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THE MACROECONOMIC EFFECTS OF REDUCING A CENTRAL BANK MONETARY POLICY PORTFOLIO: A MODEL-BASED EVALUATION

by Anna Bartocci*, Alessandro Notarpietro* and Massimiliano Pisani*

Abstract

We use a New Keynesian model with financial market segmentation, calibrated to the euro area, to analyze the macroeconomic effects of a reduction in the stock of long-term sovereign bonds held by a central bank, as the latter does not reinvest the principal payments from maturing bonds. In the model, this reduction affects real and financial variables because a preferred habitat assumption holds for some investors. According to our results, the reduction, by inducing a rise in long-term interest rates, has recessionary and disinflationary effects. These effects are amplified if the central bank does not adequately reduce the policy rate, or if financial markets overreact in the short run to the announcement of the monetary policy portfolio reduction.

JEL Classification: E31, E32, E58.

Keywords: dynamic general equilibrium model, monetary policy, euro area, central bank balance sheet, non-standard monetary policy measures.

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1 Introduction[1]

Since the onset of the global financial crisis, central bank asset purchases – also broadly defined as quantitative easing (QE) – have been an important monetary policy tool for central banks. After monetary policy rates had been cut to their effective lower bound (ELB), the aim of QE was to reduce long-term interest rates in order to stimulate economic activity and achieve the inflation target in the medium term. In particular, the European Central Bank (ECB) launched the Asset Purchase Programme (APP) in 2015 to help secure price stability when the scope for further policy rate cuts was becoming constrained by the ELB.[2]

In December 2021 the ECB started a normalization of monetary policy by announcing the end of the net asset purchases under the PEPP (starting from March 2022) and the gradual reduction of those under the APP from the second quarter of 2023. Such portfolio normalization process continued during an extraordinary sequence of interest rate hikes – started in July 2022 and concluded in September 2023, in response to a large increase in EA inflation – and during the subsequent easing phase, which began in June 2024 once inflation started to return to target.

In this paper we evaluate the macroeconomic effects of reducing the central-bank monetary-policy portfolio by simulating a dynamic general equilibrium model with household heterogeneity and financial market segmentation. Our aim is to characterize the macroeconomic effects of the portfolio reduction (PR) as such, possibly under different assumptions on the monetary policy rate response. Thus, we do not intend to analyze PR as a major instrument during a monetary policy tightening. PR is caused by the central bank not reinvesting the principal payments from maturing long-term sovereign bonds. It has real effects because a preferred habitat assumption holds for some investors, as in Chen et al. (2012). The model is calibrated to the EA, following Bartocci et al. (2023). We simulate several scenarios in which the central bank announces in a credible way its monetary-policy-portfolio reduction (PR henceforth), which is therefore fully anticipated by households and firms. In all scenarios it is assumed that the supply of long-term bonds issued by the government is constant. Importantly, our analysis focuses on the

[1]The views expressed in this paper are those of the authors alone and should not be attributed to the Bank of Italy or the Eurosystem. We thank Michele Caivano, Stefano Neri, and Fabrizio Venditti for useful comments. All errors are of the authors.

[2]There is large evidence suggesting that the APP was successful in lowering long-term interest rates, stimulating economic activity and raising inflation at times when price pressures were weak. See Neri and Siviero (2019).

transmission of the PR via long-term interest rates and their term premium component, while it abstracts from other transmission channels such as, for instance, the banking sector (we leave this issue for future research).

According to our results, PR, by inducing a rise in long-term interest rates, has recessionary and disinflationary effects. The central bank can limit the recessionary and disinflationary effects of the PR and, thus, stabilize macroeconomic conditions, via a prompt reduction in the policy rate. We consider two alternative cases: either the central bank adjusts the policy rate according to a Taylor-type rule, or it keeps it unchanged in the initial quarters. PR's design and financial markets' reaction are relevant as well for the macroeconomic effects. The size of the recessionary impact is larger in the case of financial market overreaction to the announcement and higher persistence of the PR.

Our paper contributes to the literature on the macroeconomic effects of PR programs. Du et al. (2024), using an event-study approach, document that PR programs have been successful so far in seven advanced economies including the EA, in allowing central banks to unwind their securities holding with a very modest tightening in financial conditions and no meaningful disruption to market functioning. They show that in the EA, the cumulative effect of all PR announcements in 2021-2023 is an increase in 15-20bp in the yield of 10-year maturity government bonds. Moreover, Du et al. (2024) stress that the effects of PR so far are much smaller than simply the reverse of the effects of QE programs, arguably reflecting the fact that the latter were launched in periods of market stress. Unlike Du et al. (2024), we provide a structural model-based analysis.

Some empirical contributions focus on the US pre-pandemic experience with quantitative tightening (QT) in 2017-2019. Smith and Valcarcel (2023) find no significant effect of US QT announcements and show that that balance sheet normalization generally lacked the large announcement effects that characterized QE. Ludvigson (2022) finds large stock market reactions of QT, but little evidence that high-frequency measures of forecasts of inflation or real GDP growth respond to QT news events.

On a more theoretical ground, Cantore and Meichtry (2023) simulate a New Keynesian model with savers and borrowers and find that, when close to the ELB, raising the nominal interest rate prior to unwinding quantitative easing minimizes the economic costs of monetary policy normalization. Kumhof and Salgado-Moreno (2024) develop a DSGE model and find that permanent QT has significant negative effects on financial and real variables.

More generally, we contribute to the literature on non-standard monetary policy measures, that till now has mainly focused on QE, while our focus is on PR.[3] On the theoretical side, Gertler and Karadi (2011) develop a model with financial intermediaries. They find that during a crisis the balance sheet constraints on private intermediaries tighten, raising the net benefits from central bank intermediation. Krishnamurthy and Vissing-Jorgensen (2011) find that QE works through several channels that affect particular assets differently. Specifically, they find evidence for a signaling channel, a unique demand for long-term safe assets, and an inflation channel. Karadi and Nakov (2021) analyze optimal asset-purchase policies in a macroeconomic model with banks, which face occasionally-binding balance-sheet constraints. They find that the optimal exit from large central bank balance sheets is gradual. Coenen et al. (2023) simulate the ECB's New AreaWide Model of the EA and show that a combination of imperfectly credible forward guidance, asset purchases, and fiscal stimulus is almost equally effective as fully credible forward guidance, especially when asset purchases enhance the credibility of the forward-guidance policy via a signaling effect. Sims et al. (2023) develop a New Keynesian model to assess the impact of QE. According to their results, the use of QE significantly mitigates the costs of a binding zero lower bound. Sims and Wu (2021) build a quantitative DSGE model that includes QE, forward guidance, and negative interest rates. They show that endogenous QE via a feedback rule can largely mitigate the costs of a binding zero lower bound. Cui and Sterk (2021) develop an heterogeneous-agent model and find that QE interventions greatly dampened the U.S. Great Recession, by expanding household liquidity.

On the empirical front, a large number of contributions document the effects of QE.[4] In the case of the US, Swanson (2021) finds that forward guidance and large-scale asset purchases had substantial and highly statistically significant effects on bond yields, stock prices, and exchange rates, comparable in magnitude to the effects of the federal funds rate in normal times. Sims

[3]For a survey, see Benigno et al. (2023).

[4]Bhattarai and Neely (2022) provide a survey of the theoretical and empirical contributions on QE. Calibrated modeling and vector autoregressive (VAR) exercises imply that these policies also improved macroeconomic outcomes.

and Wu (2020) find that the observed expansion of the Federal Reserve's balance sheet over the zero lower bound period provides stimulus equivalent to cutting the policy rate to 2 percentage points below zero.

In the case of the the ECB pandemic asset purchases, Bernardini and Conti (2023) estimate a vector autoregressive (VAR) model using EA data and find that both purchase announcements and actual purchases are relevant in influencing bond yields and stock prices. Bernardini and De Nicola (2020) find that the actual purchases affect market prices over and above purchase announcements, and that adjusting their pace and composition according to market conditions can boost the overall effectiveness of a programme. Lhuissier and Nguyen (2021) look at asset purchases conducted within the period 2015-19 and estimate a proxy structural VAR model. They nd that an immediate increase in asset purchases of one percent of GDP leads to a maximum impact in industrial production and consumer prices by 0.15 percent and 0.06 percent, respectively. Eser et al. (2023) estimate that the stock of current and expected future ECB (APP) holdings has reduced the 10-year yield by almost 1 percentage point. This reduction was persistent, with a half-life of five years.

As stated above, while our framework borrows from, and speaks to the theoretical and empirical literature on QE, this paper focuses on the macroeconomic effects of a PR announcement.

The paper is organized as follows. The next section briefly describes the simulated model. Section 3 illustrates the simulated scenarios. Section 4 presents and discusses the results. Section 5 concludes.

2 Main model features

We initially provide a short description of the main mechanisms underlying the transmission of PR in our model (Section 2.1). We then provide more details in an overview of the model (Section 2.2). We then describe the main elements of financial market segmentation, related to the households' problems (Section 2.3 and Section 2.4) and the capital producers' problem (Section 2.5), the central bank reaction function (Section 2.6), the fiscal authority budget constraint and the fiscal rule (Section 2.7), the equilibrium (Section 2.8), and, finally, the calibration of the model (Section 2.9).

2.1 The transmission of PR: a bird's eye view

We provide a sketch of the model, focusing on the elements that characterize the transmission of PR. The model features financial market segmentation along the lines of Chen et al. (2012), so that PR has real effects. In each EA region, there are two types of households: restricted and unrestricted (in the RW there is a standard representative household). Restricted households have access only to the domestic long-term sovereign bond market and, jointly with unrestricted households, own shares of domestic capital producers. Restricted households are crucial for central bank interventions in the secondary market for long-term sovereign bonds to have real effects in our model. Since these households cannot arbitrage between short-term and long-term bonds, their consumption decisions directly depend only upon the long-term interest rate, rather than the short-term rate. Therefore, the monetary policy authority can affect their consumption decisions by intervening in the secondary market for long-term sovereign bonds.

Unrestricted households have multiple investment opportunities, which include domestic short- and long-term sovereign bonds, and riskless international short-term bonds traded with savers of other countries. They hold domestic firms operating in the final and intermediate sectors other than capital producers.

The central bank sets the nominal interest rate to stabilize inflation and output according to a Taylor rule. Moreover, it can intervene in the (secondary) market for long-term sovereign bonds. In our simplified framework, there is only one type of long-term bonds (see Section 2.9 for details on the calibration of its maturity). Formally, denoting $B^L_{CB,t}$ the quantity of long-term sovereign bonds held by the central bank at time t and P^L_t their price (which is inversely related to the interest rate they pay, denoted R^L_t), the following condition holds:

$$P^L_t B^L_{CB,t} = \bar{P}^L \bar{B}^L_{CB} + \varepsilon^{CB}_t, \tag{1}$$

where $\bar{P}^L, \bar{B}^L_{CB}$ are the steady-state values of the bond's price and bond position, respectively, and ε^{CB}_t is an exogenous shock to the central bank balance sheet. Dividing both sides by the price P_t^L, it is possible to express the quantity of long-term bonds held in the central bank's monetary policy portfolio as follows:

$$B_{CB,t}^L = \frac{\bar{P}^L \bar{B}_{CB}^L}{P_t^L} + \frac{\varepsilon_t^{CB}}{P_t^L}. \tag{2}$$

The calibration of the central bank balance sheet shock ε_t^{CB} disciplines the evolution of the balance sheet. The setup originally developed by Chen et al. (2012) aimed at capturing the effects of net asset purchases of long-term bonds by the central bank. In such case, a "QE shock" corresponds to a positive value for ε_t^{CB}. We adopt the same framework to study the case of PR. If the central bank does not reinvest the principal payments from maturing securities at all, then $\varepsilon_t^{CB} = -\bar{P}^L \bar{B}_{CB}^L$ and the central bank balance sheet eventually shrinks to zero. If instead the central bank aims at shrinking the size of its balance sheet from its initial value $\bar{B}_{CB}^L$ to a smaller value, then it will calibrate the shock ε_t^{CB} to a value $-\alpha \bar{P}^L \bar{B}_{CB}^L$, with $0 < \alpha < 1$. Importantly, the simplified structure of the model, which includes only one representative long-term sovereign bonds, does not permit to distinguish between a no-reinvestment policy and net asset sales. In our simulations, we discipline the calibration of the shock ε_t^{CB} by resorting to the recent experience of the ECB, which announced a gradual end of reinvestment, but no net asset sales.

The transmission of a central bank balance sheet shock works via the financial market segmentation assumption. In the case of QE, the exogenous expansion in the central bank demand for long-term bonds increases their price and reduces the corresponding yield, inducing restricted households to sell the bonds and invest more in physical capital, and using part of the savings to finance consumption plans. The same holds true, to a lesser extent, for unrestricted households. The resulting increase in aggregate demand sustains consumer prices. In the case of PR, the transmission is conceptually the same, although with the opposite sign.

Two remarks are in order. First, QE is typically implemented when the monetary policy rate is stuck at its ELB, which implies nonlinear dynamics and crucially affects the transmission. To the opposite, PR is implemented away from the ELB and therefore its transmission is not affected by its nonlinear effects (see Cantore and Meichtry, 2023 on this point). Second, in the case of PR, the response of financial markets may differ from the one observed in QE. We account for this possibility in Section 4.3.

2.2 Overview

The model represents the world economy composed of three regions: Home and the rest of the EA (REA), which constitute the EA, and the rest of the world (RW). The size of the world economy is normalized to unity. Home, REA, and RW have sizes equal to s^H, s^{REA}, and $\left(1 - s^H - s^{REA}\right)$, respectively (with $0 < s^H, s^{REA} < 1$, and $s^H + s^{REA} < 1$).[5]

Home and the REA share the currency and the central bank. The latter sets the nominal interest rate, which reacts to EA-wide inflation and output according to a Taylor rule. Moreover, the EA central bank can sell domestic long-term sovereign bonds in each EA region. The presence of the RW outside the EA allows us to take into account the role of the nominal exchange rate and extra-EA trade in the transmission mechanism of central bank sovereign bond purchases, which are potentially relevant channels given that the EA is a relatively open economy (in Section 4.5 we check how the results change when reducing the degree of openness of the EA economy).

