

# Essays in Monetary Economics



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# Introduction

This dissertation presents three self-contained chapters which discuss topics within monetary economics.

Chapter 1 analyzes the transmission channels that drive the effect of monetary policy on consumption inequality using a tractable Two-Agent New Keynesian (TANK) models with search-and-matching frictions and wage rigidities. I make a distinction between credit-constrained households and unconstrained households and find that an expansionary monetary policy shock decreases consumption inequality between those two households through three channels: (i) the income composition channel, through fluctuations in labour and profit income, (ii) the savings redistribution channel, through fluctuations in real interest rate, and (iii) the earnings heterogeneity channel, through fluctuations in unemployment. The results are in line with the empirical evidence. This chapter is published in the *Journal of Money, Credit, and Banking* (August 2023, Volume 55, Issue 5).

Chapter 2 studies the macroeconomic consequences, and specifically the international spillovers of an energy price cap, motivated by the European energy crisis in 2022. During this crisis some Euro Area countries introduced price caps on energy, while others did not, leading to about 30 percentage points higher energy inflation in uncapped countries. This chapter investigates the trade-offs policymakers face with energy price caps in a two-country currency union model with shared energy supply. The cooperative, optimal outcome is for neither country to impose a price cap, since the cap is a costly market distortion. However, capping allows a country to avoid a crisis at the cost of negative spillovers on the uncapped country, characterized by high inflation and lower output. The quantitative model with non-homothetic preferences and substitutability of energy sources shows that the cost of the price cap exceeds the cost of such spillovers, explaining why some countries capped prices while

others did not. Moreover, I show that the spillovers from price caps contributed to about 10 (0.5) percentage points of energy (headline) inflation in the uncapped Euro Area countries in 2022. Targeted transfers, an alternative policy to the price cap, is a cheaper and more effective way to boost consumption of the poor without creating divergence within the union.

Chapter 3 revisits a classic question in open-economy macroeconomics — What is the optimal degree of exchange rate stabilization in an open economy? — by introducing Diagnostic Expectations (DE) into a standard New Keynesian small open-economy model. DE is a departure from the Rational Expectations hypothesis which, through an overreaction of agents' beliefs, generates additional endogenous macroeconomic volatility. As a first pass at disciplining the model with data, we find that the inclusion of DE can help resolve key empirical exchange rate puzzles identified in the literature such as the exchange rate disconnect and forward premium puzzles. In terms of optimal monetary policy, we find that the model with DE can alter the welfare rankings of selected exchange rate regimes established in earlier studies. In particular, under reasonable assumptions regarding the strength of DE, simulations suggest that an exchange rate peg could be welfare superior to a policy that targets consumer price index (CPI) inflation. Importantly, extreme model parameterizations are not needed to justify exchange rate stabilization.

# Chapter 1

## The Effect of Monetary Policy on Consumption Inequality: An Analysis of Transmission Channels through TANK Models

**Abstract** What transmission channels drive the effect of monetary policy on consumption inequality? This paper investigates this question with tractable Two-Agent New Keynesian (TANK) models with search-and-matching frictions and wage rigidities. I make a distinction between credit-constrained households and unconstrained households and find that an expansionary monetary policy shock decreases consumption inequality between those two households through three channels: (i) the income composition channel, through fluctuations in labour and profit income, (ii) the savings redistribution channel, through fluctuations in real interest rate, and (iii) the earnings heterogeneity channel, through fluctuations in unemployment. The results are in line with the empirical evidence.

**Keywords** constrained households, consumption inequality, monetary policy, transmission channels

**JEL codes** E17, E24

### 1.1 Introduction

In this paper I study the effects of monetary policy on consumption inequality through tractable Two-Agent New Keynesian (TANK) models with search-and-matching frictions and wage rigidities. Distributional consequences of monetary policy are also of interest to central bankers, even though such consequences are not their primary concern (Carney, 2016; Draghi, 2016; Yellen, 2016). The main contribution of this paper is that it replicates analytically and tractably the main transmission channels of monetary policy to inequality found in empirical literature.

This paper investigates the transmission channels that drive the effect of monetary policy to consumption inequality. I develop a TANK model based on the model proposed by Debortoli and Galí (2018) in which a fraction of the households are credit-constrained and consume hand-to-mouth. The rest of the population have access to the asset market and smooth consumption. I add search-and-matching frictions<sup>1</sup> following the methods by Blanchard and Galí (2010) and Dolado et al. (2019) and obtain the Search-and-Matching TANK (SAMTANK). With the search-and-matching frictions I allow for unemployment, which according to empirical literature is important in the dynamics of inequality under monetary policy shocks (Coibion et al., 2017; Lenza & Slacalek, 2021). I allow for wage rigidities following the method by Gertler and Trigari (2009) to amplify the effect of unemployment.

My main result is that expansionary monetary policy shocks decrease consumption inequality through the savings redistribution channel, the income composition channel, and the earnings heterogeneity channel. The existing literature differentiates between two kinds of transmission channels: (i) inflation channels, capturing the redistributive effect when goods or asset prices change as a consequence of monetary policy, and (ii) income channels, capturing the redistributive effect of real changes, e.g. in output or employment, from monetary

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<sup>1</sup>Commonly known as the Diamond-Mortensen-Pissarides frictions, as proposed by Mortensen and Pissarides (1994)

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policy (Nakajima, 2015). The savings distribution channel is an inflation channel, whereas the income composition channel and the earnings heterogeneity channels are income channels.

The savings distribution channel explains distributional effects by changes in real interest rates (Doepke & Schneider, 2006; Guerello, 2018). In my models changes in the real interest rate affect the consumption of unconstrained households but not of constrained households. Therefore, changes in real interest rates have an asymmetric effect on the types of households.

The income composition channel takes into account the differences between the sources of income of households and how monetary policy affects these sources (Davtyan, 2017). Most low-income households only depend on labour income, while more privileged households also enjoy income from capital and profits. The models in this paper feature such a setup too. When monetary policy affects different sources of income heterogeneously, the income composition channel is at work (Guerello, 2018).

The earnings heterogeneity channel explains the heterogeneous effects of monetary policy on inequality through different labour market conditions of low- and high-income households (Casiraghi et al., 2018). For example, unemployment rate and job separation rate is higher for relatively low-skilled people who are most likely to be in low-income households (Hobijn & Şahin, 2009). Moreover, matching efficiency of vacancies and unemployed people fluctuates more with output for low-income groups (Lenza & Slacalek, 2021). I incorporate these features in my models. So, when expansionary monetary policy stimulates the labour market, it favours the low-income households more and decreases inequality through the earnings heterogeneity channel.

In the SAMTANK with wage rigidities, the main model of this paper, the three channels reduce consumption inequality after an expansionary monetary policy shock in the following way: The real interest rate decreases after an expansionary shock, after which unconstrained households increase their consumption to smooth consumption (savings distribution channel). The expansionary shock

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stimulates the economy and wages increase, which has a positive effect on the consumption of the constrained (income composition channel). This effect is amplified by the substantial drop in the unemployment of constrained households, after which they can consume even more (earnings heterogeneity channel). The increase in consumption for the constrained is higher than that for the unconstrained, and therefore the consumption inequality decreases after an expansionary monetary policy shock.

The main result is in line with existing research on monetary policy and inequality, both empirical and theoretical, which in general conclude that expansionary monetary policy shocks decrease inequality and vice versa (Coibion et al., 2017; Ampudia et al., 2018; Debortoli & Galí, 2018; Furceri et al., 2018; Broer et al., 2020; Lenza & Slacalek, 2021). My paper confirms the empirical finding by Lenza and Slacalek (2021) that the earnings heterogeneity channel plays an important role in the transmission of monetary policy to inequality. Moreover, Coibion et al. (2017) empirically identify the income composition channel and the savings distribution channel in the transmission. Some researchers like Davtyan (2017) and Dolado et al. (2019) conclude the opposite to the above. Davtyan (2017) empirically finds that contractionary monetary policy decreases income inequality. They assign the difference of their result to the common findings to the fact that their research takes the top 1% of the income distribution into account. Moreover, researchers like Casiraghi et al. (2018) find that the effects of monetary policy on inequality are negligible.

This paper contributes to the pool of literature on heterogeneous agent models. The motivation for New Keynesian literature to use heterogeneous agent models comes from empirical findings by researchers such as Campbell and Mankiw (1989, 1991) and Baker and Yannelis (2017) that a significant proportion of households, from 25% to 70%, consume their current-period income hand to mouth. This type of behaviour is in contrast with the consumption smoothing behaviour that many macroeconomic models assume. Ampudia et al. (2018) empirically find that hand-to-mouth households account for a disproportionate

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share in the consumption response to monetary policy. To incorporate such households in New Keynesian models, researchers adopt the TANK framework in which a fraction of the households are credit-constrained.<sup>2</sup> In such a TANK setup, Bilbiie (2008) finds that constrained households play an important role in the transmission mechanism of monetary policy. There are other ways to divide households into types, such as workers and capitalists, as in Broer et al. (2020), or high-skilled and low-skilled workers, as in Dolado et al. (2019). In my model specification, constrained households only earn labour income while unconstrained ones earn both labour and profit income. Therefore, the constrained could be seen as workers and the unconstrained as capitalists.

