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* Views expressed are those of the author and do not necessarily reflect official positions of De Nederlandsche Bank.

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Energy and Monetary Policy in the Euro Area*

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Abstract

We develop and estimate an open economy DSGE model for the euro area in which imported energy, priced in foreign currency, enters both consumption and production. Global energy prices and the exchange rate therefore jointly determine domestic inflation. We find that energy and exchange-rate disturbances account for the bulk of short-run volatility in headline euro area inflation, with energy price shocks driving most of the post-pandemic surge. Because energy and non-energy goods are poor substitutes, an adverse energy price shock raises import values, deteriorating the trade balance and depreciating the real exchange rate through the net-foreign-asset and UIP channels. The exchange-rate channel strengthens monetary transmission and improves the short-run inflation-output trade-off relative to a non-energy economy. Optimal policy can exploit this channel rather than looking through energy price shocks. However, the case for looking through such shocks becomes stronger when the central bank assigns a greater weight to output gap stabilization and prices become stickier.

***Keywords*:** Monetary policy, Inflation, Energy, Bayesian estimation.
***JEL codes*:** E52, E31, E32.

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1 Introduction

The surge in euro area inflation since 2021 has renewed interest in the role of external shocks and the appropriate conduct of monetary policy in open economies. A defining feature of this episode has been the sharp increase in energy prices, driven by global supply disruptions, geopolitical tensions, and exchange rate movements. These developments have not only raised headline inflation directly but have also propagated through production costs, wage setting, and expectations, thereby affecting core inflation and real economic activity. At the time of writing this paper, inflationary pressures have once again increased on both sides of the Atlantic due to ongoing geopolitical uncertainty stemming from tensions in the Middle East. Understanding how such shocks transmit and how monetary policy should optimally respond to them remains a central challenge for policymakers. Recent ECB communication highlights that monetary policy cannot directly offset higher energy prices but must assess when such shocks spill over into broader inflation dynamics via indirect and second-round effects (Lagarde, 2026).

In this paper, we study how energy price shocks and open-economy channels shape the inflation-output stabilization trade-off faced by monetary policy in the euro area. In particular, we ask how the presence of imported energy goods and exchange-rate pass-through alters both the transmission of monetary policy and the optimal policy response to supply side disturbances. When energy enters both household consumption and firms' production processes, exchange-rate movements induced by monetary policy affect inflation through multiple channels. Beyond the conventional demand and competitiveness effects, exchange-rate fluctuations directly influence the domestic price of imported energy and indirectly affect firms' marginal costs. Consequently, the inflation-output trade-off faced by the central bank may differ from that implied by non-energy or closed-economy frameworks.

Canonical New Keynesian DSGE models typically abstract from energy or treat it in a stylized manner, while widely used open economy extensions focus primarily on exchange rate dynamics and incomplete pass-through (Gali and Monacelli, 2005). As a result, existing frameworks generally capture either open economy transmission without energy or energy shocks without exchange-rate amplification. They are therefore not well suited to explain the interaction between imported energy prices, exchange rates, and inflation dynamics that has characterized the post-Covid euro area experience.

We develop and estimate a small open economy DSGE model of the euro area that explicitly incorporates energy in both consumption and production. Energy goods are imported and priced in foreign currency, so that global energy prices and exchange rate movements jointly determine domestic inflation. The model features nominal price and wage rigidities, investment frictions, and household heterogeneity, and is estimated using Bayesian methods on euro area and US data (the latter as a proxy for the rest of the world). This framework allows us to jointly assess the transmission of energy shocks, the role of exchange rate movements, and the implications for monetary policy design.

Our contribution is threefold. First, we show that energy price shocks account for a substantial fraction of short-run inflation fluctuations and play a central role in explaining the post-pandemic euro area inflation surge. Second, we demonstrate that the open economy dimension materially alters monetary policy transmission through exchange-rate movements, which directly affect imported energy prices and firms' marginal costs. As a result, the inflation-output trade-off faced by the central bank differs from that implied by standard non-energy frameworks. Third, building on the growing literature on policy counterfactuals and optimal policy projections (de Groot et al., 2021; Hebden and Winkler, 2021; McKay and Wolf, 2023), we characterize the optimal policy-rate path and compare its macroeconomic implications to those generated by the estimated historical Taylor rule for the euro area.

Following an energy price shock, the optimal policy rate path depends crucially on the weight assigned to output-gap stabilization in the loss function. For a moderate weight, the optimal path lies somewhat above the estimated rule in the short run but converges to it thereafter, delivering similar inflation and output dynamics. For a low weight — consistent with a strict price-stability objective — the path is considerably more aggressive, largely offsetting the rise in headline inflation. This effect operates primarily through a strong appreciation of the euro, which mitigates the rise in the domestic-currency price of imported energy. Given that the euro area is a net energy importer, this effect feeds through to both consumer prices and firms' marginal costs. However, the same appreciation sharply deteriorates the trade balance, so inflation stabilization is achieved at the cost of a deeper contraction in economic activity, reflecting both the tighter stance and the loss of external demand. In general, the optimal policy path also becomes more aggressive as intermediate-goods prices become more flexible: a steeper Phillips curve makes headline inflation more responsive to the indirect effects of energy prices, raising the return to a forceful response. Our results thus indicate that the extent of a *look through* approach to an energy price shock depends crucially on the degree of price stickiness in the intermediate goods sector as well as on the weight on output gap stabilization. The case for a *look through* approach to energy price shocks weakens with the degree of price flexibility and the weight on output gap stabilization.

To assess the role of energy and open-economy channels in shaping the optimal policy response, we compare the optimal interest-rate path following a price mark-up shock in the baseline open-economy model with that in a counterfactual economy that excludes both energy and exchange-rate effects.[1] In the baseline model, the optimal policy rate path lies below that implied by the estimated Taylor rule. Because the shock depresses output relatively more than it raises inflation, the central bank optimally tolerates a somewhat higher inflation peak in exchange for a milder recession, aided by a weaker real appreciation that reduces pressure on the trade balance. To isolate the importance of energy and exchange-rate channels, we then impose on the baseline model the optimal policy path derived from the counterfactual non-energy economy following an identical price mark-up shock. This path is even more accommodative, producing a smaller output contraction but a noticeably higher inflation peak. The comparison highlights the contribution of energy and exchange-rate channels in shaping the optimal inflation-output trade-off and the associated policy-rate path.

Our paper contributes to and bridges several strands of the literature. First, it builds on the New Keynesian open economy framework developed by Gali and Monacelli (2005), and extended in contributions such as Corsetti et al. (2008) and De Paoli (2009), which emphasize the role of exchange rates and international risk-sharing in monetary policy transmission. While this literature provides a tractable benchmark for analyzing open economy stabilization, it typically abstracts from energy and commodity inputs, thereby limiting its ability to analyze large terms-of-trade shocks. Second, we contribute to the large literature on oil and energy shocks. A substantial body of work shows that oil price fluctuations have sizable and state-dependent effects on macroeconomic outcomes (Hamilton, 2009; Kilian, 2008, 2009), and that their transmission depends on the underlying source of the shock as well as the policy response (Blanchard and Galí, 2010). DSGE-based analyses, such as Leduc and Sill (2004), further highlight that energy shocks generate important policy trade-offs by acting as cost-push disturbances.

More recently, Afrouzi et al. (2024) show that energy-driven relative price shocks can propagate beyond headline inflation and generate persistent movements in core inflation through production linkages and heterogeneous price rigidities. Similarly, Gagliardone and Gertler (2026) build and estimate a closed-economy model with energy (oil) for

[1] We focus on a price mark-up shock as the counterfactual economy excludes energy goods.

the United States and find that both oil shocks and policy accommodation played important roles in the post-pandemic rise in inflation. However, much of this literature is conducted in closed-economy settings or abstracts from exchange-rate dynamics. Our paper shows that in an open economy, exchange-rate movements create additional direct and indirect channels through which energy shocks affect inflation, output, and the monetary policy trade-off. Relatedly, Drechsel et al. (2026) study the design of optimal monetary policy responses to commodity price shocks in advanced and emerging market economies. Consistent with their findings, we show that when the central bank places a moderate weight on output stabilization and prices remain sufficiently sticky, a *look-through* approach to energy price shocks is optimal. At the same time, our framework highlights how the desirability of such an approach depends on the degree of price rigidity and the strength of exchange-rate transmission.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 discusses the estimation strategy and data. Section 4 reports the empirical results. Section 5 analyzes monetary policy, including the characterization of optimal policy paths. Section 6 concludes.

2 The model

In this section, we provide a full description of the model. We extend the model of Albonico et al. (2024) in two dimensions, namely in allowing for energy goods in consumption and output and in considering a small open economy setup. We model the small open economy in the spirit of Gali and Monacelli (2005) and Justiniano and Preston (2010). Specifically, the domestic small open economy is of measure one, while the rest of the world behaves similarly to a closed economy. The domestic economy exports domestically produced intermediate goods to the rest of the world while it imports energy goods which are assumed to be an endowment. The household sector consists of two types, namely Ricardian (or optimizing), representing fraction $1-\theta$ of the population, and rule-of-thumb (RoT) households, representing fraction θ, respectively. Labor unions representing each type of labor set nominal wages infrequently leading to wage stickiness and a wage Phillips curve. On the supply side of the economy, there are two sectors, namely a final goods and an intermediate goods sector. The government runs a balanced budget on all dates, adjusting the collected lump-sum taxes from both types of households to finance its expenditures. Finally, the central bank sets the nominal interest rate according to a Taylor rule.

2.1 Households

Both Ricardian, denoted by o, and RoT households, denoted by rt consume *core* (non-energy) and energy final goods. The consumption basket thus, C_t^k, of household type $k = \{o, rt\}$, is a composite of *core* consumption goods, $C_{q,t}^k$, and imported commodity goods, X_t^k:

$$C_t^k = \left[(1-\mu)^{\frac{1}{\eta}} \left(C_{q,t}^k\right)^{\frac{\eta-1}{\eta}} + (\mu)^{\frac{1}{\eta}} \left(X_t^k\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} . \tag{1}$$

where $\mu \in [0,1]$ measures the share of commodity goods in the consumption basket and η the elasticity of substitution between core consumption goods and energy goods. The core consumption goods, $C_{q,t}$, are purchased from core consumption goods firms and are produced only domestically. Expenditure minimization leads to the corresponding demand schedules for core and energy goods of each household type:

$$C_{q,t}^k = (1-\mu)\left(\frac{P_t}{P_{CPI,t}}\right)^{-\eta} C_t^k, \tag{2}$$

$$X_t^k = \mu\left(\frac{\varepsilon_t P_{x,t}^*}{P_{CPI,t}}\right)^{-\eta} C_t^k. \tag{3}$$

for $k = \{o, rt\}$, where P_t is the price of *core* goods, $P_{x,t}^*$ is the price of energy goods denominated in foreign currency, while ε_t is the nominal effective exchange rate defined as the domestic currency price of a basket of foreign currencies.[2] $P_{CPI,t}$ is the headline index defined as:

$$P_{CPI,t} = \left[(1-\mu)\left(P_t\right)^{1-\eta} + \mu\left(\varepsilon_t P_{x,t}^*\right)^{1-\eta}\right]^{\frac{1}{1-\eta}} . \tag{4}$$

We follow Haque et al. (2021) and assume that energy goods are an imported endowment whose price relative to the price of the *core* goods is defined as $s_t \equiv \varepsilon_t P_{x,t}^*/P_t$. We decompose the relative price of energy goods further, by defining the foreign (or world) relative price of energy, $s_t^* = P_{x,t}^*/P_{CPI,t}^*$, where $P_{CPI,t}^*$ is the foreign headline price index. Diving both sides of (4) by P_t, yields

$$\frac{P_{CPI,t}}{P_t} = \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{1}{1-\eta}} . \tag{5}$$

Moreover, defining the real exchange rate as $ReR_t = \varepsilon_t P_{CPI,t}^*/P_{CPI,t}$, the home relative

[2] Since we consider a small open economy model for the euro area, we treat the foreign block as the rest of the world, giving thereby the nominal exchange rate the interpretation of the nominal effective exchange rate.

price of energy can be written as follows:

$$\left[\frac{\varepsilon_t P_{x,t}^*}{P_{CPI,t}}\right] = s_t \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} = ReR_t s_t^* \tag{6}$$

where s_t^* follows a log-stationary AR(1) process. The determination of the price of *core* goods, P_t, is discussed in the description of the intermediate goods sector below. We now turn to the optimization problems of the two types of households.

2.1.1 Ricardian households

The Ricardian households consume final core and energy goods exhibiting external habits in the aggregate consumption, C_t, supply labor, h_t^o,[3] to the intermediate goods firms, hold one-period domestic nominal government bonds that are in zero net supply, B_t^o, foreign one-period bonds, $B_t^{o,*}$, issued in the foreign currency and invest in physical capital, K_t^o. They also pay lump-sum taxes, T_t^o. Their utility is separable in consumption and leisure. Thus, they maximize their lifetime utility:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{1-\sigma} \left[c_t^o - (\varepsilon_{FS,t} - 1) - b\left(c_{t-1} - (\varepsilon_{FS,t-1} - 1)\right) \right]^{1-\sigma} - \frac{(h_t^o)^{1+\phi_l}}{1+\phi_l} \right\} \tag{7}$$

subject to their budget constraint:

$$\begin{aligned} &P_{CPI,t} C_t^o + P_t I_t^o + \frac{B_{t+1}^o}{\varepsilon_{b,t} R_t} + \frac{\varepsilon_t B_{t+1}^{o,*}}{(1-\psi_t(\varepsilon B^*; \varepsilon_{\psi,t})) R_t^*} \\ &= B_t^o + \varepsilon_t B_t^{o,*} + h_t^d \int_0^1 W_t^j \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj + P_{CPI,t} d_t^o + \left[R_t^k u_t^o - a\left(u_t^o\right) P_t\right] K_t^o - T_t^o \end{aligned} \tag{8}$$

and the capital accumulation equation:

$$K_{t+1}^o = (1-\delta) K_t^o + \varepsilon_{I,t} \left[1 - S\left(\frac{I_t^o}{I_{t-1}^o}\right)\right] I_t^o \tag{9}$$

where β is the subjective discount factor, σ is the degree of relative risk aversion, ϕ_l, is the inverse of the Frisch elasticity of labor supply, b is the degree of habit formation,

[3] We outline the labor market structure in section 2.3 below.

and δ the capital depreciation rate. W_t denotes the nominal wage, d_t^o are real dividends $(\frac{D_t^o}{P_{CPI,t}})$ from intermediate good firm ownership, and R_t is the gross nominal interest rate on one-period domestic nominal government bonds. R_t^* is the gross nominal interest rate on one-period foreign nominal government bonds.[4] Note that c_t^o represents the stationary (detrended) level of Ricardian households' real consumption and is defined as $c_t^o \equiv C_t^o/z_t$, where z_t represents the labor-augmenting permanent technology shock as further described below. Similarly, $c_t \equiv C_t/z_t$. We borrow from Cardani et al. (2022) and introduce a *forced savings* shock, $\varepsilon_{FS,t}$. The *forced savings* shock allows us to capture the sharp decline in private consumption during the COVID-19 episode. $\varepsilon_{b,t}$ is a risk premium shock on home bonds and $\varepsilon_{I,t}$ an investment-specific shock, each following a stationary $AR(1)$ log-process. I_t^o and R_t^k denote investment in physical capital and the rental rate of capital respectively, while u_t^o denotes capital utilization while the process for $a(u_t^o)$ is specified as follows:

$$a\left(u_t^o\right) = \gamma_{u1}\left(u_t^o - 1\right) + \frac{\gamma_{u2}}{2}\left(u_t^o - 1\right)^2 \tag{10}$$

The function $S(.)$ in (9) captures investment adjustment costs and is a quadratic function in investment in physical capital:

$$S\left(\frac{I_t^o}{I_{t-1}^o}\right) = \frac{\gamma_I}{2}\left(\frac{I_t^o}{I_{t-1}^o} - g_z\right)^2 \tag{11}$$

Following Benigno (2009), Schmitt-Grohe and Uribe (2003) and Justiniano and Preston (2010), function $\psi_t(.)$ attached to foreign bonds has the interpretation of a debt elastic interest rate premium and is specified as follows:

$$\psi_t(\varepsilon B^*; \varepsilon_{\psi,t}) = \chi\left(exp\left(\frac{\varepsilon_t B_t^*}{P_{CPI}GDP} - b_y^*\right) - 1\right) - \varepsilon_{\psi,t}, \tag{12}$$

where the debt elastic premium depends on the economy-wide net foreign asset position, B_t^*. Specifically, the premium depends on the real quantity of outstanding foreign debt expressed in terms of domestic currency as a share of steady state gross domestic product, GDP. $\varepsilon_{\psi,t}$ is a foreign risk premium shock and b_y^* denotes the steady state net foreign asset holdings as a share of gross domestic product.[5]

[4] Foreign bond holdings, $B_t^{o,*}$ should be thought of as a portfolio of foreign riskless short-term assets.

[5] The full derivation of the first order conditions of the household maximization problem is provided in Appendix A.

2.2 Rule-of-Thumb households

Rule-of-Thumb households are excluded from financial markets. They consume core and energy goods with their total consumption given by, C_t^{rt}, and supply labor, h_t^{rt}, to intermediate goods firms, while they also pay lump-sum taxes, T_t^{rt}. They thus have a static optimization problem, maximizing their period utility:

$$U_t^{rt} = \frac{1}{1-\sigma}\left(c_t^{rt} - bc_{t-1}\right)^{1-\sigma} - \frac{\left(h_t^{rt}\right)^{1+\phi_l}}{1+\phi_l} \tag{13}$$

subject to their period budget constraint:

$$P_{CPI,t}C_t^{rt} = h_t^d \int_0^1 W_t^j \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj - T_t^{rt} + P_{CPI,t}z_t\Big[\left(\varepsilon_{FS,t}-1\right) - \frac{1}{6}\sum_{i=8}^{13}\left(\varepsilon_{FS,t-i}-1\right)\Big] \tag{14}$$

whose consumption is determined by their budget constraint above, which binds in every period t, except during the COVID-19 pandemic. Following Cardani et al. (2022), we assume that during this episode these liquidity constraint households also accumulate *forced savings*, as captured by $\varepsilon_{FS,t}$, that will be spent gradually when exiting from the pandemic.

2.3 Labor market

We consider a continuum of unions, each of which represents a certain labor type j. Following Colciago (2011) Wage decisions are made by labor type specific unions j. Effective labor input hired by firm z is a CES function of the quantities of the different labor types employed,

$$h_t^z = \left(\int_0^1 (h_t^{j,z})^{\frac{1}{1+\lambda_{w,t}}} dj\right)^{1+\lambda_{w,t}} \tag{15}$$

where $\lambda_{w,t}$ stands for the possibly time-varying wage net markup. Each union j sets W_t^j, households supply as many hours to the labor market j, so that

$$h_t^j = \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} h_t^d \tag{16}$$

where h_t^d is aggregate labor demand from intermediate goods firms.

We follow Gali et al. (2007) and assume the fraction of rule-of-thumb and Ricardian consumers is uniformly distributed across worker types (and hence across unions) so that aggregate demand for labor type j is split uniformly across the households. This means that both types of households $i = \{o, rt\}$ work the same number of hours (even if that is not optimal for them, because they would be willing to trade given the different consumption levels) because of the union structure. Hence, $h_t^o = h_t^{rt} = h_t$. The individual hours worked are therefore common across households. Note this is also then the total demand for labor because the sum of the two households have measure one, as usual, so from the point of view of hours worked is as if we are in a representative agent framework:

$$h_t^i = h_t = \int_0^1 h_t^j dj \qquad \text{for } i = \{o, rt\}.$$

Combining this expression with (16):

$$h_t = h_t^d \int_0^1 \left(\frac{W_t^j}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj.$$

The common labor income is given by: $h_t^d \int_0^1 W_t^j \left(\frac{W_t^j}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj.$

2.3.1 Wage setting

Wages are staggered à la Calvo (1983). Union j receives permission to optimally reset the nominal wage with probability $(1 - \xi_w)$. Those unions which cannot reset the wage adjust it according to the following scheme:

$$W_t^j = g_{z,t} \pi_{CPI,t-1}^{\chi_w} \bar{\pi}_{CPI}^{1-\chi_w} W_{t-1}^j$$

where $\pi_{CPI,t} = \frac{P_{CPI,t}}{P_{CPI,t-1}}$ and $\bar{\pi}_{CPI} = \pi_{CPI}$ is steady state CPI inflation (or trend inflation). Therefore, these wages are partially indexed to the economy-wide growth trend $(g_{z,t})$, past inflation and trend inflation (with χ_w capturing the degree of indexation to past inflation).

The union for type j that sets optimally the wage $\tilde{W}_t^j$ at a generic period t maximizes the weighted sum of the expected discounted utilities of the Ricardian and the Rule-of-Thumb households. We provide a full derivation of the maximization problem of the union in Appendix A. Given Calvo wage stickiness, the aggregate wage index W_t of the union reads as follows:

$$W_t = \left[\xi_w \left(g_{z,t} \pi_{CPI,t-1}^{\chi_w} \bar{\pi}_{CPI}^{1-\chi_w} W_{t-1} \right)^{\frac{1}{\lambda_{w,t}}} + (1 - \xi_w) \left(\tilde{W}_t \right)^{\frac{1}{\lambda_{w,t}}} \right]^{\lambda_{w,t}}$$

2.4 Final goods firms

Final good firms are perfectly competitive producing a final good, Q_t, which they sell only domestically. To produce the final good, they combine a continuum of domestic intermediate goods $y_{H,t}^z$ using a Dixit-Stiglitz aggregator:

$$Q_t = \left(\int_0^1 \left(y_{H,t}^z \right)^{\frac{1}{1+\lambda_{p,t}}} dz \right)^{1+\lambda_{p,t}} \tag{17}$$

where $\lambda_{p,t}$ is the price net markup, which is assumed to be a stationary $AR(1)$ process. Taking as given prices P_t and P_t^z, the final goods producing firms maximize profits by choosing quantities $y_{H,t}^z$

$$\max_{y_{H,t}^z} P_t Q_t - \int_0^1 P_t^z y_{H,t}^z dz$$

subject to the production function (17). This optimization problem yields the following first order condition for each variety z, implying that the demand for the individual intermediate good $y_{H,t}^z$ depends negatively in the relative price and positively on the domestic aggregate demand:

$$y_{H,t}^z = \left(\frac{P_t^z}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Q_t. \tag{18}$$

2.5 Intermediate goods firms

Intermediate firms z are monopolistically competitive and use as inputs capital services, $u_t^z K_t^z$, labor services, h_t^z, and commodity goods, X_t^z. The production technology reads as follows:

$$Y_t^z = \varepsilon_{a,t} \left\{ (1 - \alpha_x)^{\frac{1}{\epsilon}} \left[(u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right]^{\frac{\epsilon-1}{\epsilon}} + \alpha_x^{\frac{1}{\epsilon}} (X_t^z)^{\frac{\epsilon-1}{\epsilon}} \right\}^{\frac{\epsilon}{\epsilon-1}} - z_t \Phi \tag{19}$$

where α_x denotes the share of commodity goods used in the production process and ϵ is the constant elasticity of substitution between the capital-labor bundle and the commodity inputs. The capital-labor bundle is assumed to be produced with a Cobb-Douglas function, with α denoting the capital services' share. $\varepsilon_{a,t}$ represents a (stationary) technology shock, Φ are fixed costs of production[6] and z_t represents the labor-augmenting permanent technology shock. The growth rate of z_t, $g_{z,t}$ is stationary and in the estimation we assume it is constant.