The model structure is similar to that of Bartocci et al. (2023).

All households supply differentiated labour services to domestic firms in the intermediate sector and act as wage setters in monopolistically competitive labour markets, charging a wage markup over their marginal rate of substitution between consumption and leisure.

On the production side, there are (i) firms that, under perfect competition, produce a final private consumption good, a final public consumption, and a final investment good, (ii) firms that, under monopolistic competition, produce intermediate tradable and nontradable goods, and (iii) capital producers.

The three final goods are sold domestically and are produced combining available intermediate goods using a constant elasticity of substitution production function. The resulting bundles for consumption and investment goods can have different compositions.

Intermediate tradable and nontradable goods are produced combining domestic capital and

[5]In each region, size refers to the overall population and to the number of firms operating in each sector. The split of the EA in two regions is not strictly necessary, because we assume in our simulations that PR is simultaneously and uniformly implemented in both regions. Results would continue to hold if we modeled the EA as a single bloc. Equations are reported in the Appendix.

labour. The two productive factors are mobile across the tradable and nontradable intermediate sectors. The assumption of differentiated intermediate goods gives firms market power. Thus, firms are price setters and restrict output to create excess profits. Intermediate tradable goods can be sold domestically and abroad. Markets for tradable goods are assumed to be segmented, so that firms can set a different price in each of the three regions.

The capital producers are firms that optimally choose investment in physical capital to maximize profits under perfect competition, subject to the law of capital accumulation and quadratic adjustment costs on investment, taking prices as given. They rent capital to domestic firms producing intermediate goods, and rebate profits to domestic restricted and unrestricted households.

In line with other dynamic general equilibrium models of the EA (e.g. Warne et al., 2008; Gomes et al., 2010), we include adjustment costs on real and nominal variables, to ensure that consumption, investment, and prices react gradually to a shock. On the real side, consumption habits and quadratic costs prolong the adjustment of consumption and investment, respectively. On the nominal side, quadratic costs make wages and prices sticky.[6]

2.3 Restricted households

There exists a continuum of restricted households j', with $j' \epsilon (s^U s^H, s^H]$, where $0 \leq s^U \leq 1$ denotes the unrestricted households' population share (see below). Their preferences are additively separable in consumption and labor effort. The generic restricted household j' receives utility from consumption $C_R(j')$ and disutility from labor $L_R(j')$. The household's expected lifetime utility is

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta_R^t \left[\frac{\left(C_{R,t}\left(j'\right) - habC_{R,t-1}\right)^{1-\sigma}}{(1-\sigma)} - \frac{L_{R,t}\left(j'\right)^{1+\tau}}{1+\tau} \right] \right\}, \tag{3}$$

where E_0 denotes the expectation conditional on information set at date 0, β_R is the discount factor ($0 < \beta_R < 1$), $1/\sigma$ is the elasticity of intertemporal substitution ($\sigma > 0$), and $1/\tau$ is the labor Frisch elasticity ($\tau > 0$). The parameter hab ($0 < hab < 1$) represents external habit formation in consumption.[7] Restricted households have access only to the market of long-term

[6] See Rotemberg (1982).

[7] Following common practice in the New Keynesian literature, the assumption of cashless economy holds in the model.

sovereign bonds. Their budget constraint is

$$P_t^L B_{R,t}^L(j') - P_t^L R_t^L B_{R,t-1}^L(j') = \Pi_t^{prof}(j') + W_{R,t}(j') L_{R,t}(j') - P_t C_{R,t}(j') - AC_{R,t}^W(j'), \quad (4)$$

where $B_{R,t}^L(j')$ is the amount of long-term sovereign bonds, $\Pi_t^{prof}(j')$ are profits from ownership of the Home capital producers, $W_{R,t}(j')$ is the nominal wage, P_t the consumption deflator. The long-term sovereign bonds have price P_t^L and are formalized as perpetuities paying an exponentially decaying coupon $\kappa^L \in (0,1]$, following Woodford (2001). The implied gross yield to maturity at time t on the long-term bond is defined as

$$R_t^L = \frac{1}{P_t^L} + \kappa^L. \quad (5)$$

Finally, households act as wage setters in a monopolistically competitive labor market. Each household j' supplies one particular type of labor services which is an imperfect substitute to services supplied by other households. It sets its nominal wage $W_{R,t}(j')$ taking into account the labor demand and quadratic adjustment costs AC_R^W à la Rotemberg (1982):

$$AC_{R,t}^W(j') \equiv \frac{\kappa_W}{2}\left(\frac{W_{R,t}(j')/W_{R,t-1}(j')}{\pi_{t-1}^{ind_W}\bar{\pi}^{1-ind_W}} - 1\right)^2 W_{R,t}L_{R,t}, \quad (6)$$

where $\kappa_W > 0$ and $0 \leq ind_W \leq 1$ are parameters regulating wage stickiness and indexation, respectively, the variable $\pi_t \equiv P_t/P_{t-1}$ is the consumer price (gross) inflation, and $\bar{\pi}$ is the inflation target of the central bank. As for price adjustment costs, indexation to past inflation and central bank target allows to get nominal wage dynamics that respectively reflects inertia and (long-run) forward-lookingness, in line with estimated dynamic general equilibrium models of the EA (Coenen et al., 2018). The adjustment costs are proportional to the per-capita (average) wage bill of restricted households, $W_{R,t}L_{R,t}$.[8]

[8]The implied first order conditions are reported in the Appendix.

2.4 Unrestricted households

There exists a continuum of unrestricted households, indexed by j, with $j \epsilon (0, s^U s^H]$. These households have the same type of preferences as restricted households described in Eq. 3, thus they consume and supply labor. The only difference is the discount factor, β_U, which can be different from that of restricted households (this allows us to obtain a well-defined steady state). Home unrestricted households have access to multiple financial assets, all denominated in euros (i.e., the domestic currency): the short-term (one-period) sovereign bond B^G, exchanged with the domestic government and paying the EA (gross) monetary policy rate R_t; the short-term private bond B^P, exchanged with REA unrestricted and RW households and paying the (gross) interest rate R^P; the long-term sovereign bond B_U^L which is exchanged with the domestic restricted households, domestic government and, because of the presence of the central bank in the market for long-term sovereign bonds, the EA central bank. Thus, unrestricted households have several opportunities to smooth consumption when facing a shock. The budget constraint of the generic unrestricted household j is

$$\begin{aligned}
&B_t^G(j) - B_{t-1}^G(j) R_{t-1} \\
&+B_t^P(j) - B_{t-1}^P(j) R_{t-1}^P (1-\phi_{B,t-1}) \\
&+P_t^L B_{U,t}^L(j) - P_t^L R_t^L B_{U,t-1}^L(j) = \\
&W_{U,t}(j) L_{U,t}(j) + \Pi_t^P(j) - P_t C_{U,t}(j) \\
&-TAX_t(j) - AC_{U,t}^W(j) - AC_{U,t}^B(j).
\end{aligned} \tag{7}$$

The dividends $\Pi_t^P(j)$ are from ownership of domestic monopolistic firms and domestic capital producers (claims to firms' profits are not internationally tradable). The term $\phi_{B,t}$ represents an exponential adjustment costs, needed to stabilize the position in the internationally traded bond.[9] The term $TAX_t(j)$ represents lump-sum taxes.[10] Unrestricted households supply labor

[9] The adjustment cost is defined as

$$\phi_{B,t} \equiv \phi_{b1} \frac{\exp\left(\phi_{b2}\left(B_t^P - \bar{B}^P\right)\right) - 1}{\exp\left(\phi_{b2}\left(B_t^P - \bar{B}^P\right)\right) + 1}, \text{ with } \phi_{b1}, \phi_{b2} > 0$$

where B_t^P and $\bar{B}^P$ are the period t and steady-state positions of the representative Home unrestricted household, respectively. Both are taken as given in the maximization problem.

[10] We make this assumption consistent with the fact that restricted households are a modelling-device to have PR producing real effects. To allow restricted households to pay lump-sum taxes would further complicate the analysis

services under monopolistic competition and face quadratic adjustment costs $AC^{W}_{U,t}(j)$ when setting nominal wages. This adjustment cost is similar to the one paid by restricted households (see Eq. 6). Unrestricted households also pay adjustment costs $AC^{B}_{U,t}(j)$ on long-term sovereign bond holdings.[11] First-order conditions imply no-arbitrage conditions for the unrestricted households.[12] Thus, in equilibrium the interest rates paid by the different bonds are expected to be equal to the monetary policy rate R_t, net of the spreads induced by the longer maturity and the adjustment costs.[13]

2.5 Capital goods producers

There exists a continuum of mass $0 \leq s^H \leq 1$ of firms c that produce private physical capital. They optimally choose capital K_t and investment I_t to maximize profits subject to the law of capital accumulation, the adjustment costs on investment, and taking prices as given. The law of capital accumulation is

$$K_t(c) = (1-\delta) K_{t-1}(c) + \left(1 - AC^I_t(c)\right) I_t(c),$$

where $0 < \delta < 1$ is the depreciation rate. The adjustment cost on investment AC^I_t is

$$AC^I_t(c) \equiv \frac{\psi_I}{2} \left(\frac{I_t(c)}{I_{t-1}(c)} - 1 \right)^2, \text{ with } \psi_I > 0.$$

Capital producers rent existing physical capital stock $K_{t-1}(c)$ at the nominal rate R^K_t to domestic firms producing intermediate tradable and nontradable goods. Investment is a final nontradable good, composed of intermediate tradable (domestic and imported) and nontradable goods. Cap-

and the main message, as it would introduce an across-household redistributive issue in the paper. Moreover, given that (i) unrestricted households have access to multiple financial markets, and thus can smooth out taxes, and (ii) taxes are lump-sum, the distortionary "fiscal channel" of the taxes themselves should be relatively small and, thus, should not greatly affect the overall picture, whose focus is to assess the non-standard monetary policy measures per se (and not their fiscal dimension).

[11] We assume a standard quadratic form for the adjustment cost, that is,

$$AC^{B}_{U,t}(j) \equiv \frac{\phi_{b^L}}{2} \left(P^L_t B^L_{U,t}(j) - \bar{P}^L \bar{B}^L_U \right)^2, \text{ with } \phi_{b^L} > 0,$$

where $\bar{P}^L \bar{B}^L_U$ is the (symmetric) steady-state value of the long-term sovereign bond. The adjustment cost guarantees that the bond holdings follow a stationary process and that the economy converges to the steady state.

[12] The implied first-order conditions are reported in the Appendix.

[13] See Chen et al. (2012) for the details. Our calibration implies that households can modify their financial positions without facing relevant adjustment costs.

ital producers buy it in the corresponding market at price P_I.[14] Because of the adjustment costs on investment, a "Tobin's Q" holds. When maximizing profits with respect to capital and investment, capital producers discount profits using the stochastic discount rates of restricted and unrestricted households, aggregated according to the corresponding population shares.

2.6 The central bank

The EA central bank sets the policy rate R_t following a standard Taylor rule:

$$\frac{R_t^4}{\overline{R}^4} = \left(\frac{R_{t-1}^4}{\overline{R}^4}\right)^{\rho_R} \left(\frac{\pi_{EA,t,t-3}}{\overline{\pi}_{EA}^4}\right)^{(1-\rho_R)\rho_\pi} \left(\frac{GDP_{EA,t}}{GDP_{EA,t-1}}\right)^{\rho_{GDP}}, \tag{8}$$

where R is the (gross) quarterly monetary policy rate (thus, R^4 is the annualized rate). The parameter ρ_R $(0 < \rho_R < 1)$ captures inertia in interest-rate setting, while the term $\bar{R}$ represents the steady-state gross nominal policy rate. The parameters ρ_π and $\rho_{GDP} > 0$ are the weights of yearly EA consumer price inflation rate $\pi_{EA,t,t-3} \equiv P_t/P_{t-4}$ in deviation from the (annualized) inflation target $\bar{\pi}_{EA}^4$, and the gross growth rate of GDP $(GDP_{EA,t}/GDP_{EA,t-1})$, respectively. The consumer price inflation rate is a geometric average of Home and REA inflation rates, with weights equal to the corresponding (steady-state) regional GDP (as a share of EA steady-state GDP). EA GDP is the sum of Home and REA GDP.[15]

Finally, the EA central bank can reduce the amount of Home and REA long-term sovereign bonds' held in its balance sheet, labelled B_{CB}^L and B_{CB}^{L*}, respectively. The central bank intervenes in each regional long-term sovereign bond market and decides to not reinvest principal payments from maturing bonds, which implies a shrinkage of the size of its monetary policy porftolio of securities.[16] The value of the supply of long-term sovereign bonds by the regional governments is kept constant across simulations. The net reduction in the EA central bank holdings of local long-term sovereign bonds in each EA region is proportional to region-specific GDP. The market

[14] Like the consumption basket, the investment bundle is a composite of tradable and nontradable intermediate goods. The composition of the consumption and investment bundles may differ.

[15] A similar equation describes monetary policy in the RW region.

[16] We assume for simplicity that the central bank's monetary policy portfolio only includes long-term sovereign bonds. In reality, other types of securities, such as corporate bonds, are also held, although in a relatively smaller share. See Bartocci et al. (2017) for an analysis of the macroeconomic effects of corporate bond purchases.

clearing condition for the long-term sovereign bonds of the Home region is

$$\int_0^{s^U s^H} B^L_{U,t}(j)dj + \int_{s^U s^H}^{s_H} B^L_{R,t}(j')dj' + B^L_{CB,t} = B^L_{G,t}, \tag{9}$$

where $B^L_{CB,t} > 0$ are the central bank net asset holdings and $B^L_{G,t}$ the government supply of long-term bonds. A similar condition holds for the REA region.