A more complicated way to incorporate household heterogeneity is through Heterogeneous Agent New Keynesian (HANK) models, widely developed since Kaplan et al. (2018). Such models consider a continuum of households with often a distribution in agents' wealth. HANK models may contain more information, but TANK models are more tractable. Debortoli and Galí (2018) compare the dynamics in an otherwise identical TANK and HANK model and conclude that the TANK approximates the HANK well regarding the transmission mechanism of monetary policy to consumption inequality. Therefore, I use the TANK model by Debortoli and Galí (2018) as the baseline model for my research.

I focus on consumption inequality when looking at the effect of monetary policy on inequality. This type of inequality is easier to track in the heterogeneous household setup. Fisher et al. (2016) find that trends in wealth, income, and consumption inequality are similar for individuals. Also, Ampudia et al. (2018) conclude that the effect of monetary policy on income and wealth inequality are qualitatively similar, though smaller for wealth inequality.

I present the rest of the paper as following: In the next section I outline the SAMTANK model with sticky wages and in Section 1.3 I discuss its calibration. In Section 1.4 I analyse the transmission mechanism of three models: the SAMTANK with sticky wages, the SAMTANK with flexible wages, and the simple TANK,

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<sup>2</sup>Some literature refer to constrained/hand-to-mouth households as non-Ricardian households, and unconstrained households as Ricardian households.

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without labour market frictions. In Section 1.5 I confirm that the results are in line with the empirical evidence. Moreover, in Section 1.6 I discuss the implications of the results for a HANK model. Lastly, in Section 1.7 I draw the main conclusions of this paper.

### 1.2 Model

In this section I outline the Search-and-Matching Two-Agent New Keynesian (SAMTANK) model with sticky wages. I base it on the TANK model developed by Debortoli and Galí (2018) and follow closely the approach by Dolado et al. (2019) and Gertler and Trigari (2009) when incorporating the labour frictions and wage rigidities respectively.

In the SAMTANK with sticky wages there are two time-invariant types of households:  $\lambda$  constrained households and  $1 - \lambda$  unconstrained households, where  $\lambda \in (0, 1)$ . Constrained, or hand-to-mouth, households only earn wage income and do not have access to the credit market. Therefore, they consume their per-period income. Unconstrained households earn wage and profit income and have full access to the credit market. As a consequence, they can smooth consumption over their lifetime. I assume a complete financial market setup such that there is perfect insurance against idiosyncratic unemployment risk within a household type. The full list of equations relevant to the equilibrium dynamics expressed in log-deviations from the zero-inflation steady state is in Appendix A.1.

#### 1.2.1 Labour market

Due to the perfect insurance assumption, I can express each type of household as a representative agent that splits its time endowment as the following:

$$1 = n_t^k + u_t^k$$

where  $n_t$  and  $u_t$  are the employment rate and unemployment rate respectively amongst households of type  $k \in \{c, u\}$ . Superscript  $k = c$  indicates that the

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household is of the constrained type and  $k = u$  that it is of the unconstrained type. Aggregate measures of unemployment are:

$$U_t^c = \lambda u_t^c, \quad U_t^u = (1 - \lambda)u_t^u, \quad \text{and} \quad U_t = U_t^c + U_t^u.$$

The matching function matches the unemployed  $U_t^k$  with vacancies  $v_t^k$ :

$$m_t^k(\psi_t^k, v_t^k, U_t^k) \equiv m_t^k = \psi_t^k (v_t^k)^\zeta (U_t^k)^{1-\zeta}$$

where  $\psi_t^k$  is the matching efficiency in the labour market of the household of type  $k$ , and  $\zeta$  is the matching elasticity with respect to vacancies. The labour market for constrained and unconstrained households are separate since the labour market conditions differ per type. The matching efficiency parameter  $\psi_t^k$  is not time-invariant and fluctuates with output deviations from steady state:

$$\psi_t^k = \bar{\psi}^k + (Y_t - \bar{Y})^{\mu^k}$$

where  $\bar{\psi}^c < \bar{\psi}^u$  and  $\mu^c > \mu^u$ , so that  $\psi_t^u$  is higher in steady state while  $\psi_t^c$  is more procyclical. These characteristics are in line with empirical evidence that high-income households have a higher matching efficiency, but that for low-income ones it is more procyclical (Gebel & Giesecke, 2011; Barnichon & Figura, 2015; Wolcott, 2018; Lenza & Slacalek, 2021). I define labour market tightness  $\theta_t^k$ , the probability of filling a vacancy  $q(\theta_t^k)$ , and the probability of finding a job  $p(\theta_t^k)$  as in standard search-and-matching literature:

$$\theta_t^k = \frac{v_t^k}{U_t^k}, \quad q(\theta_t^k) = \frac{m_t^k}{v_t^k}, \quad \text{and} \quad p(\theta_t^k) = \frac{m_t^k}{U_t^k} = \psi_t^k (\theta_t^k)^\zeta.$$

The transition dynamics in the labour market depends on an exogenous job separation rate  $\gamma^k$ :

$$n_t^k = (1 - \gamma^k)n_{t-1}^k + q(\theta_t^k)v_t^k \quad \text{or} \quad n_t^k = (1 - \gamma^k)n_{t-1}^k + p(\theta_t^k)u_t^k. \quad (1.1)$$

So, the unemployed can find a job at the beginning of the each period and become employed.

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### 1.2.2 Households

The representative households of both types maximise their identical lifetime utility given by  $\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \mathcal{U}(c_t^k)$  where  $\beta \in [0, 1)$  is the discount factor.  $c_t^k = \left( \int_0^1 c_t^k(i)^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}$  is a consumption index where  $c_t^k(i)$  is the quantity of good  $i$  consumed by household of type  $k$  in period  $t$ .  $\epsilon$  is the elasticity of substitution across goods. The utility function takes the standard form:

$$\mathcal{U}(c_t^k) = \frac{(c_t^k)^{1-\sigma}}{1-\sigma},$$

where  $\sigma$  is the coefficient of constant relative risk-aversion.

Households maximise their lifetime utility subject to the budget constraint and the transition dynamics in the labour market (1.1). The nominal budget constraint of the constrained households is:

$$\int_0^1 P_t(i) c_t^c(i) di = W_t^c n_t^c + P_t T_t^c + P_t b u_t^c$$

for  $t = 0, 1, 2, \dots$  where  $P_t(i)$  is the price of good  $i$  at time  $t$ .  $W_t$  is the nominal wage per unit of labour,  $T_t$  indicates real government transfers, and  $b$  is real unemployment benefits.  $P_t = \int_0^1 (P_t(i)^{1-\epsilon})^{\frac{1}{1-\epsilon}} di$  is the aggregate price index.

The nominal budget constraint of the unconstrained households is:

$$\int_0^1 P_t(i) c_t^u(i) di + B_t = W_t^u n_t^u + R_{t-1} B_{t-1} + \frac{1-\delta}{1-\lambda} D_t + P_t T_t^u + b u_t^u$$

for  $t = 0, 1, 2, \dots$  where  $B_t$  are purchases of one-period bonds with interest rate  $R_t$ . Unconstrained households have access to firm profits, but the fiscal authority taxes  $\delta D_t$  and uses it for fiscal transfers.

I aggregate consumption and labour as follows:

$$\begin{aligned} C_t^c &= \lambda c_t^c, & C_t^u &= (1-\lambda) c_t^u, & C_t &= C_t^c + C_t^u \\ N_t^c &= \lambda n_t^c, & N_t^u &= (1-\lambda) n_t^u, & N_t &= N_t^c + N_t^u. \end{aligned}$$

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### 1.2.3 Firms

There is a continuum of firms  $i \in [0, 1]$  and each firm produces a differentiated good  $i$ , so that there is monopolistic competition. The production technology is the same across firms:

$$Y_t(i) = A_t N_t(i) \quad (1.2)$$

where  $N_t(i) = N_t^c(i) + N_t^u(i) = \lambda n_t^c(i) + (1 - \lambda)n_t^u(i)$ .  $A_t$  is the total factor productivity that follows an AR(1) process  $\ln A_t \equiv a_t = \rho_a a_{t-1} + \varepsilon_t^a$ , where  $\varepsilon_t^a \sim_{\text{i.i.d.}} \mathcal{N}(0, \sigma_a^2)$  is an exogenous technology shock.

Firms face quadratic adjustment costs  $\mathcal{R}(\cdot) = \frac{\xi}{2} P_t Y_t \left( \frac{P_t(i)}{P_{t-1}(i)} - 1 \right)^2$  as proposed by Rotemberg (1982). In addition, they face the demand curve:

$$Y_t(i) = \left( \frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t. \quad (1.3)$$

Firms maximise over the following expression for lifetime profit subject to the production function (1.2), the demand curve (1.3), and the transition dynamics in the labour market (1.1):

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \left[ \frac{P_t(i)}{P_t} Y_t(i) - \frac{W_t^c}{P_t} N_t^c(i) - \frac{W_t^u}{P_t} N_t^u(i) - \frac{\xi}{2} Y_t \left( \frac{P_t(i)}{P_{t-1}(i)} - 1 \right)^2 - \kappa (v_t^c(i) + v_t^u(i)) \right]$$

where  $\Lambda_{t,t+1} = \beta \left( \frac{c_{t+1}}{c_t} \right)^{-\sigma}$  is the stochastic discount factor and  $\kappa$  the real cost of posting a vacancy.