2.5.1 Price setting

Prices are sticky à la Calvo (1983). Firm z receives permission to optimally reset its price with probability $(1-\xi_p)$. The firm can also export its good abroad. It sets one price for its good regardless of the destination market, engaging thus in producer currency pricing. This means that the law of one price holds. Those firms which cannot reset the price adjust it according to the following scheme:

$$P_t^z = \pi_{t-1}^{\chi_p} \bar{\pi}^{1-\chi_p} P_{t-1}^z$$

where $\bar{\pi}$ is the gross inflation objective. Since the representative intermediate good firm sells its good both domestically and abroad it faces a domestic and a global demand. The domestic demand is given by (18) while, along the lines of Justiniano and Preston (2010) the global demand for firm z's good is given by:

$$y_{H,t}^{*,z} = \left(\frac{P_t^z}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} ReR_t^{\nu} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\nu}{1-\eta}} Y_t^*. \tag{20}$$

Parameter ν denotes the elasticity of substitution between home and foreign goods. We can write the total demand for the intermediate variety z as:

$$Y_t^z = y_{H,t}^z + y_{H,t}^{*,z} \tag{21}$$

and combining the expressions for the demand functions (18) and (20) we can rewrite the total demand for variety z as follows:

$$Y_t^z = \left(\frac{P_t^z}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \underbrace{\left[Q_t + ReR_t^{\nu} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\nu}{1-\eta}} Y_t^*\right]}_{\equiv Y_t^D} \tag{22}$$

Firms maximize the expected discounted sum of their profits by choosing the optimal

[6] Fixed costs are scaled by trend growth to ensure stationarity.

relative price, $\tilde{P}_t^z \equiv \frac{P_t^z}{P_t}$. The maximization problem thus of the firm reads as follows:

$$\max_{\tilde{P}_t^z} E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \frac{\Lambda_{t+s}^o}{\Lambda_t^o} \left[\frac{\tilde{P}_t^z \pi_{t,t+s-1}^{\chi_p} \bar{\pi}^{s(1-\chi_p)}}{P_{t+s}} Y_{t+s}^z - \frac{MC_{t+s}^z}{P_{t+s}} Y_{t+s}^z \right]$$

subject to

$$Y_{t+s}^z = \left(\frac{\tilde{P}_t^z \pi_{t,t+s-1}^{\chi_p} \bar{\pi}^{s(1-\chi_p)}}{P_{t+s}} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \underbrace{\left[Q_{t+s} + ReR_{t+s}^{\nu} \left((1-\mu) + \mu s_{t+s}^{1-\eta} \right)^{\frac{\nu}{1-\eta}} Y_{t+s}^* \right]}_{\equiv Y_{t+s}^D} \tag{23}$$

where $\pi_{t,t+s-1} = \{1 \text{ for } s = 0, \pi_t \cdot \pi_{t+1} \cdot ... \cdot \pi_{t+s-1} \text{ for } s = 1, 2....\}$. Full derivation of the first order conditions are provided in the online Appendix A.

2.6 Fiscal and Monetary policy

We assume that the government runs a balanced budget on all dates, adjusting lump-sum taxes to finance its expenditures fully:

$$T_t = P_t G_t, \tag{24}$$

where we make a simplifying assumption that the government buys only non-energy goods. The law of motion of G_t is discussed in section 3 below.

The monetary authority sets the nominal interest rate according to a standard Taylor rule with some degree of interest rate smoothing:

$$\frac{R_t}{R} = \varepsilon_{R,t} \left(\frac{R_{t-1}}{R} \right)^{\phi_R} \left[\left(\frac{\pi_{CPI,t}}{\pi_{CPI}} \right)^{\phi_\pi} \left(\frac{GDP_t}{GDP_t^f} \right)^{\phi_y} \right]^{1-\phi_R} \tag{25}$$

where GDP_t represents the gross domestic product in this economy and GDP_t^f denotes the level of output in the absence of nominal price and wage rigidities, while $\varepsilon_{R,t}$ is an *i.i.d.* monetary policy shock.

2.7 Aggregation and market clearing

Aggregation in the labor market results in the following expression:

$$\begin{aligned} h_t &= \int_0^1 h_t^j dj \\ &= h_t^d \int_0^1 \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj \\ &= s_{W,t} h_t^d \end{aligned}$$

where $s_{W,t} = \int_0^1 \left(\frac{W_t^j}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} dj$ is wage dispersion across the differentiated labor services.

Aggregation in the market for physical capital yields, with the utilization rate being common across firms:

$$u_t K_t = u_t \int_0^1 K_t^z dz.$$

Aggregation in the home goods market yields the following market clearing condition:

$$Y_t = s_{P,t} Y_t^D = s_{P,t} \left[Q_t + ReR_t^{\nu} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\nu}{1-\eta}} Y_t^* \right]. \tag{26}$$

where $s_{P,t} = \int_0^1 \left(\frac{P_t^z}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}}$ is the price dispersion across differentiated goods and Y_t^D has been defined in equation (22) above.

Final good output is used for investment and non-energy consumption goods:

$$Q_t = C_{q,t} + I_t + G_t. \tag{27}$$

In nominal terms, we obtain:

$$P_t Y_t^D = \int_0^1 P_t^z Y_t^z dz.$$

Note that both $s_{W,t}$ and $s_{P,t}$ vanish in the log-linearized version of the model. Firms' aggregate demand for the commodity good is given by:

$$X_t^f = \int_0^1 X_t^z dz = \int_0^1 \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} \left(\frac{MC_t^z}{\varepsilon_t P_{x,t}^*}\right)^{\epsilon} \left(Y_t^z + z_t\Phi\right) dz$$
$$= \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} mc_t^{\epsilon} s_t^{-\varepsilon} \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{\varepsilon}{1-\eta}} \left(s_{P,t} Y_t^D + z_t\Phi\right) \tag{28}$$

where using the symmetry of equilibrium, $MC_t^z = MC_t$, and in the last equality we have made use of the definition of the real marginal cost, $mc_t = MC_t/P_{CPI,t}$, the headline price index equation (5), and the relative price of energy, $s_t = \varepsilon_t P_{x,t}^*/P_t$. Equilibrium in the commodity goods market:

$$X_t = \theta X_t^{rt} + (1-\theta) X_t^o + X_t^f$$

Rewriting using the optimal demand schedules for households and firms:

$$X_t = \theta\mu \left(\frac{\varepsilon_t P_{x,t}^*}{P_{CPI,t}}\right)^{-\eta} C_t^{rt} + (1-\theta)\mu \left(\frac{\varepsilon_t P_{x,t}^*}{P_{CPI,t}}\right)^{-\eta} C_t^o + X_t^f$$
$$= \mu s_t^{-\eta} \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{\eta}{1-\eta}} C_t + \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} mc_t^{\epsilon} s_t^{-\varepsilon} \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{\varepsilon}{1-\eta}} \left(s_{P,t} Y_t^D + z_t\Phi\right) \tag{29}$$

where we have used the headline price index equation (5) and the definition of aggregate consumption, $C_t = \theta C_t^{rt} + (1-\theta) C_t^o$.

Finally, equilibrium in home bond market requires:

$$\int_0^{1-\theta} B_t^o do = 0. \tag{30}$$

Since Ricardian households also hold foreign bonds, $B_t^{o,*}$, note that foreign bond market clearing is handled in the Net foreign assets section below.

The main macroeconomic variables are summarized as follows:

$$
\begin{aligned}
C_t &= \theta C_t^{rt} + (1-\theta) C_t^o \\
C_{q,t} &= \theta C_{q,t}^{rt} + (1-\theta) C_{q,t}^o \\
h_t &= \theta h_t^{rt} + (1-\theta) h_t^o \\
K_t &= (1-\theta) K_t^o \\
I_t &= (1-\theta) I_t^o \\
D_t &= (1-\theta) D_t^o \\
T_t &= \theta T_t^{rt} + (1-\theta) T_t^o \\
X_t &= \theta X_t^{rt} + (1-\theta) X_t^o + X_t^f .
\end{aligned}
$$

2.8 Net foreign assets and resource constraint

The domestic economy's net foreign assets equal the economy-wide net holdings of foreign bonds (denominated in foreign currency) and evolve according to the following expression:

$$\frac{B_{t+1}^*}{R_t^*} = B_t^* + \frac{TB_t}{\varepsilon_t} \tag{31}$$

where:

$$TB_t = P_t y_{H,t}^* - \varepsilon_t P_{x,t}^* X_t \tag{32}$$

where $y_{H,t}^* = \int_0^1 y_{H,t}^{*,z} dz$ is the foreign demand for the home-produced intermediate goods, see equation (20). Combining the market clearing conditions, together with the budget constraints of the two types of households, the budget constraint of the government, and the law of motion of net foreign assets, we arrive at the economy's resource constraint:

$$
\begin{aligned}
& C_t + \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} (G_t + I_t) + \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1-\nu}{\eta-1}} ReR_t^{\nu} Y_t^* - s_t \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} X_t \\
&= \left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} GDP_t - \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} a(u_t) K_t \\
&+ z_t \theta \Big[(\varepsilon_{FS,t} - 1) - \frac{1}{6} \sum_{i=8}^{13} (\varepsilon_{FS,t-i} - 1) \Big]
\end{aligned}
\tag{33}
$$

Finally, we define the GDP deflator, $P_{GDP,t}$, from:

$$P_t \equiv \left[(1-\alpha_x) P_{GDP,t}^{1-\epsilon} + \alpha_x \left(\varepsilon_t P_{x,t}^* \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}} \tag{34}$$

which implies that value-added, or GDP, is defined as:

$$\left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x} \right)^{\frac{1}{1-\epsilon}} GDP_t = \left((1-\mu) + \mu s_t^{1-\eta} \right)^{\frac{1}{\eta-1}} \left(s_{P,t} Y_t^D - s_t X_t^f \right) \tag{35}$$

or,

$$\left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x} \right)^{\frac{1}{1-\epsilon}} GDP_t = s_{P,t} Y_t^D - s_t^{1-\epsilon} \alpha_x \left(\varepsilon_{a,t} \right)^{\epsilon-1} mc_t^{\epsilon} \left((1-\mu) + \mu s_t^{1-\eta} \right)^{\frac{\epsilon}{1-\eta}} \left(s_{P,t} Y_t^D + z_t \Phi \right) \tag{36}$$

2.9 Foreign block

Similar to Justiniano and Preston (2010), we assume that the foreign block is exogenous such that $Y_t^* = C_t^*$. The model is closed assuming foreign demand, $y_{H,t}^*$, for the domestically produced intermediate good as specified in (20). This demand function is standard in small open economy models (see Kollmann, 2002; McCallum and Nelson, 2000). Since the foreign block is treated as a closed economy not importing a commodity good, we have that $P_{CPI,t}^* = P_{GDP,t}^*$. We take the foreign block as exogenous and assume that foreign output (in log-linear terms), $\hat{Y}_t^*$, foreign CPI inflation, π_t^*, and the foreign interest rate (in log-linear terms), $\hat{R}_t^*$, each follows a stationary AR(1) process.

3 Estimation

We estimate the model over the sample period 1999:Q1 to 2023:Q4 using Bayesian techniques. Given the small open economy setting, we estimate the model on quarterly euro area and US data, the latter as a proxy for the rest of the world. Specifically, our data set consists of the following euro area series: the growth rate in real (per-capita) GDP, consumption, investment and wages, hours worked (log, demeaned and HP filtered), headline (HICP) and core (HICP excluding energy) inflation rates, and the shadow rate estimate from Krippner (2013) (as an indicator for the European Central Bank's effective monetary policy stance; demeaned). Additionally, for the foreign block (using US as a proxy) we use the following data series: the growth rate in real (per-capita) US GDP, headline US (CPI) inflation rate, the US shadow rate estimate from

Krippner (2013) (as an indicator for the Federal Reserve Board's effective monetary policy stance; demeaned), and the real exchange rate (euro/dollar, demeaned).[7]

The measurement equations that relate the macroeconomic data (observables) to the endogenous variables of the model read as follows:

$$\begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINV_t \\ dlWAG_t \\ lHOURS_t^{gap} \\ dlHICP_t \\ dlHICPxEn_t \\ SIR_t \\ dlGDP_t^{US} \\ dlCPI_t^{US} \\ SIR_t^{US} \\ dlReR_t \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \bar{\pi} \\ \bar{\pi} \\ 0 \\ 0 \\ \bar{\pi} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \widehat{gdp}_t - \widehat{gdp}_{t-1} \\ \widehat{c}_t - \widehat{c}_{t-1} \\ \widehat{i}_t - \widehat{i}_{t-1} \\ \widehat{w}_t - \widehat{w}_{t-1} \\ \widehat{h}_t \\ \widehat{\pi_{cpi,t}} \\ \widehat{\pi}_t \\ \widehat{R}_t \\ \widehat{gdp}_t^* - \widehat{gdp}_{t-1}^* \\ \widehat{\pi_{cpi,t}^*} \\ \widehat{R}_t^* \\ \widehat{ReR}_t - \widehat{ReR}_{t-1} \end{bmatrix}, \tag{37}$$

where $\bar{\pi}$ is the quarterly steady-state net inflation rate (assuming the same level in foreign block). Note that *dl* denotes the percentage change measured as log difference, l denotes the log, and hatted variables denote log deviations from steady state.

We consider twelve shock processes in the estimation. The first seven are the same as in Smets and Wouters (2007): a stationary technology shock, a risk premium shock, an investment shock, a price and a wage markup shock, a monetary policy shock, and a government spending shock. The first five shocks are assumed to follow autoregressive processes of order 1, AR(1), with i.i.d. normally distributed innovations. The two markup shocks also have a MA(1) component. The monetary policy shock is assumed to be i.i.d., while the government spending shock is also correlated with the technology shock as in Smets and Wouters (2007). We also include an energy price shock which follows an AR(1) process. Turning to the foreign block, we include *foreign* demand, cost-push, monetary policy and exchange rate shocks. Moreover, as explained in subsection 2.1.1, we also consider a forced savings shock, which is assumed to be i.i.d. and allows us to capture the sharp decline (and its subsequent rebound) in private consumption

[7] We also demean real (per-capita) GDP, consumption, investment and wages prior to estimation.

Table 1: Calibrated parameters

Parameter	Description	Value
β	discount factor	0.9975
δ	depreciation rate	0.025
$\frac{1}{\lambda_p - 1}$	steady state net price markup	0.33
g_{GDP}	government spending-to-GDP ratio	0.32
crt/co	steady state consumption ratio between the two HHs' types	1
μ	energy share in consumption basket (OECD ICIO tables, 2021)	0.05
ε	EoS between energy and non-energy inputs in production	0.55
ν	EoS between home and foreign goods	1.5
α	capital share	0.3
α_x	energy share in production	0.04
s	steady state relative price of energy goods	1
Φ	fixed production costs (taken from EAGLE for the EA)	0.30
by_s	steady state net foreign assets (share of GDP)	0
χ	elasticity in the transaction cost function on foreign bond holdings	0.01
ρ^p_{ma}	moving average component of price markup shocks	0.5
ρ^w_{ma}	moving average component of wage markup shocks	0.5

Notes: Own assumptions. Most of the calibrated values are borrowed from the literature.

during the COVID-19 pandemic.[8]

3.1 Calibration and priors

Some of the parameters are calibrated, while the rest are estimated using standard Bayesian methods. Table 1 lists the values of all calibrated parameters. Most of these parameters are standard. The discount factor β is calibrated to be 0.9975, which implies a steady-state real interest rate of 1.8 percent in annual terms at the prior mean. The depreciation rate of capital δ is fixed at 0.025, while the capital share used in production is 30%. The elasticity of the demand for goods λ_p is 4, which implies a steady state net price markup of 33%. Government spending-to-GDP ratio is set to 32%, in line with its sample mean. We assume that the steady state consumption ratio between the Rule-of-Thumb and Ricardian households is 1. The share of energy goods in the consumption basket is calibrated based on the OECD's Inter-Country Input-Output tables (2021 edition). The parameter a_x in the production function is calibrated so that the share of energy input over production, i.e., $\frac{x^f}{y}$, is equal to 5%. The elasticity of substitution (EoS) between energy and non-energy inputs in the production function of intermediate goods producers is set to 0.55, which is close to Coenen et al. (2024) and Garcia et al.

[8]The forced savings shock is active only during 2020:Q1–2022:Q4, with its innovation variance restricted to zero outside this period.

(2026). The elasticity of substitution between home and foreign goods is set to 1.5 in line with other open-economy studies (Corsetti et al., 2008; Gali and Monacelli, 2005; De Paoli, 2009; Justiniano and Preston, 2010). The steady state relative price of energy goods is set to 1, while the net foreign assets position (as a share of GDP) is assumed to be 0 in steady state. The moving average components of both price and wage markup shocks are calibrated to 0.5.

Table 2 reports the prior distributions for the structural parameters (top panel) and the exogenous processes (middle and bottom panels) that drive the dynamics of the economy. Starting with the parameters describing the monetary policy rule, the reaction to inflation and the output gap are described by a Gamma prior distribution with mean 1.7 and 0.12, and standard deviations of 0.25 and 0.05, respectively. The interest rate smoothing parameter is assumed to follow a Beta prior distribution around a mean of 0.75 with a standard deviation of 0.1. The relative risk aversion parameter is assumed to be Normal around a mean of 1.5 with a standard deviation of 0.1, the inverse Frisch elasticity of labour supply is described by a Gamma prior distribution with mean 2 and standard deviation of 0.5, while the habit parameter is assumed to fluctuate according to a Beta prior distribution around a 0.5 mean with a 0.1 standard deviation. The prior of investment adjustment costs is described by a Gamma distribution with mean 4 and a standard deviation of 1, while the capital utilization elasticity is assumed to follow a Beta distribution with prior mean 0.5 and a standard deviation of 0.15. The parameters describing the price and wage setting are borrowed from Smets and Wouters (2007), implying an average length of price and wage adjustments of half a year. The prior mean for the share of RoT consumers, θ, is based on the euro-area estimates reported by Slacalek et al. (2020).

3.2 Posterior estimates

Table 2 presents the posterior distributions of the structural parameters. The estimated monetary policy rule implies a relatively strong response to inflation, with the posterior mean of the inflation coefficient ϕ_π equal to 2.09. The response to the output gap is modest, with ϕ_Y estimated at 0.06, indicating that monetary policy mainly focuses on inflation stabilization, which is in line with the ECB's primary objective of price stability. Interest rate smoothing is pronounced, with a high degree of gradualism in policy adjustments.

Turning to preferences and nominal rigidities, the estimated coefficient of relative risk aversion σ is 1.53, broadly consistent with standard calibrations. The estimate of

Table 2: Prior and posterior distribution of parameters

Parameter		Prior distribution			Posterior distribution			
		Distribution	Mean	St. dev.	Mode	Mean	90% HPD	
TR response to inflation	ϕ_π	Gamma	1.70	0.25	2.07	2.09	1.72	2.44
TR response to output gap	ϕ_Y	Gamma	0.12	0.05	0.05	0.06	0.02	0.10
TR interest rate smoothing	ϕ_R	Beta	0.75	0.10	0.91	0.91	0.89	0.93
Relative risk aversion	σ	Normal	1.50	0.10	1.55	1.53	1.37	1.68
Inverse Frisch elasticity	ϕ_l	Gamma	2.00	0.50	1.26	1.50	0.89	2.10
Habits	b	Beta	0.50	0.10	0.36	0.37	0.33	0.42
Investment adjustment costs	γ_I	Gamma	4.00	1.00	4.06	4.68	3.29	6.04
Calvo price stickiness	ξ_p	Beta	0.50	0.10	0.91	0.91	0.88	0.93
Calvo wage stickiness	ξ_w	Beta	0.50	0.10	0.62	0.64	0.58	0.70
Price indexation	χ_p	Beta	0.50	0.15	0.80	0.75	0.58	0.92
Wage indexation	χ_w	Beta	0.50	0.15	0.18	0.20	0.08	0.33
Capital utilization elasticity	σ_u	Beta	0.50	0.15	0.72	0.72	0.60	0.83
RoT share	θ	Beta	0.22	0.10	0.07	0.09	0.04	0.13
EoS btw energy and core consumption goods	η	Gamma	0.50	0.20	0.49	0.51	0.22	0.79
Steady-state inflation	$\overline{\pi}$	Gamma	0.50	0.10	0.50	0.50	0.42	0.58
Shocks persistence								
Risk premium	ρ_b	Beta	0.50	0.20	0.82	0.80	0.74	0.87
Investment specific	ρ_i	Beta	0.50	0.20	0.14	0.20	0.04	0.34
Price markup	ρ_p	Beta	0.50	0.20	0.59	0.61	0.51	0.72
Wage markup	ρ_w	Beta	0.50	0.20	0.97	0.96	0.92	0.99
Government spending	ρ_g	Beta	0.30	0.20	0.93	0.93	0.89	0.96
Productivity	ρ_a	Beta	0.50	0.20	0.41	0.40	0.28	0.53
Energy price	ρ_s	Beta	0.50	0.20	0.95	0.94	0.93	0.96
Foreign demand	ρ_{y_s}	Beta	0.50	0.20	0.90	0.90	0.83	0.96
Foreign monetary policy	ρ_{R_s}	Beta	0.50	0.10	0.91	0.91	0.88	0.93
Foreign cost-push	ρ_{π_s}	Beta	0.50	0.20	0.60	0.60	0.45	0.75
Foreign risk premium	$\rho_{\tilde{\psi}}$	Beta	0.50	0.20	0.97	0.97	0.95	0.98
Gov. spending-TFP correlation	ρ_{gy}	Normal	0.50	0.25	-0.17	-0.16	-0.46	0.14
Shocks standard deviations								
Risk premium	σ_b	Inv. Gamma	0.50	2.00	0.20	0.22	0.14	0.30
Investment specific	σ_i	Inv. Gamma	0.50	2.00	0.79	0.81	0.67	0.95
Monetary policy	σ_r	Inv. Gamma	0.50	2.00	0.13	0.13	0.11	0.14
Price markup	σ_p	Inv. Gamma	0.50	2.00	0.12	0.12	0.10	0.14
Wage markup	σ_w	Inv. Gamma	0.50	2.00	0.21	0.21	0.16	0.26
Government spending	σ_a	Inv. Gamma	0.50	2.00	2.01	2.06	1.80	2.31
Productivity	σ_g	Inv. Gamma	0.50	2.00	1.02	1.04	0.89	1.19
Energy price	σ_s	Inv. Gamma	2.00	2.00	7.25	7.38	6.52	8.22
Foreign demand	σ_{R_s}	Inv. Gamma	0.50	2.00	1.22	1.24	1.10	1.39
Foreign monetary policy	$\sigma_{\tilde{\psi}}$	Inv. Gamma	0.50	2.00	0.16	0.17	0.15	0.19
Foreign cost-push	σ_{y_s}	Inv. Gamma	0.50	2.00	0.40	0.41	0.36	0.46
Foreign risk premium	σ_{π_s}	Inv. Gamma	0.50	2.00	0.24	0.26	0.19	0.33
Forced saving	$\sigma_f s$	Inv. Gamma	0.10	0.10	2.10	2.30	1.46	3.11

Notes: Posterior means, standard deviations, and 90% highest posterior density intervals (computed as 5th and 95th percentiles) are based on two chains of 2,000,000 Metropolis-Hastings draws each, with first half of the draws discarded, and a final acceptance rate of 36%.

the habit formation parameter b suggests moderate persistence in consumption. The inverse of the Frisch elasticity of labor supply ϕ_l implies a relatively elastic labor supply. Nominal rigidities are sizeable: the Calvo probability of not adjusting prices is estimated at 0.91, while nominal wage rigidity is somewhat lower at 0.64. The degree of backward-looking behavior is stronger in price-setting ($\chi_p = 0.75$) than in wage-setting ($\chi_w = 0.20$).