2.7 Fiscal authority

Fiscal policy is set at the regional level. The government budget constraint is

$$B^S_{G,t} - B^S_{G,t-1}R_{t-1} + P^L_t B^L_{G,t} - P^L_t R^L_t B^L_{G,t-1} \leq P_{N,t}C_{G,t} - TAX_t, \tag{10}$$

where $B^S_{G,t}$, $B^L_{G,t}$ are short-term and long-term nominal sovereign bonds, respectively ($B^S_{G,t}, B^L_{G,t} > 0$ is public debt). The short-term bond is a one-period nominal bond issued in the domestic bond market that pays the (gross) monetary policy interest rate R_t. The variable $C_{G,t}$ represents government purchases of goods and services, which are assumed to be constant at their steady-state level. Consistent with the empirical evidence, C_G is fully biased towards the intermediate nontradable good and is therefore multiplied by the corresponding price index $P_{N,t}$.[17] The variable $TAX_t > 0$ denotes lump-sum taxes paid by households. The government follows the fiscal rule

$$\frac{tax_t}{tax_{t-1}} = \left(\frac{b^s_{G,t}}{\bar{b}^s_G}\right)^{\phi_1} \left(\frac{b^s_{G,t}}{b^s_{G,t-1}}\right)^{\phi_2}, \tag{11}$$

where the parameters $\phi_1, \phi_2 > 0$ call for an increase (reduction) in lump-sum taxes as a ratio to GDP (tax_t) whenever the current-period short-term public debt as a ratio to GDP ($b^s_{G,t}$) is above (below) the target and increasing (decreasing) over time.[18] We choose lump-sum taxes to stabilize public finance as they are non-distortionary, i.e., they do not enter the first-order

[17] See Corsetti and Mueller (2006).

[18] The definition of nominal GDP is

$$GDP_t = P_t C_t + P^I_t I_t + P_{N,t}C_G + P^{EXP}_t EXP_t - P^{IMP}_t IMP_t, \tag{12}$$

where P_t, $P_{I,t}$, $P_{N,t}$, P^{EXP}_t, P^{IMP}_t are the prices of private consumption, private investment, public consumption (given the assumption of its fully biased composition towards intermediate nontradable goods), exports, and imports, respectively.

conditions of households and firms.[19] We assume that the the supply of long-term sovereign bonds $B^L_{G,t}$ by the government is kept constant at its initial steady-state level, so that changes in the long-term interest rate are entirely due to the non-standard monetary policy measures.[20]

2.8 Equilibrium

In each country the initial asset positions, preferences, technologies, and budget constraints are the same for households belonging to the same type and for firms belonging to the same sector. Moreover, profits from ownership of domestic monopolistically competitive firms are equally shared among unrestricted households. Profits from ownership of domestic capital producers are distributed to restricted and unrestricted households according to the corresponding population shares, and are equally shared within each type. Thus, we consider the representative household for each type (restricted and unrestricted). Moreover, we consider the representative firm for each sector (final nontradable, intermediate tradable, and intermediate nontradable) and the representative capital producer. The implied symmetric equilibrium is a sequence of allocations and prices such that, given initial conditions and considered shocks, households and firms satisfy their corresponding first order conditions, the monetary rules, the fiscal rules, and the government budget constraints hold, and all markets clear.

2.9 Calibration

The model is calibrated at quarterly frequency. Table 1 reports the steady-state great ratios.

Model parameters are set to match these ratios and in line with previous studies and estimates available in the literature. The chosen calibration yields impulse response functions to a standard monetary policy shock (+25 basis points) for GDP and inflation in each EA region that are in

[19]Lump-sum taxes are paid by unrestricted households only. In this way we are able to isolate the response of restricted households to PR from the indirect fiscal adjustments implied by the program. However, the Ricardian equivalence does not hold because restricted households hold long-term sovereign bonds but are not subject to lump-sum taxes. Thus, our assumption on the distribution of lump-sum taxes or, equivalently, on the initial distribution of public debt implies that sovereign bond holdings are net wealth.

[20]We include only the short-term debt in the fiscal rule for two reasons. First, we hold the supply of long-term government bonds fixed, B^L_G, so as to isolate the direct demand effects of PR. The (implicit) assumption is that in steady state the central bank always and fully reinvests the principal payments from bonds. Second, we use the fiscal rule to stabilize the short-term debt and therefore the overall public debt, since the long-term component is kept constant. We take into account this distinction when we calibrate the model and more specifically the fiscal target $\bar{b}^s_G$, as reported in Table 1. A similar fiscal rule holds in the REA. In the RW, the fiscal rule holds for the overall public debt, as there is no distinction between short- and long-term domestic sovereign bonds.

line with the workhorse estimated models of the EA in the literature, e.g. Coenen et al. (2018).[21] Moreover, the responses of the main variables, particularly those of the long-term interest rates in response to previous public sector purchase programme announcements are broadly similar to those reported by Burlon et al. (2018) and Burlon et al. (2017).[22]

Table 2 contains parameters for preferences and technology. We assume perfect symmetry between REA and RW unless differently specified. The discount factor of Home and REA unrestricted households is set to 0.9994, so that the steady-state short-term interest rate is equal to 0.24 per cent on an annual basis. The discount factor of restricted households determines the steady-state value of the long-term interest rate and is set to 0.995, so that in steady state the long-term interest rate is equal to 2.01 per cent, the spread between short- and long-term bond being 1.77 percentage points. In each EA region the share of restricted households is set to 0.5.

The value for the intertemporal elasticity of substitution, $1/\sigma$, is 1. The inverse Frisch labor elasticity is set to 3.0. Habit is set to 0.98. The depreciation rate of capital is set to 0.025.

In the production functions of tradables and nontradables, the elasticity of substitution between labor and capital is set to 0.93. To match investment-to-GDP ratios, the bias towards capital in the production function of tradables is set to 0.56 in Home and, in REA and in RW, to 0.46. The corresponding value in the production function of nontradables is set to 0.53 in Home and 0.43 in REA and RW. In the final consumption and investment goods the elasticity of substitution between domestic and imported tradable is set to 1.5, while the elasticity of substitution between tradables and nontradables is set to 0.5, as empirical evidence suggests that it is harder to substitute tradables for nontradables than to substitute across tradables. The biases towards the domestically produced good and composite tradable good are chosen to match the Home and REA import-to-GDP ratios. In the consumption bundle the bias towards the domestic tradable is 0.68 in Home, 0.59 in REA, and 0.90 in RW. The bias towards the composite tradable is set to 0.68 in Home and to 0.50 in REA and RW. For the investment basket, the bias towards the domestic tradable is 0.50 in Home, 0.49 in REA, and 0.90 in RW. The bias towards the composite tradable is 0.78 in Home, and 0.70 in REA and in RW.

[21] See also Warne et al. (2008).

[22] Most of the literature includes models that are either calibrated or estimated on samples that do include the sovereign debt crisis, but typically exclude the Covid 19 period. Also for this reason we run a sensitivity on some of the key parameters of the model.

Table 3 reports gross mark-up values. In the Home tradable and nontradable sectors and in the Home labor market the mark-up is set to 1.08, 1.29, and 1.63, respectively (the corresponding elasticities of substitution across varieties are set to 13.3, 4.4, and 2.6). In the REA tradable and nontradable sectors and in the REA labor market the gross mark-ups are respectively set to 1.11, 1.23, and 1.33 (the corresponding elasticities are set to 10.1, 5.2, and 4.0). The same values are chosen for the corresponding parameters in the RW.

Table 4 contains parameters that regulate the dynamics. Adjustment costs on investment change are set to 7.5. Nominal wage quadratic adjustment costs are set to 800. In the tradable sector, we set the nominal adjustment cost parameter to 600 for Home tradable goods sold domestically, in REA and in RW. The same parameterization is adopted for REA and RW. Nominal price adjustment costs are set to 700 in the nontradable sector. For the adjustment costs on long-term sovereign bond positions, parameters are calibrated so that the response of the long-term interest rates to the sovereign bond purchases by the central bank should be in line with existing evidence for the EA.[23]

Table 5 reports the parametrization of the systematic feedback rules followed by the monetary authorities. The central bank of the EA targets the contemporaneous EA-wide consumer price inflation (the corresponding parameter is set to 1.7) and the output growth (the parameter is set to 0.1). Interest rate is set in an inertial way and hence its previous-period value enters the rule with a weight equal to 0.92. The values are identical for the corresponding parameters of the Taylor rule in the RW.

Table 6 reports the parametrization of the systematic feedback rules followed by the fiscal authorities. In the fiscal policy rule (Eq. 11) we set $\phi_1 = 0.05$ and $\phi_2 = 10.01$ for Home, and $\phi_1 = \phi_2 = 1.01$ for the REA and the RW. We assume that lump-sum transfers are used as a fiscal instrument.

[23] See Altavilla et al. (2015). The calibration of the elasticity is the same as that used to assess the macroeconomic effects of the ECB APP in Bartocci et al. (2023). See also results reported in Neri and Siviero (2019).

3 Simulations

We construct alternative scenarios aiming at capturing the macroeconomic effects of PR. The latter is due to the central bank not reinvesting the principal payments from maturing long-term sovereign bonds.

In all simulations, with one exception, the policy rate follows the Taylor rule, Eq. 8. PR is implemented through an announced sequence of shocks in the initial 6 quarters, while from quarter 7 onwards, central bank holdings of long-term sovereign bonds remain constant at a new value, lower than the initial one. The path of the announced PR is illustrative. Its calibration broadly tracks the evolution of net assets held by the ECB in its monetary policy portfolio in 2022Q3-2024Q1.[24]

Thus, PR is fully anticipated by households and firms, as it is announced by the central bank in a credible way in the initial period of the simulation. The supply of long-term bonds issued by the government is constant in nominal terms.

The first (benchmark) scenario evaluates the macroeconomic effects of PR (Section 4.1).

The second scenario investigates the role of the policy rate response for the transmission of PR, by assuming that the central bank does not follow the Taylor rule in the initial six quarters, but instead keeps the policy rate constant at the baseline level and announces the measure at the beginning of the simulation (Section 4.2).

The third scenario explores the case of investors being reluctant to buy long-term sovereign bonds because the reduced role played by a large player such as the central bank in determining the demand for those bonds unavoidably implies a decrease in the equilibrium sovereign bond price and higher long-term interest rates. Consistently, the elasticity of long-term interest rate to PR is higher than in the benchmark calibration (Section 4.3).

The fourth scenario considers investors' overreaction, interpretable in terms of investors' panic possibly associated with mis-understanding the announcement of PR (for example because investors have the perception of a front-loaded and sudden PR) which implies an increase in the long-term rate in excess of that consistent with the fundamentals, that is, with the benchmark

[24]See IMF (2024). While our calibration borrows from the recent ECB experience, we do not aim at exactly replicating the actual ECB PR strategy, but instead we want to provide some numerical counterfactual results.

case (Section 4.4).

Finally, a sensitivity analysis evaluates how the macroeconomic effects of PR are affected by: (a) PR persistence (that is, the fact that PR can be persistent but not permanent as in the benchmark simulations, Section 4.5.1); (b) indexation to past inflation and to the central bank target in wage- and price-setting decisions (Section 4.5.2); (c) EA trade openness (Section 4.5.3).

We remark that our aim is to characterize the macroeconomic effects of the PR as such, possibly under different assumptions on the monetary policy rate response. Thus, we do not intend to analyze PR as a major instrument during a monetary policy tightening.

4 Results

4.1 Macroeconomic effects of PR

Fig. 1 reports responses of the main EA-wide macroeconomic variables to PR, which is gradually implemented by the central bank under the benchmark assumption that the policy rate follows the Taylor rule (black continuous lines). The reduction in the holdings is implemented via a halt in reinvestments of the principal payments from maturing securities.

PR creates an excess supply of long-term bonds in the market. Households anticipate the overall excess supply of bonds that they have to absorb. The price of long-term bonds decreases, to induce private investors to absorb the excess supply. Thus, the interest rate paid by the long-term bonds increases (as illustrated by Eq. 5). Consistent with the higher long-term interest rate, households decrease their demand for consumption and investment in physical capital. The drop in investment in physical capital is in absolute terms larger than that in consumption, because households – especially the unrestricted, who have access to multiple financial instruments – smooth their consumption over time. Imports decrease, in line with the lower aggregate demand. Export decrease as well, because of the appreciation of the nominal exchange rate, due to the increase in the long-term interest rate. The persistently lower aggregate demand induces firms to reduce both production and prices. Thus, inflation decreases in the short and medium run (in the long run inflation returns to its baseline level, i.e., to the central bank target, while it is slightly and temporarily above the baseline between the 20th and 30th quarter). The central bank mildly reduces the policy rate according to the Taylor rule (see Eq. 8) in the attempt to stabilize the fall in inflation and economic activity.

Our results show that a 2% of GDP permanent PR implies an increase in long-term interest rates of about 10bp. Similar figures are reported in the literature for QE episodes. For the case of the EA, Altavilla et al. (2015) report that a 10% of EA GDP increase in central bank long-term bond holdings compresses their yields by around 65 basis points. More recently, Eser et al. (2023) estimate that the stock of current and expected future ECB (APP) holdings has reduced the 10-year yield by almost 1 percentage point.

4.2 Constant policy rate

In the previous section it was assumed that the central bank follows the Taylor rule, which commands a systematic reduction in the policy rate in response to lower inflation and economic activity due to PR.

We now assume that the central bank keeps the policy rate constant at the baseline level for the initial six quarters, instead of decreasing it, and then resumes following the Taylor rule. The purpose of this exercise is to disentangle the stabilising role of the policy rate in correspondence of the PR shock.

Fig. 1 shows the results (red dashed lines). Compared to the benchmark case, PR has larger disinflationary and recessionary effects. Unrestricted households anticipate that the real interest rate will decrease less, because the nominal interest rate does not initially decrease and expected inflation, instead, decreases.[25] Thus, they decrease consumption and investment to a larger extent than in the benchmark case. Lower aggregate demand further reduces economic activity and inflation. Restricted households' consumption is, instead, hardly affected, because it directly reflects the dynamics of the long-term interest rate, whose response does not greatly change across the two considered cases.