Combining the first order condition with respect to  $P_t(i)$ , imposing the symmetric equilibrium conditions  $P_t(i) = P_t$  and  $Y_t(i) = Y_t$ , and taking log-deviations lead to the standard New Keynesian Philips Curve (NKPC) for Rotemberg (1982) pricing expressed in real marginal cost  $\hat{\mu}_t$ :

$$\hat{\pi}_t = \beta \mathbb{E}_t \hat{\pi}_{t+1} + \frac{\epsilon}{\xi \mathcal{M}} \hat{\mu}_t$$

where where  $\pi_{t+1} = \frac{P_{t+1}}{P_t}$  is gross inflation and  $\mathcal{M} = \frac{\epsilon}{\epsilon-1}$  is the optimal price markup without adjustment costs. Hatted values are log-linear deviations from the zero-inflation steady state.<sup>3</sup>

<sup>3</sup>See Appendix A.1 for details.

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Combining the first order conditions with respect to  $N_t^k(i)$  and  $v_t^k(i)$  gives the hiring condition:

$$\frac{\kappa}{q(\theta_t^k)} = \mu_t A_t - \frac{W_t^k}{P_t} + (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} \frac{\kappa}{q(\theta_{t+1}^k)} \right] \quad (1.4)$$

of which the last term is the discounted forgone costs of posting a vacancy if the worker is still hired next period. So, the equation sets equal the expected cost and benefit of posting a vacancy.

I combine the log-linearised versions of the production function (1.2), the budget constraints of the households, and the goods market clearing condition (1.14) below to express real marginal cost:

$$\hat{\mu}_t = \left( \frac{\sigma}{s_c} + \varphi \right) \hat{y}_t - \sigma \kappa \frac{s_v}{s_c} \hat{v}_t - (1 + \varphi) a_t$$

where  $s_c = \frac{\bar{C}}{\bar{Y}}$  is the steady-state share of consumption,  $s_v = \frac{\bar{v}}{\bar{Y}}$  the steady-state share of vacancies, and  $\hat{v}_t$  is the aggregate vacancies  $\hat{v}_t = \lambda \hat{v}_t^c + (1 - \lambda) \hat{v}_t^u$ . I arrive to the expression for the natural level of output  $y_t^n$  by setting  $\hat{\mu}_t = \hat{v}_t = 0$ :

$$\hat{y}_t^n = \frac{1 + \varphi}{\frac{\sigma}{s_c} + \varphi} a_t.$$

Finally, aggregate real profits of the firms are:

$$\frac{D_t}{P_t} = Y_t \left( 1 - \frac{\xi}{2} (\pi_t - 1)^2 \right) - \frac{W_t^c}{P_t} N_t^c - \frac{W_t^u}{P_t} N_t^u - \kappa (v_t^c + v_t^u).$$

### 1.2.4 Wage bargaining

Households and firms split the surplus from a match in the labour market by Nash bargaining. I add nominal wage rigidities with a similar approach to that of Gertler and Trigari (2009). Households and firms negotiate the nominal wage at the beginning of each period. When an unemployed finds a job in that period, they take as given the wage that has been negotiated at the beginning of that period by those that were already employed. The staggered bargaining problem is:

$$\begin{aligned} & \max_{W_t^k} \left[ \mathcal{W}_t^k (W_t^k, \mathbf{s}_t)^{\eta^k} \mathcal{J}_t^k (W_t^k, \mathbf{s}_t)^{1-\eta^k} \right] \\ \text{subject to } & W_{t+1}^k = \begin{cases} W_t^k & \text{with probability } \alpha^k \\ W_{t+1}^{*k} & \text{with probability } 1 - \alpha^k \end{cases} \end{aligned}$$

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where  $s_t$  is the set of variables defining the aggregate state,  $\eta^k$  is the bargaining power of the household of type  $k$ ,  $\mathcal{W}_t^k$  is the workers' surplus of being hired,  $\mathcal{J}_t^k$  is the firms' surplus of having an employee, and  $\alpha$  is the probability that wages are non-negotiable in a period.  $\alpha$  is thus a measure of wage stickiness and is independent of the negotiation history in previous periods. The solution to this problem is:

$$\eta^k \mathcal{J}_t^k (\Gamma_t^{\mathcal{W}})^k = (1 - \eta^k) \mathcal{W}_t^k (\Gamma_t^{\mathcal{J}})^k \quad (1.5)$$

$$\text{where } \mathcal{W}_t^k = W_t^k - P_t b + (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} (1 - p(\theta_{t+1}^k)) \mathcal{W}_{t+1}^k \right] \quad (1.6)$$

$$\mathcal{J}_t^k = \frac{\kappa}{q(\theta_t^k)} = P_t \mu_t A_t - W_t^k + (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} \frac{\kappa}{q(\theta_{t+1}^k)} \right] \quad (1.7)$$

$$(\Gamma_t^{\mathcal{W}})^k = \left( \frac{\partial \mathcal{W}_t^k}{\partial W_t^k} \right) = 1 + \alpha^k (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} (1 - p(\theta_{t+1}^k)) (\Gamma_{t+1}^{\mathcal{W}})^k \right] \quad (1.8)$$

$$\text{and } (\Gamma_t^{\mathcal{J}})^k = - \left( \frac{\partial \mathcal{J}_t^k}{\partial W_t^k} \right) = 1 + \alpha^k (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} (\Gamma_{t+1}^{\mathcal{J}})^k \right]. \quad (1.9)$$

When  $\alpha^k = 0$  there are no wage rigidities and the bargaining solution (1.5) reduces to its standard version  $\eta^k \mathcal{J}_t^k = (1 - \eta^k) \mathcal{W}_t^k$ . We can interpret  $(\Gamma_t^{\mathcal{J}})^k$  and  $(\Gamma_t^{\mathcal{W}})^k$  as the stakes of firms and workers respectively in the wage. Since  $0 < p(\theta_{t+1}^k) < 1$ , the firms' stake  $(\Gamma_t^{\mathcal{J}})^k$  is bigger than the workers' stake  $(\Gamma_t^{\mathcal{W}})^k$ . Firms have a longer horizon because the negotiated wage also applies to the new workers hired in that period. The workers' horizon is only that of the duration of their employment at the firm. Therefore, stakes are smaller for workers than for firms.

I can rewrite the solution to the bargaining problem (1.5) as:

$$H_t^k \mathcal{J}_t^k = (1 - H_t^k) \mathcal{W}_t^k \quad (1.10)$$

where  $H_t^k = \frac{\eta^k}{\eta^k + (1 - \eta^k)(\Gamma_t^{\mathcal{J}})^k / (\Gamma_t^{\mathcal{W}})^k}$  is the effective bargaining power of households. The effective bargaining power is increasing in the bargaining power of households  $\eta^k$ , decreasing in the firms' stake in the wage  $(\Gamma_t^{\mathcal{J}})^k$ , and increasing in the workers' stake  $(\Gamma_t^{\mathcal{W}})^k$ .

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Plugging in the workers' surplus (1.6) and the firms' surplus (1.7) into the rewritten solution gives the wage determination equation:

$$\frac{W_t^k}{P_t} = (1 - H_t^k) b + H_t^k \left( \mu_t A_t + (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} p(\theta_{t+1}^k) \frac{\kappa}{q(\theta_{t+1}^k)} \right] \right). \quad (1.11)$$

When the households have no bargaining power, i.e.  $\eta^k = H_t^k = 0$ , the bargained wage is equal to the households' reservation wage and when the firms have no bargaining power, i.e.  $\eta^k = H_t^k = 1$ , it is equal to the firms' reservation wage.

Substituting the wage determination equation (1.11) into the hiring condition (1.4) gives the job creation condition:

$$\frac{\kappa}{q(\theta_t^k)} = (1 - H_t^k) (\mu_t A_t - b) + (1 - \gamma^k) \mathbb{E}_t \left[ \Lambda_{t,t+1} (1 - H_t^k p(\theta_{t+1}^k)) \frac{\kappa}{q(\theta_{t+1}^k)} \right]. \quad (1.12)$$

Finally, I construct a wage index to obtain the average nominal wage in the economy:

$$W_t^k = (1 - \alpha^k) W_t^{*k} + \alpha^k W_{t-1}^k.$$

### 1.2.5 Monetary and fiscal policies

The monetary policy authority follows a standard Taylor rule, responding to deviations of inflation from its steady-state value and to deviations of the output from its natural level, the output under flexible prices. The monetary authority sets the nominal interest rate  $R_t$  according to the Taylor rule:

$$R_t = \frac{1}{\beta} \left( \frac{\pi_t}{\bar{\pi}} \right)^{\phi_\pi} \left( \frac{Y_t}{Y_t^n} \right)^{\phi_y} \exp(\nu_t)$$

where the monetary policy shock  $\nu_t$  follows an AR(1) process  $\nu_t = \rho_\nu \nu_{t-1} + \varepsilon_t^\nu$  and  $\varepsilon_t^\nu \sim_{\text{i.i.d.}} \mathcal{N}(0, \sigma_\nu^2)$  is the exogenous monetary policy shock.<sup>4</sup>

<sup>4</sup>Results are quantitatively and qualitatively similar when I use a persistent Taylor rule with independent and identically distributed shocks:

$$\begin{aligned} \hat{R}_t &= \rho_R \hat{R}_{t-1} + (1 - \rho_R) \hat{R}_t^* \\ \hat{R}_t^* &= \phi_\pi \hat{\pi}_t + \phi_y \hat{y}_t + \varepsilon_t^R, \end{aligned}$$

where  $\varepsilon_t^R \sim_{\text{i.i.d.}} \mathcal{N}(0, \sigma_R^2)$ .