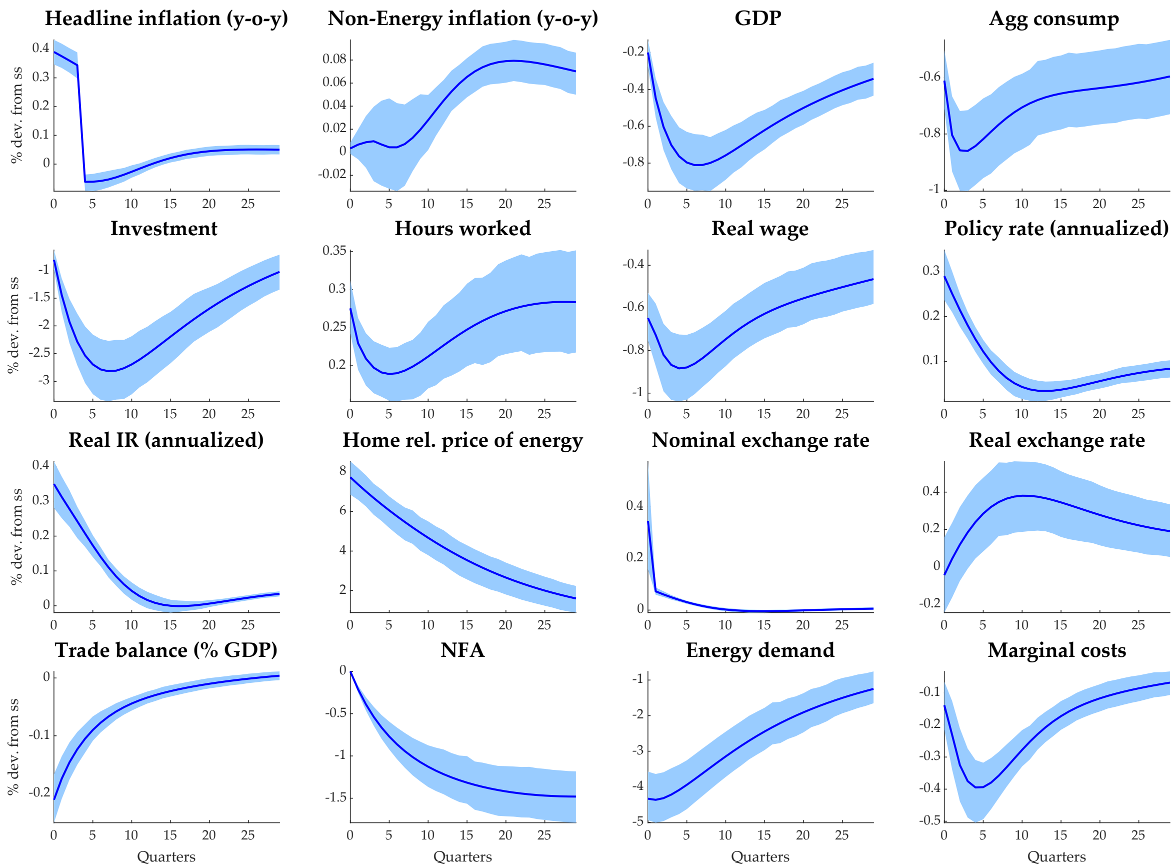
Estimates related to investment dynamics and capital utilization suggest important real rigidities. The estimate of the investment adjustment cost parameter γ_I points to a notable degree of inertia in capital formation. The share of rule-of-thumb households θ is estimated at 9%, implying that about one in ten households consume out of current income in the euro area.

The model also features energy and open economy dimensions, both of which are critical for understanding recent euro area inflation dynamics. The elasticity of substitution between core and energy goods in consumption η is estimated to be around 0.51, suggesting low substitutability.

The estimated shock processes are generally highly persistent. Of particular relevance for our analysis, energy-price shocks exhibit substantial persistence ($\rho_s = 0.94$), suggesting that energy-market disturbances can have long-lasting effects on inflation dynamics. Persistence is also high for wage-markup, government-spending, and foreign-sector shocks, underscoring the importance of both domestic and external sources of macroeconomic fluctuations in the euro area. Turning to the shock volatilities, the energy-price shock stands out with a posterior standard deviation of 7.38, substantially larger than that of any other disturbance in the model. This finding highlights the exceptional volatility of energy markets over the sample period and is consistent with the prominent role of energy shocks in driving recent inflation developments. The standard deviations of other shocks, such as monetary policy, markup, and productivity disturbances, are within typical ranges found in the literature.

Overall, the estimated parameters highlight the importance of price and wage rigidities, and exogenous disturbances – particularly energy shocks – in shaping the euro area's inflation and output dynamics. These features are essential for replicating the observed macroeconomic responses and assessing the transmission of monetary policy in an open economy framework.

Figure 1: Impulse response functions to an adverse energy price shock



Notes: The solid blue lines represent responses of selected key variables at the posterior mean with the shaded blue areas capturing the 90% credible intervals (computed as 5th and 95th percentiles) to a one standard deviation adverse energy price shock. Positive values of the exchange rate imply a depreciation of the euro. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

4 Energy price shocks and inflation dynamics

4.1 Impulse responses to an energy price shock

Figure 1 displays the impulse response functions of key variables to a one standard deviation adverse energy price shock. An unanticipated increase in energy prices triggers a rise in headline CPI inflation and a contraction in economic activity, consistent with the effects of a standard supply shock. The surge in headline inflation is short-lived because the shock causes a jump in the *level* of the relative price of energy, which then goes back to the steady state, thus displaying negative inflation along the adjustment path. The impact on non-energy inflation is muted initially but starts to build up and stays persistent in the quarters that follow.

The rise in headline CPI inflation reflects both direct and indirect channels. The direct channel operates through the energy component of the consumer price index, $P^*_{x,t}$, as shown in equation (4), which leads to an immediate jump in headline inflation. At the same time, higher energy prices raise the marginal costs of intermediate goods producers (see equation (42) in Section 5.1). However, the associated decline in aggregate demand reduces firms' demand for labor, putting downward pressure on real wages. Given the relatively large share of labor in production costs, the decline in wages more than offsets the increase in energy costs, causing marginal costs to fall and keeping the response of non-energy inflation muted in the short-run. Once wages start to adjust, marginal costs start to rise which together with higher energy prices start pushing non-energy inflation higher. Moreover, the increase in the price of energy hurts consumers both directly and indirectly via the induced decline in real wages.

The exchange-rate channel provides an important amplification mechanism. Following the increase in the world price of energy, the real exchange rate depreciates persistently, raising the domestic relative price of energy beyond the direct effect of the shock itself (see equation (6)). The key mechanism is the low degree of substitutability between energy and non-energy goods in consumption and production ($\eta \approx 0.5$ and $\varepsilon = 0.55$), which makes the demand for energy by households and firms relatively insensitive to changes in its relative price (see equations (3) and (28), respectively).[9] As a result, the reduction in energy demand is insufficient to offset the increase in its price, causing the value of energy imports to rise. The trade balance therefore deteriorates and, through the balance-of-payments identity (31), net foreign assets, B^*_t, decline.

We establish that the interaction between the elasticities of substitution in consumption and production, η and ε, and the expenditure share of energy, μ, is crucial for determining whether an adverse energy price shock leads to a deterioration of the trade balance. The first condition that is necessary to hold for a deterioration of the trade balance in this case requires that:[10]

$$\underbrace{\frac{1}{1-\mu}}_{\substack{\text{marginal impact of the}\\ \text{energy price effect}}} > \underbrace{\eta\frac{x-x^f}{x} + \varepsilon\frac{x^f}{x}\left(1-\alpha_x\left(\frac{\lambda_p}{\lambda_p-1}\right)^{1-\varepsilon}\right)}_{\substack{\text{marginal impact of the}\\ \text{energy demand effect}}}. \tag{38}$$

[9]As we show in Appendix F, the elasticity of substitution between energy and non-energy inputs in production, ε, is quantitatively important. Lower values of ε amplify the contraction in real activity and strengthen the deterioration of the trade balance following an adverse energy price shock. See Figure F.1.

[10]We provide a derivation of condition (38) in Appendix D.1.

Intuitively, the above condition states that so long as the marginal effect of higher energy prices on the trade balance exceeds the marginal decline of the demand for energy, the total impact would be a rise in the value of imports, leading to a deterioration of the trade balance, all else equal.

A second condition concerns the role of expenditure switching. We establish that there exists an upper bound on the trade elasticity, ν, below which the improvement in net exports induced by exchange-rate movements is insufficient to offset the increase in energy import costs:[11]

$$\nu < \left(\frac{1-\mu}{\mu}\right)\left[\eta\frac{x-x^f}{x} + \varepsilon\frac{x^f}{x}\left(1-\alpha_x\left(\frac{\lambda_p}{\lambda_p-1}\right)^{1-\varepsilon}\right)\right] + \frac{1}{\mu} \tag{39}$$

The trade elasticity determines the magnitude of the expenditure switching from foreign to home produced goods for foreign households. The higher the trade elasticity the stronger the sensitivity of foreign demand for home produced goods to exchange rate fluctuations. Clearly, this elasticity has to lie below certain threshold, imposed by the model's structure, for the impact of the exchange rate on the trade balance not to offset the opposing effect from the rise in energy prices.

The decline in the trade balance causes, via the balance of payment, an abrupt decline in net foreign assets which in turn outweighs the impact of the higher domestic policy rate on the nominal exchange rate. To see that consider the log-linearized UIP condition, obtained after combining the first order conditions with respect to home and foreign bonds:[12]

$$\hat{\varepsilon}_{t+1} - \hat{\varepsilon}_t = \hat{R}_t - \hat{R}^*_t + \hat{\varepsilon}_{b,t} + \underbrace{\chi\tilde{b}^*_t - \hat{\varepsilon}_{\psi,t}}_{\substack{\text{spread due to frictions} \\ \text{in intern. financial} \\ \text{markets}}} \tag{40}$$

where variables with a hat represent percentage deviations from the steady state. $\tilde{b}^*_t$ are home country's log-linearized foreign asset holdings after standardizing. The above equation shows that the debt elastic interest rate premium on foreign bonds (12) leads foreign assets playing a crucial role in determining exchange rate dynamics. The decline in foreign asset holdings works in this case in the opposite direction to the effects of the hike in the policy rate, $\hat{R}_t$, on the nominal exchange rate contemporaneously,

[11] The derivation of this condition is provided in Appendix D.2.

[12] The first order conditions with respect to home and foreign bonds are summarized by equations (46) and (47), respectively, in the online Appendix A.

highlighting the importance of international financial market frictions in order to obtain exchange rate responses after energy shocks that are consistent with historical evidence.[13]

To illustrate the importance of accounting for the energy component in both consumption and production, Figure E.1 in the Appendix examines how the macroeconomic effects change with the weight of energy in the consumption bundle (1), μ, and in the production function (19), α_x. As expected from the discussion of transmission channels above, a higher consumption share of energy (red-dashed lines), μ, amplifies the direct impact effect of an energy price shock on headline CPI inflation. Besides, a higher energy share in production (purple-dotted lines), α_x, strengthens the propagation of higher energy prices to non-energy (core) inflation over time, reflecting the role of sticky price setting in domestic goods. Taken together, these results indicate that variations in μ mainly affect the magnitude of the impact response to an energy price shock, while variations in α_x mainly influence the persistence of effects on domestic core inflation. More generally, the findings underscore that when capturing the effects of an energy price shock on the euro area economy it is important to model the energy component on both the consumption and production sides of the economy, as each channel plays a distinct and complementary role in shaping the overall response.

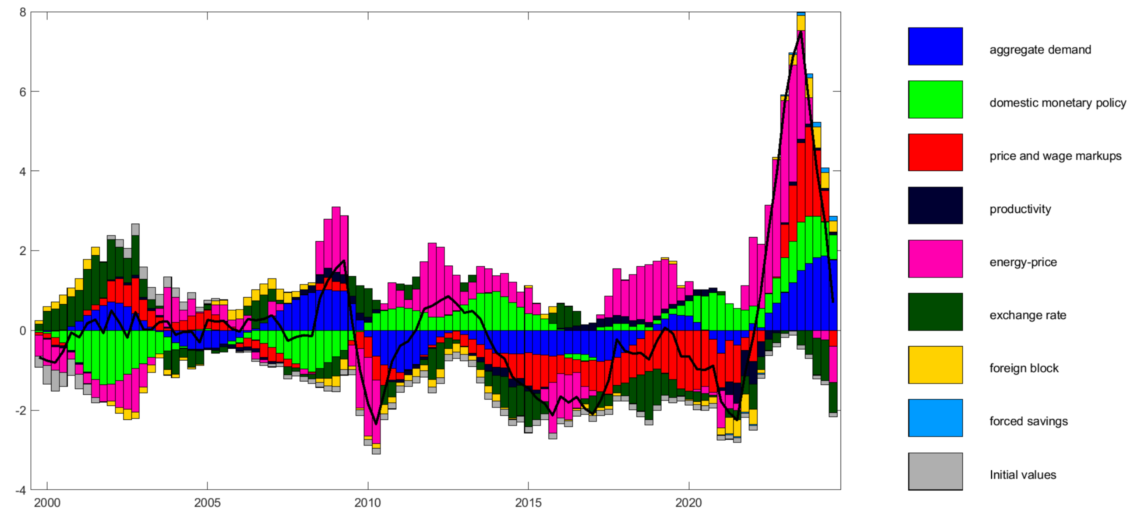
4.2 Drivers of headline CPI inflation

Panels 2a and 2b of Figure 2 present the historical decompositions of headline inflation and GDP growth, respectively. At first glance the HD for headline inflation exhibits a relevant contribution coming from energy and exchange rate shocks in the whole sample, showing the importance of considering the open economy dimension and energy as an intermediate imported good. Compared with much of the existing DSGE literature, our results attribute a more limited role to price- and wage-markup shocks and a larger role to demand-side disturbances. During the recent inflation surge, energy-price shocks

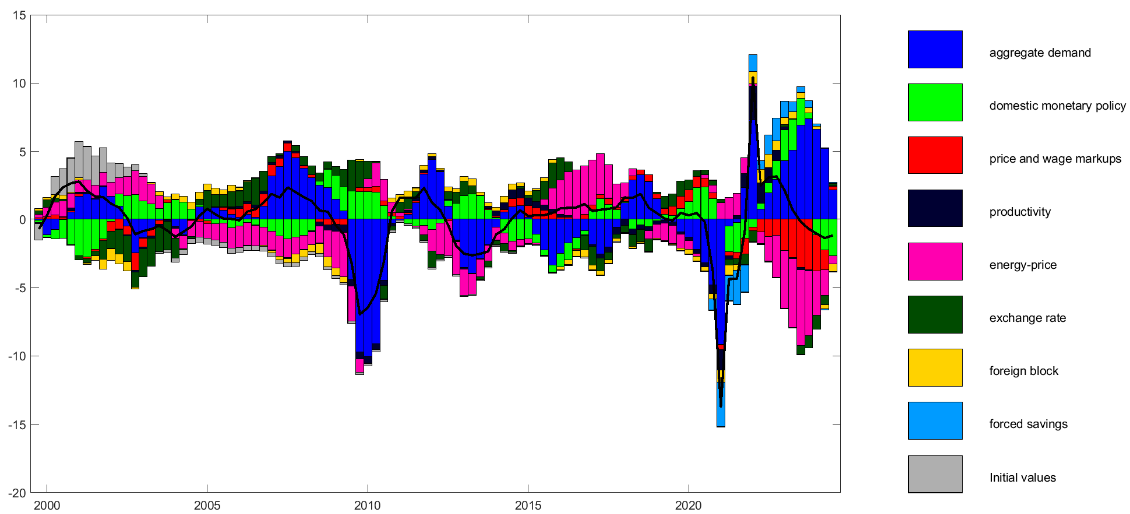
[13] A substantial body of empirical literature finds that increases in oil prices are often associated with an appreciation of the US dollar, particularly in recent decades and in relation to oil-importing economies. Early work by Amano and van Norden (1998) shows that oil prices are a key determinant of the US real exchange rate, with causality running from oil prices to the exchange rate. Subsequent studies, such as Basher et al. (2016), confirm that oil price increases can lead to a long-run appreciation of the US dollar. Similarly, Lizardo and Mollick (2010) provide evidence that oil price shocks can strengthen the US dollar, particularly against currencies of oil-importing countries. More recent research focusing on the EUR/USD exchange rate reaches comparable conclusions: Brůna and Tran (2023) find that positive oil price shocks tend to strengthen the US dollar relative to the euro. Overall, these findings are consistent with the view that higher energy prices improve the relative position of the US compared to energy-importing regions, thereby supporting dollar appreciation.

Figure 2: Drivers of headline inflation and GDP growth: a historical decomposition

(a) Annualized headline inflation (4-quarters moving average)



(b) GDP growth (y-o-y)

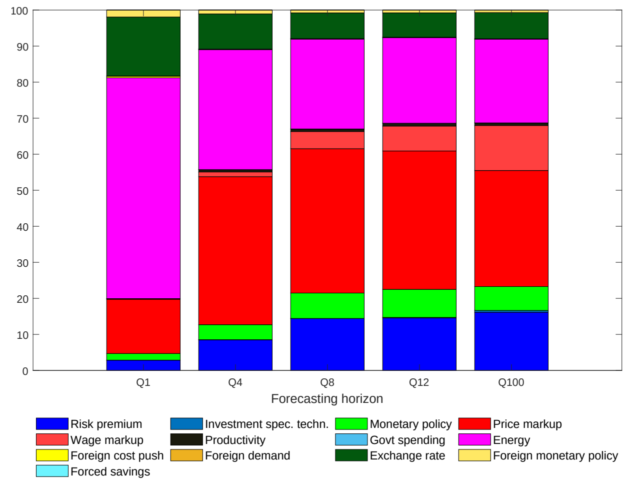


Notes: The figure shows the historical shock decomposition of headline inflation and GDP growth. Aggregate demand shocks include the risk premium, investment, and government spending shocks, while the foreign block aggregates all foreign shocks (foreign demand, foreign cost-push, and foreign monetary policy). Note that the foreign risk premium shock was relabeled as an 'exchange rate' shock and reported individually. Contributions are computed at the posterior mean of the baseline model.

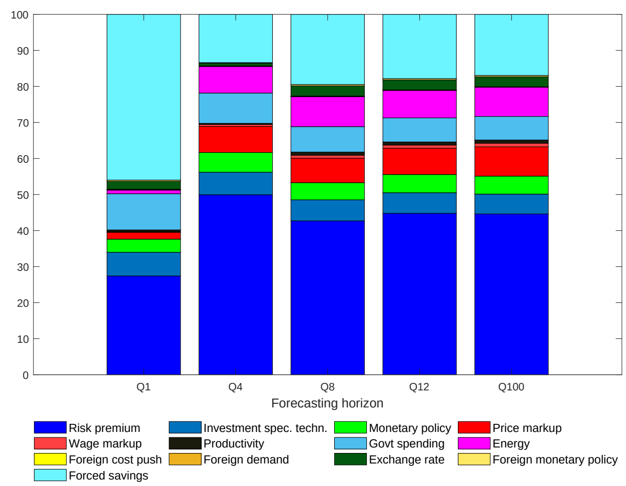
appear to have acted as the initial trigger, while markup and demand shocks contributed importantly to the subsequent escalation and persistence of inflationary pressures.

Figure 3: Sources of inflation and output fluctuations: forecast error variance decomposition

(a) Annualized headline inflation (4-quarters moving average)



(b) GDP growth (y-o-y)



Notes: The figure shows the forecast error variance decomposition (FEVD) of headline inflation (panel a) and GDP growth (panel b) at different forecasting horizons (one, four, eight, twelve, and 100 quarters, respectively). Bars report the percentage contribution of each structural shock to the total variance. Results are based on the posterior mean estimates of the baseline model.

The decomposition is broadly consistent with the view that the inflation surge was initially driven by energy-market disruptions, supply-chain bottlenecks, and constrained supply conditions.[14] At the same time, it highlights an important and growing con-

[14] Estimating the Bernanke and Blanchard (2025) model for the euro area, Arce et al. (2024) also find that inflation was mainly driven by large positive contributions of energy prices shocks between the second quarter of 2021 and the first quarter of 2023. Also similar to our findings Arce et al. (2024) find that labor market conditions, captured in our case by wage mark up shocks, also contributed to inflation towards the end of the sample. Their framework however is a closed economy abstracting thus from exchange rate or external shocks.

tribution from demand shocks as inflation accelerated. Notably, inflationary pressures originating from demand disturbances remained elevated even during the subsequent disinflation phase, while exchange-rate shocks increasingly contributed to the decline in inflation.

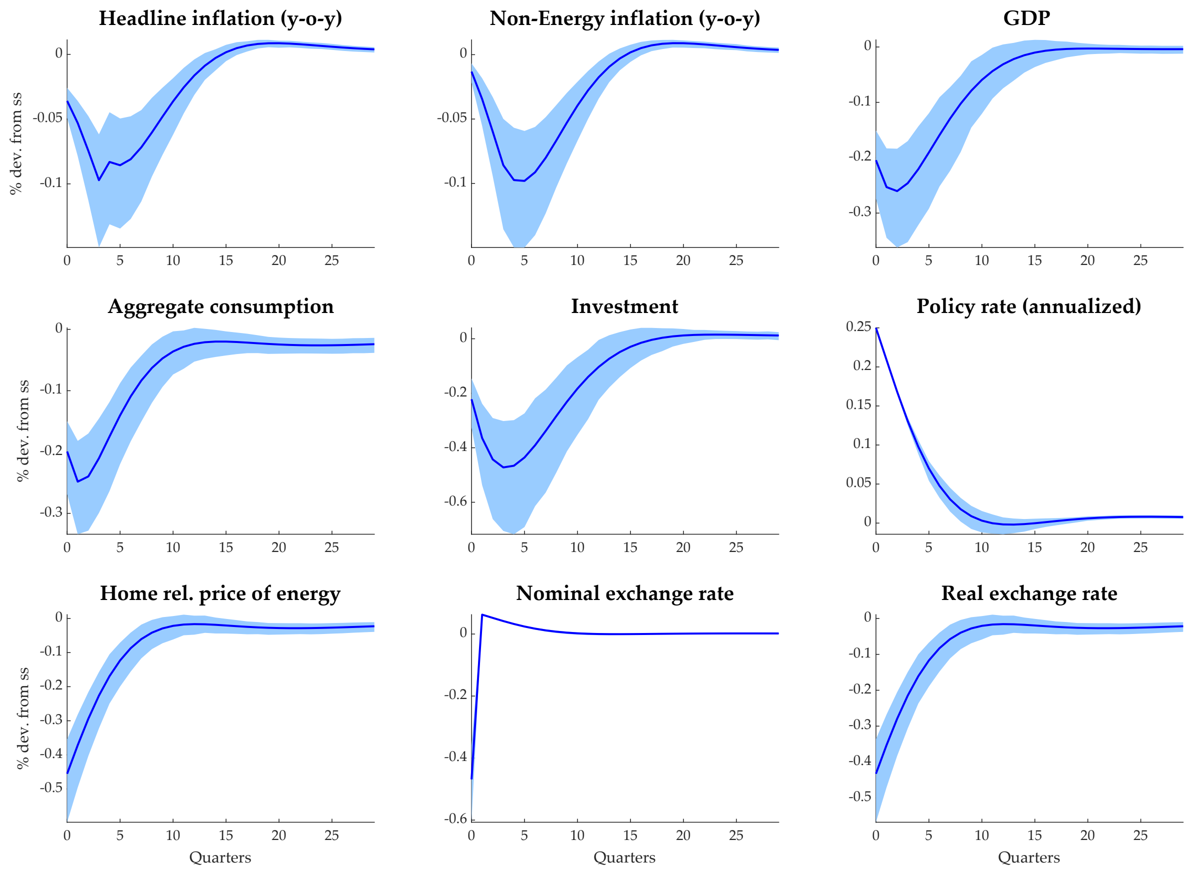
Turning to monetary policy, the historical decomposition suggests that policy remained accommodative during the early stages of the inflation surge, contributing modestly to upward pressure on prices. Following the ECB's rapid tightening cycle beginning in mid-2022, however, monetary policy moved decisively into restrictive territory, weighing on economic activity and contributing to the subsequent moderation in inflation. Taken together, the decompositions of inflation and GDP growth suggest that, while the ECB was initially slow to respond to rising inflationary pressures, it subsequently implemented a forceful tightening that played an important role in bringing inflation back under control. Naturally, these conclusions are based on ex-post analysis and the benefit from hindsight. Real-time policymaking was burdened by heightened uncertainty from the tail-end of the pandemic and the outbreak of war in Europe.[15]

The decomposition of GDP growth reveals that recent economic dynamics were driven by the combined effects of adverse supply shocks and positive demand shocks. The importance of energy and exchange-rate disturbances is also evident in the forecast error variance decomposition (FEVD) reported in Figure 3. In the short run (up to one year), fluctuations in headline HICP inflation are primarily driven by energy-price, price-markup, and exchange-rate shocks.[16] Taken together, these three shocks account for around 84 percent of the forecast error variance of annualized headline inflation up to one year. Specifically, the energy price and the exchange rate shocks alone account for around 78 and 44 percent of the forecast error variance of annualized headline for one quarter and one year horizon, respectively. These results highlight the importance of both the open-economy dimension and the explicit modelling of energy as an imported input for understanding euro area inflation dynamics.

