{2}$$

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[7] As in Anzoategui et al. (2019), we allow for variable capital utilization intensity so as not to mistakenly attribute all high frequency variation in the Solow residual to endogenous technology.

[8] Notice that when productivity grows along the balanced growth path, also the unemployment benefits grow at the same rate: $b_t = b\Psi_t$, where $\Psi_t$ is a scaling factor which ensures the existence of a balanced growth path. This guarantees that replacement rates are constant along the balanced growth path.

The net value of an additional employed worker in the family is the wage net of unemployment benefits, plus the expected continuation value from the employment relationship.

## 2.3 Production

There are three (non-innovating) production sectors in the economy. Firms in the intermediate good sector produce homogeneous goods in competitive markets using labour and capital. Their output is bought by the patent sector, whose firms own the exclusive right over their respective variety. Patented varieties are then sold to the retail sector. Retail firms assemble different patented varieties and produce the final (differentiated) goods which are then sold to households.

### 2.3.1 Intermediate good sector

Each firm in the intermediate production sector produces according to the following technology:

$$X_t = A_t \left(N_t\right)^{1-\alpha} \left(K_t\right)^{\alpha} \tag{3}$$

where $K_t = z_t k_t$ denotes aggregate effective physical capital and $A_t$ is an exogenous technology process.

The intermediate good is sold to patent producers at the relative price $p_{I,t}$. The representative firm incurs costs in hiring and training new workers. Following, e.g., Gertler and Trigari (2009) and Gertler et al. (2008), we assume that total hiring costs are convex in the hiring rate. Specifically, let us define the hiring rate as $x_t \equiv \frac{q_t v_t}{N_{t-1}}$. Hiring costs are defined as

$$hc_t = \frac{\kappa_t}{\gamma} \left(x_t\right)^{\gamma} N_{t-1}$$

where $\kappa_t = \kappa \Psi_t$ and $\Psi_t$ is a scaling factor which ensures the existence of a balanced growth path.[9]

To improve the realism of the model and the fit with the data, we also allow for nominal wage stickiness by introducing a quadratic adjustment cost function of the nominal wage $W_t$:

$$c_t^W = \frac{\phi^w \Psi_t}{2} \left(\pi_t^w - g_t^R\right)^2$$

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[9] The assumption of convex hiring costs is based on two considerations. First, from an economic point of view, the degree of convexity $\gamma$ allows us to smooth out vacancy creation and to produce realistically persistent hiring dynamics. Moreover, as discussed for instance in Faccini and Yashiv (2020) and Fujita and Ramey (2007), the micro evidence indicates that hiring costs are indeed convex, and that most of these costs are post-match costs related to training workers as opposed to pure vacancy posting costs. Second, from a technical point of view, the presence of convex hiring costs allows the model to meet two consistency requirements even in the presence of large shocks and long simulations: (1) that the hiring rate never turns negative, and (2) that the equilibrium wage always remains within the wage bands defined by the bargaining set.

where $\pi_t^w = \frac{W_t}{W_{t-1}}$ denotes wage inflation, $\phi^w \geq 0$ determines the size of these costs and $g_t^R$ is the level of wage inflation used as reference for the adjustment costs. If $g_t^R = g^W$ the reference of wage adjustment costs is trend wage inflation $g^W$; for $g^R = 1$ wage adjustment costs are zero when the wage is unchanged; finally, $g_t^R = \pi_{t-1}^{\varsigma}$ captures the case of partial indexation of wages to past inflation, with $\varsigma \in (0,1)$ representing the degree of indexation. Notice that in most of the analysis we assume that $g^R = 1$. Therefore, a higher inflation target leads to static and dynamic wage distortion costs, which tend to decrease output, consumption and welfare.

The representative firm maximizes expected profits:[10]

$$\mathbb{E}_t \left\{ \sum_{j=0}^{\infty} \beta_{t,t+j} \left[ \begin{array}{c} p_{I,t+j} \left( A_{t+j} \left( N_{t+j} \right)^{1-\alpha} \left( K_{t+j} \right)^{\alpha} \right) \\ - \left( w_{t+j} + c_{t+j}^W \right) N_{t+j} - hc_{t+j} - r_{Kt+j} K_{t+j} \end{array} \right] \right\}$$

subject to the sequence of law of motions of labour, $N_t = (1 - \rho + x_t) N_{t-1}$. Maximization leads to a standard capital demand condition:

$$r_{Kt} = p_{I,t} \alpha \frac{X_t}{K_t}$$

and to the hiring creation condition:

$$\kappa_t (x_t)^{\gamma-1} = p_{I,t} (1-\alpha) \frac{X_t}{N_t} - \left( w_t + c_t^W \right) + \mathbb{E}_t \beta_{t,t+1} \left[ (1-\rho) \kappa_{t+1} (x_{t+1})^{\gamma-1} + \frac{(\gamma-1)}{\gamma} \kappa_{t+1} (x_{t+1})^{\gamma} \right]$$

where $\beta_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t}$ is the stochastic discount factor.

Finally, for later use, let us define $J_t$ as the value of having a new worker after adjustment costs are sunk:[11]

$$J_t = p_{I,t} (1-\alpha) \frac{X_t}{N_t} - \left( w_t + c_t^W \right) + \mathbb{E}_t \beta_{t,t+1} \left[ (1 - \rho + x_{t+1}) J_{t+1} - \frac{\kappa_{t+1}}{\gamma} (x_{t+1})^{\gamma} \right] \quad (4)$$

### 2.3.2 Patent good sector

Each patent producer $j$ produces a differentiated variety transforming one unit of the intermediate good $X_t^j$ into one unit of their patented good:

$$Y_{S,t}^j = X_t^j$$

where $Y_{S,t}^j$ is the quantity of the patented good produced by patent producer $j$ and $p_{S,t}^j$ is the corresponding real price.

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[10] In principle, one should also include the inequality constraint requiring the hiring rate to remain positive: $x_t \geq 0$. Since in our simulations this constraint is never violated, we abstract from it in this paper.

[11] See, e.g., Gertler et al. (2008) and Sala et al. (2012) for a similar formulation and a discussion.

As it is common in the literature, we allow for the possibility that, due to the threat of entry by imitators (see, e.g., Anzoategui et al. (2019), and Benigno and Fornaro (2018)), the desired mark-up $\mu^{I,C}$ is lower than the optimal unconstrained mark-up $\mu^{I,U} = \frac{1}{\nu}$, where $\nu < 1$ governs the elasticity of substitution between patented goods (see equation 10). In equilibrium, the optimal price is a constant markup over the price of intermediate goods, $p_{I,t}$:

$$p^j_{S,t} = \mu^{I,C} p_{I,t}$$

and profits depend on the demand for patented goods and are thus pro-cyclical:

$$\Pi^j_t = \left(\mu^{I,C} - 1\right) p_{I,t} Y^j_{S,t}$$

The value $V^j_t$ of owning exclusive rights to produce the patented good $j$ using the respective patent $j$ is given by the present value of the current and future monopoly profits:

$$V^j_t = \Pi^j_t + (1 - \delta_Z)\, \mathbb{E}_t \beta_{t,t+1} V^j_{t+1} \tag{5}$$

where $\delta_Z$ is the patent obsolescence rate.

### 2.3.3 Retail sector

There is a measure one of monopolistic retailers indexed by $i$ on the unit interval, each of them producing one differentiated product. These differentiated goods are then assembled to become the final composite good:

$$Y_t = \left[ \int_0^1 \left(Y^i_t\right)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}} \tag{6}$$

where $\epsilon$ represents the elasticity of substitution between retail goods. Therefore, the demand function for each retailer for its product is:

$$Y^i_t = \left(\frac{P^i_t}{P_t}\right)^{-\epsilon} Y_t \tag{7}$$

where $P^i_t$ is the price of the final good $i$ and the aggregate price index is $P_t = \left[\int_0^1 \left(P^i_t\right)^{1-\epsilon} di\right]^{\frac{1}{1-\epsilon}}$.

Retailers produce the final retail good using a composite of patented goods $Y^j_{S,t}$, according to the following CES production function:

$$Y^i_t = \left[ \int_0^{Z_t} \left(Y^j_{S,t}\right)^{v} dj \right]^{\frac{1}{v}} \tag{8}$$

where $Z_t$ is the number of patents in use at date $t$.

We introduce nominal rigidities for retailers assuming firms face Rotemberg-style quadratic costs of adjusting prices:

$$\Gamma_{Pt}^{i} = \frac{\phi^{p}}{2}\left(\pi_{t}^{i} - \pi_{t}^{R}\right)^{2} \tag{9}$$

where $\pi_t^i = \frac{P_t^i}{P_{t-1}^i}$ and $\pi_t^R$ is the inflation rate used as reference for the adjustment costs. If $\pi_t^R = \pi^*$ adjustment costs are 0 when inflation is equal to the inflation target $\pi^*$; for $\pi_t^R = 1$ adjustment costs are zero when there are no price changes. The case $\pi_t^R = \pi_{t-1}^{\varsigma}$ corresponds to the case of partial indexation, with $\varsigma \in (0,1)$ representing the degree of indexation. In most of the analysis we will assume that the reference inflation rate is $\pi_t^R = 1$. Therefore, through this channel increasing the inflation target introduces price distortions which tend to reduce consumption, output and welfare.[12]

Retail firms maximize expected profits

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left\{ \left[ \frac{P_t^i}{P_t} - \Gamma_{Pt}^{i} \right] Y_t^i - \int_{0}^{Z_t} p_{S,t}^{j} Y_{S,t}^{j} dj \right\}$$

subject to quadratic price adjustment costs $\Gamma_{Pt}^{i}$, to the Dixit–Stiglitz demand function faced by each retailer (7), and to the retailer production function (8).