Overall, the two simulations (without and with constant policy rate) suggest that PR has recessionary and disinflationary effects and that the response of the monetary policy rate is key

[25]The ex-ante real interest rate is the relevant real interest rate for consumption decisions of unrestricted households, because it enters their Euler equation. In each period it is equal to the product between the current nominal policy rate and the inverse of the expected next-period inflation.

for their size. The less the central bank accompanies PR with a reduction in the policy rate, the larger – in absolute terms – the negative effects of PR on economic activity and inflation dynamics.

4.3 Higher elasticity of long-term interest rate to PR

In the previous sections it was implicitly assumed that the elasticity of long-term interest rates to PR is the same as the one observed during QE. However, it could be argued that the elasticity observed during QE may not apply to PR, as investors may be reluctant to buy a category of assets whose value may be expected to decrease, due to the lack of demand by the central bank.[26] Thus, the elasticity of the long-term interest rate to PR could be higher than the elasticity to central bank's purchases and, thus, than some generic average elasticity. To take into account this possibility, we calibrate the elasticity of long-term interest rate to PR to a higher value than in the benchmark calibration. Following the (given) PR, the long-term interest rate is assumed to increase on impact by roughly 0.2 annualized pp, instead of 0.1 annualized pp.[27]

Fig. 2 contains the results under the new elasticity (red dashed line) and, for the sake of comparison, under the benchmark one (black continuous line). Results change quantitatively but non qualitatively. Consistent with the larger increase in the long-term interest rate, households decrease demand for consumption and investment to a larger extent than in the benchmark scenario. Firms respond to the additional decrease in demand by further reducing production and prices. Thus, economic activity and inflation decrease to a larger extent. The drop in output is roughly twice as much as in the benchmark. Both consumption and investment responses almost double in absolute terms. Similarly, inflation decline is more pronounced relative to the benchmark case. Both imports and exports decrease relatively more, following the larger decrease in aggregate demand and the larger appreciation of the exchange rate, respectively. Consistent with the Taylor rule, the central bank responds to the stronger disinflationary effects by reducing the policy rate relatively more than in the benchmark case.

[26] This issue is admittedly controversial. Since QE is typically performed during periods of financial distress, interest-rate elasticity may actually be higher compared to the one observed during PR episodes. We do not consider such case in our analysis.

[27] We obtain the new value of the elasticity by changing the value of the parameter in the quadratic cost paid by households to adjust their position in long-term sovereign bonds.

Overall, the intensity of PR recessionary and disinflationary effects depends on the size of the (equilibrium) increase in the long-term interest rate to PR, which is affected by the portfolio choices of investors in correspondence of the PR announcement.

4.4 Financial markets' overreaction to PR

In the previous sections, the financial markets' response to PR was assumed to be smooth. However, it cannot be excluded that financial markets overreact to the PR announcement.[28] The overreaction would consist in private investors suddenly becoming less willing to hold long-term sovereign bonds of the same class of the maturing securities in the central bank's monetary policy portfolio. This is more likely to be the case if the announcement of PR is not clearly connected to macroeconomic developments, which may be perceived as a negative shock by financial markets. This would induce a sharp decrease in sovereign bond price and a sharp increase in long-term interest rates, to a larger extent than the responses dictated by changes in fundamental factors (including the PR announcement).[29] We model the overreaction in a stylized way by imposing an exogenous positive risk premium shock on the interest rate paid by the long-term sovereign bond. The shock materializes on impact, is equal to about 1 annualized pp, and lasts one quarter.[30]

Fig. 3 reports the results (red dashed line). Relative to the benchmark case (no-overreaction, black continuous line), the larger increase in the overall long-term interest rate induces a larger drop in aggregate demand for consumption and investment in physical capital, as households, in equilibrium, rebalance their economic choices towards sovereign bonds and away from spending (red dashed lines). Imports decrease to a larger extent because of the larger drop in aggregate demand. Exports drop more because of the larger exchange rate appreciation. Firms respond by reducing production and prices relatively more. Both economic activity and inflation decrease

[28]Lu and Valcarcel (2024) suggest that during US QT2, which began in January 2022, all the balance sheet announcements exerted a significant influence on yield spreads and conclude that QT2 shows a stronger market response upon implementation. While QT1 took place during a period of relative calm in financial markets, there was substantial financial turbulence during QT2.

[29]A well known example, in the case of the US economy, is the so-called "tamper tantrum". On May 22, 2013, the Federal Reserve Chair Ben Bernanke announced that the Fed would start tapering asset purchases at some future date, which sent a negative shock to the market, causing bond investors to start selling their bonds. As a result, the yield on 10-year U.S. Treasuries rose from around 2% in May 2013 to around 3% in December.

[30]The shock multiplies the long-term rate in the household's Euler equation. Thus, in this simulation the interest rate paid by the long-term bond held by the households has a temporary risk premium.

to a much larger extent. The central bank reacts by reducing more the policy rate to face the larger deterioration in macroeconomic conditions.

The recessionary effects are further amplified if the risk premium shock holds and the long-term interest rate has higher elasticity to PR (set to the same value as in Section 4.3, see blue dotted lines in the charts).

Overall, if PR triggers a financial market overreaction, the implied inflation decrease could be larger. The central bank would reduce the policy rate to a larger extent.[31]

4.5 Sensitivity

In this section we run a sensitivity analysis on the persistence of PR, price and wage indexation to past inflation, EA trade openness with the RW.

4.5.1 PR persistence

In previous simulations it was assumed that after the end of PR, in the sixth quarter, the central bank keeps its long-term sovereign bond holdings at the new lower level. We now assume that from quarter 7 onwards, PR is assumed to evolve according to an AR(1) process, as follows:

$$B_{CB,t}^{L} = (1 - \rho_{CB})\,\overline{B}_{CB}^{L} + \rho_{CB} B_{CB,t-1}^{L}, \tag{13}$$

where $\overline{B}_{CB}^{L}$ are the steady-state central bank holdings of long-term sovereign bonds. We set the persistence parameter equal to 0.98. Thus, PR is a prolonged but, in comparison with the benchmark case, temporary policy measure. This case corresponds to the central bank gradually increasing the reinvestment of the principal payments from maturing bonds up to full reinvestment, that is, the initial steady-state level of reinvestment. The Taylor rule is assumed to be always active.

Fig. 4 reports the results. Relative to the benchmark case, the long-term interest rate increases to a lesser extent (red dashed line), because the overall PR, which is fully anticipated by households, is smaller. Aggregate demand decreases less, because both unrestricted and restricted

[31]The policy rate reduction would be possible as long as the policy rate does not hit the (binding) ELB.

households reduce their consumption and investment spending to a lesser extent. Firms, thus, reduce aggregate production and prices by less. The implied fall of the inflation rate is much smaller. The central bank reduces the policy rate less in response to the relatively higher inflation, consistent with the Taylor rule.

Overall, the persistence of the program is key for its macroeconomic effects. The larger the anticipated degree of persistence, that is, the more economic agents anticipate that PR is a permanent measure, the more disinflationary and recessionary the effects of PR and, thus, the larger the drop in the policy rate needed to stabilize inflation and economic activity.

4.5.2 Price and wage indexation to past inflation

In the benchmark calibration, current wage- and price-setting decisions are mainly indexed to past inflation, given that, in the wage and price equations, past inflation's weight is set to 0.95 and, correspondingly, the weight of central bank target to 0.05. We assume a weight of past inflation equal to 0.5 (red dashed line) and, alternatively, to 0.05 (blue dotted line). The weight of the central bank is set to 0.5 and 0.95, respectively.

Fig. 5 shows the results. Compared to the benchmark case, inflation decreases less persistently under the assumption that wage- and price-setting decisions are mainly indexed to the central bank target. Thus, the policy rate decreases by less. Given the degree of substitutability between short- and long-run bonds, the more contained drop of the policy rate spills-over to a larger increase in the long-term interest rate. Consumption and investment decrease more, inducing a larger reduction in the economic activity.

Overall, the impact of PR on inflation and economic activity depends on the degree of indexation of wage- and price-setting decisions. The larger the indexation to past inflation, the bigger the drop in inflation and the more contained the output reduction.

4.5.3 EA trade openness

It is now assumed that EA trade with th RW is lower than in the benchmark calibration. The weights of EA goods in RW consumption basket are decreased by 30%. The same reduction applies to RW goods in EA consumption baskets.

Fig. 6 reports the results (red dashed lines). Qualitatively, results do not greatly change with respect to the benchmark scenario (black continuous line). PR has disinflationary and recessionary effects, so that the central bank has to reduce the policy rate to stabilize inflation. Quantitatively, the disinflationary effects are slightly larger. Given the larger home bias, the euro appreciates to a larger extent, inducing a larger drop in imports of RW goods and a larger drop in inflation, via the larger decrease in imported inflation and because of the larger effect of the drop in EA aggregate demand (the two EA regions are more commercially integrated among one another). Consistent with the larger reduction in inflation, the central bank reduces the policy rate to a larger extent than in the benchmark case to stabilize economic activity.

Overall, trade openness is relevant for price dynamics in the after of PR. Specifically, lower trade openness favors further inflation reduction.

5 Concluding remarks

We have simulated a general equilibrium model calibrated to the EA to assess the macroeconomic effects of PR. The central bank should reduce the policy rate promptly if it wants to limit the recessionary and disinflationary effects of PR and, thus, stabilize macroeconomic conditions. Financial markets' reaction and PR's design are relevant as well for PR macroeconomic effects. The size of the recessionary impact is larger in case of market overreaction to the announcement and a permanent PR. Overall, the interplay of standard and non-standard monetary policy measures is relevant, implying that central bank decisions should take into account the multiple monetary policy tools that are activated and, thus, affect macroeconomic conditions.

Our analysis can be further extended. We have considered PR as a discretionary policy measure. Alternatively, it could be endogenized via a rule that links the reduction in central bank holdings to macroeconomic and financial conditions. Moreover, the international dimension could be further explored, by evaluating the interaction of standard and non-standard measures implemented in both EA and rest of the world. In addition, it would be interesting to explore some form of state-dependent pricing, to capture, for instance, the observed increase in the frequency of price adjustment in the face of large shocks. We leave these issues for future research.

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Table 1: Main variables (steady-state values)

	H	REA	RW
Macroeconomic variables			
Private consumption	57.6	58.4	55.7
Public consumption	20.0	20.0	20.0
Private Investment	19.8	19.0	21.7
Imports	25.0	17.5	4.0
GDP	3.4	17.0	79.6
Financial variables			
Long-term public debt (% of annual GDP)	121	93	–
Share held by:			
Central bank	16	16	–
Unrestricted households	50	50	–
Restricted households	34	34	–

Note: H=Home; REA=rest of the EA; RW= rest of the world. Variables in % of GDP. GDP as percentage of world GDP.

Table 2: Preferences and technology

Parameter	H	REA	RW
Unrestricted households' discount factor $\beta_U, \beta_U^*, \beta^{**}$	0.9994	0.9994	0.9994
Restricted households' discount factor β_R, β_R^*	0.995	0.995	–
Intertemporal elasticity of substitution $1/\sigma$	1.0	1.0	1.0
Habit (households and entrepreneurs) *hab*	0.98	0.98	0.98
Inverse of Frisch elasticity of labor supply τ	3.0	3.0	3.0
Share of unrestricted households s_U, s_U^*	0.5	0.5	1.0
Share of restricted households $1 - s_U$, $1 - s_U^*$	0.5	0.5	–
Share of capital producers ownership			
Unrestricted households $share_U$,$share_U^*$	0.06	0.06	1.0
Restricted households $1 - share_U$,$1 - share_U^*$	0.94	0.94	–
Depreciation rate of capital δ,δ^*,δ^{**}	0.025	0.025	0.025
Tradable intermediate goods			
Substitution between factors of production $\rho_Y, \rho_Y^*, \rho_Y^{**}$	0.93	0.93	0.93
Bias towards capital $\gamma_{k,H}, \gamma_{k,REA}^*, \gamma_{k,RW}^{**}$	0.56	0.46	0.46
Bias tws restr. households' labour $\gamma_{L_R,H}, \gamma_{L_R,REA}^*, \gamma_{L_R,RW}^{**}$	0.10	0.10	–
Nontradable intermediate goods			
Substitution between factors of production $\rho_Y, \rho_Y^*, \rho_Y^{**}$	0.93	0.93	0.93
Bias towards capital $\gamma_{k,NT}, \gamma_{k,NT}^*, \gamma_{k,NT}^{**}$	0.53	0.43	0.43
Bias tws restr. households' labour $\gamma_{L_R,NT}, \gamma_{L_R,NT}^*, \gamma_{L_R,NT}^{**}$	0.10	0.10	–
Final consumption goods			
Subst. btw. dom. and imported goods $\eta_T, \eta_T^*, \eta_T^{**}$	1.50	1.50	1.50
Bias towards domestic tradable goods $a_{H,C}, a_{REA,C}^*, a_{RW,C}^{**}$	0.68	0.59	0.90
Subst. btw. tradables and nontradables $\rho_C, \rho_C^*, \rho_C^{**}$	0.50	0.50	0.50
Bias towards tradable goods $\gamma_{pr_{c,T}}, \gamma_{pr_{c,T}}^*, \gamma_{pr_{c,T}}^{**}$	0.68	0.50	0.50
Final investment goods			
Subst. btw. dom. and imported goods $\eta_T, \eta_T^*, \eta_T^{**}$	1.50	1.50	1.50
Bias towards domestic tradable goods $a_{H,I}, a_{REA,I}^*, a_{RW,I}^{**}$	0.50	0.49	0.90
Subst. btw. tradables and nontradables $\rho_I, \rho_I^*, \rho_I^{**}$	0.50	0.50	0.50
Bias towards tradable goods $\gamma_{pr_{i,T}}, \gamma_{pr_{i,T}}^*, \gamma_{pr_{i,T}}^{**}$	0.78	0.70	0.70
Exp. decaying coupon (long-term sovereign bond)			
κ^L	0.974	0.974	
Country size			
s^H, s^{REA}, $1 - s^H - s^{REA}$	0.004	0.266	0.73

Note: H=Home; REA=rest of the EA; RW= rest of the world. "*" refers to REA, "**" to RW.