[15] These results are in line with a 2024 De Nederlandsche Bank analysis —"The monetary policy response to high inflation"— which discusses at length the monetary policy response during the recent euro area inflation surge.

[16] The exchange-rate shock accounts for approximately 77 percent of fluctuations in the real exchange rate at horizons of up to one year.

Figure 4: Impulse response functions to a monetary policy tightening



Notes: The solid blue lines represent responses of selected key variables at the posterior mean with the shaded blue areas capturing the 90% credible intervals (computed as 5th and 95th percentiles) to a 25 basis points increase in the policy rate on impact. Negative values of the exchange rate imply an appreciation of the euro. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

5 Monetary policy transmission, stabilization trade-offs, and optimal policy

5.1 Monetary policy transmission mechanism

Figure 4 displays the impulse responses to a 25 basis points increase in the policy rate on impact. As expected, both headline and non-energy inflation decrease, as well as all the real variables, in a persistent and hump-shaped manner. The increase in the policy rate causes an appreciation of the nominal exchange rate, which leads to a real appreciation despite the slowdown in inflation—see bottom right panel—and, thus, a decrease in the relative price of energy that reinforces the decline in inflation. Hence, the open economy dimension amplifies the effects of monetary policy on inflation.

The inflation response reflects an additional transmission channel that is absent in standard closed-economy environments. In our framework, monetary policy affects the domestic price of imported energy through the exchange rate. Since energy enters both household consumption and firms' production decisions, exchange-rate movements influence headline inflation, $\hat{\pi}_{cpi,t}$, directly and indirectly through firms' marginal costs. These mechanisms can be seen more clearly by combining the log-linearized aggregate price index (5), expressed in growth rates, with the domestic Phillips curve in the intermediate goods sector:[17]

$$\hat{\pi}_{cpi,t} = \beta E_t \hat{\pi}_{t+1} + \underbrace{\kappa \widehat{mc}_t}_{\text{indirect ReR effects}} + \underbrace{\mu(1+\kappa)\hat{s}_t - \mu \hat{s}_{t-1}}_{\text{direct ReR effects}} \tag{41}$$

where

$$\widehat{mc}_t = -\hat{\varepsilon}_{a,t} + \alpha \left(1 - \alpha_x mc^{\epsilon-1}\right) \hat{r}_t^k + (1-\alpha)\left(1 - \alpha_x mc^{\epsilon-1}\right) \hat{w}_t + \alpha_x mc^{\epsilon-1}(1-\mu)\hat{s}_t \tag{42}$$

with

$$\hat{s}_t = \frac{1}{1-\mu}\left(\widehat{ReR}_t + \hat{s}_t^*\right). \tag{43}$$

The expressions above show that movements in the real exchange rate have both direct and indirect effects on headline CPI inflation. The direct effects stem from the imported energy price, $\hat{s}_t$. Following a monetary policy tightening, the real exchange rate appreciation lowers the domestic currency price of imported energy, thereby exerting downward pressure on headline inflation. The indirect effects arise because energy is also used as an input in the production of domestic intermediate goods. The lower relative price of energy reduces firms' marginal costs, amplifying the decline in core and, therefore, headline inflation. Obviously, the magnitude of indirect effects depend on the degree of price stickiness in the intermediate goods sector, ξ_p. Consequently, exchange-rate movements generated by monetary policy strengthen the disinflationary effects of a monetary contraction through both consumption and production channels.

While the exchange-rate channel reinforces the disinflationary effects of monetary

[17] We have assumed zero indexation ($\chi_p = 0$) and no price mark-up shocks for the sake of exposition. In the expression below $\kappa = \frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}$.

policy, the response of GDP to a monetary policy shock is more nuanced. On the demand side, there are two effects working in opposite directions. A tightening of monetary policy leads to an appreciation of the domestic currency, strengthening households' purchasing power and alleviating the downward pressure stemming from the fall in real wages and the decline in the present discounted value of wealth for Ricardian households. This mitigates the decline in the demand for energy goods. At the same time, the real appreciation harms domestic firms' international competitiveness, shrinking the trade balance and putting downward pressure on domestic output. The international expenditure-switching effect is stronger than its domestic counterpart because the elasticity of substitution between energy and non-energy goods ($\eta \approx 0.5$) is lower than the trade elasticity ($\nu = 1.5$), making exports more sensitive to exchange rate movements than imports. Consequently, the recessionary effects of the real appreciation dominate.

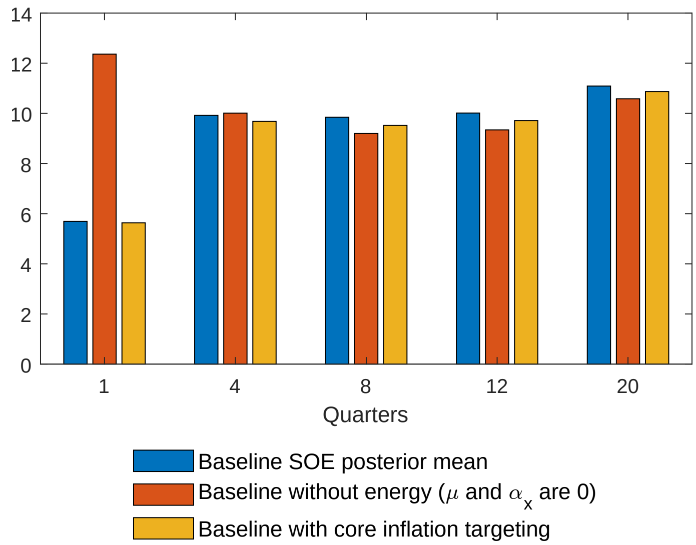
The previous discussion suggests that exchange-rate movements generated by monetary policy affect inflation through additional channels that are absent in standard closed-economy environments. An important question is whether these channels alter the inflation-output stabilization trade-off faced by the central bank. To quantify this effect, Figure 5 compares the stabilization trade-off in the estimated SOE model with two counterfactual environments: (i) a version of the model without energy (μ and α_x are set to zero) and (ii) a version in which monetary policy targets core, rather than headline, inflation. Figure 5 plots the ratio of cumulative output losses to the cumulative percentage change in inflation over different horizons, up to five years. The figure shows that the open economy dimension helps monetary policy stabilize inflation at a substantially lower output cost in the first quarter compared to the counterfactual economy where the share of energy, and hence the exposure to exchange rate fluctuations, is absent. The stabilization costs become slightly larger at longer horizons owing to the resulting loss in international competitiveness.

5.2 Monetary policy response to an energy price shock

The presence of these additional channels raises an important policy question: should monetary policy react aggressively to energy-driven inflationary pressures, or should the central bank partially look through them?

Figure 5 provides a first answer by comparing the output-inflation stabilization trade-off under headline and core inflation targeting (blue versus yellow bars). While the trade-off under core inflation targeting is similar to the baseline on impact, it improves modestly at longer horizons. The key reason is that, by construction, a core-

Figure 5: Output-inflation stabilization trade-offs

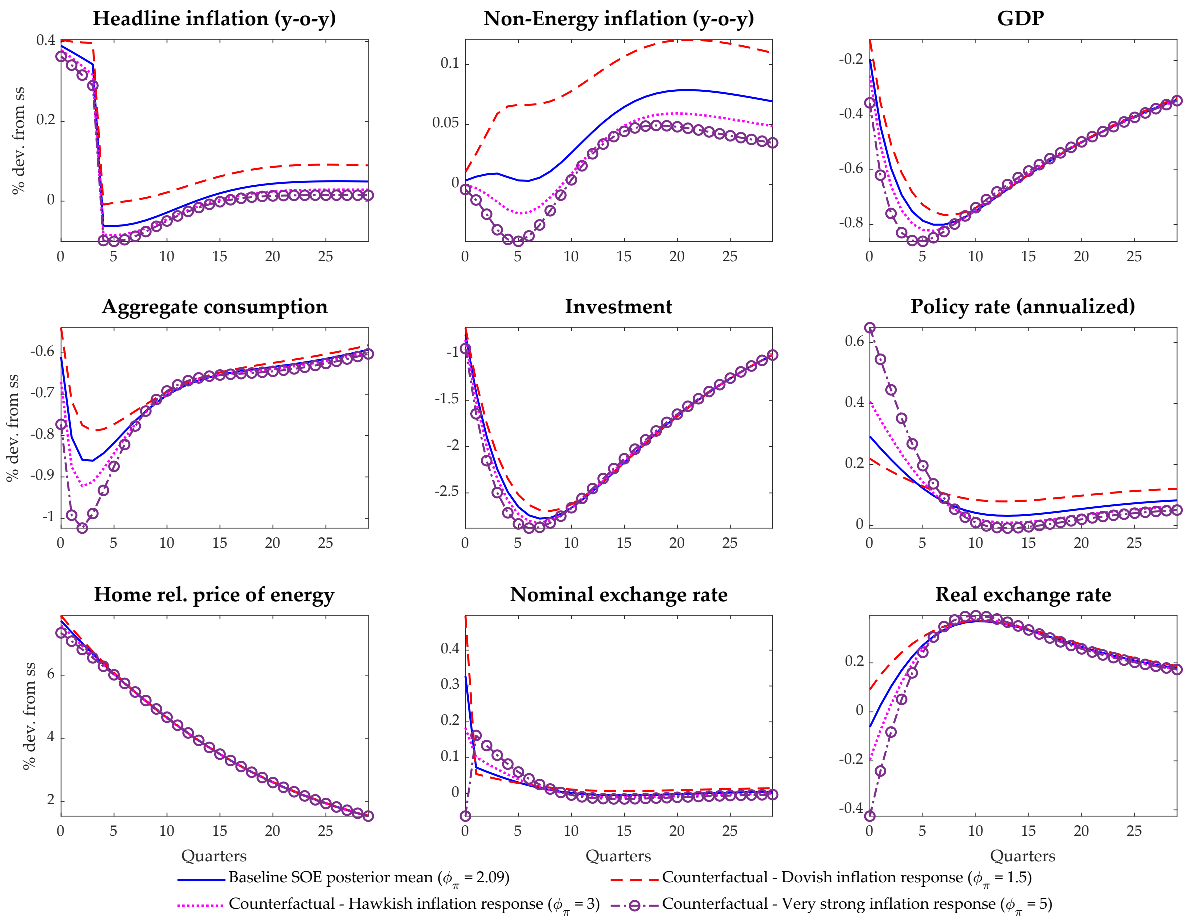


Notes: The figure reports the ratio of cumulative output losses to the cumulative percentage change in inflation at different horizons: on impact (one quarter) and over one, two, three, and five years. The ratio is shown for the baseline small open economy (SOE) model, the counterfactual without energy, and a counterfactual in which monetary policy targets core (non-energy) inflation.

inflation-targeting central bank reacts less aggressively to fluctuations originating in the energy sector. In particular, when policy responds only to non-energy inflation, it partially abstracts from the direct effect of imported energy prices on headline inflation and therefore exploits the exchange-rate channel to a lesser extent than under headline inflation targeting. As a result, the policy tightening following an energy-price shock is weaker, leading to a smaller appreciation of both the nominal and real exchange rate. Inflation therefore declines more gradually, as the direct and indirect exchange-rate channels discussed above become less powerful. At the same time, the weaker appreciation limits the deterioration in international competitiveness and the associated decline in exports, resulting in a milder contraction in economic activity. Taken together, these results suggest that partially looking through energy-price shocks can improve the inflation-output stabilization trade-off.

The comparison between headline and core inflation targeting provides one way of assessing the degree to which monetary policy should accommodate energy-price shocks. We now investigate this issue more directly by varying the response coefficient on inflation in the Taylor rule, i.e., ϕ_π. Specifically, Figure 6 shows how different degrees of aggressiveness of the monetary policy response to inflation affect the transmission of an energy-price shock. A lower value of ϕ_π corresponds to a more accommodative

Figure 6: Impulse response functions to an energy price shock under alternative degrees of monetary policy 'hawkishness'



Notes: The figure reports selected impulse responses following an adverse (one standard deviation) energy price shock across different degrees of monetary policy 'hawkishness': $\phi_\pi = 2.09$ (baseline) *versus* $\phi_\pi = 1.5/3/5$ ('dovish', 'hawkish', or 'very strong'). Positive values of the exchange rate imply a depreciation of the euro. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

policy stance and can therefore be interpreted as a greater willingness to look through energy-driven inflationary pressures. Conversely, a higher value of ϕ_π implies a more forceful policy response aimed at limiting the pass-through of the shock to broader inflation.

As expected, a milder policy response ($\phi_\pi = 1.5$) results in higher and more persistent headline and core inflation. In this case, the initial depreciation of the nominal exchange rate is stronger leading to a real depreciation as well on impact. The decline in aggregate demand is milder and marginal costs increase on impact, and stay positive for longer. Conversely, a more aggressive response to inflation ($\phi_\pi = 5$) induces an appreciation of the exchange rate and substantially limits the pass-through of the energy-price shock to both headline and non-energy inflation. The stronger monetary tightening dampens aggregate demand and lowers marginal costs more rapidly, leading to a faster stabilization of inflation. Interestingly, these gains are achieved with only modest additional output costs. Hence, a forceful monetary policy response goes a long way in curbing the transmission of energy-price shocks to underlying inflation.

5.3 Optimal policy path

Following the above experiments with the Taylor rule inflation coefficient, ϕ_π, in this section we implement optimal policy projections drawing on de Groot et al. (2021), Hebden and Winkler (2021) and McKay and Wolf (2023). We first derive the implied optimal policy path conditional on an adverse energy price shock identical to the one considered in Figure 1. Subsequently, we derive the optimal path for the policy rate conditional on a price mark-up shock. We assume that the central bank chooses the optimal policy path under commitment by minimizing the loss function:

$$\mathcal{L}_t = \hat{\pi}^2_{CPI,t} + \gamma_y \left(\widehat{gdp}_t - \widehat{gdp}^f_t\right)^2 + \gamma_R \left(\hat{R}_t - \hat{R}_{t-1}\right)^2 \tag{44}$$

where we set γ_y and γ_R to 0.048 and 0.236, respectively, following Giannoni (2014).

Energy shock. Figure 7 displays the optimal policy path following the energy shock and the implied paths for headline inflation, GDP and the real exchange rate. It shows three alternative cases, namely one with a weight on output gap in the loss function equal to the one mentioned above (medium weight), one with a low weight ($\gamma_y = 0.0001$) and one with a high weight ($\gamma_y = 0.25$), and compare them to our baseline, where monetary policy is following the estimated Taylor rule (blue-dashed lines).

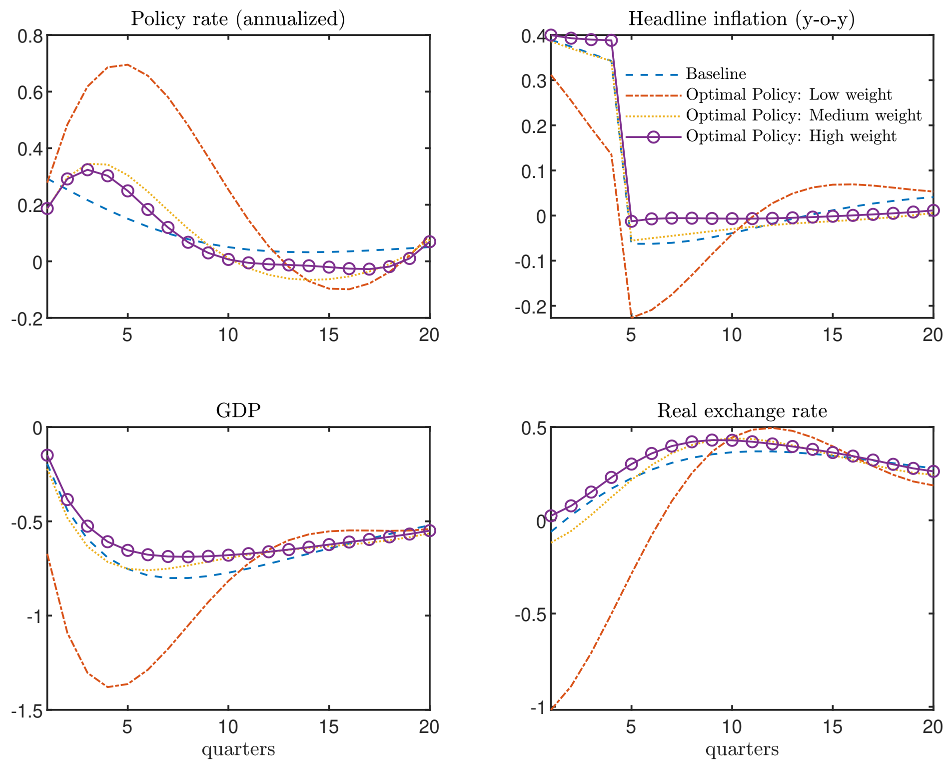
As the weight on output-gap stabilization declines, the central bank adopts a progressively more aggressive policy stance, mitigating the inflationary effects of higher energy prices more forcefully. In the limiting case of a negligible weight on output stabilization, the policy rate rises substantially above the path implied by the estimated Taylor rule, largely offsetting the increase in headline inflation. This comes, however, at the cost of a significantly deeper contraction in economic activity, driven by sharper declines in consumption and investment. The tighter policy stance also induces a stronger appreciation of the euro, which exacerbates the deterioration of the trade balance and further depresses economic activity.

In contrast, when the central bank places a medium or high weight on output-gap stabilization, the optimal policy path involves a more gradual adjustment. Interest rates rise by slightly less than implied by the estimated Taylor rule on impact and increase only gradually thereafter, converging towards the estimated policy path over the medium term. As a result, inflation and output dynamics remain broadly similar to those observed under the estimated rule. These findings are consistent with policy prescriptions that advocate partially accommodating the direct and indirect effects of energy price shocks on inflation, and are closely related to the results of Drechsel et al. (2026). More generally, our results suggest that when output gap stabilization receives a non-negligible weight, optimal policy resembles a *look-through* approach to energy price shocks, tolerating a temporary increase in inflation in order to avoid excessive losses in economic activity (Lagarde, 2026).

A key parameter for the transmission of energy price shocks interacting with the potency of monetary policy is the Calvo price stickiness parameter, ξ_p. Figure 8 considers three cases, namely one where this parameter lies at the estimated posterior mean ($\xi_p = 0.91$), and two more cases where it is set below it, namely $\xi_p = 0.75$ and $\xi_p = 0.66$, respectively. The weight on the output gap is now set back to 0.048, corresponding to the medium-weight case, in all three experiments. The central finding is that, as price stickiness decreases, the implied optimal policy path becomes more aggressive. The intuition is that greater price flexibility steepens the Phillips curve, giving rise to two effects. First, a steeper Phillips curve increases the importance of indirect effects of the rise in energy price as the sensitivity of headline inflation to movements in marginal costs of intermediate goods firms, that in turn depend on the energy price, rises. All else equal, this amplifies the response of headline inflation and therefore calls for a stronger monetary policy response. Second, it improves the monetary policy stabilization trade-off, since inflation can be stabilized more effectively for a given output cost.

The more aggressive policy stance also induces a stronger real appreciation of the euro. While this further deteriorates the trade balance and exerts additional downward pressure on output, it also dampens the rise in the domestic-currency price of energy, mitigating both the direct and indirect effects of the shock on headline inflation. By containing inflationary pressures, the tighter stance also limits the decline in real wages, thereby supporting consumption and moderating the contraction in economic activity. Taken together, these mechanisms imply a more aggressive optimal policy response as prices become more flexible. Consequently, the case for a *look-through* approach to energy price shocks weakens as price rigidity declines.

Figure 7: Optimal policy projections for alternative output gap weights

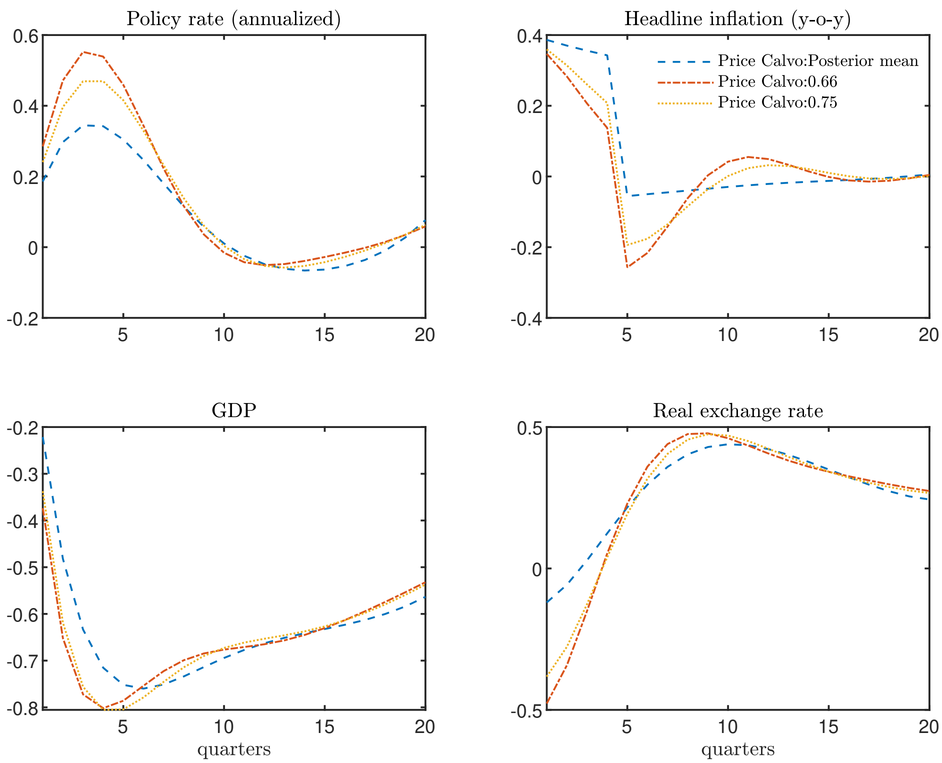


Notes: Optimal policy projections. The blue-dashed lines depict the impulse responses of the interest rate, inflation and the output in the estimated small open economy model (SOE) following a one standard deviation energy price shock, where the central bank follows the estimated Taylor rule. The red-dotted lines depict the resulting impulse responses under the optimal policy path with a low output gap weight in the loss function. The yellow-dashed-doted lines depict the resulting impulse responses under the optimal policy path with a medium output gap weight in the loss function while the purple-circled lines depict the resulting impulse responses under the optimal policy path with a high output gap weight in the loss function

Price mark-up shock. We now turn to computing the optimal policy path conditional on a price mark-up shock. This exercise allows us to examine how the energy channel and the open economy structure affect the optimal policy response, by comparing the baseline model with a version in which the energy channel is switched off, i.e., $\mu = \alpha_x = 0$. This comparison was, of course, not possible in the case of an energy shock.