Let us denote by

$$p_{S,t} = \left\{ \int_{0}^{Z_t} \left(p_{S,t}^{j}\right)^{\frac{v}{v-1}} dj \right\}^{\frac{v-1}{v}}$$

the aggregate real price of the composite of patented goods, $\left[\int_0^{Z_t} \left(Y_{S,t}^j\right)^v dj\right]^{\frac{1}{v}}$. The first order conditions for retail firms earn a demand function for each variety

$$Y_{S,t}^{j} = \left(\frac{p_{S,t}^{j}}{p_{S,t}}\right)^{-\frac{1}{1-v}} Y_t^i \tag{10}$$

and a Phillips curve:

$$\Gamma'_{Pt}\pi_t = \epsilon\left(p_{S,t} + \Gamma_{Pt}\right) - (\epsilon - 1) + \beta \mathbb{E}_t \left[ \left(\frac{\lambda_{t+1}}{\lambda_t}\right) \frac{Y_{t+1}}{Y_t} \Gamma'_{Pt+1}\pi_{t+1} \right]$$

where we have used the fact that, in equilibrium, all retail firms set the same price and produce the same quantities. Price inflation dynamics depend on two main factors: the cost of the aggregate composite good $p_{S,t}$, which represents the marginal cost of final good retailers, and the evolution of price adjustment costs, which mainly depend on expected inflation in period $t+1$.

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[12] In the Appendix, we provide results for the case of price and wage indexation as, for high inflation targets, economic agents could call for inflation compensation for not incurring large costs from price adjustments.

## 2.4 Innovation

Innovators develop new patents by conducting R&D. They use the final good as input and sell their innovation to patent producers. Assuming perfect competition, the price of an innovation equals its value to the patent producers, $V_t^j$ (see equation 5).

The number of new inventions evolves according to:

$$Z_{t+1} = \vartheta_t S_t^{RD} + (1 - \delta_Z) Z_t$$

where $S_t^{RD}$ is the R&D expenditure and $\vartheta_t$ represents the productivity of the R&D sector, which is taken as given by innovating firms. Following Comin and Gertler (2006), its functional form is:

$$\vartheta_t = \chi Z_t \left[ (\Psi_t)^\tau \left( S_t^{RD} \right)^{(1-\tau)} \right]^{-1}$$

where $\tau \in [0, 1]$ is the elasticity of innovations with respect to R&D and $\Psi_t$ is a scaling factor that ensures balanced growth. This specification of the product innovation efficiency combines a congestion externality effect capturing decreasing returns to R&D investment, $\partial\vartheta/\partial S^{RD} < 0$, with a knowledge spillover á la Romer (1990), where new discoveries facilitate new innovative ideas, $\partial\vartheta/\partial Z > 0$.

The payoff to innovation are the discounted future profits, i.e. $\mathbb{E}_t \beta_{t,t+1} V_{t+1}$. Thus free entry implies that the expected sales revenues equal costs:

$$\mathbb{E}_t \beta_{t,t+1} V_{t+1} \left( Z_{t+1} - (1 - \delta_Z) Z_t \right) = S_t^{RD}$$

which implies at the margin:

$$\frac{1}{\vartheta_t} = \mathbb{E}_t \beta_{t,t+1} V_{t+1} \tag{11}$$

This condition is crucial in the model, because it pins down the total amount of R&D investment and therefore the equilibrium growth rate of TFP and output in the economy.

## 2.5 Downward wage rigidity and wage determination

Search frictions in the labour market generate a surplus associated with each employment relationship generated in the intermediate good sector. This fact has two important consequences. First, it implies that, without further assumptions, the equilibrium wage is not uniquely pinned down in our model: any wage path that generates a positive surplus for both workers and firms is privately efficient and thus consistent with equilibrium (Hall, 2005). Second, it means that once workers and firms have matched, workers enjoy some monopoly power over their wage and therefore have no longer incentives to bid the wage down. As discussed by Dupraz et al. (2022), theses two properties allow for DWR in a search and matching model that is robust to Barro (1977)'s critique that wage stickiness should neither interfere with the efficient job formation nor lead to inefficient job destruction.

Following Acharya et al. (2021) and Dupraz et al. (2022), we incorporate downward nominal wage rigidity into the model by assuming the following wage rule:

$$W_t = \max(\iota W_{t-1}, W_t^*)$$

where $W_t^*$ is the desired nominal wage that would emerge in absence of the lower bound on nominal wages and $\iota \in (0,1)$ is a parameter limiting how much nominal wages can fall between dates $t-1$ and $t$. A value of $\iota = 1$ implies that nominal wages cannot fall, while $\iota \in (0,1)$ means that nominal wages can adjust downwards to some extent. The wage rule can be rewritten in terms of real wages as follows:

$$w_t = \max\left(\iota \frac{w_{t-1}}{\pi_t}, w_t^*\right)$$

which shows that, even when nominal wages are not free to adjust downward, real wages can still decrease when inflation is positive. This is the main reason why positive inflation may "grease the wheels" of the labour markets (Tobin, 1972).

We assume that the desired real wage $w_t^*$ that the parties would choose in the absence of the occasionally binding constraint is a solution of Nash bargaining:

$$\arg\max_{W_t^*}\left[(J_t)^{1-\eta}\left(V_t^E\right)^{\eta}\right]$$

where $\eta$ is the bargaining power of workers and $V_t^E$ and $J_t$ are the values of an employment relationship for the worker and the firm (equations (2) and (4)), respectively. Bargaining over the nominal wage yields the following condition for the desired real wages:

$$w_t^* = (1-\varpi_t)\left\{b_t - \mathbb{CV}_t^W\right\} + \varpi_t\left\{p_{I,t}(1-\alpha)\frac{X_t}{N_t} - c_t^W + \mathbb{CV}_t^F\right\}$$

where $\mathbb{CV}_t^F = \mathbb{E}_t\left[\beta_{t,t+1}\left\{(1-\rho+x_{t+1})J_{t+1} - \frac{\kappa_{t+1}}{\gamma}(x_{t+1})^{\gamma}\right\}\right]$ is the continuation value of the relationship for firms and $\mathbb{CV}_t^W = \mathbb{E}_t\beta_{t,t+1}(1-\rho)(1-f_{t+1})V_{t+1}^E$ the one for workers. The variable $\varpi_t$ is the "effective" bargaining power of workers:

$$\varpi_t = \frac{\eta}{\eta + (1-\eta)\left(1+\tau_{t,t+1}^W\right)} \tag{12}$$

and $\tau_{t,t+1}^W = \frac{\partial c_t^W}{\partial W_t}P_t + \mathbb{E}_t\beta_{t+1}\left((1-\rho+x_{t+1})\frac{\partial c_{t+1}^W}{\partial W_t}P_t\right)$ captures the marginal costs of wage adjustments. Equation (12) shows that in the presence of wage adjustment costs, the effective bargaining power of workers becomes state-dependent. Specifically, since $\frac{\partial c_t^W}{\partial W_t} > 0$, $\varpi_t$ increases during periods of declining wages, dampening the fluctuations of nominal wages. In this way wage adjustment costs tend to limit wage fluctuations, and reduce the probability of hitting the occasionally binding constraint on wage adjustments.

## 2.6 Monetary policy

We assume the Central Bank sets the short term nominal interest rate by reacting to the inflation and output levels in the economy:

$$R_t = (R_{t-1})^{\varphi_r} \left[ r \left( \frac{\pi_t}{\pi^*} \right)^{\varphi_\pi} \left( \frac{\hat{Y}_t}{\hat{Y}_{ss}} \right)^{\varphi_y} \right]^{1-\varphi_r} \varepsilon_t^m \tag{13}$$

where $\hat{Y}_t = Y_t/\Psi_t$ is detrended output, and $\varphi_\pi$ and $\varphi_y$ are the response coefficients to inflation and detrended output. $\varphi_r$ captures interest rate smoothing.

## 2.7 Market clearing, aggregation and TFP

Aggregate market clearing conditions are found by aggregating across all retailers $i$ and patented good producers $j$. The market clearing condition for intermediate goods $X_t$ implies

$$X_t = \int_0^{Z_t} X_t^j dj = Z_t X_t^j$$

where we have assumed symmetry across firms. Similar conditions hold for aggregate profits of patented good producers and the value of patents.

Final output, net of price and wage adjustment costs, is used for consumption, investment in physical capital, R&D investment, and hiring costs:

$$Y_t (1 - \Gamma_{Pt}) - c_t^W N_t = C_t + I_t + S_t^{RD} + \frac{\kappa_t}{\gamma} (x_t)^\gamma N_{t-1} \tag{14}$$

In our model, sustained total factor productivity (TFP) growth arises endogenously through the accumulation of new patented goods that facilitate the production of final retail goods. This is reflected in the production function, which after aggregation and using equilibrium conditions, is given by:

$$Y_t = Z_t^{\left(\frac{1}{v}-1\right)} A_t (N_t)^{1-\alpha} (z_t k_t)^\alpha \tag{15}$$

Consequently, two measures of TFP can be distinguished. Aggregate, non-adjusted, TFP is measured as:

$$TFP_t = \frac{Y_t}{N_t^{1-\alpha} k_t^\alpha} = Z_t^{\left(\frac{1}{v}-1\right)} A_t z_t^\alpha \tag{16}$$

while utilization-adjusted TFP is determined endogenously as

$$TFP_t^{util} = Z_t^{\left(\frac{1}{v}-1\right)} A_t$$

Therefore, even when corrected for the variable utilization of capital, $TFP_t^{util}$ varies not only with the exogenous technological component $A_t$, but also with the endogenous stock of intangible capital $Z_t$. In the following, we will mainly study the dynamics of aggregate TFP as described by equation (16), since our empirical measure of TFP corresponds to this non-adjusted measure.

As described by equation (15), output in the long run is growing endogenously with the stock of intangible capital. To ensure balanced growth, we assume that the scaling factor is

$$\Psi_t = Z_t^{\Upsilon}$$

where $\Upsilon = \frac{\left(\frac{1}{v}-1\right)}{(1-\alpha)}$.