Table 3: Gross mark-ups

	Mark-ups and elasticities of substitution		
	Tradables	Nontradables	Wages
H	1.08 ($\theta_T = 13.3$)	1.29 ($\theta_N = 4.4$)	1.63 ($\theta_L = 2.6$)
REA	1.11 ($\theta_T^* = 10.1$)	1.23 ($\theta_N^* = 5.2$)	1.33 ($\theta_L^* = 4.0$)
RW	1.11 ($\theta_T^{**} = 10.1$)	1.23 ($\theta_N^{**} = 5.2$)	1.33 ($\theta_L^{**} = 4.0$)

Note: H=Home; REA=rest of the EA; RW= rest of the world. "*" refers to REA, "**" to RW.

Table 4: Real and nominal adjustment costs

Parameter	H	REA	RW
Real adjustment costs			
Investment ψ_I, ψ_I^*,ψ_I^{**}	7.50	7.50	7.50
Nominal adjustment costs			
Wages κ_W, κ_W^*, κ_W^{**}	800	800	800
Index. to past infl. ind_W, ind_W^*, ind_W^{**}	0.95	0.95	0.95
Home tradables κ_H, κ_H^* κ_H^{**}	600	600	600
REA trad. κ_{REA}, κ_{REA}^* κ_{REA}^{**}	600	600	600
RW trad. κ_{RW}, κ_{RW}^* κ_{RW}^{**}	600	600	600
Nontradables κ_N, κ_N^*, κ_N^{**}	700	700	700
Index. to past inflation ind, ind^*, ind^{**}	0.95	0.95	0.95
Adjustment costs on bonds			
Unr. households long-term b. ϕ_{b^L}, $\phi_{b^L}^*$	0.00012	0.00085	–
Unrest. households short-term bond.			
ϕ_{b1}, ϕ_{b1}^{**}	0.0015	–	0.0015
ϕ_{b2}, ϕ_{b2}^{**}	0.0030	–	0.0030

Note: H=Home; REA=rest of the EA; RW= rest of the world. "* " refers to REA, "** " to RW.

Table 5: Monetary policy rule

Parameter	EA	RW
Monetary policy rule		
Lagged interest rate ρ_R, ρ_R^{**}	0.92	0.92
Inflation ρ_π, ρ_π^{**}	1.70	1.70
GDP growth $\rho_{GDP}, \rho_{GDP}^{**}$	0.10	0.10

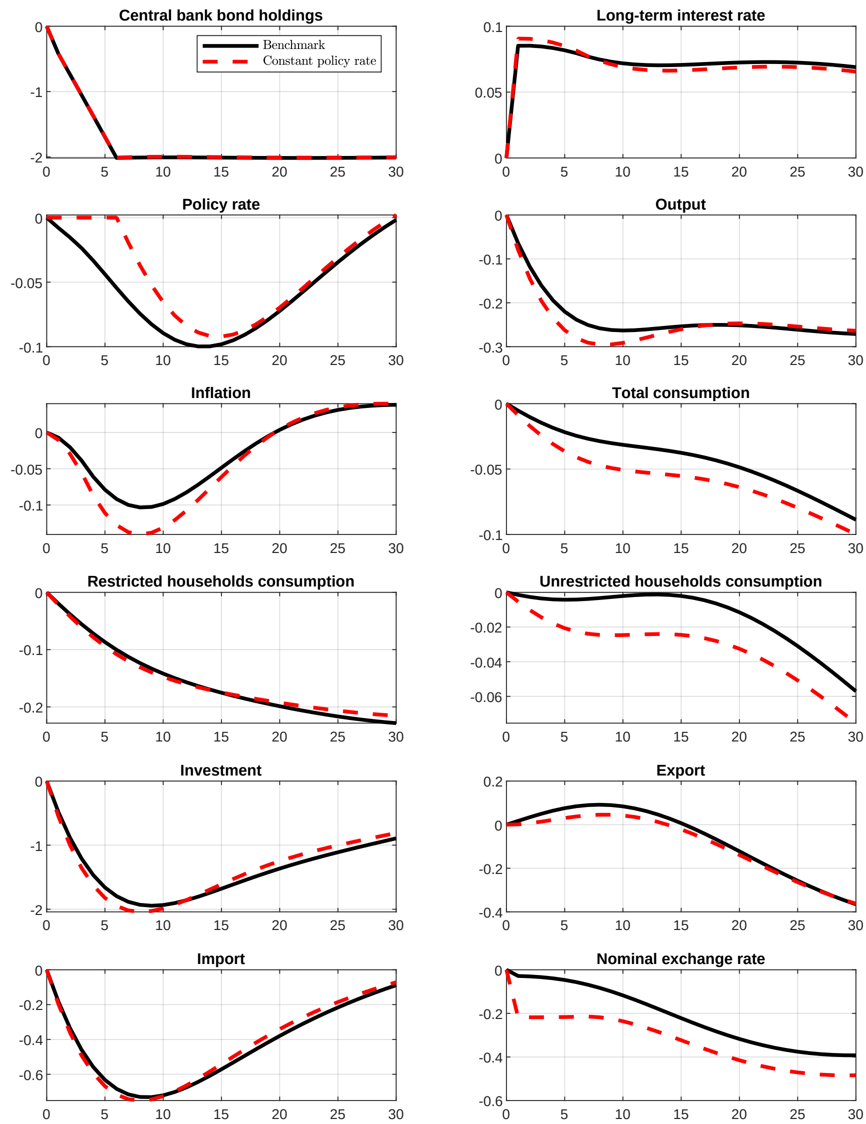
Note: EA= euro area; RW= rest of the world; "* " refers to EA, "** " to RW.

Table 6: Fiscal policy rule

Parameter	H	REA	RW
$\phi_1, \phi_1^*, \phi_1^{**}$	0.05	1.01	1.01
$\phi_2, \phi_2^*, \phi_2^{**}$	10.01	1.01	1.01

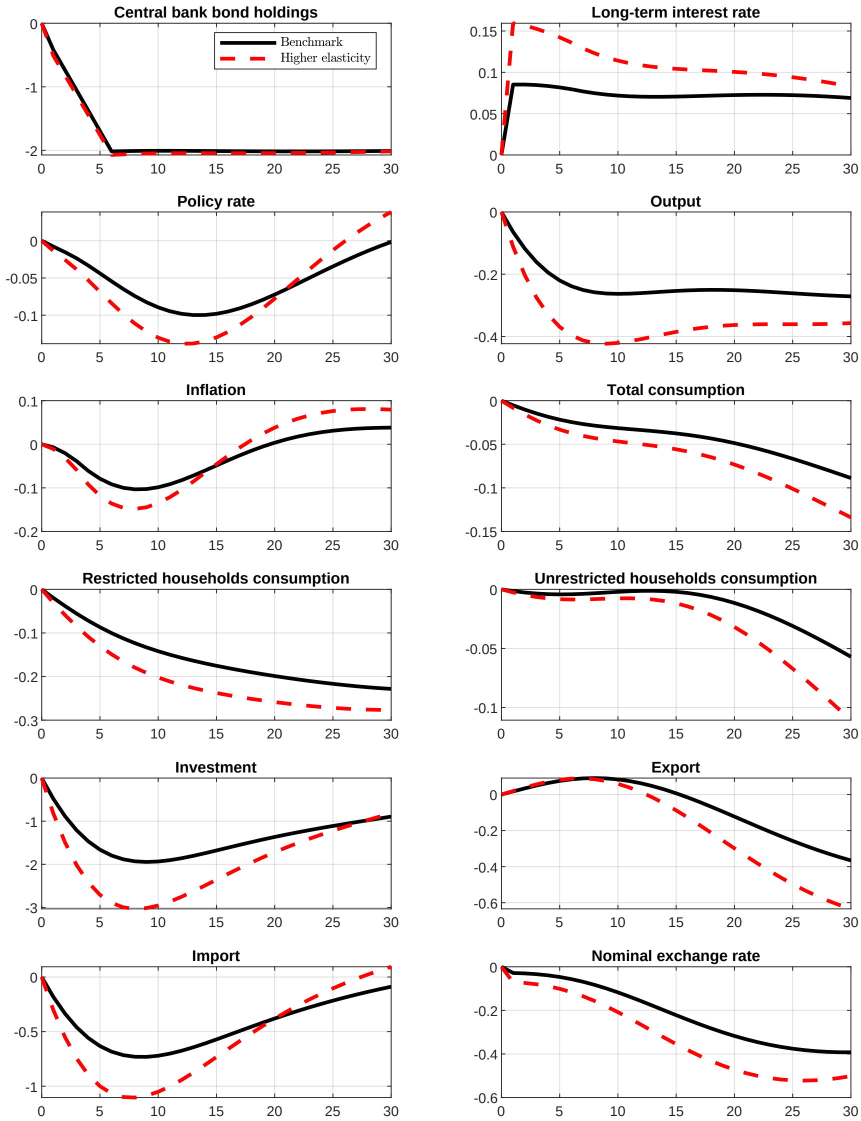
Note: H=Home; REA=rest of the EA (*); RW= rest of the world (**).

Figure 1: PR: benchmark vs constant policy rate in the initial six quarters



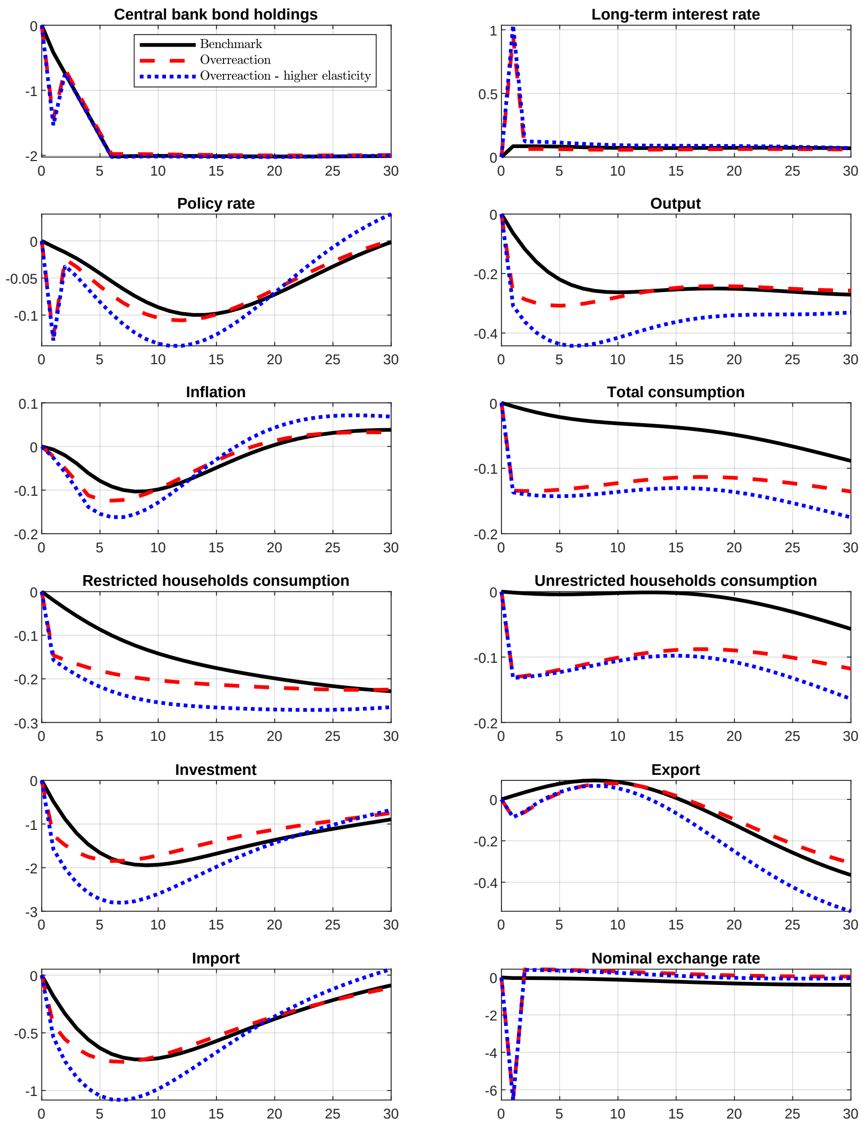
Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state; for inflation, the policy rate and the long-term interest rate, annualized pp. deviations; for central bank holdings: ratio to annualized GDP, percentage-point deviation from steady-state ratio. Nominal exchange rate: positive (negative) value is a depreciation (an appreciation) of the euro.