Specifically, we assess the importance of the energy channel for the central bank's optimal policy decision by considering the response of the baseline economy when the central bank uses the 'mispecified' model, namely a model without energy. We therefore conduct the following counterfactual exercise. We first compute the optimal policy rate path implied by the counterfactual non-energy economy following a one standard deviation mark-up shock. We then impose that same policy rate path on the baseline

Figure 8: Optimal policy projections for alternative price Calvo parameter values



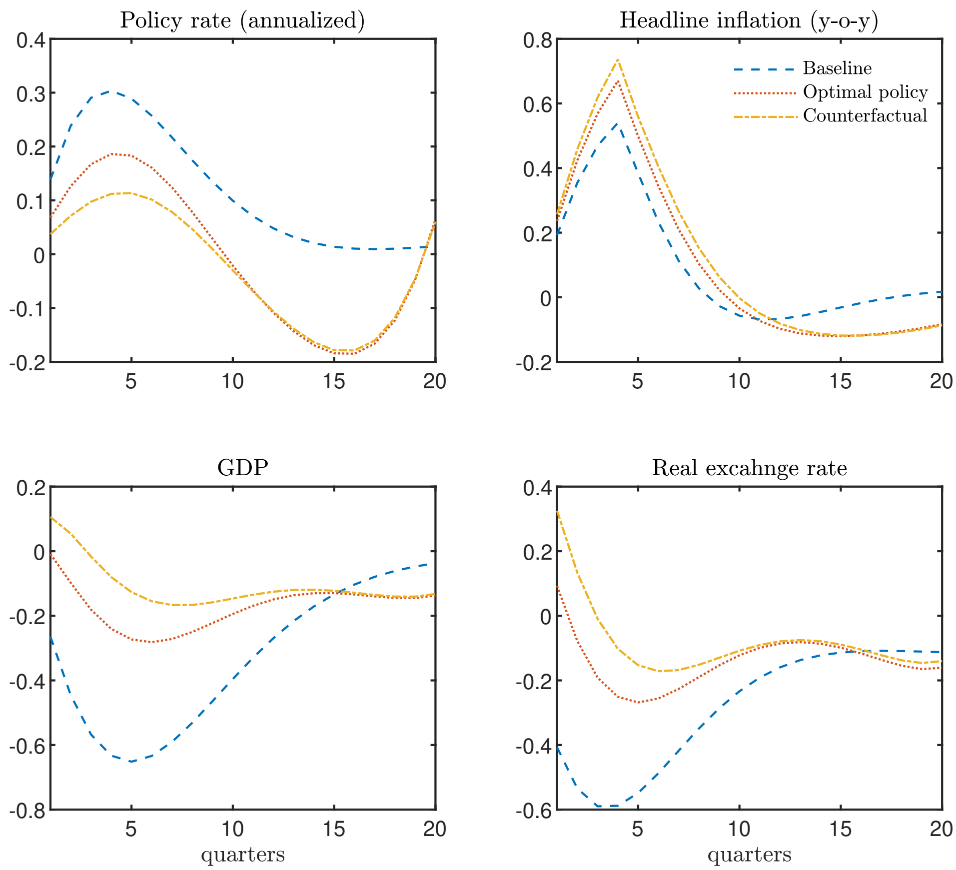
Notes: Optimal policy projections. The blue-dashed lines depict the impulse responses under an optimal policy rate path with a price Calvo parameter at the estimated posterior mean. The yellow-dashed-doted lines depict the impulse responses under an optimal policy rate path with a price Calvo parameter equal to 0.75 while the the red-dotted lines depict the impulse responses under an optimal policy rate path with a price Calvo parameter equal to 0.66

model, hit by the same shock.

Figure 9 displays the optimal policy projection results and the counterfactual following the price mark-up shock. For convenience, we also display the responses from the estimation of the baseline small-open economy model where the central bank follows the estimated Taylor rule (blue-dashed lines). Under the optimal policy rate path (red-dashed lines), the path lies below the estimated one from the baseline (blue-dashed). Thus, the induced recession is milder relative to the baseline at the expense of a higher peak in headline CPI inflation. The less aggressive policy path results in a weaker real appreciation of the euro avoiding thus the output losses of a stronger appreciation. Consequently, both domestic demand and overall economic activity experience a more moderate decline.

Turning to the counterfactual scenario (yellow-dashed dotted), using the non-energy

Figure 9: Optimal policy projections and counterfactual paths



Notes: Optimal policy projections. The blue dashed lines depict the impulse responses of the interest rate, inflation and the output in the small open economy model (SOE) following a one standard deviation price mark-up shock. The red-dotted lines depict the resulting impulse responses under the optimal policy path following the same one-standard deviation price mark-up shock. The yellow-dashed-doted lines depict the counterfactual impulse responses when the optimal policy rate path from the counterfactual non-energy economy setup (i.e., $\alpha_x = \mu = 0$) is imposed in the baseline SOE model.

model would prescribe a more accommodative policy path compared to the other two cases. When applied to the baseline open economy model, this policy rate path results in a considerably milder trough in economic activity compared to the other two cases at the expense of a higher peak in headline inflation. The more accommodative stance leads to a real depreciation on impact followed by a milder real appreciation both of which lessen the burden on the trade balance compared to the baseline and the optimal policy case. At the same time, a milder appreciation is counterproductive in stabilizing inflation. Hence, a central bank using a 'mispecified' model with no energy would cause higher inflation. In the baseline model, the central bank, instead, realizes that the exchange rate channel strengthens the monetary policy effectiveness in controlling inflation and uses it, prescribing a more hawkish optimal path, achieving a faster stabilization.

6 Conclusions

This paper develops and estimates a small open economy DSGE model of the euro area with an explicit role for energy in both the consumption basket and as input in the production process. By incorporating imported energy goods and exchange rate dynamics, the model provides a framework to analyze inflation developments and monetary policy in an environment characterized by large external shocks. The estimated model highlights the central role of energy price fluctuations in driving recent inflation dynamics and shows that the open economy dimension significantly shapes the transmission of both shocks and policy responses.

Our results emphasize three main findings. First, energy price shocks account for a substantial share of short-run inflation variation and are key to understanding the recent surge in euro area inflation. Second, the exchange rate acts as an important amplification channel for monetary policy, strengthening its effect on inflation while mitigating output costs, and thereby improving the inflation-output trade-off over horizons of up to one year relative to a non-energy economy setting. Third, the characterization of optimal monetary policy shows that the appropriate policy response to an energy shock differs from the one implied by the estimated Taylor rule. Rather than responding aggressively and immediately to inflationary pressures following energy price shocks, the optimal strategy implies a more gradual and persistent adjustment of the policy rate, akin to a *looking through* approach, for moderate weights on output gap stabilization in the loss function and elevated degrees of price stickiness. However, as the weight on output gap stabilization declines and as prices become more flexible the case for a *look through* approach to an energy price shock becomes weaker.

These findings have important implications for monetary policy design. They suggest that policy prescriptions derived from models that abstract from energy or open economy channels may be misleading in environments characterized by large terms-of-trade shocks. The timing and persistence of policy adjustments are crucial, and the exchange-rate channel may call for a more aggressive response to energy shocks. Explicitly accounting for the interaction between energy prices and exchange-rate dynamics is therefore essential for the design of effective policy, especially in energy-dependent economies. These findings resonate with the ECB's recent emphasis on risk-based, scenario-driven policymaking in an environment characterized by recurring supply shocks and heightened uncertainty (Lagarde, 2026).

Several avenues for future research remain. Extending the framework to incorporate richer forms of household heterogeneity, nonlinearities, or occasionally binding constraints could further refine the analysis of distributional effects and policy trade-offs. In addition, modeling endogenous energy supply or the transition toward alternative energy sources may provide useful insights into the evolving role of energy in macroeconomic stabilization. We leave these extensions for future work.

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A The full non-linear model

This appendix describes the full set of non-linear equilibrium conditions of the model.
Households:

$$\left(c_t^o - (\varepsilon_{FS,t} - 1) - b\left(c_{t-1} - (\varepsilon_{FS,t-1} - 1)\right)\right)^{-\sigma} \frac{1}{z_t} = \Lambda_t^o \tag{45}$$

$$\beta \frac{\Lambda_{t+1}^o R_t}{P_{CPI,t+1}} - \frac{\Lambda_t^o}{\varepsilon_{b,t} P_{CPI,t}} = 0 \tag{46}$$

$$\beta \frac{\Lambda_{t+1}^o R_t^* \varepsilon_{t+1}}{P_{CPI,t+1}} \left(1 - \psi_t(\varepsilon B^*; \varepsilon_{\psi,t})\right) - \frac{\Lambda_t^o \varepsilon_t}{P_{CPI,t}} = 0 \tag{47}$$

$$ReR_t = \varepsilon_t P_{CPI,t}^* / P_{CPI,t} \tag{48}$$

$$\begin{aligned} -\Lambda_t^o \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} + \Lambda_t^o Q_t^o \varepsilon_{I,t} \left\{1 - \gamma_I \left(\frac{I_t^o}{I_{t-1}^o} - g_z\right) \frac{I_t^o}{I_{t-1}^o} - \frac{\gamma_I}{2} \left(\frac{I_t^o}{I_{t-1}^o} - g_z\right)^2\right\} \\ + \Lambda_{t+1}^o Q_{t+1}^o \varepsilon_{I,t+1} \beta \gamma_I \left(\frac{I_{t+1}^o}{I_t^o} - g_z\right) \left(\frac{I_{t+1}^o}{I_t^o}\right)^2 = 0 \end{aligned} \tag{49}$$

$$\Lambda_{t+1}^o \beta \left[\frac{R_{t+1}^k}{P_{CPI,t+1}} u_{t+1}^o - a\left(u_{t+1}^o\right) \left[(1-\mu) + \mu s_{t+1}^{1-\eta}\right]^{\frac{1}{\eta-1}}\right] - \Lambda_t^o Q_t^o + \Lambda_{t+1}^o Q_{t+1}^o \beta (1-\delta) = 0 \tag{50}$$

$$\frac{R_t^k}{P_{CPI,t}} - \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} \left[\gamma_{u1} + \gamma_{u2}\left(u_t^o - 1\right)\right] = 0 \tag{51}$$

$$K_{t+1}^o = (1-\delta) K_t^o + \varepsilon_{I,t} \left[1 - S\left(\frac{I_t^o}{I_{t-1}^o}\right)\right] I_t^o \tag{52}$$

$$\begin{aligned} C_t^{rt} = w_t h_t^{rt} + \left(\widetilde{TR}_t^{rt} - \tilde{T}_t^{rt}\right) \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} s_t^{\frac{\alpha_x}{\alpha_x - 1}} GDP_t \\ + \left((\varepsilon_{FS,t} - 1) - \frac{1}{6} \sum_{i=8}^{13} (\varepsilon_{FS,t-1} - 1)\right) \end{aligned} \tag{53}$$

$$C_t^k = \left[(1-\mu)^{\frac{1}{\eta}} \left(C_{q,t}^k\right)^{\frac{\eta-1}{\eta}} + (\mu)^{\frac{1}{\eta}} \left(X_t^k\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{54}$$

$$C_{q,t}^{k}=(1-\mu)\left(\frac{P_{t}}{P_{CPI,t}}\right)^{-\eta}C_{t}^{k} \tag{55}$$

$$X_{t}^{k}=\mu\left(\frac{\varepsilon_{t}P_{x,t}^{*}}{P_{CPI,t}}\right)^{-\eta}C_{t}^{k} \tag{56}$$

Wage setting:
The maximization problem of the union thus reads as follows:

$$\max_{\tilde{W}_{t}^{j}} E_{t}\sum_{s=0}^{\infty}(\xi_{w}\beta)^{s}\left\{\frac{1-\theta}{1-\sigma}\left[C_{t+s}^{o}-(\varepsilon_{FS,t+s}-1)-b\left(C_{t+s-1}-(\varepsilon_{FS,t+s-1}-1)\right)\right]^{1-\sigma}+\right.$$
$$\left.\frac{\theta}{1-\sigma}\left(C_{t+s}^{rt}-bC_{t+s-1}\right)^{1-\sigma}-\frac{h_{t+s}^{1+\phi_{l}}}{1+\phi_{l}}\right\} \tag{57}$$

subject to

$$P_{CPI,t+s}C_{t+s}^{o}+P_{CPI,t+s}I_{t+s}^{o}+\frac{B_{t+s+1}^{o}}{\varepsilon_{b,t+s}} \tag{58}$$
$$= R_{t+s-1}B_{t+s}^{o}+P_{CPI,t+s}d_{t+s}^{o}-T_{t+s}^{o}+\left[R_{t+s}^{k}u_{t+s}^{o}-a\left(u_{t+s}^{o}\right)P_{CPI,t+s}\right]K_{t+s}^{o} \tag{59}$$
$$+h_{t+s}^{d}\int_{0}^{1}\tilde{W}_{t}^{j}g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_{w}}\bar{\pi}_{CPI}^{1-\chi_{w}}\left(\frac{\tilde{W}_{t}^{j}g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_{w}}\bar{\pi}_{CPI}^{1-\chi_{w}}}{W_{t+s}}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}}dj \tag{60}$$

and

$$P_{CPI,t+s}C_{t+s}^{rt} \tag{61}$$
$$= h_{t+s}^{d}\int_{0}^{1}\tilde{W}_{t}^{j}g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_{w}}\bar{\pi}_{CPI}^{1-\chi_{w}}\left(\frac{\tilde{W}_{t}^{j}g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_{w}}\bar{\pi}_{CPI}^{1-\chi_{w}}}{W_{t+s}}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}}dj \tag{62}$$
$$-T_{t+s}^{rt}+P_{CPI,t+s}\left(\varepsilon_{FS,t+s}-\frac{1}{6}\sum_{i=8}^{13}\varepsilon_{FS,t+s-i}\right) \tag{63}$$

and

$$h_{t+s}^{i}=h_{t+s}^{d}\int_{0}^{1}\left(\frac{\tilde{W}_{t}^{j}g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_{w}}\bar{\pi}_{CPI}^{1-\chi_{w}}}{W_{t+s}}\right)^{-\frac{1+\lambda_{w,t+s}}{\lambda_{w,t+s}}}dj$$

where

$$\pi_{CPI,t,t+s-1} = \begin{cases} 1 & \text{for } s = 0 \\ \left(\frac{P_{CPI,t}}{P_{CPI,t-1}}\right)\left(\frac{P_{CPI,t+1}}{P_{CPI,t}}\right)...\left(\frac{P_{CPI,t+s-1}}{P_{CPI,t+s-2}}\right) & \text{for } s = 1,2,.. \end{cases} \tag{64}$$

(65)

and $g_{z,t,t+s} = \prod_{s=1}^{s} g_{z,t+s}$. Notice that, in writing down the problem, we have assumed that the union takes into account the fact that firms allocate labor demand uniformly across different workers of type j, independently of their household type. It follows that, in the aggregate, we will have $h_t^o = h_t^{rt} = h_t$. The aggregate wage index W_t of the union reads as follows:

$$W_t = \left[\xi_w \left(g_{z,t}\pi_{CPI,t-1}^{\chi_w}\bar{\pi}_{CPI}^{1-\chi_w}W_{t-1}\right)^{\frac{1}{\lambda_{w,t}}} + (1-\xi_w)\left(\widetilde{W}_t\right)^{\frac{1}{\lambda_{w,t}}}\right]^{\lambda_{w,t}} \tag{66}$$

The first order condition reads as follows:

$$0 = E_t \sum_{s=0}^{\infty} (\xi_w \beta)^s h_{t+s}^j$$

$$\left\{ \begin{array}{c} \tilde{W}_t^j \frac{g_{z,t,t+s}\pi_{CPI,t,t+s-1}^{\chi_w}\bar{\pi}_{CPI}^{1-\chi_w}}{P_{t+s}z_{t+s}} \left(1 - \frac{1+\lambda_{w,t}}{\lambda_{w,t}}\right) \left[(1-\theta)\left(c_{t+s}^o - \varepsilon_{FS,t} - b(c_{t+s-1} - \varepsilon_{FS,t-1})\right)^{-\sigma} + \theta\left(c_{t+s}^{rt} - bc_{t+s-1}\right)^{-\sigma}\right] \\ + \frac{1+\lambda_{w,t}}{\lambda_{w,t}} \left[(1-\theta)\left(c_{t+s}^o - bc_{t+s-1}\right)^{-\sigma} MRS_{t+s}^o + \theta\left(c_{t+s}^{rt} - bc_{t+s-1}\right)^{-\sigma} MRS_{t+s}^{rt}\right] \end{array} \right\} \tag{67}$$

Final good firms: Final good firms are perfectly competitive producing a final good, Q_t, which they sell only domestically. To produce the final good, they combine a continuum of domestic intermediate goods $y_{H,t}^z$ using a Dixit-Stiglitz aggregator:

$$Q_t = \left(\int_0^1 y_{H,t}^z dz^{\frac{1}{1+\lambda_{p,t}}}\right)^{1+\lambda_{p,t}} \tag{68}$$

where $\lambda_{p,t}$ is the price markup, which is assumed to be a stationary $AR(1)$ process. They maximize profits:

$$\max_{y_{H,t}^z} P_t Q_t - \int_0^1 P_t^z y_{H,t}^z dz \tag{69}$$

subject to (68). This optimization problem results in their demand function:

$$y_{H,t}^z = \left(\frac{P_t^z}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Q_t. \tag{70}$$

Perfect competition results in zero profits which implies the following expression for the aggregate (non-energy) core price index:

$$P_t = \left[\int_0^1 (P_t^z)^{-\frac{1}{\lambda_{p,t}}} dz\right]^{-\lambda_{p,t}}. \tag{71}$$

Intermediate goods firms

Intermediate firms z are monopolistically competitive and use as inputs capital services, $u_t^z K_t^z$, labor services, h_t^z, and commodity goods, X_t^z. The production technology reads as follows:

$$Y_t^z = \varepsilon_{a,t}\left\{(1-\alpha_x)^{\frac{1}{\epsilon}}\left[(u_t^z K_t^z)^{\alpha}(z_t h_t^z)^{1-\alpha}\right]^{\frac{\epsilon-1}{\epsilon}} + \alpha_x^{\frac{1}{\epsilon}}(X_t^z)^{\frac{\epsilon-1}{\epsilon}}\right\}^{\frac{\epsilon}{\epsilon-1}} - z_t\Phi \tag{72}$$

where α_x denotes the share of commodity goods used in the production process and ϵ is the constant elasticity of substitution between the capital-labor bundle and the commodity inputs. The capital-labor bundle is assumed to be produced with a Cobb-Douglas function, with α denoting the capital services' share. $\varepsilon_{a,t}$ represents a (temporary) technology shock, Φ are fixed costs of production and z_t represents the labor-augmenting permanent technology shock. The intermediate good firm z's profits are defined as follows:

$$P_t^z Y_t^z - R_t^k u_t^z K_t^z - W_t h_t^z - \varepsilon_t P_{x,t}^* X_t^z \tag{73}$$

Cost minimization, subject to the production function (72), results in the following first-order conditions (FOCs), where the Lagrangian multiplier is MC_t^z, which represents firm z's nominal marginal cost:

$$\frac{\partial}{\partial u_t^z K_t^z} = -R_t^k + MC_t^z \varepsilon_{a,t} \left\{ (1-\alpha_x)^{\frac{1}{\epsilon}} \left((u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} + \alpha_x^{\frac{1}{\epsilon}} (X_t^z)^{\frac{\epsilon-1}{\epsilon}} \right\}^{\frac{1}{\epsilon-1}} \cdot \tag{74}$$

$$\cdot (1-\alpha_x)^{\frac{1}{\epsilon}} \alpha \frac{\left((u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}}}{u_t^z K_t^z} = 0 \tag{75}$$

$$\frac{\partial}{\partial h_t^z} = -W_t + MC_t^z \varepsilon_{a,t} \left\{ (1-\alpha_x)^{\frac{1}{\epsilon}} \left((u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} + \alpha_x^{\frac{1}{\epsilon}} (X_t^z)^{\frac{\epsilon-1}{\epsilon}} \right\}^{\frac{1}{\epsilon-1}} \cdot \tag{76}$$

$$\cdot (1-\alpha_x)^{\frac{1}{\epsilon}} (1-\alpha) \frac{\left((u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}}}{h_t^z} = 0 \tag{77}$$

$$\frac{\partial}{\partial X_t^z} = -\varepsilon_t P_{x,t}^* + MC_t^z \varepsilon_{a,t} \left\{ (1-\alpha_x)^{\frac{1}{\epsilon}} \left((u_t^z K_t^z)^{\alpha} (z_t h_t^z)^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} + \alpha_x^{\frac{1}{\epsilon}} (X_t^z)^{\frac{\epsilon-1}{\epsilon}} \right\}^{\frac{1}{\epsilon-1}} \alpha_x^{\frac{1}{\epsilon}} (X_t^z)^{-\frac{1}{\epsilon}} = 0 \tag{78}$$

Combining the above FOCs yields the following expression for the real marginal cost (defined as $mc_t^z \equiv MC_t^z / P_{CPI,t}$):

$$mc_t^z = (\varepsilon_{a,t})^{-1} \left[(1-\alpha_x) \alpha^{-\alpha(1-\epsilon)} (1-\alpha)^{-(1-\alpha)(1-\epsilon)} \left(r_t^k \right)^{\alpha(1-\epsilon)} (w_t)^{(1-\alpha)(1-\epsilon)} + \alpha_x \frac{s_t^{1-\epsilon}}{\left(\mu s_t^{1-\eta} + 1 - \mu \right)^{\frac{1-\epsilon}{1-\eta}}} \right]^{\frac{1}{1-\epsilon}} \tag{79}$$

where $w_t \equiv W_t / P_{CPI,t}$ denotes real wages and $r_t^k \equiv R_t^k / P_{CPI,t}$ is the real marginal product of capital services.