# 3 Calibration and solution method

In this section, we discuss the calibration strategy, the solution method and the model fit relative to the moments of the euro area data for the variables of interest.

## 3.1 Calibration

The model is calibrated at the quarterly frequency. The values of the parameters are chosen to capture the main structural features of the euro area and are close to the standard values used in the literature. The empirical targets correspond to the euro area in the period 1999q1 to 2019q4.

**Long run inflation target and average growth**. In the baseline calibration, we assume that the central bank targets an annualized inflation of 1.8 percent, consistent with the official inflation objective of the European Central Bank at the time of "below, but close to 2 percent". The scale parameter $\chi$ is chosen to match the average annual TFP growth rate of 0.83 percent. This corresponds to an average output growth rate of 1.2 percent which is only slightly larger than the value of 1.11 percent found in the data.

**Preferences**. The discount factor $\beta$ is set to 0.997, as in Amano and Gnocchi (2022). The elasticity of substitution of retail goods is $\epsilon = 6$, corresponding to a steady state markup in the retail sector of about 20 percent.

**Wage and price adjustment costs**. We set the degree of price rigidity, $\phi^p$, to a value that corresponds to a Calvo parameter of 0.58 which represents a mean price duration of about 7 months. This value is very close to the values used in Coibion et al. (2012) and Amano and Gnocchi (2022), and only slightly below the value of 0.63 assumed by Fahr and Smets (2010). The wage adjustment cost parameter $\phi^w$ is set to match the observed relative volatility of employment. We get $\phi^w = 10.5$.[13] Regarding the level of the occasionally binding constraint on nominal wages, in the baseline calibration we set $\iota = 1$, as in Acharya et al. (2021) and Dupraz et al.

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[13] We target the relative employment volatility instead of the wage volatility because of the well known difficulties in measuring aggregate wages in the data. See, e.g., Justiniano et al. (2013).

(2022). In robustness exercises, we also consider the case of a negative effective lower bound on wage inflation.

**Labour markets**. The steady state unemployment rate is set to 9 percent and the quarterly job separation rate to $\rho = 0.06$. The implied value for the job finding rate is $f = 0.378$. These values are in line with the empirical analysis by Elsby et al. (2009) for a number of continental European countries. The quarterly job filling rate is set to $q = 0.6$. The workers' bargaining power $\eta$ and the elasticity of job matches with respect to vacancies, $\zeta$, are both set to 0.5, as it is standard in the literature, see, e.g., Blanchard and Galí (2010). As in Cacciatore and Fiori (2016) we set the real unemployment benefits, $b$, by targeting a replacement rate of $b/w = 0.62$ in steady state, close to the average replacement rate in the euro area. We assume quadratic hiring costs ($\gamma = 2$), as in Gertler and Trigari (2009). The hiring costs parameter $\kappa$ and the matching efficiency parameter $\bar{m}$ are determined through steady state relationships. The implied total hiring costs are 1.31 percent of total output, in line with Faccini and Yashiv (2020), who calibrate them on the basis of German and Swiss micro-data.

**R&D sector**. Following Guerron-Quintana and Jinnai (2019) we set the patent obsolescence rate to $\delta_Z = 0.03$. The elasticity of new technologies to R&D is calibrated to 0.85, in between the values chosen by Kung and Schmid (2015) and Guerron-Quintana and Jinnai (2019).

**Production.** We set the elasticity of intermediate production to capital, $\alpha$, to 0.3. Following Anzoategui et al. (2019), we set $v = 0.74$ to produce an elasticity of substitution of 3.85 between patented goods, while the markup on patented goods is set to $\mu^{I,C} = 1.18$, in the middle of the range of the estimates in the literature. The elasticity of capital depreciation to changes in utilization is parametrized such that the steady state value of the utilization rate $z$ equals unity. We get $\phi_k = 1.30$, a value close to the ones used, e.g., in Greenwood et al. (1988) and Neiss and Pappa (2005). The quarterly capital depreciation rate is set to $\delta = 0.02$, corresponding to an annual depreciation rate of 8 percent. The investment adjustment cost is set to $\Theta_I = 0.17$, in order to broadly match the relative standard deviation of investment to GDP. The steady state value of technology, $A$, is chosen so that output in the steady state of the detrended system is normalized to one.

**Monetary policy.** We calibrate the parameter governing the sensitivity of interest rate to inflation to $\varphi_\pi = 1.5$, the sensitivity to output to $\varphi_y = 0.1$ and the degree of interest rate smoothing to $\varphi_r = 0.85$.

**Shock processes.** In the baseline calibration, we consider three sources of variation: monetary policy shocks, exogenous TFP shocks and risk premium shocks. The persistence and volatility of the risk premium shocks are calibrated to $\rho_\varrho = 0.92$ and $\sigma_\varrho = 0.2$ percent. These values are close to the calibrated parameters used in Coibion et al. (2012), to the estimated values in Anzoategui et al. (2019) and Andrade et al. (2019) for the US and in Andrade et al. (2021) for the euro area. The persistence parameter of the exogenous technology shocks is set to $\rho_Z = 0.95$, as standard in the literature. The volatility of the exogenous technology shocks is set to $\sigma_z = 0.45$ percent in order to match the average volatility of GDP per capita. The standard deviation of monetary policy shocks is set to 0.1 percent, consistent with the estimates by Christoffel et al. (2009).

Table 1: **Calibration baseline model**

| **Parameters** | **Values** | **Source** |
|---|---|---|
| Inflation target | 1.8 | Pre-2021 ECB Strategy review |
| Steady-state growth rate | 1.2 | Average TFP growth rate = 0.83% |
| Price rigidity $\phi^p$ | 16.37 | Calvo parameter = 0.58 |
| Wage rigidity $\phi^w$ | 10.5 | Match $std(N_t/Y_t)$ |
| Discount factor $\beta$ | 0.997 | Amano and Gnocchi (2022) |
| Elast. new patents to R&D $\tau$ | 0.85 | Kung and Schmid (2015) |
| Patent obsolescense rate $\delta_Z$ | 0.03 | Guerron-Quintana and Jinnai (2019) |
| **Shocks** | | |
| Std. dev. interest rate $\sigma_m$ | 0.1% | Christoffel et al. (2009) |
| Autocorr. exog. tech. $\rho_z$ | 0.95 | Sahuc and Smets (2008) |
| Std. dev. exog. tech. $\sigma_z$ | 0.45% | Match $std(y)$ |
| Autocorr. of risk premium $\rho_\varrho$ | 0.92 | Anzoategui et al. (2019); Andrade et al. (2021) |
| Std. dev. risk premium $\sigma_\varrho$ | 0.2% | Anzoategui et al. (2019); Andrade et al. (2021) |

The table shows the calibration of selected parameters for the baseline model.

**Benchmark models.** In our analysis, we compare our baseline model to three, nested, benchmark models: a model with DWR but exogenous growth (*Exo. growth - DWR*), a model with endogenous productivity but with symmetric wage rigidity, (*Endo. growth - Sym.*), and a model where we shut down both DWR and endogenous growth (*Exo. growth - Sym.*). This allows us to study the individual contributions of DWR and endogenous growth and to which extent their interaction matters. All benchmark models include search and matching unemployment. The models without DWR are obtained by simply abstracting from the occasionally binding constraint on wage adjustment. The models with exogenous growth are a version of our model with constant R&D investment intensity. This is equivalent to specifying an exogenous trend growth component in productivity.[14] To facilitate comparison, the calibration of the benchmark models is identical to the one of the baseline model with endogenous growth and DWR.

## 3.2 Solution method and model fit

The model is solved at the second order by using the DynareOBC toolkit for solving models with occasionally binding constraints by Holden (see e.g. Holden (2016)

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[14] See Kung and Schmid (2015) for a similar strategy.

and Holden et al. (2020)).[15] The algorithm allows computing accurate solutions accounting for precautionary behavior associated with the bound. However, producing average impulse responses at this high level of accuracy is computationally difficult. Therefore, following Holden et al. (2020), for consistency we solve the model at the second order but treat the bounds in a perfect-foresight manner throughout. This choice also allows a closer comparison with previous research (e.g. Coibion et al. (2012) and Amano and Gnocchi (2022)), which adopt an identical perfect-foresight assumption but solve the model at the first order. It can be shown that the main results of the paper are not affected by this choice.

Table 2: **Long-run means**

| | UR | $\Delta y$ | $\Delta TFP$ | $\pi$ | $\pi^w$ |
|---|---|---|---|---|---|
| Steady-state | 9.00 | 1.20 | 0.84 | 1.80 | 3.00 |
| Data | 9.41 | 1.11 | 0.83 | 1.68 | 2.07 |
| DWR model - End. growth | 9.55 | 1.14 | 0.80 | 2.13 | 3.27 |

The table shows the long run mean (percent, annualized) of selected variables in the steady state of the model, in the euro area data and in the baseline model.

Tables 2 and 3 compare the first and second moments of the data with those predicted by our baseline model.[16] The moments of the model are obtained by simulating 101000 periods, discarding the first 1000 observations. Long run means of output, TFP growth and inflation are annualised and expressed in percentage terms. Second moments are obtained by filtering the actual and simulated data with the HP(1600) filter.

Overall, the model does a good job in matching most of the moments of the data. In particular, the model reproduces very closely the long-run means of unemployment, output and TFP growth, although the long run mean of price inflation and, especially, wage inflation is slightly larger than in the data (Table 2).[17] Moreover, the model replicates well absolute and relative standard deviations of the data, and the co-movements of the main variables with output (Table 3).

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[15] DynareOBC is available at https://github.com/tholden/dynareOBC.

[16] The Appendix provides long-run means and second moments also for the benchmark models.