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Fiscal policy determines the distribution of the taxed part of the firms' profits  $\delta D_t$ . I slightly alter the transfer rule proposed by Debortoli and Galí (2018) to accommodate for unemployment benefits:

$$T_t^c = (1 - \tau)(\delta D_t - b(U_t^c + U_t^u)) \quad \text{and} \quad T_t^u = \left(1 + \frac{\tau\lambda}{1 - \lambda}\right) (\delta D_t - b(U_t^c + U_t^u))$$

so that  $\lambda T_t^c + (1 - \lambda)T_t^u = \delta D_t - b(U_t^c + U_t^u)$ . Thus, total unemployment benefits are less than the tax income from firms' profits, and the fiscal policy authority distributes the remaining part to households depending on the value of  $\tau$ . By setting  $\tau = 1$  the fiscal policy authority transfers the remaining tax revenue from the profits,  $\delta D_t - b(U_t^c + U_t^u)$ , to unconstrained households. As only unconstrained households have access to the non-taxed part of the profits  $(1 - \delta)D_t$ ,  $\tau = 1$  implies that all profits, except the part allocated to unemployment benefits, go to unconstrained households. By setting  $\tau = 0$  the fiscal authority distributes the remaining taxed profits uniformly across all households.

### 1.2.6 Heterogeneity

To answer the main question of the paper, I need to track the heterogeneity between the two different types of households. As in Debortoli and Galí (2018) I define the heterogeneity factor as an index of the consumption gap between the representative constrained and unconstrained household:  $\omega_t = 1 - \frac{c_t^c}{c_t^u}$ . The higher the heterogeneity factor, the more inequality there is between the two households. Decomposing the consumption gap, I obtain:

$$\begin{aligned} \omega_t &= 1 - \frac{c_t^c}{c_t^u} \\ &= 1 - \frac{W_t^c n_t^c + T_t^c + b u_t^c}{W_t^u n_t^u + \frac{1-\delta}{1-\lambda} D_t + T_t^u + b u_t^u} \\ &= \frac{(1-\lambda)(W_t^u n_t^u - W_t^c n_t^c) + (1-\delta(1-\tau))(Y_t(1-\frac{\xi}{2}(\pi_t-1)^2) - W_t^u n_t^u - W_t^c n_t^c - \kappa v_t)}{(1-\lambda)W_t^u n_t^u + (1-\delta\lambda(1-\tau))(Y_t(1-\frac{\xi}{2}(\pi_t-1)^2) - W_t^u n_t^u - W_t^c n_t^c - \kappa v_t)} \end{aligned} \quad (1.13)$$

where the third equality sets  $b = 0$ . I log-linearise the last equation so that there is a link between the heterogeneity factor and the production side. See Appendix

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A.1 for more details. Rewriting the first line of (1.13), I obtain an expression that links aggregate consumption with the heterogeneity factor  $\omega_t$ :

$$C_t = c_t^u(1 - \lambda\omega_t).$$

### 1.2.7 Market clearing

Market clearing in the goods market requires  $Y_t(i) = C_t^c(i) + C_t^u(i) = C_t(i)$  for all  $i \in [0, 1]$  and all  $t = 0, 1, 2, \dots$ . Defining aggregate output as  $Y_t = \left(\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di\right)^{\frac{\epsilon}{\epsilon-1}}$ , I reach the goods market clearing condition:

$$Y_t = C_t + Y_t \frac{\xi}{2} (\pi_t - 1)^2 + \kappa V_t \quad (1.14)$$

where  $V_t = V_t^c + V_t^u = \lambda v_t^c + (1 - \lambda)v_t^u$ .

## 1.3 Calibration

I calibrate the model with values either common in New Keynesian literature or with values found in the empirical literature. Credit-constrained households are characterised by, amongst others, lower income and less possession of assets (Jappelli, 1990). So, throughout the paper I assume that constrained households are poorer compared to unconstrained ones who have access to the credit market. Moreover, I assume that constrained households are low-skilled workers and the unconstrained ones are high-skilled workers. Each period is a quarter of a year. I display the baseline calibration of parameters in Table 1.1. In Appendix A.4 I perform some robustness checks with different calibrations.

The share of constrained households  $\lambda$  is a key parameter in the model. I set this parameter at  $\lambda = 40\%$ . Campbell and Mankiw (1989) estimate that about 30% to 70% of the households consume their current income in the United States between 1953 and 1986. In their follow-up research with data from some other countries like United Kingdom and France, Campbell and Mankiw (1991) estimate a range between 25% and 70% in about the same time period.

I calibrate the parameters typical to New Keynesian models as in most of the standard New Keynesian literature. I set the coefficient of constant relative

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**Table 1.1:** Baseline calibration of parameters

<i>Parameter</i>	<i>Description</i>	<i>Value</i>
<b>Households</b>		
$\lambda$	Fraction of constrained households	0.4
$\sigma$	Coefficient of constant relative risk-aversion	1
$\beta$	Discount factor	0.99
$\epsilon$	Elasticity of substitution across goods	9
<b>Firms</b>		
$\rho_a$	Technology shock persistence	0.9
$\xi$	Adjustment costs parameter	93.20
<b>Monetary and fiscal policy</b>		
$\phi_\pi$	Taylor-coefficient on inflation	1.5
$\phi_y$	Taylor-coefficient on output	0.125
$\rho_\nu$	Monetary policy shock persistence	0.5
$\delta$	Tax rate on firms' profits	0.266
$\tau$	Fiscal policy rule	1
<b>Labour market</b>		
$\zeta$	Matching elasticity	0.5
$\psi^c$	Steady-state matching efficiency, $c$	0.25
$\psi^u$	Steady-state matching efficiency, $u$	0.30
$\mu^c$	Matching procyclicality, $c$	1.5
$\mu^u$	Matching procyclicality, $u$	0.5
$\gamma^c$	Separation rate, $c$	0.025
$\gamma^u$	Separation rate, $u$	0.015
$\theta^c$	Steady-state labour market tightness, $c$	1.3
$\theta^u$	Steady-state labour market tightness, $u$	0.9
$\eta^c$	Bargaining power, $c$	0.5
$\eta^u$	Bargaining power, $u$	0.5
$\kappa$	Real cost of posting vacancies	0.05
<b>Wage rigidities</b>		
$\alpha^c$	Stickiness of wages, $c$	5/6
$\alpha^u$	Stickiness of wages, $u$	3/4

risk-aversion  $\sigma$ , discount factor  $\beta$ , and elasticity of substitution across goods  $\epsilon$  as  $\sigma = 1$ ,  $\beta = 0.99$  and  $\epsilon = 9$ . The last implies that profits are 9% of aggregate output.

For the monetary policy rule I calibrate the coefficient on inflation  $\phi_\pi = 1.5$  and on output gap  $\phi_y = 0.125$  as proposed by Taylor (1993). In line with standard New Keynesian literature, I set the persistence of the monetary policy shock at  $\rho_\nu = 0.5$  and that of the technology shock at  $\rho_a = 0.9$ .

I set the tax rate on firms' profits at  $\delta = 0.266$ , the average corporate tax rate between 2000 and 2018 in the Organisation for Economic Co-operation and Development countries (OECD, 2020). I set the fiscal policy rule parameter as  $\tau = 1$  so that all profits go to unconstrained households. Piketty and Goldhammer (2014) show that in advanced economies most profits go to the wealthiest.

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I set the Rotemberg (1982) price-adjustment costs parameter  $\xi$  such that the slope of the New Keynesian Philips Curve (NKPC) matches the slope of the NKPC under Calvo (1983) price rigidities for a Calvo parameter of 0.75. This value implies an expected price duration of four quarters, which is consistent with empirical evidence (Galí & Monacelli, 2008). When the Calvo parameter is 0.75, the corresponding Rotemberg price-adjustment costs is  $\xi = \frac{(\epsilon-1)0.75}{(1-0.75)(1-0.75\beta)} \approx 93.20$ .

For the labour market frictions, I calibrate the cost of posting vacancies at  $\kappa = 0.05$  as in standard New Keynesian literature, which is also in line with empirical evidence by Cooper et al. (2007).