Price setting of Intermediate Goods Firms

Prices are sticky a la Calvo (1983). Firm z receives permission to optimally reset its price with probability $(1-\xi_p)$. The firm can also export its good abroad. It sets one price for its good regardless of the destination market, engaging thus in producer currency pricing. This means that the law of one price holds. Those firms which cannot reset the price adjust it according to the following scheme:

$$P_t^z = \pi_{t-1}^{\chi_p} \bar{\pi}^{1-\chi_p} P_{t-1}^z \tag{80}$$

where $\bar{\pi}$ is the gross inflation target. Since the representative intermediate good firm sells its good both domestically and abroad it faces a domestic and a foreign demand. The domestic demand is given by (18) while the foreign demand for firm z's good is given by:

$$\tilde{y}^{*,z}_{H,t} = \left(\frac{P^z_t}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} ReR^{\nu}_t \left((1-\mu) + \mu s^{1-\eta}_t\right)^{\frac{\nu}{1-\eta}} Y^*_t \tag{81}$$

where ReR_t is the real exchange rate defined as $ReR_t \equiv \varepsilon_t P^*_{CPI,t}/P_{CPI,t}$, and $P^*_{CPI,t}$ is the foreign headline price index. Parameter ν denotes the elasticity of substitution between home and foreign goods. Combining (18) and (81), we can write the total demand for the intermediate variety z as follows:

$$Y^z_t = \tilde{y}^z_{H,t} + \tilde{y}^{*,z}_{H,t} \tag{82}$$

and combining the expressions for the demand functions (18) and (81) we can rewrite the total demand for variety z as follows:

$$Y^z_t = \left(\frac{P^z_t}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \underbrace{\left[Q_t + ReR^{\nu}_t \left((1-\mu) + \mu s^{1-\eta}_t\right)^{\frac{\nu}{1-\eta}} Y^*_t\right]}_{\equiv Y^D_t} \tag{83}$$

The problem of the firm is:

$$\max_{\tilde{P}^z_t} E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \frac{\Lambda^o_{t+s}}{\Lambda^o_t} \left[\frac{\tilde{P}^z_t \pi^{\chi_p}_{t,t+s-1} \bar{\pi}^{s(1-\chi_p)}}{P_{t+s}} Y^z_{t+s} - \frac{MC^z_{t+s}}{P_{t+s}} Y^z_{t+s}\right]$$

subject to

$$Y^z_{t+s} = \left(\frac{\tilde{P}^z_t \pi^{\chi_p}_{t,t+s-1} \bar{\pi}^{s(1-\chi_p)}}{P_{t+s}}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \underbrace{\left[Q_{t+s} + ReR^{\nu}_{t+s} \left((1-\mu) + \mu s^{1-\eta}_{t+s}\right)^{\frac{\nu}{1-\eta}} Y^*_{t+s}\right]}_{\equiv Y^D_{t+s}} \tag{84}$$

where:

$$\pi_{t,t+s-1} = \{1 \text{ for } s = 0, \pi_t \cdot \pi_{t+1} \cdot ... \cdot \pi_{t+s-1} \text{ for } s = 1, 2....\}$$

Firms maximize the expected discounted sum of their profits by choosing the optimal relative price, $\frac{P^z_t}{P_t}$. The first-order condition reads as follows:

$$E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \frac{\Lambda^o_{t+s}}{\Lambda^o_t} \left[\frac{P^z_t}{P_t} \pi_{t,t+s-1}^{\chi_p\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \bar{\pi}^{s(1-\chi_p)(1-\lambda_{p,t+s})} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}-1} Y^D_{t+s} \right.$$
$$\left. - (1+\lambda_{p,t+s}) \frac{MC^z_{t+s}}{P_{t+s}} \pi_{t,t+s-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-s(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y^D_{t+s} \right] = 0 \tag{85}$$

Detrending yields:

$$E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \frac{\tilde{\Lambda}^o_{t+s} z_t}{\tilde{\Lambda}^o_t z_{t+s}} \left[\frac{P^z_t}{P_t} \pi_{t,t+s-1}^{\chi_p\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \bar{\pi}^{s(1-\chi_p)\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}-1} Y^D_{t+s} \right.$$
$$\left. - (1+\lambda_{p,t+s}) \frac{MC^z_{t+s}}{P_{t+s}} \pi_{t,t+s-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-s(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y^D_{t+s} \right] = 0 \tag{86}$$

$$E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \frac{\tilde{\Lambda}^o_{t+s} z_t}{\tilde{\Lambda}^o_t} \frac{Y^D_{t+s}}{z_{t+s}} \left[\frac{P^z_t}{P_t} \pi_{t,t+s-1}^{\chi_p\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \bar{\pi}^{s(1-\chi_p)\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}-1} \right.$$
$$\left. - (1+\lambda_{p,t+s}) \frac{MC^z_{t+s}}{P_{t+s}} \pi_{t,t+s-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-s(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \right] = 0 \tag{87}$$

$$E_t \sum_{s=0}^{\infty} (\beta\xi_p)^s \tilde{\Lambda}^o_{t+s} y^D_{t+s} \left[\frac{P^z_t}{P_t} \pi_{t,t+s-1}^{\chi_p\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \bar{\pi}^{s(1-\chi_p)\left(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}\right)} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}-1} \right.$$
$$\left. - (1+\lambda_{p,t+s}) \frac{MC^z_{t+s}}{P_{t+s}} \pi_{t,t+s-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-s(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \pi_{t,t+s}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \right] = 0 \tag{88}$$

where $\tilde{\Lambda}^o_{t+s} = \Lambda^o_{t+s} z_t$ and $y^D_t = Y^D_t / z_t$. The optimal relative price written recursively reads as follows:

$$\frac{P^z_t}{P_t} = \frac{F_{1,t}}{F_{2,t}} \tag{89}$$

where

$$F_{1,t} = (1+\lambda_{p,t})\,\tilde{\Lambda}_t^o \frac{MC_t^z}{P_t} \pi_{t-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} y_t^D + \beta\xi_p E_t \pi_{t+1}^{\frac{1+\lambda_{p,t+1}}{\lambda_{p,t+1}}} F_{1,t+1} \tag{90}$$

$$F_{2,t} = \pi_{t-1}^{\chi_p(1-\lambda_{p,t})} \bar{\pi}^{(1-\chi_p)(1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}})} \tilde{\Lambda}_t^o y_t^D + \beta\xi_p E_t \pi_{t+1}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t+1}}-1} F_{2,t+1} \tag{91}$$

Using the definition for the real marginal cost, $mc_t = MC_t/P_{CPI,t}$ (given the symmetry of equilibrium, all firms face the same marginal cost, i.e., $MC_t = MC_t^z$), we may write $F_{1,t}$ as follows:

$$F_{1,t} = (1+\lambda_{p,t})\,\tilde{\Lambda}_t^o mc_t \left[(1-\mu)+\mu s_t^{1-\eta}\right]^{\frac{1}{1-\eta}} \pi_{t-1}^{-\chi_p \frac{1+\lambda_{p,t}}{\lambda_{p,t}}} \bar{\pi}^{-(1-\chi_p)\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} y_t^D + \beta\xi_p E_t \pi_{t+1}^{\frac{1+\lambda_{p,t}}{\lambda_{p,t+1}}} F_{1,t+1}. \tag{92}$$

Fiscal and monetary policy

As mentioned in the main text, we assume that the government runs a balanced budget at all dates, adjusting lump-sum taxes to finance its expenditures fully:

$$T_t = P_t G_t \tag{93}$$

or in real terms:

$$\frac{T_t}{P_{CPI,t}} = \frac{P_t}{P_{CPI,t}} G_t \tag{94}$$

Using the definition (5), we may write:

$$\frac{T_t}{P_{CPI,t}} = \left[(1-\mu)+\mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} G_t \tag{95}$$

which after adjusting for growth becomes:

$$\tau_t = \left[(1-\mu)+\mu s_t^{1-\eta}\right]^{\frac{1}{\eta-1}} g_t \tag{96}$$

where $\tau_t = \frac{T_t}{z_t P_{CPI,t}}$ and $g_t = \frac{G_t}{z_t P_{CPI,t}}$.

The monetary authority sets the nominal interest rate according to a Taylor rule:

$$\frac{R_t}{R} = \varepsilon_{R,t} \left(\frac{R_{t-1}}{R}\right)^{\phi_R} \left[\left(\frac{\pi_{CPI,t}}{\pi_{CPI}}\right)^{\phi_\pi} \left(\frac{GDP_t}{GDP_t^f}\right)^{\phi_y}\right]^{1-\phi_R} \tag{97}$$

where GDP_t represents the gross domestic product in this economy (defined below in equation 35) and GDP_t^f denotes the level of output in the absence of nominal price and wage rigidities, while $\varepsilon_{R,t}$ is an *i.i.d.* monetary policy shock.

Aggregation and market clearing:

$$h_t = s_{W,t} h_t^d \tag{98}$$

$$u_t K_t = u_t \int_0^1 K_t^z dz \tag{99}$$

$$\int_0^1 P_t^z Y_t^z dz = P_t Y_t^D \tag{100}$$

$$X_t = \mu s_t^{-\eta} \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{\eta}{1-\eta}} C_t + \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} mc_t^{\epsilon} s_t^{-\varepsilon} \left[(1-\mu) + \mu s_t^{1-\eta}\right]^{\frac{\varepsilon}{1-\eta}} \left(s_{P,t} Y_t^D + z_t \Phi\right) \tag{101}$$

$$Y_t = s_{P,t} Y_t^D = s_{P,t} \left[Q_t + ReR_t^{\nu} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\nu}{1-\eta}} Y_t^*\right] \tag{102}$$

$$Q_t = C_{q,t} + I_t + G_t \tag{103}$$

$$C_{q,t} = \theta C_{q,t}^{rt} + (1-\theta) C_{q,t}^{o} \tag{104}$$

$$C_t = \theta C_t^{rt} + (1-\theta) C_t^{o} \tag{105}$$

$$h_t = \theta h_t^{rt} + (1-\theta) h_t^{o} \tag{106}$$

$$K_t = (1-\theta) K_t^{o} \tag{107}$$

$$I_t = (1-\theta) I_t^{o} \tag{108}$$

$$B_t = (1-\theta) B_t^{o} \tag{109}$$

$$D_t = (1-\theta) D_t^{o} \tag{110}$$

$$T_t = \theta T_t^{rt} + (1-\theta) T_t^{o} \tag{111}$$

Net foreign assets and the trade balance:

Net foreign assets evolve as follows:

$$\frac{B_{t+1}^*}{R_t^*} = B_t^* + \frac{TB_t}{\varepsilon_t} \tag{112}$$

where the trade balance reads:

$$TB_t = P_t y^*_{H,t} - \varepsilon_t P^*_{x,t} X_t. \tag{113}$$

Adjusting the law of motion of net foreign assets for growth we receive:

$$\frac{b^*_{t+1}}{R^*_t} = \frac{b^*_t}{g_{z,t}\pi^*_{CPI,t}} + \frac{tb_t}{ReR_t} \tag{114}$$

where $b^*_{t+1} = \frac{B^*_{t+1}}{z_t P_{CPI,t}}$. Working in a similar manner with the trade balance, we receive:

$$tb_t = \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} \left(y^*_{H,t} - s_t x_t\right) \tag{115}$$

where $tb_t = \frac{TB_t}{z_t P_{CPI,t}}$.

GDP deflator and GDP definition

The GDP deflator reads as follows:

$$P_t^{1-\epsilon} \equiv \left[(1-\alpha_x) P_{GDP,t}^{1-\epsilon} + \alpha_x \left(\varepsilon_t P^*_{x,t}\right)^{1-\epsilon}\right] \tag{116}$$

Dividing both sides by $P_t^{1-\epsilon}$ we may write:

$$\frac{P_{GDP,t}}{P_t} = \left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} \tag{117}$$

The GDP is defined as follows:

$$\left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} GDP_t = \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} \left(s_{P,t} Y_t^D - s_t X_t^f\right) \tag{118}$$

or,

$$\left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} GDP_t = s_{P,t} Y_t^D - s_t^{1-\epsilon} \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} mc_t^{\epsilon} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\epsilon}{1-\eta}} \left(s_{P,t} Y_t^D + z_t \Phi\right) \tag{119}$$

which after adjusting for growth becomes:

$$\left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} gdp_t = y_t - s_t^{1-\epsilon} \alpha_x \left(\varepsilon_{a,t}\right)^{\epsilon-1} mc_t^{\epsilon} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{\epsilon}{1-\eta}} \left(y_t + \Phi\right)$$

where $gdp_t = GDP_t/z_t$ and $y_t = Y_t/z_t$. Note also that we have made use of the aggregation, $P_tY_t = \int_0^1 P_t^z Y_t^z dz = \int_0^1 \left(\frac{P_t^z}{P_t}\right)^{1-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} dz P_t Y_t^D = s_{P,t} P_t Y_t^D$.

Resource constraint

The resource constraint is summarized as follows:

$$C_t + \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} (G_t + I_t) + \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1-\nu}{\eta-1}} ReR_t^{\nu} Y_t^* - s_t \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} X_t$$
$$= \left(\frac{1-\alpha_x s_t^{1-\epsilon}}{1-\alpha_x}\right)^{\frac{1}{1-\epsilon}} \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} GDP_t - \left((1-\mu) + \mu s_t^{1-\eta}\right)^{\frac{1}{\eta-1}} \alpha(u_t) K_t$$
$$+ z_t \theta \Big[(\varepsilon_{FS,t} - 1) - \frac{1}{6} \sum_{i=8}^{13} (\varepsilon_{FS,t-i} - 1) \Big] \tag{120}$$

In general, we adjust variables to guarantee that the model has a balanced growth. Lower case letters stand for detrended variables, for example, $y_t = \frac{Y_t}{z_t}$, $w_t = \frac{W_t}{P_t z_t}$, $r_t^k = \frac{R_t^k}{P_t}$, $\lambda_t^o = \Lambda_t^o z_t$. Given that the model is then log-linearized, we omit price and wage dispersion variables.

B The steady state

Assumptions:

$$s = 1$$

and PPP holds at the steady state:

$$ReR = 1$$

We calibrate $\frac{x^f}{y}$ to 0.05 to get:

$$\alpha_x = \frac{\frac{x^f}{y}}{mc^{\epsilon-1}}$$

FOC for consumption:

$$(c^o - bc)^{-\sigma} = \lambda^o$$

Euler equation:

$$\frac{R}{\pi_{CPI}} = \frac{g_z}{\beta}$$

FOC investments:

$$\begin{aligned} 1 &= Q^o \varepsilon_i \left\{ 1 - \gamma_I (g_z - g_z) g_z - \frac{\gamma_I}{2} (g_z - g_z)^2 \right\} \\ &\quad + \frac{1}{g_z} Q^o \varepsilon_i \beta \gamma_I (g_z - g_z) g_z^2 \end{aligned}$$

$$Q^o = 1$$

FOC for capital:

$$\frac{1}{g_z} \beta \left\{ \left[r^k u - a(u) \right] + Q^o (1 - \delta) \right\} = Q^o$$

Note that $u = 1$, $a(u) = 0$ and $Q^o = 1$, so that:

$$\frac{\beta}{g_z} \left\{ \left(r^k - \delta \right) + 1 \right\} = 1$$

FOC for utilization:

$$r^k = \gamma_{u1} + \gamma_{u2} (u - 1)$$

Such that we can calibrate $\gamma_{u1} = r^k$.
Real marginal costs:

$$mc = \frac{\lambda_p - 1}{\lambda_p}$$

Using zero steady state profits we can solve for steady-state domestic production:

$$\frac{y + \Phi}{y} = \frac{\lambda_p}{\lambda_p - 1} = \frac{1}{mc}$$

Capital accumulation equation:

$$\frac{i}{k} = 1 - \frac{(1 - \delta)}{g_z}$$

Trade balance:

$$tb = 0$$

Then:

$$y_H^* = y^* = x$$

$$b^* = 0$$

$$\psi = 0$$

Capital-hours ratio:

$$\frac{k}{h} = g_z \frac{\alpha}{(1-\alpha)} \frac{w}{r^k}$$

Real wage:

$$w = \left[\frac{mc^{1-\epsilon} - \alpha_x}{(1-\alpha_x)\,\alpha^{-\alpha(1-\epsilon)}\,(1-\alpha)^{-(1-\alpha)(1-\epsilon)}\,(r^k)^{\alpha(1-\epsilon)}} \right]^{\frac{1}{(1-\alpha)(1-\epsilon)}}$$

Capital-output ratio:

$$\frac{k}{y} = \alpha\,(1-\alpha_x)\,\frac{(1-\alpha_x mc^{\epsilon-1})}{1-\alpha_x}\frac{g_z}{r^k}$$

Value added:

$$\frac{gdp}{y} = 1 - \frac{x^f}{y}$$

Resource constraint:

$$\frac{c}{gdp} = 1 - \frac{g}{gdp} - \frac{i}{gdp}$$

$\frac{g}{gdp} = 0.32$ (later on we define $g_{gdp} = \frac{g}{gdp}$) based on the average of government consumption over the sample, and combining this with $\frac{i}{gdp} = \frac{i}{k}\frac{k}{gdp} = \frac{i}{k}\frac{k}{y}\frac{y}{gdp}$ we get:

$$\frac{c}{gdp} = 1 - \frac{g}{gdp} - \frac{i}{gdp}$$

Using the government budget constraint we get:

$$\tau_{rt} = \frac{g}{gdp} gdp$$

Then taking $c = \frac{c}{gdp} gdp$
Using $c = \frac{c}{gdp} gdp$
Note that labor income-consumption ratio:

$$\frac{wh}{c} = (1-\alpha)\left(1-\alpha_x mc^{\epsilon-1}\right)\frac{y}{c}$$

Using this to get steady-state hours: $h = \frac{wh}{c}\frac{c}{w}$, we can then find the ROT consumption:

$$c_{rt} = w\,h - \tau_{rt}$$

Combining this with total consumption gives the consumption of the Ricardian households at the steady-state:

$$c^o = \frac{(c - \theta c_{rt})}{1-\theta}$$

Demand for energy and non-energy goods are given by:

$$x^o = \mu c^o$$

$$c_q^o = (1-\mu)c^o$$

$$x^{rt} = \mu c^{rt}$$

$$c_q^{rt} = (1-\mu)c^{rt}$$

Market clearing for energy and non-energy good:

$$x = \theta x^{rt} + (1-\theta)x^o$$

$$c_q = \theta c_q^{rt} + (1-\theta)c_q^o$$

Market clearing for the non-energy good gives: $Q = c_q + I + g$.

Finally, from the maximization problem of the intermediate good firm, we can compute the steady state values for F_1 and F_2:

$$F_1 = \frac{\lambda_p}{\lambda_p - 1} y^D \left(\frac{1}{1 - \beta\xi_p} \right) mc\tilde{\Lambda} \tag{121}$$

$$F_2 = y^D \tilde{\Lambda} \left(\frac{1}{1 - \beta\xi_p} \right) \tag{122}$$

where we have made the assumption that $\pi_{CPI} = \bar{\pi}$.

We assume that there is a 0 trade-balance in the steady-state, $tb = 0$. This means that, imports at the steady state ($\frac{x}{gdp}$) should be equal to exports ($\frac{y_H^*}{gdp}$). From the foreign demand equation we get that $y_H^* = y^*$.

C The linearized model

In the equations below variables with a tilde represent linear deviations from their steady state. The remaining variables are log-linearized.

Euler equation Ricardian Household:

$$\begin{aligned} \hat{c}_t^o = \hat{c}_{t+1}^o + b\frac{c}{c^o} \left(\hat{c}_{t-1} - \hat{c}_t \right) - \frac{1 - b\,\frac{c}{c^o}}{\sigma} \left(\hat{R}_t - \hat{\pi}_{cpi,t+1} + \hat{\varepsilon}_{b,t} \right) \\ + \frac{1}{c^o} \left(\hat{\varepsilon}_{FS,t} - \hat{\varepsilon}_{FS,t+1} \right) + \frac{b}{c^o} \left(\hat{\varepsilon}_{FS,t} - \hat{\varepsilon}_{FS,t-1} \right) \end{aligned} \tag{123}$$

Demand for non-energy goods by Ricardian households:

$$\hat{c}_{q,t}^o = \hat{c}_t^o + \mu\eta\hat{s}_t \tag{124}$$

Demand for energy goods by Ricardian households:

$$\hat{x}_t^o = \hat{c}_t^o - \eta \left(1 - \mu \right) \hat{s}_t \tag{125}$$

Investment equation and related equations, including Tobin's Q:

$$\hat{i}_t = \frac{1}{\gamma_I {g_z}^2 \left(1 + \beta \right)} \left(\hat{q}_t^o - \mu\hat{s}_t + \hat{\varepsilon}_{i,t} \right) + \frac{1}{1+\beta}\, \hat{i}_{t-1} + \frac{\beta}{1+\beta}\, \hat{i}_{t+1} \tag{126}$$

$$-\hat{R}_t - \hat{\varepsilon}_{b,t} \frac{\sigma}{1 - b\,\frac{1}{c^o}} + \hat{\pi}_{cpi,t+1} + r_k \frac{\beta}{g_z}\, \hat{r}_{k,t+1} + (1 - \delta)\, \frac{\beta}{g_z}\, \hat{q}_{t+1}^o = \hat{q}_t^o \tag{127}$$

$$\hat{r}_{k,t} = \mu\gamma_{u1}\hat{s}_t + \frac{\sigma_u}{1-\sigma_u}\,\hat{u}_t \tag{128}$$

$$\hat{k}_t = \frac{1-\delta}{g_z}\,\hat{k}_{t-1} + i^k\,\hat{i}_t + \hat{\varepsilon}_{i,t}\,\left(1+\beta\right)g_z{}^2 i^k\gamma_I \tag{129}$$

Consumption of non-Ricardian households:

$$\hat{c}^{rt}_t = \frac{wh^{rt}}{c^{rt}}\left(\hat{w}_t + \hat{h}_t\right) - \frac{\tau}{c^{rt}}\hat{\tau}^{rt}_t + \frac{1}{c^{rt}}\hat{\varepsilon}_{FS,t} - \frac{1}{6}\frac{1}{c^{rt}}\sum_{i=8}^{13}\hat{\varepsilon}_{FS,t-i} \tag{130}$$

Demand for non-energy goods by non-Ricardian households:

$$\hat{c}^{rt}_{q,t} = \hat{c}^{rt}_t + \mu\eta\hat{s}_t \tag{131}$$

Demand for energy goods by non-Ricardian households:

$$\hat{x}^{rt}_t = \hat{c}^{rt}_t - \eta\left(1-\mu\right)\hat{s}_t \tag{132}$$

Resource constraint:

$$c_{gdp}\,\hat{c}_t + g_{gdp}\hat{g}_t + i_{gdp}\,\hat{i}_t + \left(-\mu\left(g_{gdp}+i_{gdp}\right) + \frac{\mu\,\left(\nu-1\right)\,y^*}{gdp} - \frac{\left(1-\mu\right)\,x}{gdp}\right)\,\hat{s}_t + \nu\,\frac{y^*}{gdp}\,\widehat{ReR}_t$$
$$+\frac{y^*}{gdp}\,\hat{y}^*_t - \frac{x}{gdp}\,\hat{x}_t + \frac{r_k}{g_z}\,k_{gdp}\,\hat{u}_t = \widehat{gdp}_t - \left(\frac{\alpha_x}{\left(1-\alpha_x\right)}+\mu\right)\hat{s}_t + \frac{\theta}{gdp}\left(\hat{\varepsilon}_{FS,t} - \frac{1}{6}\sum_{i=8}^{13}\hat{\varepsilon}_{FS,t-i}\right) \tag{133}$$

GDP Definition:

$$\hat{y}_t = \frac{gdp}{y}\widehat{gdp}_t + \left(\frac{x^f}{y} - \frac{\alpha_x}{1-\alpha_x}\frac{gdp}{y}\right)\hat{s}_t + \frac{x^f}{y}\hat{x}^f_t$$

or,

$$\widehat{gdp}_t = \left\{\frac{\alpha_x}{1-\alpha_x} - \frac{\alpha_x mc^{\epsilon-1}\left[\left(1-\epsilon\right)+\epsilon\mu\right]}{1-\alpha_x mc^{\epsilon-1}}\right\}\hat{s}_t$$
$$-\frac{\alpha_x mc^{\epsilon-1}\left(\epsilon-1\right)}{1-\alpha_x mc^{\epsilon-1}}\hat{\varepsilon}_{a,t} - \frac{\alpha_x\epsilon mc^{\epsilon-1}}{1-\alpha_x mc^{\epsilon-1}}\widehat{mc}_t + \frac{1-\alpha_x mc^{\epsilon}}{1-\alpha_x mc^{\epsilon-1}}\hat{y}_t$$