Figure 2: PR and higher elasticity of the long-term interest rate to long-term debt



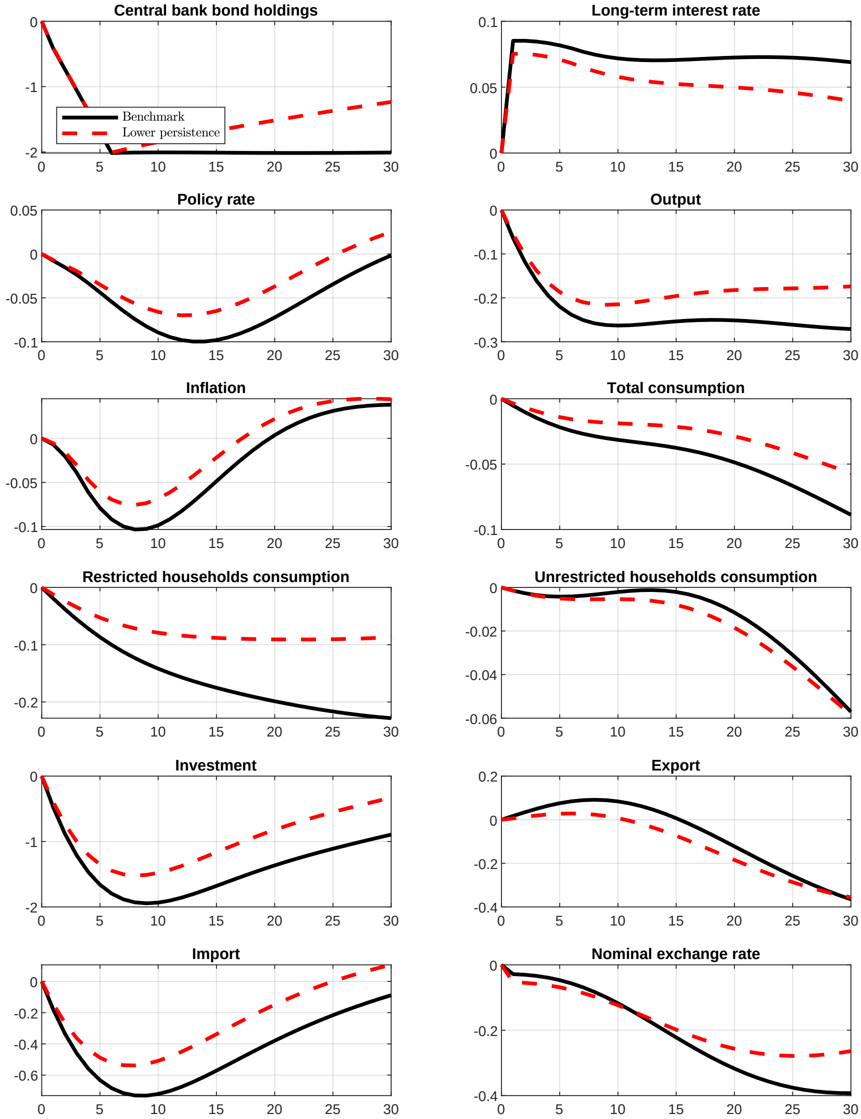
Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state; for inflation, the policy rate and the long-term interest rate, annualized pp. deviations; for central bank holdings: ratio to annualized GDP, percentage-point deviation from steady-state ratio. Nominal exchange rate: positive (negative) value is a depreciation (an appreciation) of the euro.

Figure 3: PR and financial markets' overreaction



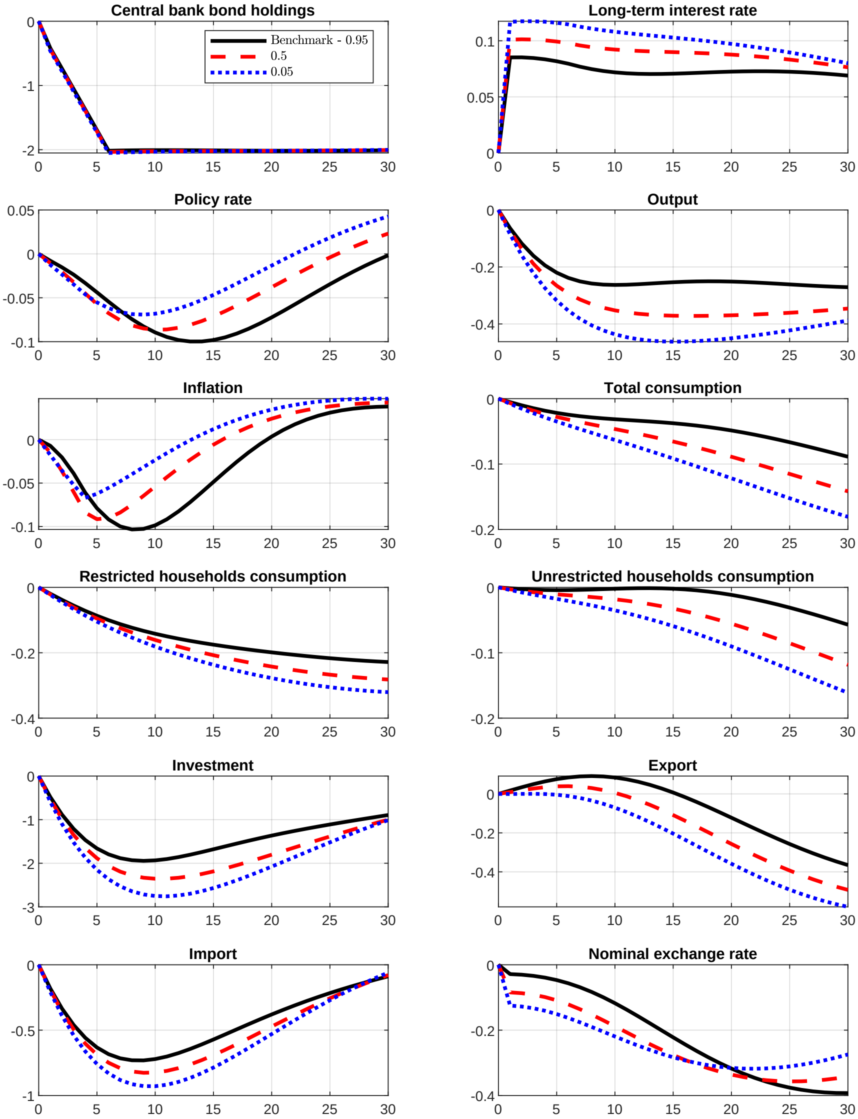
Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state; for inflation, the policy rate and the long-term interest rate, annualized pp. deviations; for central bank holdings: ratio to annualized GDP, percentage-point deviation from steady-state ratio. Nominal exchange rate: positive (negative) value is a depreciation (an appreciation) of the euro.

Figure 4: Sensitivity: lower persistence of purchase rule



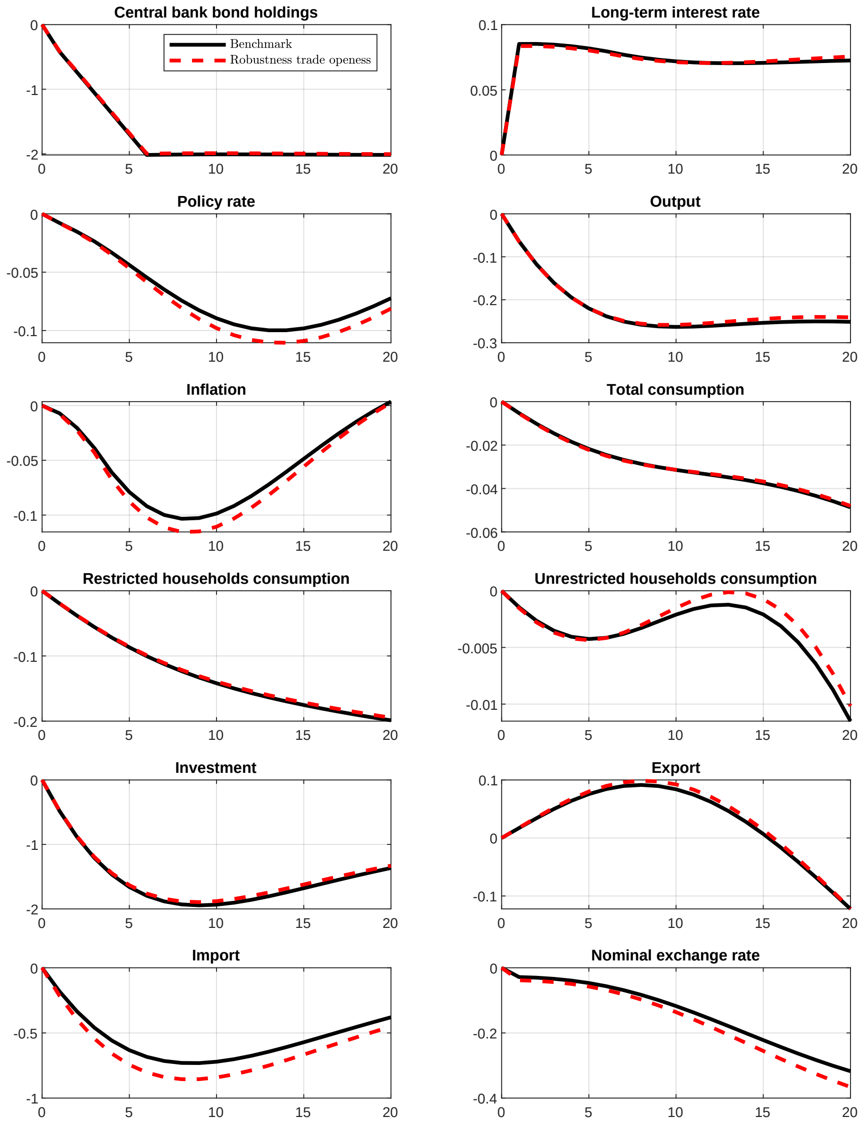
Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state. For inflation, the EA policy rate and the EA long-term interest rate, annualized pp. deviations.

Figure 5: Sensitivity: price and wage indexation to past inflation



Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state; for inflation, the policy rate and the long-term interest rate, annualized pp. deviations; for central bank holdings: ratio to annualized GDP, percentage-point deviation from steady-state ratio. Nominal exchange rate: positive (negative) value is a depreciation (an appreciation) of the euro.

Figure 6: Sensitivity: trade with the RW



Notes: horizontal axis, quarters; vertical axis, % deviations from the steady state; for inflation, the policy rate and the long-term interest rate, annualized pp. deviations; for central bank holdings: ratio to annualized GDP, percentage-point deviation from steady-state ratio. Nominal exchange rate: positive (negative) value is a depreciation (an appreciation) of the euro.

Appendix

A.1 The model

The model represents the world economy composed of three regions: Home and the rest of the EA (REA), which constitute the EA, and the rest of the world (RW). The size of the world economy is normalized to unity. Home, REA, and RW have sizes equal to s^H, s^{REA}, and $\left(1 - s^H - s^{REA}\right)$, respectively (with $0 < s^H, s^{REA} < 1$, and $s^H + s^{REA} < 1$). In each region, size refers to the overall population and to the number of firms operating in each sector.

Home and the REA share the currency and the central bank. The latter sets the nominal interest rate, which reacts to EA-wide inflation and output according to a Taylor rule. Moreover, the EA central bank can sell domestic long-term sovereign bonds in each EA region.

All households supply differentiated labour services to domestic firms in the intermediate sector and act as wage setters in monopolistically competitive labour markets, charging a wage markup over their marginal rate of substitution between consumption and leisure.

On the production side, there are (i) firms that, under perfect competition, produce a final private consumption good, a final public consumption, and a final investment good, (ii) firms that, under monopolistic competition, produce intermediate tradable and nontradable goods, and (iii) capital producers.

The three final goods are sold domestically and are produced combining available intermediate goods using a constant elasticity of substitution production function. The resulting bundles for consumption and investment goods can have different compositions.

Intermediate tradable and nontradable goods are produced combining domestic capital and labour. The two productive factors are mobile across the intermediate tradable and nontradable sectors. The assumption of differentiated intermediate goods gives firms market power. Thus, firms are price setters and restrict output to create excess profits. Intermediate tradable goods can be sold domestically and abroad. Markets for tradable goods are assumed to be segmented, so that firms can set a different price in each of the three regions.

The capital producers are firms that optimally choose investment in physical capital to maximize profits under perfect competition, subject to the law of capital accumulation and quadratic adjustment costs on investment, taking prices as given. They rent capital to domestic firms producing intermediate goods, and rebate profits to domestic restricted and unrestricted households.

We include adjustment costs on real and nominal variables, to ensure that consumption, investment, and prices react gradually to a shock. On the real side, consumption habits and quadratic costs prolong the adjustment of consumption and investment, respectively. On the nominal side, quadratic costs make wages and prices sticky.

In what follow we report equations of the Home country. Similar equations hold for REA and RW if not explicitly stated. All prices are expressed in domestic consumption units (i.e., domestic consumption is the numeraire).

A.1.1 Firms

This section reports the equations of firms operating in the intermediate- and final-good sectors. It also reports the equations of the capital producers.

A.1.1.1 Intermediate-good tradable sector

The generic firm h produces an intermediate tradable good $Y_{T,t}(h)$ under monopolistic competition. It chooses inputs, i.e., labour and capital, to minimize the production costs taking as given the technology constraint and the input prices.

- Production function

$$Y_{T,H,t}(h)^{\frac{\rho_Y-1}{\rho_Y}} = \gamma_{k,H}^{\frac{1}{\rho_Y}} K_{H,t}(h)^{\frac{\rho_Y-1}{\rho_Y}} + \gamma_{L_R,H}^{\frac{1}{\rho_Y}} L_{R,H,t}(h)^{\frac{\rho_Y-1}{\rho_Y}} + (1-\gamma_{k,H}-\gamma_{L_R,H})^{\frac{1}{\rho_Y}} L_{U,H,t}(h)^{\frac{\rho_Y-1}{\rho_Y}} \quad \text{(A.1)}$$

  where $\rho_Y > 0$ is the elasticity of substitution among inputs, $K_{H,t}(h)$, $L_{R,H,t}(h)$ and $L_{U,H,t}(h)$ are demand for capital, labour supplied by restricted households, labour supplied by unrestricted households, respectively, while the parameters $0 < \gamma_{k,H}, \gamma_{L_R,H} < 1$ $(\gamma_{k,H} + \gamma_{L_R,H} < 1)$ are the weights of capital and restricted household's labor in the production function, respectively.

- Demand for capital

$$K_{H,t}(h) = \gamma_{k,H} \left(\frac{r_{k,t}}{rmc_{H,t}} \right)^{-\rho_Y} Y_{T,H,t}(h), \tag{A.2}$$

where $r_{k,t}$ is the return on capital and rmc_t the real marginal cost of the firm.

- Demand for labour supplied by the restricted households

$$L_{R,H,t}(h) = \gamma_{L_R,H} \left(\frac{w_{R,t}}{rmc_{H,t}} \right)^{-\rho_Y} Y_{T,H,t}(h), \tag{A.3}$$

where w_R is the real wage.