[17] The relatively low wage inflation in the data can be explained by three factors: (1) output growth has been lower in recent years than what could be expected given average TFP growth; (2) average inflation has been lower than the inflation target of the European Central Bank and (3) there has been a general decline of the labor share which, at least partly, reflects compositional and measurement issues (see e.g. Cette et al. (2019)). Allowing for a lower steady state growth rate of nominal wages would reinforce the main results of our analysis.

Table 3: **Business cycle moments**

|  | $\sigma(x)/\sigma(y)$ |  | $\rho(x,y)$ |  |
|---|---|---|---|---|
| Variable ($X$) | Data | Model | Data | Model |
| Unemployment | 4.55 | 4.67 | -0.88 | -0.69 |
| Employment | 0.52 | 0.52 | 0.83 | 0.68 |
| Investment | 2.34 | 2.34 | 0.86 | 0.88 |
| Consumption | 0.55 | 0.47 | 0.84 | 0.90 |
| TFP | 0.79 | 0.81 | 0.97 | 0.95 |
| Nominal wages | 0.16 | 0.46 | 0.31 | 0.63 |
| Prices | 0.50 | 0.80 | 0.20 | 0.53 |
| Real wages | 0.46 | 0.73 | -0.13 | -0.08 |
| $\sigma(y)$ | 1.20 | 1.20 |  |  |

The table shows the HP(1600)-filtered second moments of selected variables in the euro area data and in the baseline model.

# 4 Endogenous growth dynamics with occasionally binding wage constraints

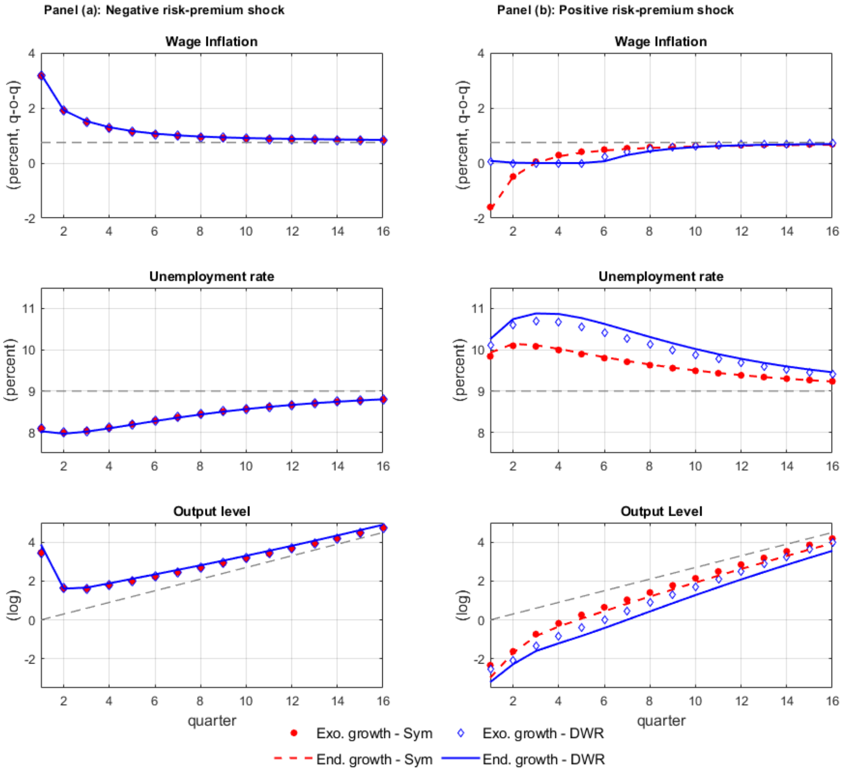
The central question we seek to address is how accounting for endogenous growth and DWR affects monetary policy making. Contrasting our baseline model with the benchmark models, we analyze first, how these features affect the impulse responses to demand shocks; second, how the dynamics translate into long-term output and unemployment performance when combined with other shocks; and third, how the long-run Phillips curve, which describes the policy trade-off faced by the monetary policy authority, is altered.

## 4.1 Permanent asymmetric response to shocks

We focus on the risk premium shock, as the relevant demand shock, which triggers a simultaneous decline in output and prices and amplifies the relevance of DWR. Using the response to demand shocks, we describe how the economy's response to temporary *symmetric* shocks can have permanent *asymmetric* effects in our model. This finding implies that medium-term dynamics are a function of the history of shocks in models accounting for endogenous growth and DWR.

Figure 2 shows the responses of wages, unemployment and the output level to large negative (left column) and positive (right column) risk premium shocks, respectively. The size of the shock corresponds to a change in the risk premium of about three percent annualized, broadly similar to episodes of significant financial distress. When starting from the steady-state growth path, a large shock is required to reach the occasionally binding constraint (OBC) for wages. This does not imply that the OBC

Figure 2: **Impulse Response to Large Negative and Positive Risk Premium Shocks**



is reached only when such large shocks occur. Conditional on the economy being already close to the OBC (e.g., following a series of smaller shocks), a relatively moderate shock would trigger similar dynamics.

A quick glance at the left column of Figure 2 reveals that the differences between the exogenous growth and endogenous growth models are rather limited, for a negative risk premium shock. The reduction of risk premiums encourages households and firms to increase consumption and investment, and leads to an increase in hiring and production. Wage inflation, however, increase relatively fast, slowing down job-creation and the ensuing unemployment reduction. Comparing the model with and without endogenous growth, one can notice that unemployment drops and output increases slightly more on impact in the endogenous growth model, reflecting the higher expected future profits, which trigger a boost to innovation in the short-term (see equation 11). The implied increase in the stock of R&D allows for a higher level of productivity, shifting the output level of the endogenous growth model up relative to its exogenous growth counter-part, but this effect is quantitatively small. DWR is irrelevant for the negative shock, making the line indistinguishable from the simple endogenous growth model.

The results are very different following a positive risk premium shock (right column of Figure 2). It is again the case that the symmetric (*without* DWR) endogenous and exogenous growth models differ only by the slight output level shift for the endogenous growth model over the medium-term. However, once DWR are considered, the unemployment response and the output contraction become more severe. This happens because inflation declines, but wage growth cannot go below zero because of the occasionally binding wage constraint. As a consequence, real wages increase during the recession, amplifying the negative impact of the shock on the labour market and the whole economy (see Erceg et al. (2000)). The associated drop in demand reduces the output level by more than in the models without DWR. However, in the model with DWR and exogenous growth, the output level converges back to trend over the medium-term, as in the models without DWR. If DWR and endogenous growth are combined this is not the case. With discounted future profits depressed by the lower demand from higher unemployment, R&D investment declines and leads to a persistent drop in intangible capital and productivity. The output level drop is stronger and more persistent, and converges to a permanently lower balanced growth path.

Comparing the impulse responses following a negative (left column of Figure 2) and positive (right column) risk premium shock one can grasp the key mechanism behind our results. Through the combinations of DWR and endogenous productivity, our model is able to (1) reproduce strong asymmetric responses of unemployment, wage inflation, and output; and (2) generate output and TFP hysteresis. Combined, these features imply that business cycle shocks can, little by little, shift down the *level* of output and TFP. Therefore, the average observed *growth* rate of the model will be lower than the one implied by the non-stochastic steady state of the model. A result only obtainable combining a strong non-linearity, as DWR, and endogenous growth.

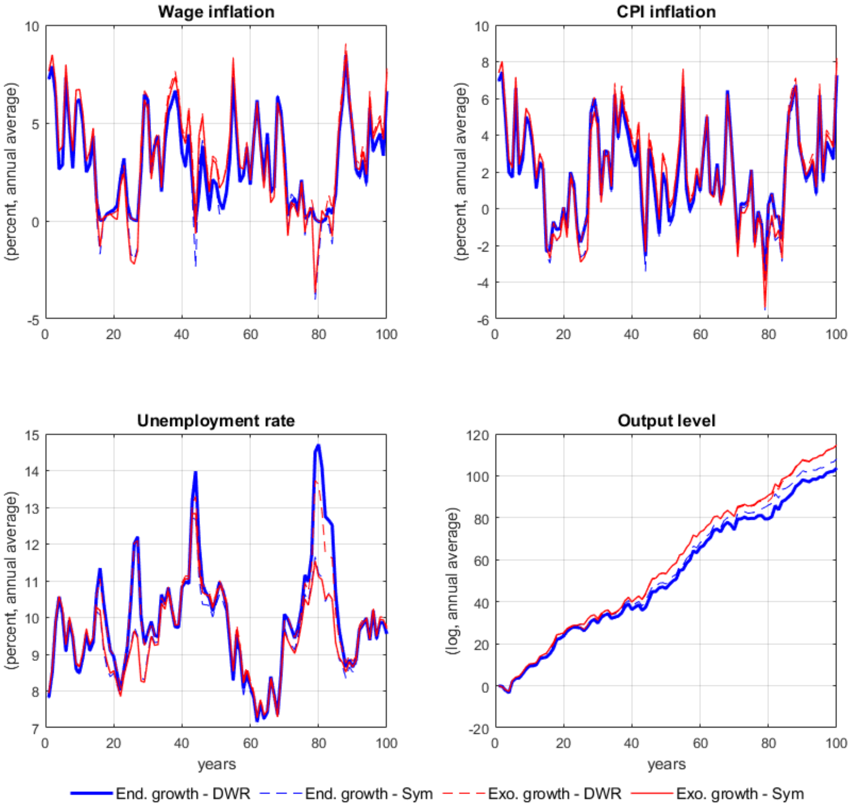
## 4.2 Long-run dynamics and output losses

In this section, we discuss the quantitative implications of DWR and R&D profitability channel for the economy's long-run dynamics. For this purpose, we simulate long samples of our quarterly models under the combination of calibrated monetary, technology and risk premium shocks described in Section 3.

As an illustrative example, Figure 3 depicts the paths for wage and price inflation, the unemployment rate and the output level obtained by extracting 100 years of simulated annual data from long simulations of the baseline model with DWR and endogenous growth and the three benchmark models. The starting conditions as well as the sequence of shocks are identical in all cases.