Total non-energy consumption:

$$\hat{c}_{q,t} = \theta\frac{c^{rt}_q}{c_q}\hat{c}^{rt}_{q,t} + \left(1-\theta\right)\frac{c^o_q}{c_q}\hat{c}^o_{q,t} \tag{134}$$

Total consumption:

$$\hat{c}_t = \theta \frac{c^{rt}}{c} \hat{c}_t^{rt} + (1-\theta) \frac{c^o}{c} \hat{c}_t^o \tag{135}$$

Price Phillips curve:

$$\hat{\pi}_t = \frac{\beta}{1+\beta\chi_p} E_t \hat{\pi}_{t+1} + \frac{\chi_p}{1+\beta\chi_p} \hat{\pi}_{t-1} + \frac{(1-\beta\xi_p)(1-\xi_p)}{(1+\beta\chi_p)\xi_p} \left(\widehat{mc}_t + \mu \hat{s}_t + \frac{\lambda_p}{1+\lambda_p} \hat{\lambda}_{p,t} \right) \tag{136}$$

Relative price of energy goods at home :

$$\hat{s}_t = \frac{1}{1-\mu} \left(\widehat{ReR}_t + \hat{s}_t^* \right) \tag{137}$$

Wage Phillips Curve:

$$\begin{aligned} \hat{w}_t = & -\left(\frac{(1-\xi_w)\,(1-\beta\,\xi_w)}{(1+\beta)\,\xi_w} \right) \left(\hat{w}_t - \frac{1}{1+\omega} \left(\widehat{mrs}_t^o + \omega\, \widehat{mrs}_t^{rt} \right) - \frac{\lambda_w}{1+\lambda_w} \hat{\lambda}_{w,t} \right) \\ & + \frac{\beta}{1+\beta}\, \hat{w}_{t+1} + \frac{1}{1+\beta}\, \hat{w}_{t-1} + \frac{\chi_w}{1+\beta}\, \hat{\pi}_{cpi,t-1} - \frac{1+\beta\,\chi_w}{1+\beta}\, \hat{\pi}_{cpi,t} + \frac{\beta}{1+\beta}\, \hat{\pi}_{cpi,t+1} \end{aligned} \tag{138}$$

$$\widehat{mrs}_t^o = \frac{\sigma}{1-b\,\frac{c}{c^o}}\, \hat{c}_t^o - \frac{b\,\sigma}{\frac{c^o}{c}-b}\, \hat{c}_{t-1} + \phi_l\, \hat{h}_t - \frac{\sigma}{c^o-b} \left(\hat{\varepsilon}_{FS,t} - b \hat{\varepsilon}_{FS,t-1} \right) \tag{139}$$

$$\widehat{mrs}_t^{rt} = \frac{\sigma}{1-b\,\frac{c}{c^{rt}}}\, \hat{c}_t^{rt} - \frac{b\,\sigma}{\frac{c^{rt}}{c}-b}\, \hat{c}_{t-1} + \phi_l\, \hat{h}_t \tag{140}$$

$$\hat{u}_t + \hat{k}_{t-1} - \hat{h}_t = \hat{w}_t - \hat{r}_t^k \tag{141}$$

Market clearing for energy:

$$\hat{x}_t = \theta\, \frac{x^{rt}}{x}\, \hat{x}_t^{rt} + (1-\theta)\, \frac{x^o}{x}\, \hat{x}_t^o + \frac{x^f}{x}\, \hat{x}_t^f \tag{142}$$

Marginal cost:

$$\widehat{mc}_t = -\hat{\varepsilon}_{a,t} + \alpha \left(1 - \alpha_x mc^{\epsilon-1} \right) \hat{r}_t^k + (1-\alpha) \left(1 - \alpha_x mc^{\epsilon-1} \right) \hat{w}_t + \alpha_x mc^{\epsilon-1} \,(1-\mu)\, \hat{s}_t \tag{143}$$

Production function:

$$\hat{y}_t = (1+\lambda_p)\left\{\hat{\varepsilon}_{a,t} + \left(1-\alpha_x mc^{\epsilon-1}\right)\left[\alpha\left(\hat{k}_t + \hat{u}_t\right) + (1-\alpha)\,\hat{h}_t\right] + \alpha_x mc^{\epsilon-1}\hat{x}_t^f\right\} \quad (144)$$

Demand for energy by the firm:

$$\hat{x}_t^f = (\epsilon-1)\,\hat{\varepsilon}_{a,t} + \epsilon\widehat{mc}_t + \frac{y}{y+\Phi}\hat{y}_t - \epsilon\,(1-\mu)\,\hat{s}_t \quad (145)$$

Headline CPI inflation:

$$\hat{\pi}_{cpi,t} = \hat{\pi}_t + \mu\,\frac{s^{1-\eta}}{(1-\mu)+\mu\,s^{1-\eta}}\,(\hat{s}_t - \hat{s}_{t-1}) \quad (146)$$

GDP deflator:

$$\hat{\pi}_{gdp,t} = \hat{\pi}_t - \frac{\alpha_x}{1-\alpha_x}\,(\hat{s}_t - \hat{s}_{t-1}) \quad (147)$$

Taylor rule:

$$\begin{aligned}\hat{R}_t &= \phi_r\,\hat{R}_{t-1} + (1-\phi_r)\left(\phi_\pi\,\hat{\pi}_{cpi,t} + \phi_y\left(\widehat{gdp}_t - \widehat{gdp}_t^f\right)\right)\\ &+ \phi_{gy}\left(\widehat{gdp}_t - \widehat{gdp}_{t-1} - \left(\widehat{gdp}_t^f - \widehat{gdp}_{t-1}^f\right)\right) + \hat{\varepsilon}_{r,t}\end{aligned} \quad (148)$$

Government Budget constraint:

$$\hat{\tau}_t = -\mu\frac{g}{gdp}\frac{gdp}{\tau}\hat{s}_t + gdp\frac{g}{gdp}\hat{g}_t \quad (149)$$

UIP:

$$\hat{\varepsilon}_{t+1} - \hat{\varepsilon}_t = \hat{R}_t - \hat{R}_t^* + \chi\tilde{b}_t^* - \hat{\varepsilon}_{\psi,t} + \hat{\varepsilon}_{b,t} \quad (150)$$

Real Exchange Rate:

$$\widehat{ReR}_t = \widehat{ReR}_{t-1} + \hat{\varepsilon}_t - \hat{\varepsilon}_{t-1} + \hat{\pi}_t^* - \hat{\pi}_{cpi,t} \quad (151)$$

Balance of payments, assuming symmetric steady-state (assuming zero net foreign asset holdings at the steady state and hence zero steady state trade balance):

$$\tilde{b}_{t+1}^* = \frac{R^*}{g_z\pi^*}\tilde{b}_t^* + R^*\widetilde{tb}_t \quad (152)$$

Trade Balance:

$$\widetilde{tb}_t = \frac{y_H^*}{gdp}\hat{y}_{H,t}^* - \frac{x}{gdp}\hat{x}_t - \frac{x}{gdp}\hat{s}_t \tag{153}$$

Foreign(or Global) Demand for home produced intermediate goods:

$$\hat{y}_{H,t}^* = \nu\widehat{ReR}_t + \nu\mu\hat{s}_t + \hat{y}_t^* \tag{154}$$

Total Demand for home produced intermediate goods :

$$\hat{y}_t = \frac{gdp}{y}\left(\frac{c_q}{gdp} + i_{gdp} + g_{gdp}\right)\hat{Q}_t + \frac{y^*}{y}\left(\nu\widehat{ReR}_t + \nu\mu\hat{s}_t + \hat{y}_t^*\right) \tag{155}$$

Final Goods market clearing condition:

$$\hat{Q}_t = \frac{gdp}{Q}\left(\frac{c_q}{gdp}\hat{c}_{q,t} + i_{gdp}\hat{i}_t + g_{gdp}\hat{g}_t\right) \tag{156}$$

Shocks:

$$\hat{\varepsilon}_{a,t} = \rho_a\,\hat{\varepsilon}_{a,t-1} + e_{a,t} \tag{157}$$

$$\hat{\varepsilon}_{b,t} = \rho_b\,\hat{\varepsilon}_{b,t-1} + e_{b,t} \tag{158}$$

$$\hat{\varepsilon}_{i,t} = \rho_i\,\hat{\varepsilon}_{i,t-1} + e_{i,t} \tag{159}$$

$$\hat{\varepsilon}_{r,t} = \rho_r\,\hat{\varepsilon}_{r,t-1} + e_{r,t} \tag{160}$$

$$\hat{g}_t = \rho_g\,\hat{g}_{t-1} + e_{g,t} \tag{161}$$

$$\hat{\lambda}_{p,t} = \rho_p\,\hat{\lambda}_{p,t-1} + e_{p,t}^{ma} - cmap\,e_{p,t-1}^{ma} \tag{162}$$

$$e_{p,t}^{ma} = e_{p,t} \tag{163}$$

$$\hat{\lambda}_{w,t} = \rho_w\,\hat{\lambda}_{w,t-1} + e_{w,}^{ma} - cmaw\,e_{w,t-1}^{ma} \tag{164}$$

$$e_{w,t}^{ma} = e_{w,t} \tag{165}$$

$$\hat{\varepsilon}_{\psi,t} = \rho_\psi\,\hat{\varepsilon}_{\psi,t-1} + e_{\psi,t} \tag{166}$$

Foreign exogenous variables:

$$\hat{R}_t^* = \rho_{R^*}\hat{R}_{t-1}^* + e_t^{R^*} \tag{167}$$

$$\hat{\pi}_t^* = \rho_{\pi^*}\hat{\pi}_{t-1}^* + e_t^{\pi^*} \tag{168}$$

$$\hat{y}_t^* = \rho_{y^*}\hat{y}_{t-1}^* + e_t^{y^*} \tag{169}$$

International relative price of energy goods:

$$\hat{s}^*_t = \rho_s\, \hat{s}^*_{t-1} + e_{s,t} \tag{170}$$

Flexible price equilibrium:

$$\begin{aligned}\hat{c}^{o,f}_t =& \hat{c}^{o,f}_{t+1} + b\frac{c}{c^o}\left(\hat{c}^f_{t-1} - \hat{c}^f_t\right) - \frac{1 - b\,\frac{c}{c^o}}{\sigma}\left(R^f_t + \hat{\varepsilon}_{b,t}\right)\\ &+ \frac{1}{c^o}\left(\hat{\varepsilon}_{FS,t} - \hat{\varepsilon}_{FS,t+1}\right) + \frac{b}{c^o}\left(\hat{\varepsilon}_{FS,t} - \hat{\varepsilon}_{FS,t-1}\right)\end{aligned} \tag{171}$$

$$\hat{c}^{o,f}_{q,t} = \hat{c}^{o,f}_t + \mu\eta\hat{s}^f_t \tag{172}$$

$$\hat{x}^{o,f}_t = \hat{c}^{o,f}_t - \eta\left(1 - \mu\right)\hat{s}^f_t \tag{173}$$

$$\hat{i}^f_t = \frac{1}{\gamma_I {g_z}^2\left(1 + \beta\right)}\left(\hat{q}^{o,f}_t - \mu\hat{s}^f_t + \hat{\varepsilon}_{i,t}\right) + \frac{1}{1+\beta}\,\hat{i}^f_{t-1} + \frac{\beta}{1+\beta}\,\hat{i}^f_{t+1} \tag{174}$$

$$-\hat{R}^f_t - \hat{\varepsilon}_{b,t}\,\frac{\sigma}{1 - b\,\frac{1}{c^o}} + r_k\frac{\beta}{g_z}\,\hat{r}^f_{k,t+1} + \left(1 - \delta\right)\frac{\beta}{g_z}\,\hat{q}^{o,f}_{t+1} = \hat{q}^{o,f}_t \tag{175}$$

$$\hat{r}^f_{k,t} = \mu\gamma_{u1}\hat{s}^f_t + \frac{\sigma_u}{1 - \sigma_u}\,\hat{u}^f_t \tag{176}$$

$$\hat{k}_t^{\,f} = \frac{1-\delta}{g_z}\,\hat{k}^f_{t-1} + i^k\,\hat{i}^f_t + \hat{\varepsilon}_{i,t}\,\left(1 + \beta\right){g_z}^2 i^k\gamma_I \tag{177}$$

$$\hat{c}^{rt,f}_t = \frac{wh^{rt}}{c^{rt}}\left(\hat{w}^f_t + \hat{h}^f_t\right) - \frac{\tau}{c^{rt}}\hat{\tau}^{rt,f}_t + \frac{1}{c^{rt}}\hat{\varepsilon}_{FS,t} - \frac{1}{6}\frac{1}{c^{rt}}\sum_{i=8}^{13}\hat{\varepsilon}_{FS,t-i} \tag{178}$$

$$\hat{c}^{rt,f}_{q,t} = \hat{c}^{rt,f}_t + \mu\eta\hat{s}^f_t \tag{179}$$

$$\hat{x}^{rt,f}_t = \hat{c}^{rt,f}_t - \eta\left(1 - \mu\right)\hat{s}^f_t \tag{180}$$

$$\begin{aligned}&c_{gdp}\hat{c}^f_t + g_{gdp}\hat{g}_t + i_{gdp}\,\hat{i}^f_t + \left(-\mu\left(g_{gdp} + i_{gdp}\right) + \frac{\mu\left(\nu - 1\right)\,y^*}{gdp} - \frac{\left(1-\mu\right)x}{gdp}\right)\hat{s}^f_t + \nu\frac{y^*}{gdp}\widehat{ReR}^f_t\\ &+ \frac{y^*}{gdp}\hat{y}^*_t - \frac{x}{gdp}\hat{x}^f_t + \frac{r_k}{g_z}k_{gdp}\,\hat{u}^f_t = \widehat{gdp}^f_t - \left(\frac{\alpha_x}{\left(1 - \alpha_x\right)} + \mu\right)\hat{s}^f_t + \frac{\theta}{gdp}\left(\hat{\varepsilon}_{FS,t} - \frac{1}{6}\sum_{i=8}^{13}\hat{\varepsilon}_{FS,t-i}\right)\end{aligned} \tag{181}$$

$$\hat{y}_t^f = \frac{gdp}{y}\widehat{gdp}_t^f + \left(\frac{x^f}{y} - \frac{\alpha_x}{1-\alpha_x}\frac{gdp}{y}\right)\hat{s}_t^f + \frac{x^f}{y}\hat{x}_t^{f,f} \tag{182}$$

$$\hat{c}_{q,t}^f = \theta\frac{\hat{c}_q^{rt}}{c_q}\hat{c}_{q,t}^{rt,f} + (1-\theta)\frac{c_q^o}{c_q}\hat{c}_{q,t}^{o,f} \tag{183}$$

$$\hat{c}_t^f = \theta\frac{\hat{c}^{rt}}{c}\hat{c}_t^{rt,f} + (1-\theta)\frac{c^o}{c}\hat{c}_t^{o,f} \tag{184}$$

$$\hat{s}_t^f = \frac{1}{1-\mu}(\widehat{ReR}_t^f + \hat{s}_t^*) \tag{185}$$

$$\hat{w}_t^f = \frac{1}{1+\omega}(\widehat{mrs}_{o,t}^f + \omega\widehat{mrs}_{rt,t}^f) \tag{186}$$

$$\widehat{mrs}_t^{o,f} = \frac{\sigma}{1-b\,\frac{c}{c^o}}\,\hat{c}_t^{o,f} - \frac{b\,\sigma}{\frac{c^o}{c}-b}\,\hat{c}_{t-1}^f + \phi_l\,\hat{h}_t^f - \frac{\sigma}{c^o-b}\,(\hat{\varepsilon}_{FS,t} - b\hat{\varepsilon}_{FS,t-1}) \tag{187}$$

$$\widehat{mrs}_t^{rt,f} = \frac{\sigma}{1-b\,\frac{c}{c^{rt,f}}}\,\hat{c}_t^{rt,f} - \frac{b\,\sigma}{\frac{c^{rt,f}}{c}-b}\,\hat{c}_{t-1}^f + \phi_l\,\hat{h}_t^f \tag{188}$$

$$\hat{u}_t^f + \hat{k}_{t-1}^f - \hat{h}_t^f = \hat{w}_t^f - \hat{r}_t^{k,f} \tag{189}$$

$$\hat{x}_t^f = \theta\,\frac{x^{rt}}{x}\,\hat{x}_t^{rt,f} + (1-\theta)\,\frac{x^o}{x}\,\hat{x}_t^{o,f} + \frac{x^f}{x}\,\hat{x}_t^{f,f} \tag{190}$$

$$\widehat{mc}_t^f = -\hat{\varepsilon}_{a,t} + \alpha\left(1-\alpha_x mc^{\epsilon-1}\right)\hat{r}_t^{k,f} + (1-\alpha)\left(1-\alpha_x mc^{\epsilon-1}\right)\hat{w}_t^f + \alpha_x mc^{\epsilon-1}(1-\mu)\,\hat{s}_t^f \tag{191}$$

$$\widehat{mc}_t^f = -\mu\hat{s}_t^f - \frac{\lambda_p}{1+\lambda_p}\hat{\lambda}_{p,t} \tag{192}$$

$$\hat{y}_t^f = (1+\lambda_p)\,\left\{\hat{\varepsilon}_{a,t} + \left(1-\alpha_x mc^{\epsilon-1}\right)\left[\alpha\left(\hat{k}_t^f + \hat{u}_t^f\right) + (1-\alpha)\,\hat{h}_t^f\right] + \alpha_x mc^{\epsilon-1}\hat{x}_t^{f,f}\right\} \tag{193}$$

$$\hat{x}_t^{f,f} = (\epsilon-1)\,\hat{\varepsilon}_{a,t} + \epsilon\widehat{mc}_t^f + \frac{y}{y+\Phi}\hat{y}_t^f - \epsilon\,(1-\mu)\,\hat{s}_t^f \tag{194}$$

$$\hat{\tau}_t^f = -\mu\frac{g}{gdp}\frac{gdp}{\tau}\hat{s}_t^f + gdp\frac{g}{gdp}\hat{g}_t \tag{195}$$

$$\widehat{RER}_{t+1}^{f} - \widehat{RER}_{t}^{f} = \hat{R}_t^f - \left(\hat{R}_t^* - \hat{\pi}_t^*\right) + \chi\tilde{b}_t^{*,f} - \hat{\varepsilon}_{\psi,t} + \hat{\varepsilon}_{b,t} \tag{196}$$

$$\tilde{b}_{t+1}^{*,f} = \frac{R^*}{g_z\pi^*}\tilde{b}_t^{*,f} + R^*\widetilde{tb}_t^f \tag{197}$$

$$\widetilde{tb}_t^f = \frac{y_H^{*,f}}{gdp}\hat{y}_{H,t}^{*,f} - \frac{x}{gdp}\hat{x}_t^f - \frac{x}{gdp}\hat{s}_t^f \tag{198}$$

$$\hat{y}_{H,t}^{*,f} = \nu\widehat{ReR}_t^f + \nu\mu\hat{s}_t^f + \hat{y}_t^* \tag{199}$$

$$\hat{y}_t^f = \frac{gdp}{y}\left(\frac{c_q}{gdp} + i_{gdp} + g_{gdp}\right)\widehat{Q}_t^f + \frac{y^*}{y}\left(\nu\widehat{ReR}_t^f + \nu\mu\hat{s}_t^f + \hat{y}_t^*\right) \tag{200}$$

$$\widehat{Q}_t^f = \frac{gdp}{Q}\left(\frac{c_q}{gdp}\hat{c}_{q,t}^f + i_{gdp}\hat{i}_t^f + g_{gdp}\hat{g}_t\right) \tag{201}$$

D Additional derivations

D.1 Derivation of expression (38) in the text

The relative price of energy in the domestic economy is summarized by (in log-linear terms):

$$\hat{s}_t = \frac{1}{1-\mu}\left(\widehat{ReR}_t + \hat{s}_t^*\right) \tag{202}$$

Plugging this expression in the log-linearized trade balance we receive:

$$\widetilde{tb}_t = \frac{y_H^*}{gdp}\hat{y}_{H,t}^* - \frac{x}{gdp}\hat{x}_t - \frac{x}{gdp}\left(\frac{1}{1-\mu}\left(\widehat{ReR}_t + \hat{s}_t^*\right)\right) \tag{203}$$

The first order derivative thus of the trade with respect to the energy price shock, $\partial\widetilde{tb}/\partial\hat{s}_t^*$, is:

$$\frac{\partial\widetilde{tb}}{\partial\hat{s}_t^*} = -\frac{x}{gdp}\frac{1}{1-\mu} \tag{204}$$

The expression above captures the price effect of energy on imports. The marginal effect of higher energy price on the demand for energy and thereby on imports is captured by the partial derivative of the trade balance with respect to the indirect effect energy price shock through the demand for energy, $\frac{\partial \widetilde{tb}}{\partial \hat{x}_t}\frac{\partial \hat{x}_t}{\partial \hat{s}_t^*}$. Combining the total definition demand for energy (190) with the demand of Ricardian and Rule-of-thumb households, (125) and (132), the demand of firms (145) for energy, the marginal cost (143) and taking the partial derivative with respect to $\hat{s}_t^*$, we arrive at:

$$\frac{\partial \widetilde{tb}}{\partial \hat{x}_t}\frac{\partial \hat{x}_t}{\partial \hat{s}_t^*} = \frac{x}{gdp}\left[\eta\frac{x-x^f}{x} + \varepsilon\frac{x^f}{x}\left(1-\alpha_x\left(\frac{\lambda_p}{\lambda_p-1}\right)^{1-\varepsilon}\right)\right] \tag{205}$$

In order thus for the price effect on imports to dominate the demand effect it must hold that:

$$\left|\frac{\partial \widetilde{tb}}{\partial \hat{s}_t^*}\right| > \frac{\partial \widetilde{tb}}{\partial \hat{x}_t}\frac{\partial \hat{x}_t}{\partial \hat{s}_t^*}$$

or that:

$$\frac{1}{1-\mu} > \eta\frac{x-x^f}{x} + \varepsilon\frac{x^f}{x}\left(1-\alpha_x\left(\frac{\lambda_p}{\lambda_p-1}\right)^{1-\varepsilon}\right)$$

which is condition (38) reported in the text.