- Demand for labour supplied by the unrestricted households

$$L_{U,H,t}(h) = (1 - \gamma_{k,H} - \gamma_{L_R,H}) \left(\frac{w_{U,t}}{rmc_{H,t}} \right)^{-\rho_Y} Y_{T,H,t}(h), \tag{A.4}$$

where w_U is the real wage.

- Optimal price of the Home intermediate good in the Home market

  The generic firm h chooses the price of its good to maximize profits subject to the demand constraint and the quadratic costs to adjust the nominal price. Thus, the firm faces (short-term) nominal rigidities. It is assumed that Home, REA and RW markets are exogenously segmented and the generic firm h price-discriminates across markets.

  The implied first-order condition (i.e., optimal price $p_{H,t}(h)$ of brand h in the Home market) is

$$\begin{aligned}(1-\theta_T)p_{H,t}(h) + \theta_T rmc_{H,t}(h) &= \kappa_H \left(\frac{P_{H,t}(h)/P_{H,t-1}(h)}{\pi_{H,t-1}^{ind_H} \bar{\pi}^{1-ind_H}} - 1 \right) \frac{P_{H,t}/P_{H,t-1}(h)}{\pi_{H,t-1}^{ind_H} \bar{\pi}^{1-ind_H}} \\ -\beta_U \frac{\lambda_{U,t+1}\pi_{t+1}^{-1}}{\lambda_{U,t}} \kappa_H & \left(\frac{P_{H,t+1}(h)/P_{H,t}(h)}{\pi_{H,t}^{ind_H} \bar{\pi}^{1-ind_H}} - 1 \right) \frac{P_{H,t+1} P_{H,t+1}(h)/P_{H,t}(h)^2 Y_{H,t+1}}{\pi_{H,t}^{ind_H} \bar{\pi}^{1-ind_H} Y_{H,t}}, \end{aligned} \tag{A.5}$$

where $\theta_T > 1$ is the elasticity of substitution among different brands produced by firms belonging to the tradable sector, $\kappa_H > 0$ is a parameter measuring the cost of adjusting the nominal price in the Home market, $P_{H,t}(h)$ is the nominal price of the intermediate good h in the Home market, $\pi_{H,t-1}$ is the previous-period sector-specific gross inflation rate in the Home market, and $\bar{\pi}$ is the central bank (gross) inflation target. The parameter $0 < ind_H < 1$ measures indexation of current prices to previous-period inflation. Correspondingly, $1 - ind_H$ measures indexation to the central bank target. Thus, the optimal price setting scheme is subject to a double indexation, i.e., to past inflation and to the central bank inflation target. The parameter $0 < \beta_U < 1$ and the variable λ_U are the domestic representative unrestricted household's discount factor and marginal utility, respectively .

Similar pricing equation hold for the price of good h in the REA and in the RW markets. Similar equations (production function, demand for capital and labor, pricing equations) hold for firms in the other intermediate tradable and nontradable sectors.

A.1.1.2 Final-good sectors

There are three sectors producing final goods: consumption goods for households, investment goods, and public sector consumption goods. Firms act under perfect competition. They choose inputs to maximize profits subject to the technology constraint and taking all prices as given.

Private consumption good

- Overall basket

  The generic firm x produces the consumption good $C_t(x)$ according to the CES production function

$$C_t(x)^{\frac{\rho_C-1}{\rho_C}} = \gamma_{pr_{c,T}}^{\frac{1}{\rho_C}} C_{T,t}(x)^{\frac{\rho_C-1}{\rho_C}} + (1-\gamma_{pr_{c,T}})^{\frac{1}{\rho_C}} C_{NT,t}(x)^{\frac{\rho_C-1}{\rho_C}}, \tag{A.6}$$

  where $\rho_C > 0$ is the elasticity of substitution between tradable and nontradable bundles, $C_{T,t}(x)$ is the bundle of the tradable intermediate goods, $C_{NT,t}(x)$ is the nontradable bundle. The parameter $0 < \gamma_{pr_{c,T}} < 1$ is the weight of the tradable consumption bundle.

- Basket of the tradable goods

  The bundle of tradable goods is a CES function of domestic and imported consumption goods, $C_{H,t}(x)$ and $C_{REA,t}(x)$, and $C_{RW,t}(x)$ respectively:

$$C_{T,t}(x)^{\frac{\eta_T-1}{\eta_T}} = a_{H,C}^{\frac{1}{\eta_T}} C_{H,t}(x)^{\frac{\eta_T-1}{\eta_T}} + a_{REA,C}^{\frac{1}{\eta_T}} C_{REA,t}(x)^{\frac{\eta_T-1}{\eta_T}} + (1 - a_{H,C} - a_{REA,C})^{\frac{1}{\eta_T}} C_{RW,t}(x)^{\frac{\eta_T-1}{\eta_T}}, \tag{A.7}$$

where the parameters $a_{H,C}$, and $a_{REA,C}$ ($0 < a_{H,C}, a_{REA,C} < 1$) are the weights of H and REA goods in the bundle ($C_{H,t}$, and $C_{REA,t}$, respectively), while $\eta_T > 0$ is the elasticity of substitution among Home, REA and RW intermediate goods.

- Basket of domestically-produced goods for consumption purposes $C_H(x)$

  The domestically-produced manufacturing good for consumption purposes C_H is a composite basket of a continuum of differentiated intermediate Home goods, each supplied by a different firm h operating in the intermediate Home sector. It is produced according to the following function:

$$C_{H,t}(x) = \left[\left(\frac{1}{s^H} \right)^{\theta_T} \int_0^{s^H} C_{H,t}(h,x)^{\frac{\theta_T-1}{\theta_T}} dh \right]^{\frac{\theta_T}{\theta_T-1}}, \tag{A.8}$$

  where $\theta_T > 1$ is the elasticity of substitution among Home intermediate brands h used as inputs by the firms x, $C_{H,t}(h,x)$.

  The basket of REA and RW goods have a structure similar to that of the Home good.

- Demand for the generic brand h

  Firm x demand for the generic brand h is

$$C_{H,t}(h,x) = \frac{1}{s^H} a_{H,C} \gamma_{pr_c,T} \left(\frac{P_{H,t}(h)}{P_{T,t}} \right)^{-\theta_T} \left(\frac{P_{H,t}}{P_{T,t}} \right)^{-\eta_T} \left(\frac{P_{T,t}}{P_t} \right)^{-\rho_C} C_t(x), \tag{A.9}$$

  where

$$P_{H,t} = \left[\int_0^{s^H} P_{H,t}(h)^{1-\theta_T} dh \right]^{\frac{1}{1-\theta_T}}, \tag{A.10}$$

$$P_{T,t} = \left[a_{H,C} P_{H,t}^{1-\eta_T} + a_{REA,C} P_{REA,t}^{1-\eta_T} + (1 - a_{H,C} - a_{REA,C}) P_{RW,t}^{1-\eta_T} \right]^{\frac{1}{1-\eta_T}}, \tag{A.11}$$

$$P_{C,t} = \left[\gamma_{pr_{c,T}} P_{T,t}^{1-\rho_C} + \left(1 - \gamma_{pr_{c,T}}\right) P_{NT,t}^{1-\rho_C} \right]^{\frac{1}{1-\rho_C}} , \tag{A.12}$$

are the price deflators of Home goods' consumption bundle, tradable consumption bundle, and overall consumption bundle, respectively. Equations similar to the price deflator of the Home goods' consumption bundle hold for the price deflator of the imported (i.e., REA and RW) goods.

Investment good

The sector producing final investment goods has a structure similar to one of the final consumption goods' sector.

Public consumption good

- Basket

  The public consumption good $C_{G,t}$, produced by the generic firm g under perfect competition, is fully biased towards the intermediate nontradable domestic brands, i.e.,

$$C_{G,t}(g) = \left[\left(\frac{1}{s^H} \right)^{\theta_N} \int_0^{s^H} C_{G,t}(n,g)^{\frac{\theta_N - 1}{\theta_N}} \, dn \right]^{\frac{\theta_N}{\theta_N - 1}} , \tag{A.13}$$

  where $\theta_N > 1$ is a parameter measuring the elasticity of substitution among intermediate nontradable brands.

A.1.1.3 Capital producers

The generic capital goods producer c produces private physical capital. It is owned by domestic unrestricted and restricted households. Capital producers optimally choose the end-of-period capital K and investment I subject to the law of capital accumulation, the adjustment costs on investment, distortionary taxes on capital income levied by the domestic government, and taking all prices as given. Capital producers rent existing physical capital stock K in a perfectly competitive market at the real rate r^K to domestic firms producing intermediate goods.

- Capital accumulation law

$$K_t(c) = (1-\delta)K_{t-1}(c) + \left[1 - \frac{\psi_I}{2}\left(\frac{I_t(c)}{I_{t-1}(c)} - 1\right)^2\right] I_t(c), \tag{A.14}$$

where $0 < \delta < 1$ is the depreciation rate and investment is subject to a quadratic adjustment cost ($\psi_I > 0$ is a parameter).

- FOC with respect to the end-of-period capital $K_t(c)$

$$\begin{aligned}
&\left(share_U \lambda_{U,t} + (1 - share_U)\,\lambda_{R,t}\right) Q_t(c) \\
&= E_t\left(share_U \beta_U \lambda_{U,t+1} + (1 - share_U)\,\beta_R \lambda_{R,t+1}\right) r^K_{t+1} \\
&+ E_t\left(share_U \beta_U \lambda_{U,t+1} + (1 - share_U)\,\beta_R \lambda_{R,t+1}\right)(1-\delta) Q_{t+1}(c),
\end{aligned} \tag{A.15}$$

where: $0 < share_U < 1$ is the share of capital producers owned by unrestricted households, while $\lambda_{U,t}$ is the representative unrestricted household's marginal utility of consumption; correspondingly, $1 - share_U$ is the share of capital producers owned by the restricted households and $\lambda_{R,t}$ is the representative restricted household's marginal utility of consumption. $Q(c)$ is the Tobin's Q (i.e., the multiplier of the capital accumulation law), r^K; $0 < \beta_U, \beta_R < 1$ the discount factors of unrestricted and restricted households, respectively (see below).

- FOC with respect to investment $I_t(c)$

$$\begin{aligned}
&\left(share_U \lambda_{U,t} + (1 - share_U)\,\lambda_{R,t}\right) p_{I,t} \\
&= Q_t(c)\left(share_U \lambda_{U,t} + (1 - share_U)\,\lambda_{R,t}\right) \times \\
&\left[1 - \frac{\psi_I}{2}\left(\frac{I_t(c)}{I_{t-1}(c)} - 1\right)^2 - \psi_I\left(\frac{I_t(c)}{I_{t-1}(c)} - 1\right)\frac{I_t(c)}{I_{t-1}(c)}\right] \\
&+ \left(share_U \beta_U \lambda_{U,t+1} + (1 - share_U)\,\beta_R \lambda_{R,t+1}\right)\psi_I \left[\left(\frac{I_{t+1}(c)}{I_t(c)} - 1\right)\frac{I^2_{t+1}(c)}{I^2_t(c)}\right].
\end{aligned} \tag{A.16}$$

A.1.2 Households

There are two types of households: unrestricted and restricted. Within the Home region, the continuum of unrestricted households j has mass s^U $(0 < s^U < 1)$. The continuum of restricted households j' has mass $1 - s^U$.

A.1.2.1 Unrestricted Households

- Preferences

Each unrestricted household j maximizes her lifetime expected utility subject to the budget constraint. The lifetime expected utility, in consumption of goods C_U, and labour L_U is

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta_U^t \left[\frac{\left(C_U\left(j\right) - habC_{U,t-1}\right)^{1-\sigma}}{\left(1-\sigma\right)} - \frac{L_{U,t}\left(j\right)^{1+\tau}}{1+\tau} \right] \right\}, \tag{A.17}$$

where E_0 is period-0 expectation term, $0 < \beta_U < 1$ the discount factor, $0 < hab < 1$ the (external) consumptions' habit parameter, $\sigma > 0$ the reciprocal of the intertemporal elasticity of substitution, and $\tau > 0$ the Frish elasticity of labour supply.

- Budget constraint

The budget constraint, in nominal terms, is

$$\begin{aligned} & B_t^G\left(j\right) - B_{t-1}^G\left(j\right) R_{t-1} \\ & + B_t^P\left(j\right) - B_{t-1}^P\left(j\right) R_{t-1}^P (1 - \phi_{B,t-1}) \\ & + P_t^L B_{U,t}^L\left(j\right) - P_t^L R_t^L B_{U,t-1}^L\left(j\right) = \\ & W_{U,t}\left(j\right) L_{U,t}\left(j\right) + \Pi_t^P\left(j\right) - P_t C_{U,t}\left(j\right) \\ & - TAX_t\left(j\right) - AC_{U,t}^W\left(j\right) - AC_{U,t}^B(j), \end{aligned} \tag{A.18}$$

where: B_t^G is the end-of-period holdings of short-term (one-period) bonds issued by the domestic government, which pays the (gross) monetary policy rate R_t; B_t^P is the bond exchanged with other domestic, REA and RW unrestricted households, which pays the (gross) interest rate R_t^P and denominated in euro currency; the function $\phi_{B,t}$ captures the costs of undertaking positions in the international bond market;[1] $B_{U,t}^L$ is the long-term sovereign bond issued by the domestic government; $W_{U,t}$ is the nominal wage; Π_t^P are profits from ownership of domestic firms, rebated to unrestricted households is a lump-sum way; $P_{C,t}$ is the consumer price deflator; $TAX_t > 0$ are lump-sum taxes paid to the government ($TAX_t < 0$ are lump-sum transfers received from the government); the last two terms are quadratic costs paid to adjust the nominal wage and the position in the long term sovereign bond, respectively:

$$AC_{U,t}^W(j) \equiv \frac{\kappa_W}{2}\left(\frac{W_{U,t}(j)/W_{U,t-1}(j)}{\pi_{t-1}^{ind_W}\bar{\pi}^{1-ind_W}} - 1\right)^2 W_{U,t}L_{U,t}, \tag{A.19}$$

where $\kappa_W > 0$ is a parameter measuring the nominal wage stickiness; $0 < ind_W < 1$ is a parameter measuring the degree of indexation to previous-period gross consumer price inflation rate, π_{t-1} and, correspondingly, $1 - ind_W$ measures the indexation to the central bank inflation target; in the bond adjustment cost;

$$AC_{U,t}^B(j) \equiv \frac{\phi_{b^L}}{2}\left(P_t^L B_{U,t}^L(j) - \bar{P}^L \bar{B}_U^L\right)^2, \text{ with } \phi_{b^L} > 0, \tag{A.20}$$

where the term $\phi_{b^L} > 0$ is a parameter, while $\bar{B}_U^L$ is the unrestricted household's steady-state position in the bond.