Three main results stand out from these simulations. First, our baseline model (with endogenous growth and DWR) is able to reproduce the plucking property of the data documented, e.g., by Dupraz et al. (2022), whereby the unemployment rate tends to increase more and faster in recessions, than it decreases during expansions. Second, departures of the trajectories of the unemployment rate across different models

Figure 3: **Wages, price, unemployment and output dynamics, 100 years**



happen exactly in the periods when the constraint on wage adjustment is binding, confirming that the presence of DWR creates the plucking property of the model irrespective of the presence of endogenous growth, although its presence amplifies unemployment responses even more. Finally, from the dynamics of the output level one can notice that the four models generate almost identical trajectories for the first thirty years of simulated data, until a series of shocks lead the economy to hit the wage constraint and drift the model economies apart. After 100 years, the output level of the baseline model is consistently and significantly below the ones of the benchmark models.

These results are confirmed when looking at the long run moments of the models. Table 4 shows the ergodic means of selected variables in our entire sample of simulated data for the four models. In the model with exogenous growth and no DWR, the model's non-linearities captured by our second order solution method slightly increase average unemployment from its steady state value of 9 to 9.19, but have no effect on the average growth rate of the economy, which remains equal to 1.20. Introducing a mechanism of endogenous growth allows business cycle shocks to affect average long run growth. This happens because, as in Barlevy (2004), in the presence of diminishing returns to R&D, business cycle shocks lead to slower growth by making R&D investment more volatile. On average, this mechanism reduces output growth by around 0.02 percentage points per year, compounding to a modest loss of around 2 percent over 100 years. On the contrary, in the model with DWR but exogenous growth, the presence of an occasionally binding constraint on wages strongly increases average unemployment, from 9.19 to 9.61, and generates a negative mean output gap of $-0.55\%$. However, this has basically no effect on the average growth rate of the economy, which remains close to 1.2. Interestingly, the presence of a negative mean output gap has a negligible effect on the long run output level, which after 100 years is almost identical to the one of the symmetric model. This happens because the long run effects of small differences in growth rates dominate over the effects of a negative mean output gap, the more so, the longer the time period considered.[18]

Table 4: **Long-run means: baseline and benchmark models**

| **Model variation** | **UR** | $Pr(w_t \leq \bar{w} \mid w_{t-1} > \bar{w})$ | $Pr(w \leq \bar{w})$ | $y^i_{t=100} - y^{Ex}_{t=100}$ | $\Delta y$ |
|---|---|---|---|---|---|
| **Benchmark** | | | | | |
| Exogenous growth | 9.19 | 0.00 | 0.00 | 0.00 | 1.20 |
| Exogenous growth & DWR | 9.61 | 0.09 | 0.20 | -0.02 | 1.20 |
| Endogenous growth | 9.15 | 0.00 | 0.00 | -2.06 | 1.18 |
| **Baseline** | | | | | |
| Endogenous growth & DWR | 9.55 | 0.11 | 0.22 | -5.78 | 1.14 |

The table shows the long-run means for baseline and benchmark models.

The presence of DWR strongly exacerbates the adverse effects of shocks under endogenous growth: not only average unemployment increases from 9.15 to 9.55, but also average growth is now reduced to 1.14. This implies an average loss in output per capita of almost 6 percentage points over 100 years. This happens despite moderate probabilities of hitting the lower wage bound. In fact, our baseline calibration implies a probability of hitting the nominal wage bound, $Pr(w_t \leq \bar{w} \mid w_{t-1} > \bar{w})$, of 11 percent. Conditional on having reached the lower bound the odds of remaining there increase, as the lack of real wage adjustments delays the recovery. This implies a frequency of quarters at the lower wage bound, $Pr(w \leq \bar{w})$, of 22 percent.[19]

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[18] To see this, let us assume that along the balanced growth path the economy grows at a constant rate $\gamma$, i.e. $\bar{Y}_t = e^{(\gamma t)} Y_0 = e^{\gamma t}$, where $Y_0$ is normalized to one. Using the identity $Y_t = \bar{Y}_t \frac{Y_t}{\bar{Y}_t}$ and denoting the output gap as $gap_t = \log\left(Y_t / \bar{Y}_t\right)$, one can decompose the output difference between model 1 and 2 after $T$ periods into:

$$\log\left(Y_{2,T}\right) - \log\left(Y_{1,T}\right) = T\left(\gamma_2 - \gamma_1\right) + \left(gap_{2,T} - gap_{1,T}\right)$$

Therefore, the longer the horizon considered $T$, the larger the relative importance of the differences in growth rates in determining the relative output levels of different economies.

[19] As shown in Section 5 and in the Appendix, our findings and conclusions are robust to lower probabilities of hitting the occasionally binding wage constraint.

## 4.3 Trade-offs for the long-run Phillips curve

Next we discuss the implications of our model for the slope of the long-run Phillips curve and as a result for the monetary policy invariance hypothesis (Blanchard, 2018; Hall and Sargent, 2018). To do so, we study how the ergodic means of output growth and the unemployment rate vary when simulating the model for values of the inflation target ranging from 0.5 to 6 percent. For each value of the inflation target, we allow the steady state of the model to adjust endogenously, thus accounting also for the long run distortions arising from price and wage rigidities. In our model, an increase of the inflation target produces two opposite effects on the economy: on the one side, it reduces the probability of hitting the occasionally binding wage constraint, thus potentially improving the long run equilibrium of the model. On the other side, a higher inflation target increases the distortions arising from quadratic price and wage adjustment costs, which in turn tend to reduce output, consumption and employment.

Figure 4 depicts the long-run Phillips curve relationship between inflation and unemployment (Panel a) and a related, but less often considered, relationship between inflation and output growth (Panel b) for the baseline and the three benchmark models. Focusing first on the traditional long-run Phillips curve (Figure 4, Panel a), we confirm the results by Benigno and Ricci (2011) and Dupraz et al. (2022) of a negative relationship between inflation and the unemployment rate. At low levels of inflation the occasionally binding constraint is hit more frequently in the two models with DWR, leading to higher unemployment which increasingly dominates the efficiency loss from price adjustment costs. This is in contrast to an almost vertical, but monotonically upward sloping Phillips curve in both benchmark models without DWR, where only price distortions matter.[20]

Our model adds a new dimension compared to Benigno and Ricci (2011) and Dupraz et al. (2022). By accounting for DWR in a model with endogenous growth, we derive a non-vertical long-run relationship between inflation and output growth (Figure 4, Panel b). Workhorse NK models imply long-run neutrality – i.e., growth is invariant to the inflation rate. This is shown by the vertical (dotted) lines in Panel b of Figure 4 for the exogenous growth models. Our model suggests a deviation from this concept even in the long run. Endogenous growth, in the absence of DWR, implies a downward sloping relationship between the inflation target and output growth: a higher inflation target increases price and wage distortions, which in turn reduce R&D investment and long-run growth (red dashed line). The combination of endogenous growth and DWR, instead, creates a new trade-off between price and wage adjustment costs and the costs related to DWR. This leads to a non-linear long-run Phillips curve (see blue line in Panel b). For low levels of the inflation target, the Phillips curve is positively sloped, but it turns downward sloping for inflation

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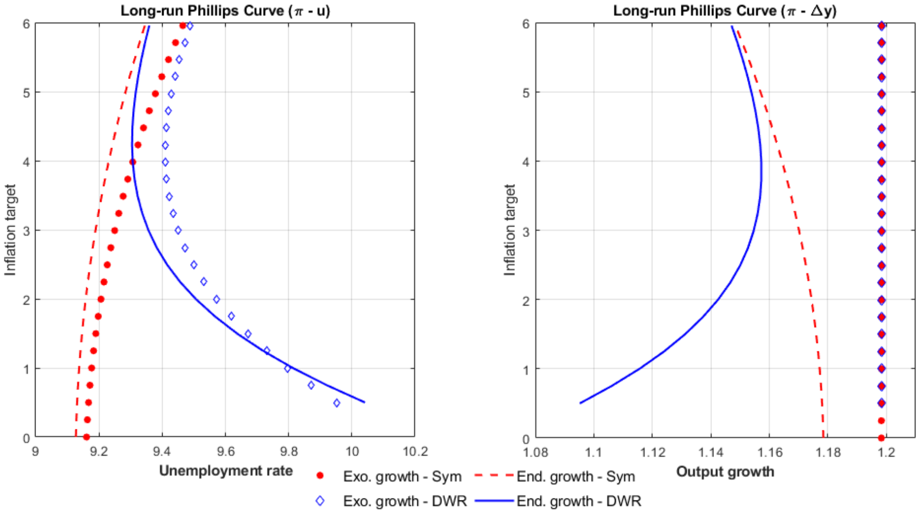
[20] In our model, the endogenous growth channel amplifies the effects of DWR compared to Benigno and Ricci (2011) and Dupraz et al. (2022). Their non-vertical long-run Phillips curve only accounts for the transitory grease-the-wheels effects from DWR.

Figure 4: **Unemployment and output growth Phillips curves**



rates above 4%. This happens because the trade-off in the traditional Phillips curve between unemployment and inflation is translated via changes in investment in R&D into corresponding changes in output growth. This effect is small on average, but becomes important if compounded for many years or in specific episodes when the wage constraint is binding. Crucially, this trade-off is not present in models which feature DWR but exogenous growth (see blue dotted line in Figure 4 Panel b, which is identical to the (red dotted) line in traditional NK models without DWR).

The extent to which the long-run inflation-output trade-off matters crucially depends on two factors: (i) the economy's long-run growth rate, and (ii) the size and persistence of demand (risk premium) shocks. The average growth rate and the inflation target are important because, together, they determine the distance of steady state wage inflation from the wage bound. The size and persistence of risk premium shocks, instead, determine the probability of having a sequence of shocks that are large enough to lead the economy to the occasionally binding wage constraint.