The matching elasticity  $\zeta$  is symmetric across the types of households. I calibrate it at  $\zeta = 0.5$  to align the standard calibration of search-and-matching models. This calibration is also in line with empirical studies such as by Blanchard and Diamond (1989). Matching efficiencies  $\psi_t^k$  move procyclically, as empirical literature shows (Barnichon & Figura, 2015; Wolcott, 2018). I calibrate the steady-state values for matching efficiency at  $\bar{\psi}^c = 25\%$  and  $\bar{\psi}^u = 30\%$  to match the estimates of Wolcott (2018) for low-skilled workers (18%-29%) and high-skilled workers (15%-36%) in the United States from 1979-2007. I set the degrees of procyclicality at  $\mu^c = 1.5$  and  $\mu^u = 0.5$ . Procyclical matching efficiencies correspond to countercyclical unemployment rates. Unemployment in lower income quintiles is more countercyclical than unemployment in higher income quintiles in the European Union (Lenza & Slacalek, 2021). Specifically, unemployment rate in lower income quintiles are 3 to 5 times more volatile. Moreover, low-skilled workers tend to have more temporary jobs which are more sensitive to output (Gebel & Giesecke, 2011). I set the procyclicality parameters such that the quantitative results for the unemployment responses are similar to the empirical evidence provided by Lenza and Slacalek (2021).

I also set the separation rate  $\gamma^k$  different per type of household:  $\gamma^c = 2.5\%$  and  $\gamma^u = 1.5\%$ . Low-skilled workers work more in temporary jobs and their risk of becoming unemployed is higher than for high-skilled workers (Gebel & Giesecke, 2011). Hobijn and Şahin (2009) estimate aggregate job separation

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rates between 0.70% and 2% in over 20 of the OECD countries between 1968 and 2006. Shimer (2005) estimate an aggregate separation rate of 3.4% in the United States from 1951 to 2003.

To finish characterising the labour market, I calibrate the steady-state labour market tightness for both types of households:  $\bar{\theta}^c = 1.3$  and  $\bar{\theta}^u = 0.9$ . Labour market tightness is on average 0.9997 in the 2000s in Switzerland (Muehleemann & Strupler Leiser, 2018). Wolcott (2018) finds that labour market tightness for low-skilled labour is about 1.5 to 2 times higher than for the high-skilled labour.

Following common practice, and to ensure efficiency in the labour market (Hosios' condition), I set the bargaining power parameter equal to the elasticity of the matching function  $\zeta$ :  $\eta^c = \eta^u = 0.5$ .

Finally, I calibrate the degrees of wage stickiness at  $\alpha^c = 5/6$  and  $\alpha^u = 3/4$ . Most medium- to large-sized firms adjust their wages, including benefits, once a year (Taylor, 1999).  $\alpha^k$  indicates the probability that the firm does not renegotiate the wage, so when wages are negotiated once per year, it would be 3/4. Wages negotiated through labour unions, which are typically for low-skilled workers, are stickier than others (Franz & Pfeiffer, 2006; Babecky et al., 2013).

### 1.4 Impulse response analysis and transmission channels

In this section I analyse the impulse responses and implications of three variations to the model I described above: (i) the full model, which is the Search-and-Matching Two-Agent New Keynesian (SAMTANK) model with sticky wages, (ii) the SAMTANK with flexible wages, obtained by setting the wage stickiness parameter  $\alpha^k$  to 0 for  $k = \{c, u\}$ , and (iii) the TANK model, obtained by shutting off the labour market frictions. I solve the models with Dynare, a software that solves dynamic stochastic general equilibrium models using perturbation techniques (Adjemian et al., 2011).

The response functions in Figure 1.1 and 1.2 are in response to a 1% decrease in the nominal interest rate, an exogenous expansionary monetary policy shock.

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Due to symmetry, a 1% increase generates exactly opposite results. I discover three channels relevant to the transmission of monetary policy to consumption inequality: income composition channel, savings redistribution channel, and earnings heterogeneity channel. Only in the SAMTANK with sticky wages we can find all three channels. In Section 1.5 I show that the SAMTANK with sticky wages matches the empirical evidence the best.

In all three versions of the model, the expansionary monetary policy shock decreases the heterogeneity factor. The TANK generates the strongest effects, whereas labour market frictions dampen the effect of monetary policy on the economy in the two SAMTANK models. In Figure 1.2 we can see that wage rigidities amplify the labour market responses. Because the effect of monetary policy is absorbed less by wages, other variables react more to monetary policy in sticky wages model. I explain this phenomenon in more detail in Appendix A.3. In Figure 1.1 you can see the same effect. Therefore, the decrease in inequality is bigger in the SAMTANK with sticky wages than its flexible wages counterpart.

For both SAMTANK models, consumption inequality decreases because the consumption of the constrained increases more after an expansionary monetary shock than that of the unconstrained. For the TANK, the latter decreases, and therefore the inequality decreases even more. I first analyse the transmission of monetary policy to the consumption of the unconstrained and then of the constrained.

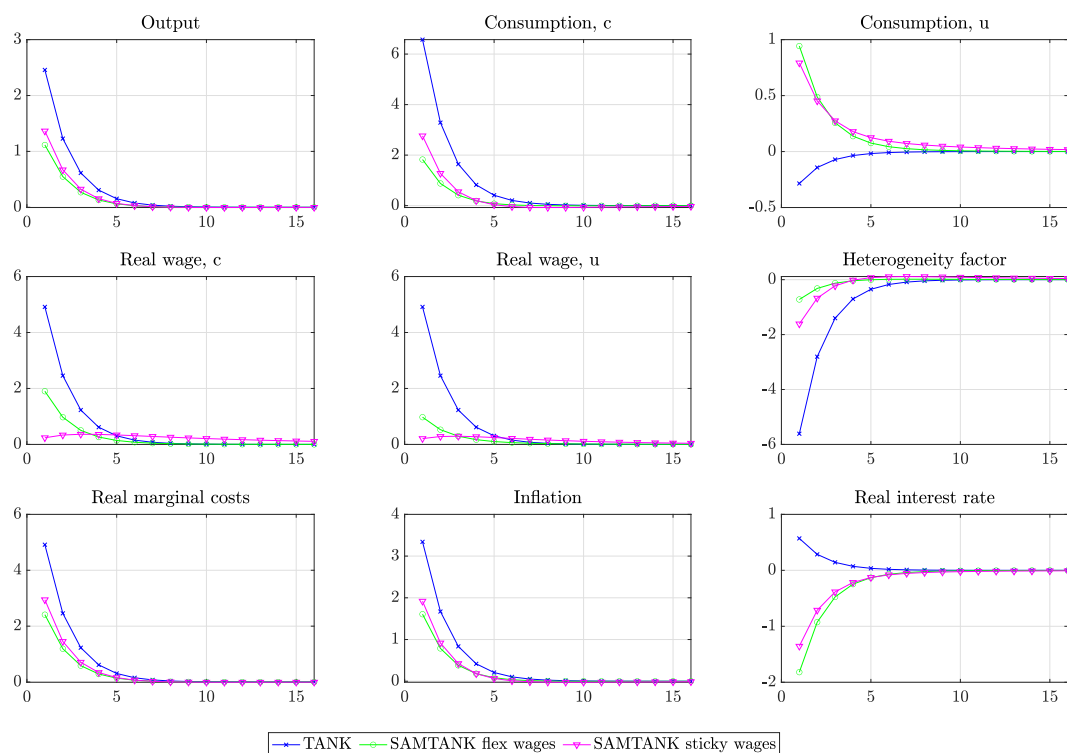
Monetary policy influences the consumption of the unconstrained through real interest rates (savings distribution channel). The real interest rate affects consumption decisions of unconstrained households because they smooth their consumption. When real interest rate decreases, unconstrained households decide to consume more and save less, as in the SAMTANK models. In the TANK the real interest rate increases slightly after the expansionary shock because the response of inflation is high enough to offset the shock.<sup>5</sup> Therefore, the

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<sup>5</sup>Bilbiie (2008) explains how an increase in interest rates could still be expansionary when there are enough constrained households and coins it the “inverse aggregate demand logic”: When contractionary effects of an increase in interest rates occur, the decrease in marginal costs

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**Figure 1.1:** IRFs to a 1% expansionary monetary policy shock: Main variables



Note: The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

consumption of the unconstrained decreases slightly in the TANK.

The income composition channel could also explain the discrepancy between responses of the consumption of unconstrained households in the TANK and the SAMTANK models. Since they earn both labour and profit income, and wages are inversely related to profits, an increase in wages does not necessarily lead to an increase in their total income. The relatively big increase in wages and marginal costs in the TANK could therefore explain the decrease in the consumption of the unconstrained.