The long-term sovereign bond is formalized as a perpetuity paying an exponentially decaying coupon $\kappa^L \in (0, 1]$. Thus, the long-term interest rate is

$$R_t^L = \frac{1}{P_t^L} + \kappa^L. \tag{A.21}$$

In what follows the first order conditions implied by the household's utility maximization subject to the budget constraint are reported.

[1] The adjustment cost in the bond markets has the following functional form:

$$\phi_{B,t} \equiv \phi_{b1}\frac{\exp\left(\phi_{b2}\left(B_t^P - \bar{B}^P\right)\right) - 1}{\exp\left(\phi_{b2}\left(B_t^P - \bar{B}^P\right)\right) + 1}, \text{ with } \phi_{b1}, \phi_{b2} > 0$$

where $\phi_{b1}, \phi_{b2} > 0$ are parameters and $\bar{B}^P$ is the steady-state position. The adjustment cost is imposed to ensure the stationarity of the net foreign asset position.

- FOC with respect to consumption $C_{U,t}(j)$

$$\lambda_{U,t}(j) = \left(C_{U,t}(j) - habC_{U,t-1}\right)^{-\sigma}, \tag{A.22}$$

where $\lambda_{U,t}$ is the marginal utility of consumption.

- FOC with respect to domestic bond $B_t^G(j)$

$$\lambda_{U,t}(j) \quad = \quad \beta_U E_t \left(R_t \pi_{t+1}^{-1} \lambda_{U,t+1}(j)\right). \tag{A.23}$$

Note that $\pi_t \equiv P_{C,t}/P_{C,t-1}$ is the gross consumer price inflation rate (thus,$\pi_{t+1} \equiv P_{C,t+1}/P_{C,t}$).

- FOC with respect to foreign bond $B_t^P(j)$

$$\lambda_{U,t}(j) \quad = \quad \beta_U E_t \left(R_t^P (1 - \phi_{B,t}) \pi_{t+1}^{-1} \lambda_{\cdot U,t+1}(j)\right). \tag{A.24}$$

- FOC with respect to long-term sovereign bond $B_{U,t}^L(j)$

$$\begin{aligned} &\lambda_{U,t}(j) P_t^L \left(1 + \phi_{b^L} \left(P_t^L B_{U,t}^L(j) - \bar{B}_U^L\right)\right) \\ &= \beta_U E_t \left(\left(1 + \kappa^L P_{t+1}^L\right) \pi_{t+1}^{-1} \lambda_{\cdot U,t+1}(j)\right). \end{aligned} \tag{A.25}$$

- FOC with respect to nominal wage $W_t(j)$

The household supplies her labour variety under monopolistic competition; she sets the nominal wage taking into account of demand by domestic firms and subject to quadratic adjustment costs of setting nominal wages. The implied optimal wage setting equation is

$$\begin{aligned} \theta_L \frac{W_{U,t}(j)^{-\theta_L(1+\tau)-1}}{W_{U,t}^{-\theta_L(1+\tau)}} L_{U,t}^{\tau} + (1-\theta_L) \frac{W_{U,t}(j)^{-\theta_L}}{W_{U,t}^{-\theta_L}} = \lambda_{U,t}(j) \kappa_W \left(\frac{W_{U,t}(j)/W_{U,t-1}(j)}{\pi_{t-1}^{ind_W} \bar{\pi}^{1-ind_W}} - 1 \right) \frac{W_{U,t}/W_{U,t-1}(j)}{\pi_{t-1}^{ind_W} \bar{\pi}^{1-ind_W}} \\ -\beta_U \lambda_{U,t+1}(j) \kappa_W \left(\frac{W_{U,t+1}(j)/W_{U,t}(j)}{\pi_t^{ind_W} \bar{\pi}^{1-ind_W}} - 1 \right) \frac{W_{U,t+1} W_{U,t+1}(j)/W_{U,t}(j)^2 L_{U,t+1}}{\pi_t^{ind_W} \bar{\pi}^{1-ind_W} L_{U,t}}, \end{aligned} \tag{A.26}$$

where the parameter $\theta_L > 1$ measures the elasticity of substitution among different labour varieties supplied by households and π_{t-1} is the previous-period gross inflation rate. The parameter $0 < ind_W < 1$ measures indexation of current-period wage to previous-period inflation. Correspondingly, $1 - ind_W$ measures indexation to the central bank target.

A.1.2.2 Restricted Households

- Preferences

The generic restricted households j' chooses consumption $C_{R,t}$ to maximize her utility function, while, in the symmetric equilibrium, she supplies an amount of labour $L_{R,t}$ equal to that chosen by the (representative) unrestricted household. The intertermporal utility function is

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta_R^t \left[\frac{\left(C_{R,t}\left(j'\right) - habC_{R,t-1}\right)^{1-\sigma}}{(1-\sigma)} - \frac{L_{R,t}\left(j'\right)^{1+\tau}}{1+\tau} \right] \right\}, \tag{A.27}$$

where $0 < \beta_R < 1$ is the houshold's discount factor, $0 < hab < 1$ the parameter measuring (external) consumption habit, $\sigma > 0$ the reciprocal of the intertemporal elasticity of substitution, $\tau > 0$ the Frish elasticity of labour supply.

- Budget constraint (in nominal terms)

$$P_t^L B_{R,t}^L\left(j'\right) - P_t^L R_t^L B_{R,t-1}^L\left(j'\right) = \Pi_t^{prof}\left(j'\right) + W_{R,t}\left(j'\right) L_{R,t}\left(j'\right) - P_t C_{R,t}\left(j'\right) \tag{A.28}$$
$$-AC_{R,t}^W\left(j'\right).$$

The household invests in domestic long-term sovereign bonds $B_{R,t}^L$; she gets profits, in a lump-sum way, from domestic capital producers Π_t^{prof} and the nominal wage $W_{R,t}$ by supplying labor. The quadratic adjustment costs on wage is:

$$AC_{R,t}^W\left(j'\right) \equiv \frac{\kappa_W}{2} \left(\frac{W_{R,t}(j')/W_{R,t-1}(j')}{\pi_{t-1}^{ind_W} \bar{\pi}^{1-ind_W}} - 1 \right)^2 W_{R,t} L_{R,t}. \tag{A.29}$$

- FOC with respect to consumption $C_{R,t}(j')$

$$\lambda_{R,t}(j') = \left(C_{R,t}(j') - habC_{R,t-1}\right)^{-\sigma}, \tag{A.30}$$

where $\lambda_{R,t}$ is the marginal utility of consumption

- FOC with respect to long-term sovereign bond $B^L_{R,t}(j')$

$$\lambda_{R,t}(j')P^L_t\left(1+\phi_{b^L}\left(P^L_t B^L_{R,t}(j')-\bar{B}^L_R\right)\right)$$
$$=\beta_R E_t\left(\left(1+\kappa^L P^L_{t+1}\right)\pi^{-1}_{t+1}\lambda_{R,t+1}(j')\right). \tag{A.31}$$

A.1.3 Monetary policy

The monetary policy rule is:

$$\frac{R^4_t}{\overline{R}^4}=\left(\frac{R^4_{t-1}}{\overline{R}^4}\right)^{\rho_R}\left(\frac{\pi_{EA,t,t-3}}{\overline{\pi}^4_{EA}}\right)^{(1-\rho_R)\rho_\pi}\left(\frac{GDP_{EA,t}}{GDP_{EA,t-1}}\right)^{\rho_{GDP}}. \tag{A.32}$$

The rule describes the central bank's monetary policy. The variable R_t is the (quarterly) gross policy rate and $\bar{R}$ its steady-state value. The parameters $0 \leq \rho_R \leq 1$, $\rho_\pi > 0$, and ρ_{GDP} measure the sensitivity of the policy rate to its lagged value, to annual gross inflation rate $\pi_{EA,t,t-3}$ (in deviation from the annualized target), and to the quarterly gross growth rate of GDP, respectively. The lagged interest rate ensures that the policy rate is adjusted smoothly and captures the idea that the central bank prefers to avoid large changes and reversals in its policy instrument.

In the case of the EA central bank, the inflation rate in the Taylor rule is a weighted average of Home and REA inflation rates and GDP is EA GDP, that is, the sum of Home and REA output. It is moreover assumed that the EA central bank discretionally reduces its monetary policy portfolio of EA long-term sovereign bonds.

A.1.4 Fiscal policy

The Home (representative) government budget constraint in nominal terms is

$$B^S_{G,t}-B^S_{G,t-1}R_{t-1}+P^L_t B^L_{G,t}-P^L_t R^L_t B^L_{G,t-1}\leq P_{N,t}C_G-TAX_t, \tag{A.33}$$

where $B^S_{G,t}$ is the short-term (one-period) bond which pays the gross monetary policy rate R_t, $B^L_{G,t}$ is the long-term bond and P^L_t its price ($B^L_{G,t} > 0$, $B^S_{G,t} > 0$ are debts).

The government follows a fiscal rule defined on nominal lump-sum taxes paid by unrestricted households to stabilize the short-term public debt as. The fiscal rule is

$$\frac{tax_t}{tax_{t-1}} = \left(\frac{b^s_{G,t}}{\bar{b}^s_G}\right)^{\phi_1} \left(\frac{b^s_{G,t}}{b^s_{G,t-1}}\right)^{\phi_2}, \tag{A.34}$$

where the parameters $\phi_1, \phi_2 > 0$ call for an increase (reduction) in lump-sum taxes as a ratio to GDP (tax_t) whenever the current-period short-term public debt as a ratio to GDP ($b^s_{G,t}$) is above (below) the target $\bar{b}^s_G$ and increasing (decreasing) over time.

A.1.5 Market clearing conditions

This section contains the market clearing conditions of goods and bonds holding in the Home region. Similar equations hold for the REA and RW regions.

- Generic Home intermediate tradable h

$$\begin{aligned} Y_{T,H,t}(h) = {} & Y_{H,t}(h) + Y^*_{H,t}(h) \\ & + Y^{**}_{H,t}(h), \end{aligned} \tag{A.35}$$

$$Y_{H,t}(h) = \int_0^{s^H} C_H(h,x)\, dx + \int_0^{s^H} I_{H,t}(h,i)\, di, \tag{A.36}$$

$$Y^*_{H,t}(h) = \int_{s^H}^{s^H+s^{REA}} C_{H,t}(h,x^*)\, dx^* + \int_{s^H}^{s^H+s^{REA}} I_{H,t}(h,i^*)\, di^*, \tag{A.37}$$

$$Y^{**}_{H,t}(h) = \int_{s^H+s^{REA}}^{1} C_{H,t}(h, x^{**})\, dx^{**} + \int_{s^H+s^{REA}}^{1} I_{H,t}(h, i^{**})\, di^{**}, \tag{A.38}$$

- Generic Home intermediate nontradable n

$$\begin{aligned} Y_{NT,t}(n) = \int_0^{s^H} C_{NT,t}(n, x)\, dx + \\ \int_0^{s^H} I_{NT,t}(n, i)\, di + \\ \int_0^{s^H} C_{G,t}(n, g)\, dg. \end{aligned} \tag{A.39}$$

- Generic Home final nontradable consumption good x

$$\begin{aligned} C_{H,t}(x) = \int_0^{s^U s^H} C_{U,t}(x, j)\, dj + \\ \int_{s^U s^H}^{s^H} C_{R,t}(x, j')\, dj'. \end{aligned} \tag{A.40}$$

- Generic Home final nontradable investment good i

$$I_{H,t}(i) = \int_0^{s^H} I_t(i, c)\, dc. \tag{A.41}$$

- Generic Home final nontradable public consumption good g

$$C_{G,t}(g) = \frac{1}{s^H} C_{G,t}. \tag{A.42}$$

- Labour market (unrestricted households)

$$\begin{aligned} \int_0^{s^U s^H} L_{U,t}(j)\, dj = \\ \int_0^{s^H} L_{U,H,t}(h)\, dh + \int_0^{s^H} L_{U,NT,t}(n)\, dn. \end{aligned} \tag{A.43}$$

- Labour market (restricted households)

$$\int_{s^U s^H}^{s^H} L_{R,t}(j')\,dj' = \int_0^{s^H} L_{R,H,t}(h)\,dh + \int_0^{s^H} L_{R,NT,t}(n)\,dn. \tag{A.44}$$

- Capital market

$$\int_0^{s^H} K_t(c)\,dc = \int_0^{s^H} K_{H,t}(h)\,dh + \int_0^{s^H} K_{NT,t}(n)\,dn. \tag{A.45}$$

- Short-term sovereign bond

$$\int_0^{s^U s^H} B_t^G(j)\,dj = B_{G,t}^S. \tag{A.46}$$

- Long-term sovereign bond

$$\int_0^{s^U s^H} B_{U,t}^L(j)dj + \int_{s^U s^H}^{s_H} B_{R,t}^L(j')dj' + B_{CB,t}^L = B_{G,t}^L. \tag{A.47}$$

- Internationally traded bond

$$\int_0^{s^U s^H} B_t^P(j)\,dj + \int_{s^H}^{s^H + s^{U*} s^{REA}} B_t^P(j^*)\,dj^* + \int_{s^H + s^{REA}}^{1} B_t^P(j^{**})\,dj^{**} = 0. \tag{A.48}$$

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