Figure 5 shows visually the importance of these factors for the slope and position of the long run Phillips curve.[21] A lower long-term growth rate is synonym of lower steady-state productivity growth. Since wage growth in the steady-state is proportional to labour productivity growth, the distance between the wage floor and the equilibrium wage is smaller under lower steady-state TFP growth. Consequently, for identical shock distributions, the probability of being at the wage floor is increased and DWR becomes increasingly relevant. The curve reflecting the trade-off between unemployment and inflation rotates to the right for lower levels of inflation. Through the endogenous growth channel, this translates into a movement of

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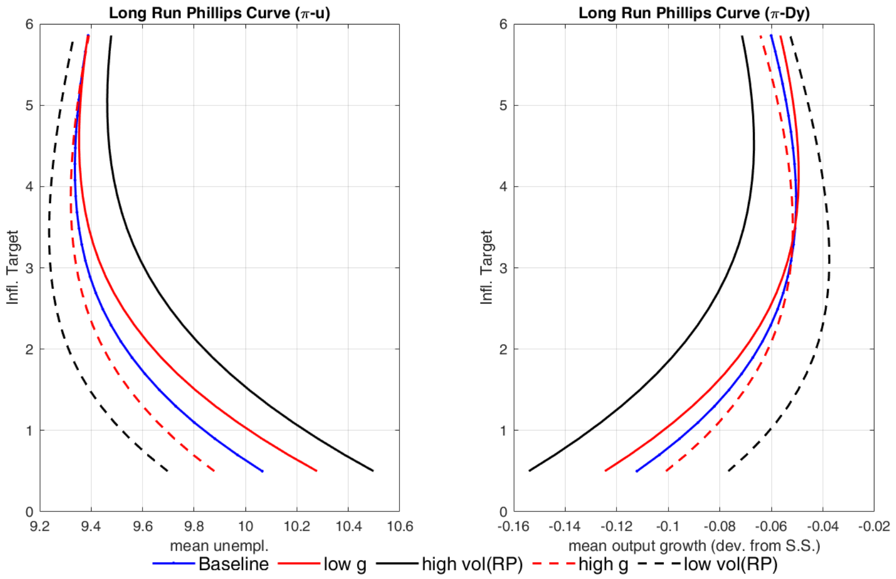
[21] The high and low growth scenarios correspond respectively to steady state growth rates of $\Delta y_{ss}^H = 1.6$ and $\Delta y_{ss}^L = 0.8$. To model the high and low risk premium volatility scenarios we change the volatility of risk premium shocks to $\sigma_\varrho^H = 0.25$ and $\sigma_\varrho^L = 0.15$ respectively.

Figure 5: **Phillips curves under different calibrations**



the curve describing the trade-off between inflation and output growth to the left, making it flatter.

Similarly, a higher volatility of risk premium shocks shifts the Phillips curve between inflation and growth to the left, implying that for a given inflation target the output loss is higher for a larger variance in risk premium shocks. The reason for the shift is that a higher volatility increases both the probability of hitting the lower wage bound, and the duration of episodes at the bound.

How large are the effects of this mechanism on the long run output level? To answer this question, Table 5 shows the average log output losses, after 100 years, of a given model with respect to the benchmark model with symmetric wages and exogenous growth. Two main results emerge. First, the combination of DWR and endogenous growth can lead to sizable long run output effects, with output losses after 100 years that range between $-11\%$ in a model with a low inflation target and high risk premium volatility, and $-3.7\%$ in a model with a high inflation target and moderate risk premium volatility. Second, in the models with DWR and exogenous growth, long run output losses are consistently below $-0.03\%$, confirming that the long run effects of the implied mean negative output gap on the long run output level are negligible.

# 5 The optimal inflation rate

Equipped with the results from the preceding section on how endogenous growth and DWR alter the trade-offs faced by monetary policy, we derive the implications for the optimal inflation target and quantify the welfare costs of deviating from

Table 5: **Long run effect on output after 100 years, $y^i_{t=100} - y^{Ex}_{t=100}$**

| | Infl.target = 1.2 | Infl.target = 1.8 | Infl.target = 3 |
|---|---|---|---|
| **DWR - Endogenous growth model** | | | |
| Baseline | -7.529 | -5.786 | -3.713 |
| Low growth ($\Delta y_{ss} = 0.8$) | -8.588 | -6.564 | -4.051 |
| High RP vol. ($\sigma_{\varrho} = 0.25$) | -11.081 | -8.896 | -5.964 |
| **DWR - Exogenous growth model** | | | |
| Baseline | -0.021 | -0.015 | -0.009 |
| Low growth ($\Delta y_{ss} = 0.8$) | -0.023 | -0.015 | -0.009 |
| High RP vol. ($\sigma_{\varrho} = 0.25$) | -0.018 | -0.015 | -0.006 |

The table shows the log percentage losses in output after 100 years relative to the model with exogenous growth and no DWR.

it. For this purpose, we first describe the welfare metric that allows us to handle the properties of our model. We then proceed with simulations to compute the welfare losses over a fine grid of inflation targets from zero to six percent to derive the optimal inflation target value and analyze how it differs as a result of DWR, endogenous growth and their combination. Finally, we show that the optimal value is robust to variations in various parameter assumptions.

## 5.1 Welfare metric

To measure welfare in a non-stationary environment, we adopt a strategy inspired by Lucas (1987) and Barlevy (2004). We define the growth rate of consumption as $g_{C,s} \equiv \frac{C_s}{C_{s-1}}$ and use $C_t = \left(\prod_{s=1}^{t} g_{C,s}\right) C_0$ to rewrite lifetime utility, $\mathcal{V}_0 = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \log(C_t)$, as

$$\mathcal{V}_0 = \frac{1}{1-\beta}\left[\log(C_0) + \mathbb{E}_0\left(\sum_{t=1}^{\infty} \beta^t \log(g_{C,t})\right)\right]$$

Therefore, unconditional welfare can be estimated as

$$\mathbb{E}\mathcal{V}_0 = \frac{1}{1-\beta}\left[\mathbb{E}\log(C_0) + \frac{\beta}{(1-\beta)}\mathbb{E}\log(g_{C,t})\right] \tag{17}$$

We can thus approximate welfare by computing the ergodic means of log consumption and log consumption growth from long simulations of the model. Notice that, since the discount factor $\beta$ is close to 1, equation (17) implies that small differences in average growth rates can have substantial welfare consequences.

In practice, we analyze welfare gains and losses of different versions of the model by computing consumption-equivalent differences from the welfare-maximizing steady state. Since changes in the inflation target affect both the non-stochastic steady state and the dynamics of the economy, we compute welfare losses in deviation from the maximum welfare level in steady state; that is the welfare of the steady state corresponding to a zero inflation. This ensures a unique reference point for welfare comparisons. Formally, the fraction of consumption that would need to be sacrificed in each period in the reference case to yield the same welfare as in the alternative case, $\gamma_{CE}$, is found as

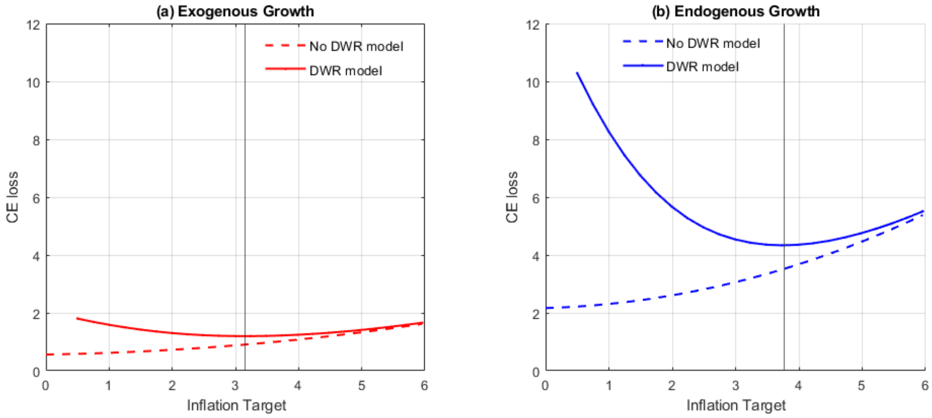
$$\gamma_{CE} = \exp((1-\beta)\,(\mathbb{E}\mathcal{V}_M - \mathbb{E}\mathcal{V}_A)) - 1$$

where $\mathbb{E}\mathcal{V}_M$ is welfare in the welfare-maximizing steady state and $\mathbb{E}\mathcal{V}_A$ denotes welfare in the alternative case under consideration.

## 5.2 The cost of deviating from optimal inflation

Figure 6 plots the consumption equivalent welfare losses of different models as a function of the annualized inflation target. The panel on the left shows the results for the exogenous growth model (with and without DWR) while the panel on the right displays analogous results for the model with endogenous productivity.

Figure 6: **Welfare losses from exogenous and endogenous growth models**



Note: *Panel (a) and Panel (b) show consumption-equivalent (CE) welfare losses for different inflation targets in models with exogenous and endogenous growth, respectively.*

Consider first the model with exogenous growth. In the absence of the occasionally binding constraint on wages, welfare costs are minimized at an inflation target of zero. This is an immediate consequence of the price and wage adjustment costs which are increasing in the level of inflation. The introduction of DWR generates a trade-off for the optimal inflation target, consistent with the trade-off shown in section 4.3 for the long-run Phillips curve. The welfare loss is U-shaped with respect to the inflation target: for low levels of the inflation target, the costs related to DWR prevail and therefore increasing the target reduces the welfare losses; for an inflation target above its optimal level the distortions related to price rigidities are larger and tend to dominate over the costs of DWR. Amidst the asymmetric nature of the occasionally binding wage constraint, the optimal inflation target is above 3 percent, well above what is implied by standard New Keynesian models.