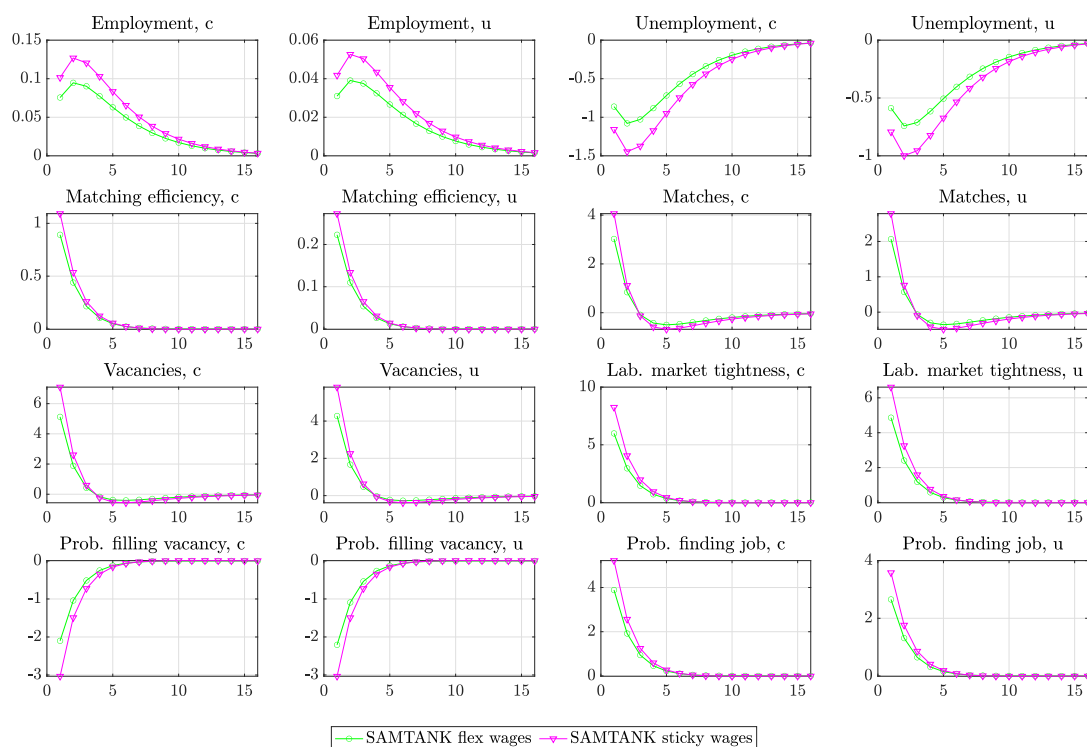
As for the constrained households, by definition the income composition channel plays a role in the transmission of monetary policy to their consumption because they consume their income hand-to-mouth. This transmission channel is visible especially in the TANK and the SAMTANK with flexible

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could generate a positive income effect for unconstrained households which increases the labour demand for a given wage.

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**Figure 1.2:** IRFs to a 1% expansionary monetary policy shock: Labour market variables



Note: The x-axis is in quarters and the y-axis is in percentages.

wages, because the increase in consumption of the constrained is similar to the increase in their wages.

In the SAMTANK with sticky wages, the income composition channel is less noticeable, though still present by definition: The consumption of constrained households increases by a lot more than the wage increase. Here, the earnings heterogeneity channel plays a crucial role. In Figure 1.2 we can see that unemployment decreases considerably after the monetary policy shock in the SAMTANK with sticky wages. The earnings heterogeneity channel increases the consumption of constrained households through an increase in their income from more matches and lower unemployment rate.

Summarised, in the SAMTANK with sticky wages the consumption inequality decreases after an expansionary monetary policy shock through three channels: the savings distribution channel, the income composition channel, and the earnings heterogeneity channel. In the SAMTANK with flexible wages and

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the simple TANK, the earnings heterogeneity channel is not detectable.

### 1.5 Comparison with empirical evidence

To check whether the models are in line with empirical evidence I compare the results of the two SAMTANK models with empirical findings by Coibion et al. (2017), Mumtaz and Theophilopoulou (2017), and Lenza and Slacalek (2021). I find that the SAMTANK with sticky wages matches the empirical evidence the best, both quantitatively through the magnitude of impulse responses, and qualitatively through relevant transmission channels.

Coibion et al. (2017) and Mumtaz and Theophilopoulou (2017) both study the effect of contractionary monetary policy shocks on income and consumption inequality in the United States and in the United Kingdom respectively. Coibion et al. (2017) use a 1% increase in nominal short-term interest rate as a contractionary monetary policy shock and Mumtaz and Theophilopoulou (2017) use a 0.1% increase. As my models are symmetric we can put a negative sign in front of my response functions to get results for a contractionary monetary policy shock. Lenza and Slacalek (2021) conduct empirical research on the effect of quantitative easing on income and wealth inequality in countries in the Euro Area. Their expansionary monetary policy shock is comparable to the shock in my models.<sup>6</sup>

I start by evaluating the unemployment responses. The SAMTANK with sticky wages replicates the empirical result by Lenza and Slacalek (2021) that the extensive margin of the labour market is more important to the transmission of monetary policy than changes in wages. They conclude that the earnings heterogeneity channel is the most relevant channel, though the income composition channel is present too. The SAMTANK with flexible wages and the simple TANK fail to identify the earnings heterogeneity channel. As is consistent with the SAMTANK models, Lenza and Slacalek (2021) show that unemployment of the

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<sup>6</sup>Lenza and Slacalek (2021) scale the expansionary monetary policy shock as a 0.3% decrease in the term spread between short- and long-term interest rates. They indicate that their shock affects output roughly the same as a 1% drop in the policy rate. Moreover, Debortoli et al. (2020) determine that standard monetary policy and quantitative easing can be seen as perfect substitutes in the United States.

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bottom two quintiles decrease more after an expansionary monetary policy shock (about -1.5%) than that of upper quintiles (not more than -1%) in Germany, Spain, France and Italy. The point estimates in Lenza and Slacalek (2021) are in line with the results of the SAMTANK with sticky wages, whereas the SAMTANK with flexible wages show a slightly dampened response.<sup>7</sup>

Comparing income responses, Lenza and Slacalek (2021) estimate an increase in income of 1.5-3% for the bottom two quintiles. With a response of about 2% in consumption of the constrained, both SAMTANK models match the results by Lenza and Slacalek (2021) well.<sup>8</sup> Mumtaz and Theophilopoulou (2017) find that wages of the bottom two quintiles decrease by less than 0.1% after a 0.1% contractionary monetary policy shock in the United Kingdom. This result is more in line with the wage response of constrained households in the SAMTANK with sticky wages.

As for the consumption responses of both types of households I observe that both SAMTANK models match the empirical evidence well. Mumtaz and Theophilopoulou (2017) show that consumption of the bottom two quintiles decrease by 0.15-0.25% after a 0.1% contractionary monetary policy shock in the United Kingdom. In the SAMTANK models the consumption of constrained households increase by about 2% after a 1% expansionary shock. The responses of the upper three quintiles are also similar to the responses in the SAMTANK models.

All in all, the SAMTANK with sticky wages matches the empirical evidence well, both qualitatively and quantitatively. Lenza and Slacalek (2021) stress the importance of the earnings heterogeneity channel, whereas Coibion et al. (2017) find the income composition channel and the savings redistribution channel important. The SAMTANK with sticky wages replicates all three channels

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<sup>7</sup>Constrained households in my models make up 40% of the population in my models, so they correspond to the bottom two quintiles of the income distribution.

<sup>8</sup>We can compare the income responses by Lenza and Slacalek (2021) with consumption responses of constrained households from my models, as these households consume their per-period income.

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and produces impulse responses that are quantitatively close to those found by empirical studies.

### 1.6 Towards a SAM-HANK

In this section, I discuss the implications of the above results for a HANK model with heterogeneous asset holdings by agents. Debortoli and Galí (2018) find that a TANK model approximates well the responses of aggregate variables, including the heterogeneity factor, of an otherwise similar HANK model. I expect similar results for the SAMTANK models in this paper, especially because they are extensions to the TANK model that Debortoli and Galí (2018) present. Moreover, I anticipate that a HANK model with search-and-matching frictions and wage rigidities could capture the same transmission channels as in the SAMTANK with sticky wages.

I expect that real interest rates affect consumption of agents with ample assets through the savings distribution channel. Such agents can fully smooth their consumption regardless of some fluctuations in their wages, and are therefore similar to the unconstrained households in my SAMTANK models. So, they increase their consumption when real interest rates decrease after an expansionary shock.

Agents with little or no assets such that their capacity to smooth consumption is very low, are similar to the constrained households in my SAMTANK models. The income composition channel and the earnings heterogeneity channel play an important role for their consumption fluctuations. Analogous to the results in my SAMTANK models, I expect the consumption of agents with very little assets to increase more than the consumption of agents with ample assets through those two channels after an expansionary monetary policy shock. Therefore, the consumption inequality between the upper tail and the lower tail of the population would decrease after such a shock.

I expect agents with intermediate asset holdings to behave as a mix of the constrained and unconstrained households in my SAMTANK models. For them, an expansionary monetary policy shock would increase their consumption through

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both real interest rates (savings distribution channel) and labour income (income composition channel and earnings heterogeneity channel). Therefore, I expect that the consumption inequality between the bottom tail and the intermediate range of agents would increase, while the inequality between the intermediate agents and the upper tail would decrease.

### 1.7 Conclusion

I identify three transmission channels that drive the effect of monetary policy to consumption inequality: income composition channel, savings redistribution channel and earnings heterogeneity channel. The models I use fall under the category of Two-Agent New Keynesian (TANK) models with credit-constrained and unconstrained agents. I analyse the transmission mechanism of three model variations: the Search-and-Matching TANK (SAMTANK) with sticky wages, the SAMTANK with flexible wages, and the simple TANK. In all models I find that an expansionary monetary policy shock decreases consumption inequality. In the TANK and the SAMTANK with flexible wages the income composition channel and the savings redistribution channel play a role in the transmission from monetary policy to consumption inequality. Adding wage rigidities amplifies the effect of unemployment on the transmission in the SAMTANK with sticky wages and therefore I identify the earnings heterogeneity channel alongside the other two channels. Since all three channels are in the SAMTANK with sticky wages, this model matches the empirical evidence the best. The results of the SAMTANK with sticky wages approximate well empirical findings by Coibion et al. (2017), Mumtaz and Theophilopoulou (2017), and Lenza and Slacalek (2021), both quantitatively and qualitatively. In particular, the presence of the earnings heterogeneity channel is the distinguishing feature of the SAMTANK with sticky wages.