D.2 Derivation of expression (39) in the text

Combining the log-linearized trade balance (203), the log-linearized foreign demand for domestically produced goods (154) as well as the log-linearized total demand for energy (190) with the demand of Ricardian and Rule-of-thumb households, (125) and (132), the demand of firms (145) for energy, the marginal cost (143) and taking the partial derivative of the trade balance with respect to the energy price shock, $\hat{s}_t$ we arrive at:

$$\frac{\partial \widetilde{tb}}{\partial \hat{s}_t^*} = \frac{\nu\mu}{1-\mu} - \varepsilon\left(1-\alpha_x mc^{\varepsilon-1}\right)\frac{x^f}{x} - \frac{x-x^f}{x}\eta - \frac{1}{1-\mu} \tag{206}$$

The expression above takes into account all the effects of a change in the energy price, from direct to indirect via exchange rate movements and the impact on foreign demand. Clearly, for the change in the energy price to have a negative impact on the trade balance it must be that $\partial\widetilde{tb}/\partial\hat{s}_t^* < 0$. Conditioning on this and solving for the trade elasticity ν, we arrive at:

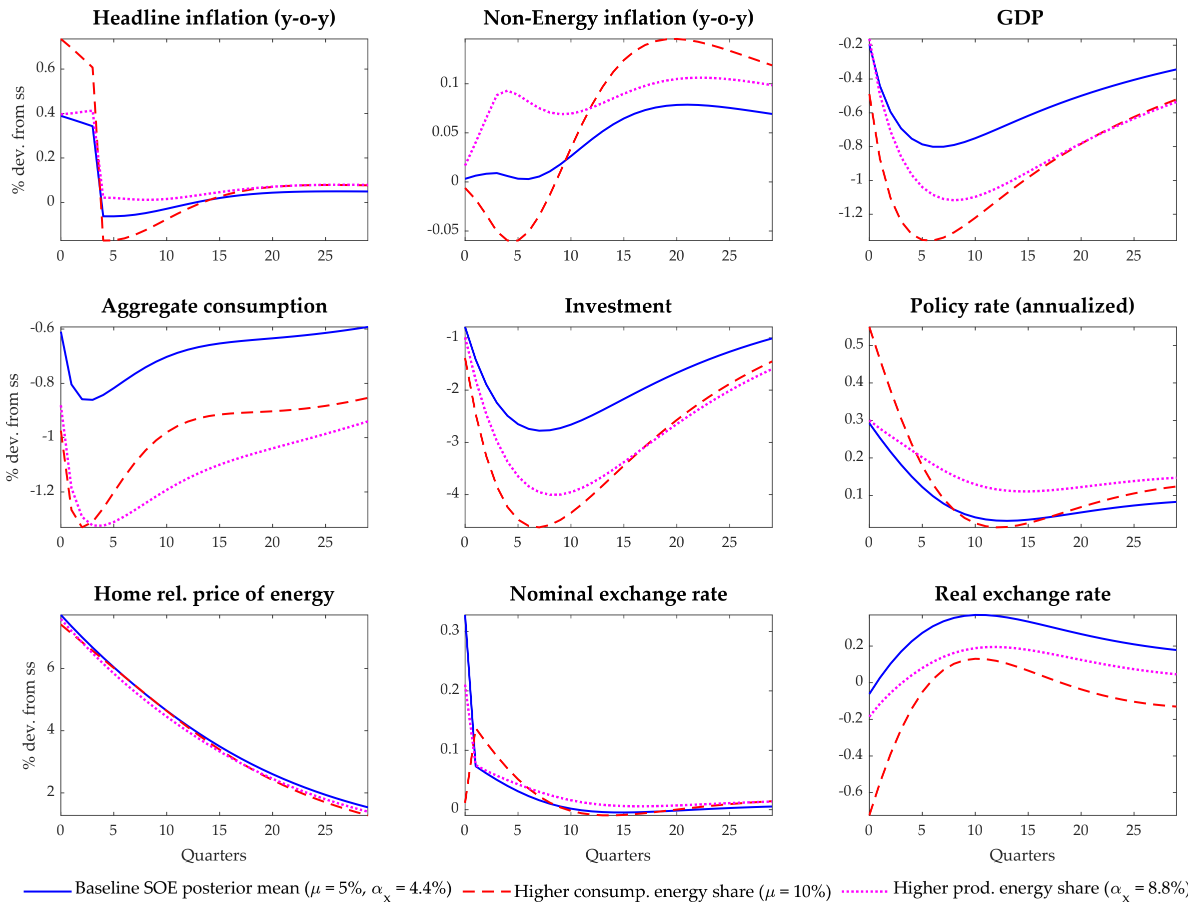
$$\nu < \left(\frac{1-\mu}{\mu}\right)\left[\eta\frac{x-x^f}{x} + \varepsilon\frac{x^f}{x}\left(1-\alpha_x\left(\frac{\lambda_p}{\lambda_p-1}\right)^{1-\varepsilon}\right)\right] + \frac{1}{\mu} \tag{207}$$

which is condition (39) reported in the text, where we have also taken into account that the trade balance is zero at the steady state (i.e. $\frac{y_H^*}{gdp} = \frac{x}{gdp}$) and have also imposed $\frac{x^{rt}}{x} = \frac{x^o}{x}$ for simplicity. Finally, we have exploited the fact the marginal cost at the steady state collapses to $mc = \frac{\lambda_p - 1}{\lambda_p}$.

E The role of energy in consumption and production

Figure E.1 examines how the impulse responses to an energy price shock change with the weight of energy in the consumption bundle, μ, and in the production function, α_x.

Figure E.1: The role of energy shares in the transmission of an energy price shock



Notes: The figure displays selected impulse response functions to an adverse energy price shock of one standard deviation. Responses are shown for alternative energy shares in consumption ($\mu = 10\%$ *versus* 5% in the baseline) and in the production function ($\alpha_x = 8.8\%$ *versus* 4.4% in the baseline). Positive values of the exchange rate imply a depreciation of the euro. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

F Limited substitutability in production and the amplification of energy shocks

Figure F.1 examines the role of the elasticity of substitution between energy and non-energy inputs in production, ε, for the transmission of an adverse energy price shock. Lower values of ε imply that firms face greater difficulties in substituting away from energy inputs when their relative price increases. The figure shows that this has important implications for both the real and nominal adjustment.

First, a lower elasticity leads to a markedly stronger contraction in real activity. GDP and consumption decline more sharply, reflecting weaker aggregate demand and limited ability of firms to adjust their input mix. Second, the dynamics of inflation are also affected. While headline inflation is only modestly impacted, non-energy inflation becomes more subdued in the short run when ε is low. This reflects the stronger decline in aggregate demand and real wages, which offsets the direct cost-push effect from higher energy prices. Third, the external adjustment is amplified. A lower elasticity leads to a larger and more persistent increase in the relative price of energy and a stronger depreciation of the real exchange rate.

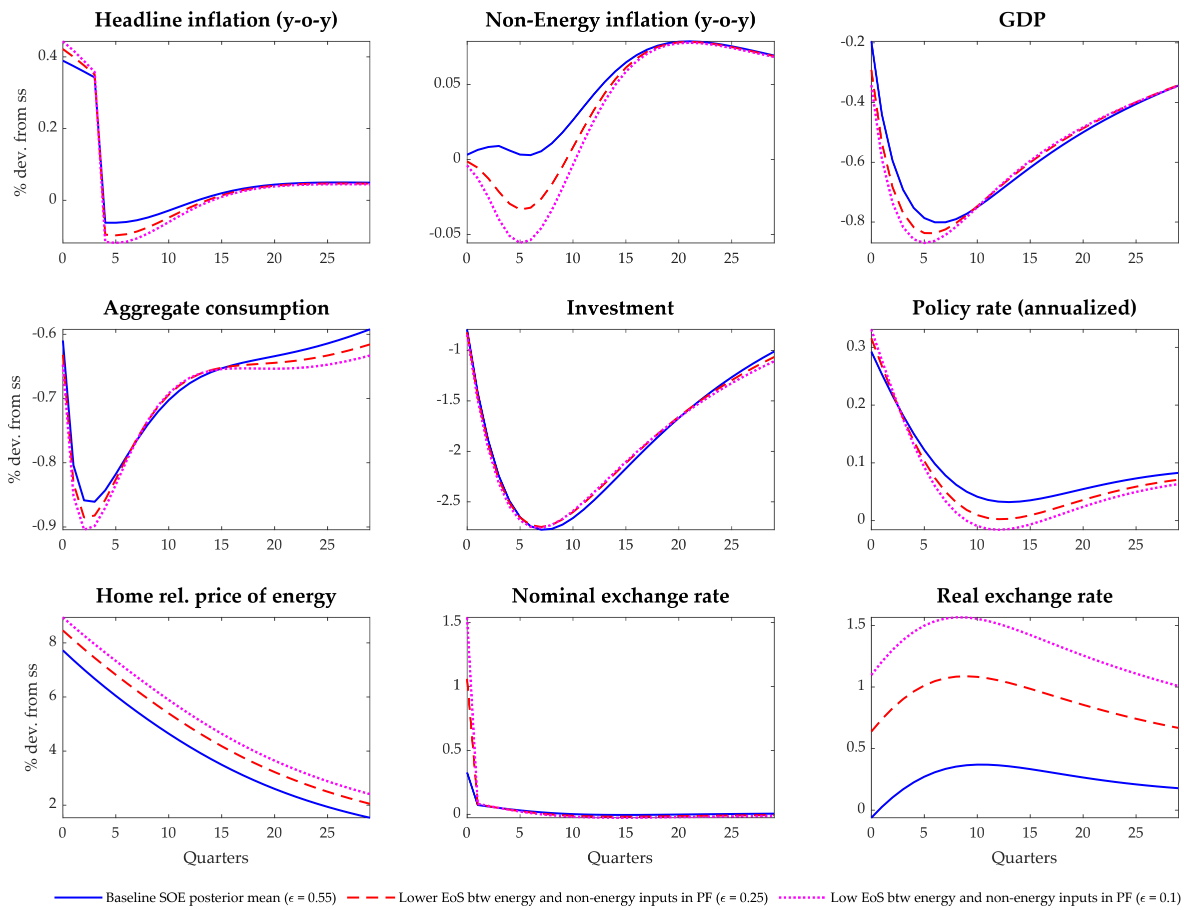
Lower values of ε also reinforce the dominance of the price effect over the demand effect in the trade balance condition (38), leading to a more pronounced deterioration of the trade balance. This leads to a larger decline in foreign assets which, via the modified UIP condition (40), explains the stronger depreciation of the euro in this case, which in turn determines the dynamics of the real exchange rate leading to a stronger and persistent real exchange rate depreciation. The stronger deterioration of the trade balance contributes too to the deeper contraction in economic activity.

Overall, these results highlight that the degree of substitutability between energy and other production inputs plays a key role in shaping the propagation of energy shocks, affecting both the magnitude of real effects and the balance between cost-push and demand-driven forces in inflation dynamics.

G Comparison with a model without energy

The importance of considering both the role of energy (in consumption and production) and exchange rate effects in explaining inflation dynamics and the recent inflation surge is the main focus of the paper. To stress this message, this section compares the results from our baseline model with the ones from a standard closed economy one, à la Smets

Figure F.1: How production substitutability shapes the propagation of energy price shocks



Notes: The figure displays selected impulse response functions to an adverse energy price shock of one standard deviation. Responses are shown for lower elasticities of substitution between energy and non-energy inputs in production ($\varepsilon = 0.25$ and 0.1 *versus* 0.55 in the baseline). Positive values of the exchange rate imply a depreciation of the euro. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

and Wouters (2003, 2007). Here we report the closed economy parameter estimates, while highlighting the key differences with respect to our baseline estimates, and show both the closed economy HD and FEVD for comparison.

G.1 Parameter estimates: open versus closed economy

The comparison of posterior estimates across the baseline open economy model and its closed economy counterpart from Table G.1.1 highlights several key differences with important implications for model dynamics.

First, the estimate for the inverse Frisch elasticity of labor supply differs across the two specifications. In the open economy model, the posterior mean of φ_l is estimated at 1.55, indicating that labor supply is slightly more inelastic–households are relatively more unresponsive to changes in real wages when deciding how much to work. In contrast, the closed economy estimate is lower at 0.99, suggesting that hours worked are more sensitive to wage fluctuations. This difference likely reflects the role of external shocks–such as energy price and exchange rate fluctuations–which introduce more frequent and larger movements in firms' labor demand. In the presence of such volatility, the model estimates a more inelastic labor supply in the open economy to limit excessive variation in hours worked. Although wage adjustment is similar in both economies, the combination of slightly more inelastic labor supply and nominal rigidities helps the model match observed dynamics where both wages and hours respond only gradually to shocks.

The investment adjustment cost parameter in the closed economy model is estimated at $\gamma_I = 4.29$, slightly below the open economy estimate of 4.65. This implies that investment is somewhat more sluggish in the open economy model, where higher adjustment costs dampen the immediate response of investment to shocks. The elasticity of capital utilization is estimated at $\sigma_u = 0.66$ in the closed economy, slightly below the open economy estimate of 0.72, indicating broadly comparable responsiveness of capital services to changes in economic conditions.

Price rigidity is estimated to be lower in the closed economy model, while wage rigidity is similar. The Calvo parameter for prices, ξ_p, is estimated at 0.80 in the closed economy, compared to 0.91 in the open economy. Wage stickiness is comparable across the two models, with $\xi_w = 0.62$ in the closed economy model versus 0.64 in the open one. This implies that nominal adjustments occur more frequently in the closed economy, allowing prices to respond more quickly to shocks.

The share of rule-of-thumb (RoT) consumers is slightly higher in the closed economy model, with θ equal to 0.16 compared to 0.09 in the open economy.[18] This suggests that while liquidity-constrained households play a role in both settings, their quantitative importance is somewhat diminished when external channels, such as exchange rate fluctuations and energy price shocks, are present.

The estimated ECB policy rule is broadly consistent across the two models. Both yield similar inflation response coefficients (with $\varphi_\pi \approx 2$) and a high degree of interest rate smoothing (with $\varphi_R \approx 0.9$), indicative of an inertial Taylor rule. The response to the output gap is modest in both cases ($\varphi_Y = 0.06$–0.08), reinforcing the primary focus on inflation stabilization.

[18] This estimated fraction of RoT consumers echoes the one in Albonico et al. (2024) for the US.

Finally, differences in shock processes reflect the role of external factors in shaping model dynamics. In the closed economy model, several shock processes exhibit slightly larger persistence. Notably, the persistence of the investment-specific shock is higher in the closed economy ($\rho_i = 0.29$ vs. 0.19). The risk premium shock is also more persistent, with $\rho_i = 0.86$ compared to 0.80 in the open economy, although the gap is modest. In contrast, the productivity shock displays a slightly lower persistence, with $\rho_a = 0.33$ in the closed economy and 0.40 in the open economy.

In terms of shock volatility, the standard deviations are broadly comparable across models, with one exception. The standard deviation of the price markup shock is notably higher in the closed economy ($\sigma_p = 0.25$ versus 0.12), possibly offsetting the absence of imported inflationary pressure. For productivity shocks, σ_a is estimated at 1.07 in the closed economy and 1.04 in the open economy, suggesting similar levels of underlying volatility in technology growth across the two settings.

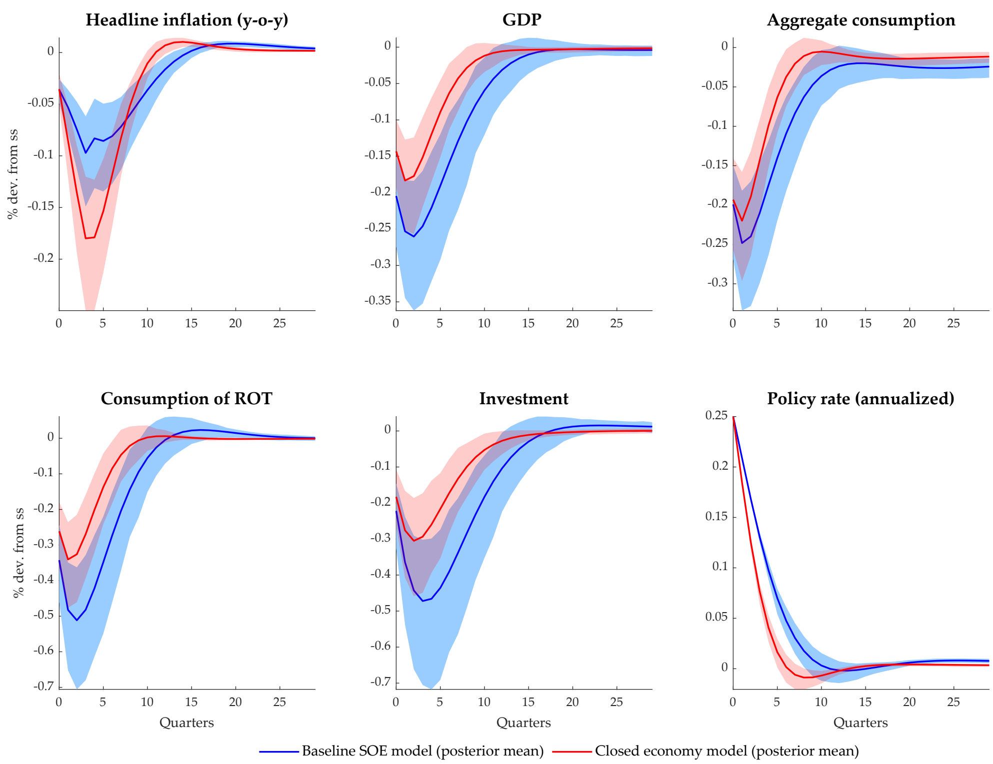
Taken together, the comparison shows that while the overall structure of the two models is similar, the inclusion of external channels–such as energy price shocks and exchange rate fluctuations–in the open economy specification influences the estimated values of several key parameters. In particular, the open economy model features a more inelastic labor supply and stronger nominal price rigidities. To compensate for the absence of these external drivers, the estimated closed economy model relies on slightly larger persistence or volatility in certain domestic shocks to match the observed data.

Table G.1.1: Prior and posterior distribution of parameters: Open *versus* Closed economy

		Prior distribution			**Posterior distribution**							
					Open economy				**Closed economy**			
Parameter		**Distribution**	**Mean**	**St. dev.**	**Mode**	**Mean**	**90% HPD**		**Mode**	**Mean**	**90% HPD**	
TR response to inflation	ϕ_π	Gamma	1.70	0.25	2.07	2.09	1.73	2.45	2.07	2.08	1.72	2.43
TR response to output gap	ϕ_Y	Gamma	0.12	0.05	0.05	0.06	0.02	0.10	0.07	0.08	0.04	0.12
TR interest rate smoothing	ϕ_R	Beta	0.75	0.10	0.91	0.91	0.89	0.93	0.91	0.91	0.89	0.93
Relative risk aversion	σ	Normal	1.50	0.10	1.55	1.53	1.38	1.69	1.47	1.46	1.30	1.62
Inverse Frisch elasticity	ϕ_l	Gamma	2.00	0.50	1.23	1.51	0.88	2.07	0.76	0.99	0.47	1.49
Habits	b	Beta	0.50	0.10	0.36	0.37	0.33	0.41	0.36	0.36	0.31	0.40
Investment adjustment costs	γ_I	Gamma	4.00	1.00	4.06	4.65	3.32	6.02	3.88	4.29	2.98	5.58
Calvo price stickiness	ξ_p	Beta	0.50	0.10	0.91	0.91	0.88	0.93	0.80	0.80	0.75	0.84
Calvo wage stickiness	ξ_w	Beta	0.50	0.10	0.62	0.64	0.58	0.70	0.61	0.62	0.56	0.68
Price indexation	χ_p	Beta	0.50	0.15	0.80	0.75	0.58	0.70	0.59	0.59	0.35	0.84
Wage indexation	χ_w	Beta	0.50	0.15	0.18	0.20	0.07	0.33	0.16	0.20	0.07	0.32
Capital utilization elasticity	σ_u	Beta	0.50	0.15	0.72	0.72	0.61	0.83	0.65	0.66	0.56	0.75
RoT share	θ	Beta	0.22	0.10	0.07	0.09	0.04	0.13	0.14	0.16	0.09	0.23
EoS btw energy & core consumption goods	η	Gamma	0.50	0.20	0.49	0.51	0.21	0.78				
Steady-state inflation	$\bar{\pi}$	Gamma	0.50	0.10	0.50	0.50	0.42	0.58	0.49	0.49	0.39	0.59
Shocks persistence												
Risk premium	ρ_b	Beta	0.50	0.20	0.82	0.80	0.74	0.87	0.86	0.86	0.80	0.91
Investment specific	ρ_i	Beta	0.50	0.20	0.14	0.19	0.04	0.33	0.28	0.29	0.12	0.46
Price markup	ρ_p	Beta	0.50	0.20	0.59	0.61	0.51	0.72	0.65	0.65	0.52	0.78
Wage markup	ρ_w	Beta	0.50	0.20	0.97	0.96	0.93	0.99	0.99	0.97	0.95	0.996
Government spending	ρ_g	Beta	0.30	0.20	0.93	0.93	0.89	0.96	0.93	0.93	0.88	0.97
Productivity	ρ_a	Beta	0.50	0.20	0.41	0.40	0.28	0.53	0.33	0.33	0.20	0.46
Energy price	ρ_s	Beta	0.50	0.20	0.95	0.94	0.93	0.96				
Foreign demand	ρ_{y_s}	Beta	0.50	0.20	0.90	0.90	0.83	0.97				
Foreign monetary policy	ρ_{R_s}	Beta	0.50	0.10	0.91	0.91	0.88	0.94				
Foreign cost-push	ρ_{π_s}	Beta	0.50	0.20	0.60	0.60	0.45	0.75				
Foreign risk premium	$\rho_{\tilde{\psi}}$	Beta	0.50	0.20	0.97	0.97	0.95	0.98				
Gov. spending-TFP correl.	ρ_{gy}	Normal	0.50	0.25	-0.17	-0.16	-0.46	0.14	-0.17	-0.18	-0.40	0.03
Shocks standard deviations												
Risk premium	σ_b	Inv.Gamma	0.50	2.00	0.20	0.22	0.14	0.29	0.15	0.16	0.10	0.21
Investment specific	σ_i	Inv.Gamma	0.50	2.00	0.79	0.81	0.67	0.95	0.83	0.88	0.70	1.06
Monetary policy	σ_r	Inv.Gamma	0.50	2.00	0.13	0.13	0.11	0.15	0.12	0.13	0.11	0.14
Price markup	σ_p	Inv.Gamma	0.50	2.00	0.12	0.12	0.10	0.14	0.24	0.25	0.21	0.29
Wage markup	σ_w	Inv.Gamma	0.50	2.00	0.21	0.21	0.16	0.26	0.22	0.22	0.16	0.28
Government spending	σ_g	Inv.Gamma	0.50	2.00	2.01	2.06	1.80	2.31	1.18	1.21	1.07	1.36
Productivity	σ_a	Inv.Gamma	0.50	2.00	1.02	1.04	0.90	1.19	1.06	1.07	0.92	1.21
Energy price	σ_s	Inv.Gamma	2.00	2.00	7.25	7.40	6.55	8.22				
Foreign demand	σ_{R_s}	Inv.Gamma	0.50	2.00	1.22	1.24	1.10	1.38				
Foreign monetary policy	$\sigma_{\tilde{\psi}}$	Inv.Gamma	0.50	2.00	0.16	0.17	0.15	0.19				
Foreign cost-push	σ_{y_s}	Inv.Gamma	0.50	2.00	0.40	0.41	0.36	0.45				
Foreign risk premium	σ_{π_s}	Inv.Gamma	0.50	2.00	0.24	0.26	0.19	0.33				
Forced saving	σ_{fs}	Inv.Gamma	0.10	0.10	2.10	2.30	1.46	3.11	1.80	1.92	1.04	2.78

Notes: Posterior means, standard deviations, and 90% highest posterior density intervals (computed as 5th and 95th percentiles) are based on two chains of 2,000,000 Metropolis-Hastings draws each, with first half of the draws discarded. The final acceptance rate for the open economy model is 33.3%, while the one for the closed economy model is 30%.

Figure G.1.1: Impulse response functions to a monetary policy tightening



Notes: The solid blue/red lines represent responses of selected key variables at the posterior mean of the baseline open/closed economy model with the corresponding shaded areas capturing the 90% credible intervals (computed as 5th and 95th percentiles) to 25 basis points increase in the policy rate on impact. Variables are expressed as percentage deviations from steady state and the policy rate is expressed in annualized terms.

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