The introduction of the R&D channel affects these results in three main ways. First, endogenous growth has a strong effect on the welfare costs. With endogenous productivity, higher price and wage distortions translate into lower average investment in R&D and TFP growth, and transform temporary shocks into more persistent deviations from the optimal allocation. Even absent DWR, endogenous growth increases welfare losses by more than 2%. In the presence of DWR, welfare costs can increase to more than 10% for inflation rates below 1 percent. Second, endogenous R&D further increases the optimal inflation target from 3.16 to 3.76 percent. This happens because with endogenous productivity, asymmetric wage adjustments give rise to permanent hysteresis effects on intangible capital, TFP and output dynamics. Third, the combination of DWR and endogenous growth generates significant welfare costs of deviating from the optimal inflation target. In models without endogenous growth, the welfare function is relatively flat and deviations from the optimal inflation target are associated with modest welfare losses: for example, increasing the inflation target from 1% to 3% decreases welfare losses by less than 0.5%. In the model with both DWR and endogenous growth, the curvature of the welfare function increases and the welfare costs of a low inflation target become substantial: the loss difference between a 1% and a 3% inflation target is around 4 percentage points.

## 5.3 Sensitivity analysis

To check robustness of the results, we analyse the sensitivity of welfare losses and the optimal inflation target to variations of the most relevant parameters of the model affecting (i) the long-term growth and R&D processes, (ii) the price and wage setting and (iii) the volatility of macro shocks. The sensitivity analysis is designed to change the key parameters in a way to reduce the importance of the endogenous growth and DWR mechanisms - thus tilting our hysteresis-price distortions trade-off and going against our main results on the value of the optimal inflation target (see the Appendix for additional sensitivity analyses).

A higher long-term growth rate of the economy (from 1.2% to 1.6%) delivers a higher steady-state nominal wage growth, hence increasing the wage buffer and making DWR less binding. This reduces the negative asymmetric effects from DWR and lowers both the welfare losses and the optimal inflation target (see Table 6, row b).

Higher wage rigidity (Table 6, row c) increases welfare losses, because it increases wage distortions, and amplifies inefficient unemployment fluctuations. However, it also lowers the optimal inflation target because it helps avoiding the occasionally binding wage constraint. Similarly, higher price rigidity (row d) makes the welfare costs from price distortions larger and call for a lower inflation target.

Our baseline model features a price setting mechanism à la Rotemberg in which all firms face convex costs of price adjustment with no staggering or price dispersion.

To a first order approximation with zero inflation, this is equivalent to the Calvo price setting in which only a share of firms at each point in time can adjust prices. However, at the second order or with trend inflation, the two models differ mainly because there is no price dispersion in the Rotemberg model (see e.g. Ascari and Sbordone (2014)). In particular, the welfare distortions introduced by a higher inflation target increase faster in the Calvo than in the Rotemberg setting. As a consequence, our baseline model with Calvo pricing (with a steady state calibrated to be equivalent to the one with Rotemberg pricing) implies higher welfare losses and call for a slightly lower inflation target (See Table 6, row e).

In a further robustness we relax the degree of DWR, by allowing a certain degree of negative wage inflation (See Table 6, row f). This allows us to check the robustness of our results to the tightness of the wage constraint and to account for composition effects and variable wage components. As expected, a lower degree of DWR reduces welfare costs of business cycle fluctuations and the optimal inflation rate. However, the optimal inflation target is still around 3% and welfare losses are close to 4%.

Another key aspect pertains to the R&D process which maps temporary shocks into long-term effects. A reduction in the elasticity of how R&D affects growth weakens the endogenous growth channel and reduces the hysteresis-distortion trade-off, implying lower welfare losses and a lower optimal inflation target (see Table 6 - row g).

Macroeconomic volatility is another important element as it increases the probability of hitting the occasionally binding constraint on nominal wages. It is mostly related to the risk premium shock (see Table 6 row h), because demand shocks tend to lower both prices and employment, thus increasing the probability that nominal wages hit the wage bound. The volatility of technology shocks has a lower effect on the optimal inflation rate (row i), because it is much less likely that such shocks lead to the occasionally binding constraint: following a negative technology shock, in fact, marginal costs and price inflation tend to increase, thus facilitating the required downward real wage adjustment.

# 6 Extensions

In this section, we consider two extensions to the model relevant for monetary policy. First, we study whether the introduction of the zero lower bound on the interest rate has a material effect on our main findings. Then we discuss alternative monetary policy rules outside the traditional Taylor-rule inflation targeting framework.

Table 6: **Sensitivity analysis**

| **Model variation** | **Optimal**<br>$\pi^*$ | **Welfare Loss**<br>$\pi = \pi^*$ |
|---|---|---|
| **a. Baseline calibration** | 3.76 | 4.34 |
| **Parameter assumptions** | | |
| b. Higher growth ($\Delta y_{ss} = 1.6$) | 3.44 | 4.31 |
| c. Higher wage rigidity ($\phi^w = 15$) | 3.52 | 4.41 |
| d. Higher price rigidity ($\phi^p = 30$) | 3.16 | 5.67 |
| e. Calvo pricing ($\theta^p = 0.58$) | 3.30 | 4.75 |
| f. Lower OBC on DWR ($-1.0\%$) | 3.00 | 3.72 |
| g. Lower R&D diffusion ($\tau = 0.60$) | 3.50 | 3.40 |
| **Shock assumptions** | | |
| h. Lower risk premium volatility ($\sigma_\varrho = 0.15$) | 3.06 | 3.05 |
| i. Smaller technology shocks ($\sigma_A = 0.4$) | 3.68 | 4.12 |

## 6.1 Zero Lower Bound

A common motivation for a higher inflation target, aside from the "greasing the wheels" effect of DWR, is the presence of a ZLB on interest rates.[22] A large body of recent research has analysed the implications of introducing the ZLB into the standard New Keynesian model for optimal monetary policy and the optimal inflation rate (see, e.g., Coibion et al. (2012), Ascari and Sbordone (2014), Amano and Gnocchi (2022), Andrade et al. (2019)). Most of these papers show that even in the presence of the ZLB, the optimal inflation target is typically below 2%. Even though episodes of ZLB can be very costly, they are infrequent. Price and wage distortions created by higher inflation targets, instead, are small but paid each period.

To analyse how adding the ZLB on interest rates affects the main results of our analysis, we assume that in normal times monetary policy is given by the same inertial Taylor rule described in equation (13):

$$R_t^* = \left(R_{t-1}^*\right)^{\varphi_r} \left[ r \left(\frac{\pi_t}{\pi^*}\right)^{\varphi_\pi} \left(\frac{\hat{Y}_t}{\hat{Y}_{ss}}\right)^{\varphi_y} \right]^{1-\varphi_r} \varepsilon_t^m \tag{18}$$

where $R_t^*$ denotes the "shadow" interest rate. Since we allow for a ZLB constraint on the nominal interest rate, the dynamics of the actual interest rate are found as:

$$R_t = \max\left\{R_t^*, 1\right\}$$

Following Coibion et al. (2012), Andrade et al. (2019) and a large body of recent literature, in this monetary policy rule, today's shadow rate $R_t^*$ depends on the lagged *shadow* policy rate, $R_{t-1}^*$, rather than the lagged *actual* rate $R_{t-1}$. This dependence

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[22] We use the term effective lower bound and zero lower bound interchangeably, but model it as ZLB. Relaxing the lower bound somewhat into negative territory has no effect on our findings.

on the lagged notional rate implies that the nominal interest rate remains lower for longer in the aftermath of ZLB episodes.[23]

Table 7: **Optimal $\pi$ target and welfare: zero lower bound**

| **Model variation** | **Optimal** | **Welfare Loss at** | | **$\Delta$ Loss** | **Frequency at** | |
|---|---|---|---|---|---|---|
| | $\pi^*$ | $\pi = \pi^*$ | $\pi = 1.8$ | ($\pi^*$ - 1.8) | DWR | ZLB |
| **Exogenous growth model** | 0.00 | 0.56 | 0.70 | -0.14 | 0.00 | 0.00 |
| with ZLB | 1.72 | 0.84 | 0.84 | -0.00 | 0.00 | 0.08 |
| with ZLB & DWR | 3.24 | 1.22 | 1.39 | -0.17 | 0.20 | 0.04 |
| with DWR | 3.16 | 1.20 | 1.35 | -0.15 | 0.20 | 0.00 |
| **Endogenous growth model** | 0.00 | 2.16 | 2.53 | -0.37 | 0.00 | 0.00 |
| with ZLB | 2.30 | 3.20 | 3.27 | -0.07 | 0.00 | 0.08 |
| with ZLB & DWR | 3.86 | 4.42 | 6.40 | -1.98 | 0.22 | 0.05 |
| **Baseline** | 3.76 | 4.34 | 6.05 | -1.72 | 0.22 | 0.00 |

The table shows the optimal inflation target implied by accounting for the zero lower bound in benchmark and baseline models.

Table 7 provides an overview of how the introduction of the ZLB changes the optimal inflation target and the welfare gains from moving to this target in the exogenous and endogenous growth models, respectively. Consistently with the literature, we find that in our benchmark NK model with exogenous growth, the ZLB causes the optimal inflation target to shift up to 1.7 percent, very close to the widely used target in advanced economies.[24] The consumption-equivalent welfare loss at this target is less than 1 percent and the ZLB is binding about 8 percent of the time. Augmenting this model with DWR, shifts the optimal inflation target slightly above 3 percent. While the frequency of hitting the ZLB declines due to DWR, it remains beneficial to aim for higher inflation to avoid higher unemployment and lower demand when the wage floor binds. However, welfare gains of moving to the higher inflation target remain limited under exogenous growth as effects are transitory.[25]

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[23] See also Consolo and Favero (2009); Hills and Nakata (2018) for a discussion of policy inertia.