A limitation of this paper is that the models only specify the share of the lower end of the distribution. They cannot for example distinguish the top 10% or 1% of the distribution. Some researchers like Davtyan (2017) find that the top end of

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the distribution contributes significantly to the transmission of monetary policy to inequality. The models in this paper cannot replicate such channels.

Having developed the extended New Keynesian models, it would be natural to follow up with optimal policy research. The conventional Taylor rule might not be the best policy in an economy with heterogeneous agents, especially when one also takes into consideration the distributional consequences of monetary policy. As Bilbiie (2008) states, the standard logic of aggregate demand and interest rates might invert when the proportion of constrained households increases.

# Appendices to Chapter 1

## A.1 Log-linear model equations

The log-linearised equations as deviations from the zero-inflation steady state describe the equilibrium dynamics in each of the models. The hatted values are  $\hat{z}_t = \log(Z_t) - \log(\bar{Z}) \approx \frac{Z_t - \bar{Z}}{\bar{Z}}$  and  $\bar{Z}$  is the steady-state value of a variable. Thus,  $\hat{z}_t$  is the percentage deviation of variable  $Z_t$  from its steady state.

### A.1.1 Labour market

$$\text{Time endowment households: } 0 = \bar{n}^k \hat{n}_t^k + \bar{u}^k \hat{u}_t^k \quad (\text{A.1})$$

$$\text{Matching function: } \hat{m}_t^k = \hat{\psi}_t^k + \zeta \hat{v}_t^k + (1 - \zeta) \hat{u}_t^k \quad (\text{A.2})$$

$$\text{Matching efficiency: } \hat{\psi}_t^k = \mu^k \hat{y}_t \quad (\text{A.3})$$

$$\text{Labour market tightness: } \hat{\theta}_t^k = \hat{v}_t^k - \hat{u}_t^k \quad (\text{A.4})$$

$$\text{Probability of filling a vacancy: } \hat{q}(\hat{\theta}_t^k) = \hat{m}_t^k - \hat{v}_t^k \quad (\text{A.5})$$

$$\text{Probability of finding a job: } \hat{p}(\hat{\theta}_t^k) = \hat{m}_t^k - \hat{u}_t^k \quad (\text{A.6})$$

$$\text{Labour market dynamics: } \hat{n}_t^k = (1 - \gamma^k) \hat{n}_{t-1}^k + \gamma^k (\hat{p}(\hat{\theta}_t^k) + \hat{u}_t^k) \quad (\text{A.7})$$

where Eq. (A.7) uses the relations  $\bar{n}^k = 1 - \bar{u}^k$  and  $\bar{u}^k = \frac{\gamma^k}{\gamma^k + \bar{p}(\theta^k)}$ .

### A.1.2 Households

$$\text{Budget constraint of constrained: } \hat{c}_t^c = \hat{w}_t^k + \hat{n}_t^k \quad (\text{A.8})$$

$$\text{Budget constraint of unconstrained: } \hat{c}_t^u = \frac{1}{\bar{c}^u} \left( \hat{w}_t^u + \hat{n}_t^u + \frac{1}{1 - \lambda} \hat{d}_t \right) \quad (\text{A.9})$$

where  $\hat{w}_t^k$  is the real wage.

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### A.1.3 Firms

$$\text{New Keynesian Philips Curve: } \hat{\pi}_t = \beta \mathbb{E}_t \hat{\pi}_{t+1} + \frac{\epsilon}{\xi \mathcal{M}} \hat{\mu}_t \quad (\text{A.10})$$

$$\text{Production function: } y_t = a_t + \hat{n}_t \quad (\text{A.11})$$

$$\text{Total factor productivity: } a_t = \rho_a a_{t-1} + \varepsilon_t^a \quad (\text{A.12})$$

$$\text{Marginal costs: } \hat{\mu}_t = \left( \frac{\sigma}{s_c} + \varphi \right) \hat{y}_t - \sigma \kappa \frac{s_v}{s_c} \hat{v}_t - (1 + \varphi) a_t \quad (\text{A.13})$$

$$\text{Natural level of output: } \hat{y}_t^n = \frac{1 + \varphi}{\frac{\sigma}{s_c} + \varphi} a_t \quad (\text{A.14})$$

$$\text{Aggregate profits: } \hat{d}_t = \frac{1}{d} \left\{ \bar{y} \hat{y}_t - \bar{w}^c \lambda \bar{n}^c (\hat{w}_t^c + \hat{n}_t^c) - \bar{w}^u (1 - \lambda) \bar{n}^u (\hat{w}_t^u + \hat{n}_t^u) - \kappa \bar{v} \hat{v}_t \right\} \quad (\text{A.15})$$

$$\text{Aggregate labour: } \hat{n}_t = \lambda \hat{n}_t^c + (1 - \lambda) \hat{n}_t^u \quad (\text{A.16})$$

### A.1.4 Staggered wage bargaining

$$\text{Wage index: } \hat{w}_t^k = (1 - \alpha^k) \hat{w}_t^{*k} + \alpha^k (\hat{w}_{t-1}^k - \hat{\pi}_t) \quad (\text{A.17})$$

$$\text{Effective bargaining power: } \hat{H}_t^k = -(1 - \bar{H}^k) \left[ (\hat{\Gamma}_t^{\mathcal{J}})^k - (\hat{\Gamma}_t^{\mathcal{W}})^k \right] \quad (\text{A.18})$$

$$\text{Firm's stake in wage: } (\hat{\Gamma}_t^{\mathcal{J}})^k = \alpha^k \beta (1 - \gamma^k) \mathbb{E}_t \left[ (\hat{\Gamma}_{t+1}^{\mathcal{J}})^k - \Delta \hat{c}_{t+1}^k \right] \quad (\text{A.19})$$

$$\text{Worker's stake in wage: } (\hat{\Gamma}_t^{\mathcal{W}})^k = \alpha^k \beta (1 - \gamma^c) \mathbb{E}_t \left[ -\bar{p}(\bar{\theta}^k) \hat{p}(\hat{\theta}_{t+1}^k) + (1 - \bar{p}(\bar{\theta}^k)) \left( (\hat{\Gamma}_{t+1}^{\mathcal{W}})^k - \Delta \hat{c}_{t+1}^k \right) \right] \quad (\text{A.20})$$

$$\text{Hiring condition: } -\hat{\psi}_t^k + (1 - \zeta) \hat{\theta}_t^k = \frac{1}{\Xi_0^k} \left( \Xi_H^k \hat{H}_t^k + \Xi_{\mu \cdot a}^k (\hat{\mu}_t + a_t) + \mathbb{E}_t \left[ \Xi_c^k \Delta \hat{c}_{t+1}^k + \Xi_{\psi}^k \hat{\psi}_{t+1}^k + \Xi_{\theta}^k \hat{\theta}_{t+1}^k \right] \right) \quad (\text{A.21})$$

where

$$\Xi_0^k = (1 - \bar{H}^k) \bar{\mu} + \xi_0 \left[ \xi_1 - \bar{H}^k \bar{\theta}^k \right], \quad \Xi_H^k = - \left[ \bar{\mu} + \xi_0 \bar{\theta}^k \right] \bar{H}^k,$$

$$\Xi_{\mu \cdot a}^k = (1 - \bar{H}^k) \bar{\mu}, \quad \Xi_c^k = -\xi_0 \left[ \xi_1 - \bar{H}^k \bar{\theta}^k \right], \quad \Xi_{\psi}^k = -\xi_0 \xi_1,$$

$$\Xi_{\theta}^k = \xi_0 \left[ (1 - \zeta) \xi_1 - \bar{H}^k \bar{\theta}^k \right], \quad \xi_0 = \beta \kappa (1 - \gamma^k), \quad \text{and} \quad \xi_1 = (\bar{\psi}^k)^{-1} (\bar{\theta}^k)^{1 - \zeta}.$$

### A.1.5 Monetary policy

$$\text{Output gap: } \tilde{y}_t = \hat{y}_t - \hat{y}_t^n \quad (\text{A.22})$$

$$\text{Taylor rule: } \hat{R}_t = \phi_{\pi} \hat{\pi}_t + \phi_y \tilde{y}_t + \nu_t \quad (\text{A.23})$$

$$\text{Monetary policy shocks: } \nu_t = \rho_{\nu} \nu_{t-1} + \varepsilon_t^{\nu} \quad (\text{A.24})$$