[24] Our benchmark NK model with exogenous growth differs from the literature mentioned above to the extent it features search and matching frictions. As in Carlsson and Westermark (2016), in our model monetary policy has an effect on the hiring process and unemployment duration. By limiting the degree of monetary policy accommodation, the ZLB increases unemployment hysteresis with persistent effects in the economy.

[25] Our results on the optimal inflation target in the presence of DWR are consistent with Dupraz et al. (2022) but contrast somehow with Coibion et al. (2012) and Amano and Gnocchi (2022). Coibion et al. (2012) and Amano and Gnocchi (2022) show that the optimal inflation target is lower in the presence of both DWR and the ZLB compared to a model that only accounts for the ZLB. The reason for this discrepancy has to do with the larger costs of DWR in our model: we also find that DWR reduce the frequency and severity of ZLB episodes, but the presence of the ZLB does not have a comparable positive effect on the frequency and severity of episodes where DWR are binding. In turn, DWR are much more costly in our model because we compute welfare in a setup with a distorted steady state, where the benefits of extra output are relatively large.

Accounting for endogenous growth shifts the optimal inflation target proportionally up compared to their exogenous growth counterpart. This reflects the amplification effect of endogenous growth, which under strong non-linearities (either due to ZLB, DWR or a combination), translates into lower average growth. While the presence of DWR reduces the frequency of hitting the ZLB, the frequency of being constrained by the wage bound remains unchanged and the average unemployment rate is higher than in the case without DWR. Hence, the optimal inflation target and the welfare gains are even higher than in our baseline model which does not account for the ZLB.

At the ZLB, our baseline model with endogenous growth and search and matching frictions provides a new perspective on how symmetric wage rigidity and (asymmetric) DWR interact. In models featuring exogenous growth and no search and matching unemployment (Coibion et al., 2012; Gali, 2013; Amano and Gnocchi, 2022; Billi and Galí, 2020), the limited adjustment in wages (either because of symmetric wage rigidity or DWR) helps reducing downward pressures on marginal labour costs and on price inflation. This reduces the likelihood of hitting the ZLB and helps monetary policy fine tuning the business cycle in the presence of adverse demand shocks.

In our model with asymmetric hysteresis, higher real wages dampen job creation by negatively affecting the hiring rate. This leads to larger and more persistent effects on unemployment. Also, limited wage adjustments in the presence of adverse shocks affect the firms' profitability channel[26] and the value of R&D and future productivity growth. As such, overall wage rigidity and DWR lead to larger and more persistent effects on unemployment and output growth.

## 6.2 Alternative Monetary Policy Rules

Our analysis so far has been conditional on a particular monetary policy rule adopted by the central bank, as captured by the traditional Taylor rule (equation 13). How would different monetary policy strategies affect the relationship between inflation, unemployment and output, and what are the corresponding welfare implications? Alternative monetary policy strategies exist with varying requirements on central bank credibility and commitment to future action. We consider three of them, ordered by their implied extent of change to the current system:

First, we analyse an **average inflation targeting** strategy which accounts for some undershooting in the past when setting the current interest rate, while leaving the

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Coibion et al. (2012) and Amano and Gnocchi (2022), instead, adopt a linear-quadratic approach in models where the difference between the marginal value of output and the marginal disutility of labor is small, implying that the benefits of extra output are small. See also Dupraz et al. (2022) for a related discussion.

[26] We thank Frank Smets for valuable discussions on this mechanism.

arguments (i.e., output and inflation) in the reaction function unchanged;

$$R_t = (R_{t-1})^{\varphi_r} \left[ r \left( \frac{\pi_t^A}{\pi^*} \right)^{\varphi_\pi} \left( \frac{\hat{Y}_t}{\hat{Y}_{ss}} \right)^{\varphi_y} \right]^{1-\varphi_r} \varepsilon_t^m$$

where $\ln \pi_t^A = \frac{1}{16} \left( \sum_{i=1}^{16} \ln \pi_{t-i} \right)$.

Second, we consider a **Taylor-rule with the unemployment rate** replacing the output term, which we write for convenience in log-form

$$\log R_t = \varphi_r \log R_{t-1} + (1-\varphi_r) \left[ \log r + \varphi_\pi \log \left( \frac{\pi_t}{\pi^*} \right) - \varphi_u \left( ur_t - ur_{ss} \right) \right] + \log \varepsilon_t^m$$

where $\varphi_u = 1/4$.[27]

Finally, we inspect a **price level targeting** regime replacing the inflation rate with the price level to fully offset any undershooting of inflation in the past:

$$R_t = (R_{t-1})^{\varphi_r} \left[ r \left( \frac{P_t}{\tilde{P}_t} \right)^{\varphi_\pi^{PLT}} \left( \frac{\hat{Y}_t}{\hat{Y}_{ss}} \right)^{\varphi_y} \right]^{1-\varphi_r} \varepsilon_t^m$$

where $\tilde{P}_t$ is the price level target and $\varphi_\pi^{PLT} = 1$ as in one of the exercises of Andrade et al. (2021).

An assessment of the relative costs associated with transitioning from the current to any future policy regime and the likely success of doing so is beyond the scope of this paper. Nevertheless, it is probably safe to assume that moving to a price level targeting regime, which relies heavily on credibility about future actions, is more challenging to communicate and implement than changing parameters in the existing policy reaction function. In what follows, we focus entirely on the optimal inflation target and the welfare implications under the three policy options, ignoring issues like inflation expectations' de-anchoring, parameter uncertainty, transition dynamics which can be important in practice.

Table 8 reports the optimal inflation target, welfare implications and some descriptive statistics for the different monetary policy options. Average inflation targeting allows for a somewhat lower inflation target compared to the baseline Taylor rule. However, under the optimal inflation target, still close to 3 percent, welfare losses are *higher* than in the baseline model (4.6 versus 4.3), because incomplete interest rate adjustment to prevailing economic conditions not only delays the lift off when exiting recessions, but also limits interest rate cuts when entering them. With a similar delayed policy adjustment during boom phases, this amplifies the business cycle with higher welfare costs. Hence, in our model the gains from moving to an average inflation targeting regime are not evident.

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[27] The weight on unemployment in the Taylor rule is chosen using a mapping between the baseline Taylor rule with output and the one with unemployment. In particular, $\varphi_u = 1/4$ corresponds to the implied value of the Okun's law elasticity between unemployment and output of 0.4. This is broadly the mid-point of estimates for euro area countries, which ranges between 0.3 and 0.5 (See Ball et al. (2017)). Results are robust to mild variations of this parameter.

Table 8: **Optimal $\pi$ target and welfare: monetary policy rules**

| **Model variation** | **Optimal** | **Welfare Loss at** | | **Δ Loss** | **Statistics at $\pi = 1.8$** | | |
|---|---|---|---|---|---|---|---|
| | $\pi^*$ | $\pi = \pi^*$ | $\pi = 1.8$ | ($\pi^*$ - 1.8) | $P(\Delta w = 0)$ | $\mu(UR)$ | $\mu(\Delta y)$ |
| **Alternative policy** | | | | | | | |
| Average inflation targeting | 3.09 | 4.61 | 5.25 | -0.64 | 0.21 | 9.42 | 1.15 |
| Response to UR | 2.49 | 3.23 | 3.09 | -0.14 | 0.15 | 9.26 | 1.17 |
| Price level targeting | 0.95 | 1.03 | 1.16 | -0.14 | 0.01 | 9.06 | 1.19 |
| **Baseline** | 3.76 | 4.34 | 6.05 | -1.72 | 0.22 | 9.55 | 1.14 |

The table shows the optimal inflation target implied by variations to the baseline monetary policy rule specification.

# 7 Conclusion

Central banks in advanced economies pursue a monetary policy framework aimed at achieving an inflation target of about two percent. From a theoretical perspective, the optimal inflation rate in standard New Keynesian models is lower than 2 percent, even accounting for the zero lower bound. These models abstract from an important observation: following severe crises, the level of output can shift permanently below its pre-crisis trend. As a corollary, traditional models imply limited welfare costs of deviating from the optimal inflation target, because policy mistakes can only have transitory, but no permanent effects on output.

We propose an endogenous growth model with downward wage rigidity (DWR) to allow for such dynamics. The inclusion of DWR in a frictional labour market with search and matching unemployment introduces an important non-linearity into the model. This results in asymmetric business cycle fluctuations that resemble those of the plucking theory in which the unemployment rate is characterised by sudden jumps at the start of a recession and slower declines during a recovery. The introduction of endogenous growth allows for the possibility that aggregate demand shocks have sizeable permanent output effects in the economy. Such effects become even larger if the prevailing economic environment features low inflation and low growth.

The model gives rise to three novel results. *First*, endogenous growth and DWR combined generate a long-run trade-off between output growth and inflation by transforming temporary symmetric shocks into permanent asymmetric effects on output. *Second*, this deviation from the monetary policy invariance hypothesis implies significant welfare gains of adopting the optimal inflation target, well in excess of what is implied by standard New Keynesian models. And *third*, the welfare-maximizing optimal inflation target is more than two percent, for a set of parameter values calibrated to match the euro area economy. We find these results robust to plausible variations in parameter values and assumptions of the model.

Our work provides a rationale for revisiting the monetary policy framework in view of the secular trend decline in productivity growth, which has become more entrenched following the Global Financial Crisis. Increasing the inflation target is one avenue to limit welfare losses in such a context. As shown in an extension, price level targeting could also reduce welfare costs significantly, but would require a shift in the monetary policy framework with new and different challenges. An alternative, possibly simpler policy option, within the inflation targeting framework exists: a shift toward increasing the weight of the unemployment rate in the monetary policy reaction function. This would allow the inflation target to be maintained close to the current 2 percent level while reducing welfare costs substantially. Our model suggests that the unemployment rate can capture better than output the asymmetry arising from downward wage rigidity. Monetary policy can, by acting directly on the key mechanism leading to hysteresis, lead to non-trivial welfare improvements.

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