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### A.1.6 Heterogeneity

$$\text{Relation with consumption: } \hat{c}_t = \hat{c}_t^u - \frac{\lambda}{1 - \lambda\omega} \hat{\omega}_t \quad (\text{A.25})$$

$$\text{Labour share of output: } \hat{s}_t^{wn \cdot k} = \hat{w}_t^k + \hat{n}_t^k - \hat{y}_t \quad (\text{A.26})$$

$$\text{Heterogeneity factor: } \hat{\omega}_t = \frac{1}{\Omega_n \Omega_d} \left\{ \begin{array}{l} [(1-\lambda)^2 \delta(1-\tau) \bar{s}^{wn \cdot u} - (1-\lambda)(1-\delta\lambda(1-\tau)) \bar{s}^{wn \cdot c}] \\ - (1-\delta(1-\tau)) \delta \lambda (1-\tau) \bar{\mu} \hat{\mu}_t \\ + [(1-\lambda) \bar{s}^{wn \cdot c} - (1-\lambda)^2 \delta(1-\tau) \bar{\mu}] \bar{s}^{wn \cdot u} \hat{s}_t^{wn \cdot u} \end{array} \right\} - \frac{1-\lambda}{\Omega_n} \bar{s}^{wn \cdot c} \hat{s}_t^{wn \cdot c} \quad (\text{A.27})$$

where

$$\Omega_n = (1 - \lambda)(\bar{s}^{wn \cdot u} - \bar{s}^{wn \cdot c}) - (1 - \delta(1 - \tau))\bar{\mu},$$

$$\text{and } \Omega_d = (1 - \lambda)\bar{s}^{wn \cdot u} - (1 - \delta\lambda(1 - \tau))\bar{\mu}.$$

### A.1.7 Market clearing

$$\text{Aggregate consumption: } \hat{c}_t = \lambda \hat{c}_t^c + (1 - \lambda) \hat{c}_t^u \quad (\text{A.28})$$

$$\text{Aggregate vacancies: } \hat{v}_t = \lambda \hat{v}_t^c + (1 - \lambda) \hat{v}_t^u \quad (\text{A.29})$$

$$\text{Goods market clearing: } \hat{y}_t = s_c \hat{c}_t + \kappa s_v \hat{v}_t \quad (\text{A.30})$$

$$(\text{A.31})$$

### A.1.8 Dynamic IS equation and natural real interest rate

$$\text{IS equation: } \tilde{y}_t = \mathbb{E}_t \tilde{y}_{t+1} - \frac{s_c}{\sigma} (i_t - \mathbb{E}_t \pi_{t+1} - r_t^n) - \kappa s_v \mathbb{E}_t [\Delta \hat{v}_{t+1}] + \frac{\lambda}{1 - \lambda\omega} s_c \mathbb{E}_t [\Delta \hat{\omega}_{t+1}] \quad (\text{A.32})$$

where  $\Delta$  is a difference operator with  $\Delta Z_{t+1} = Z_{t+1} - Z_t$ .

$$\text{Natural real interest rate: } r_t^n = -\frac{\sigma}{s_c} (1 - \rho_a) \frac{1 + \varphi}{\frac{\sigma}{s_c} + \varphi} a_t \quad (\text{A.33})$$

## A.2 Steady-state values obtained from calibrated parameters

- Job finding probabilities:  $\bar{p}(\bar{\theta}^c)$  and  $\bar{p}(\bar{\theta}^u)$

$$\bar{p}(\bar{\theta}^k) = \bar{\psi}^k (\bar{\theta}^k)^\zeta$$

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$$\bar{p}(\bar{\theta}^c) = 0.285 \quad \text{and} \quad \bar{p}(\bar{\theta}^u) = 0.285$$

Empirically, Hobijn and Şahin (2009) estimate job finding probabilities in OECD countries between 1968 and 2006 and range between around 5% in some European countries to over 50% in the United States.

- Vacancy filling probabilities:  $\bar{q}(\bar{\theta}^c)$  and  $\bar{q}(\bar{\theta}^u)$

$$\bar{q}(\bar{\theta}^k) = \bar{\psi}^k (\bar{\theta}^k)^{-(1-\zeta)}$$

$$\bar{q}(\bar{\theta}^c) = 0.220 \quad \text{and} \quad \bar{q}(\bar{\theta}^u) = 0.316$$

- Unemployment rates:  $\bar{u}^c$  and  $\bar{u}^u$

$$\bar{u}^k = \frac{\gamma^k}{\gamma^k + \bar{p}(\bar{\theta}^k)}$$

$$\bar{u}^c = 0.081 \quad \text{and} \quad \bar{u}^u = 0.050$$

Empirical evidence shows that unemployment under low-skilled workers are higher (Oesch, 2010).

- Employment rates:  $\bar{n}^c$  and  $\bar{n}^u$

$$\bar{n}^k = 1 - \bar{u}^k$$

$$\bar{n}^c = 0.919 \quad \text{and} \quad \bar{n}^u = 0.950$$

- Real marginal costs:  $\bar{\mu}$

When normalising prices to 1, marginal cost equals the inverse of the markup.

$$\bar{\mu} = \frac{1}{\mathcal{M}} = \frac{\epsilon - 1}{\epsilon}$$

$$\bar{\mu} = 0.889$$

- Wages:  $\bar{W}^c$  and  $\bar{W}^u$

$$\bar{W}^k = \bar{\mu} - \gamma^k \beta \frac{\kappa}{\bar{q}(\bar{\theta}^k)}$$

which is from the firms' first order condition w.r.t.  $N_t^k(i)$  (1.4).

$$\bar{W}^c = 0.883 \quad \text{and} \quad \bar{W}^u = 0.887$$

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- Shares of wages times labour:  $s^{wn\cdot c}$  and  $s^{wn\cdot u}$

$$s^{wn\cdot k} = \frac{\bar{W}^k \bar{N}^k}{\bar{Y}}$$

$$s^{wn\cdot c} = 0.325 \quad \text{and} \quad s^{wn\cdot u} = 0.505$$

where  $\bar{Y} = 1$ .

- Share of consumption and vacancies:  $s_c$  and  $s_v$

$$s_c = s^{wn\cdot c} + s^{wn\cdot u} + 0.01\epsilon \quad \text{and} \quad s_v = 1 - s_c$$

$$s_c = 0.830 \quad \text{and} \quad s_v = 0.170$$

- Heterogeneity factor:  $\omega$

$$\omega = 1 - \frac{s^{wn\cdot c} + (1 - \tau)0.01\epsilon}{s^{wn\cdot u} + \tau 0.01\epsilon}$$

$$\omega = 0.454$$

- Partial derivatives of workers' and firms' surplus:  $(\bar{\Gamma}^{\mathcal{W}})^c$ ,  $(\bar{\Gamma}^{\mathcal{W}})^u$ ,  $(\bar{\Gamma}^{\mathcal{J}})^c$  and  $(\bar{\Gamma}^{\mathcal{J}})^u$

$$(\bar{\Gamma}^{\mathcal{W}})^k = \frac{1}{1 - \theta_w \beta (1 - \gamma^k) (1 - \bar{p}(\theta^k))} \quad \text{and} \quad (\bar{\Gamma}^{\mathcal{J}})^k = \frac{1}{1 - \theta_w \beta (1 - \gamma^k)}$$

$$(\bar{\Gamma}^{\mathcal{W}})^c = 2.587 \quad \text{and} \quad (\bar{\Gamma}^{\mathcal{W}})^u = 2.633$$

$$(\bar{\Gamma}^{\mathcal{J}})^c = 8.682 \quad \text{and} \quad (\bar{\Gamma}^{\mathcal{J}})^u = 9.424$$

- Effective bargaining power of the households:  $\bar{\Theta}^c$  and  $\bar{\Theta}^u$

$$\bar{\Theta}^k = \frac{\eta^k}{\eta^k + (1 - \eta^k) (\bar{\Gamma}^{\mathcal{J}})^k / (\bar{\Gamma}^{\mathcal{W}})^k}$$

$$\bar{\Theta}^c = 0.239 \quad \text{and} \quad \bar{\Theta}^u = 0.228$$

### A.3 The effect of wage rigidities on labour market variables

Here I investigate the mechanisms of the SAMTANK and SAMTANK-SW further to examine the effect of wage stickiness  $\alpha^k$  on labour market variables. Firstly, the wage stickiness has a direct effect in the wage bargaining process through the bargaining power. In the SAMTANK this bargaining power  $\eta^k$  is time-invariant. In the SAMTANK-SW it takes the form  $H_t^k = \frac{\eta^k}{\eta^k + (1-\eta^k)(\Gamma_t^{\mathcal{J}})^k / (\Gamma_t^{\mathcal{W}})^k}$  with the workers' stake in the wage  $(\Gamma_t^{\mathcal{W}})^k$  given by (1.8) and the firms' stake in the wage  $(\Gamma_t^{\mathcal{J}})^k$  given by (1.9) which both depend on the wage stickiness parameter  $\alpha^k$ . The effect of  $\alpha^k$  on the workers' stake and firms' stake are:

$$\begin{aligned} \frac{\partial(\Gamma_t^{\mathcal{W}})^k}{\partial\alpha^k} &= (1 - \gamma^k)\mathbb{E}_t \left[ \Lambda_{t,t+1}^k (1 - p(\theta_{t+1}^k)) \frac{\partial(\Gamma_{t+1}^{\mathcal{W}})^k}{\partial\alpha^k} \right] \\ \text{and } \frac{\partial(\Gamma_t^{\mathcal{J}})^k}{\partial\alpha^k} &= (1 - \gamma^k)\mathbb{E}_t \left[ \Lambda_{t,t+1}^k \frac{\partial(\Gamma_{t+1}^{\mathcal{J}})^k}{\partial\alpha^k} \right]. \end{aligned}$$

As  $0 < p(\theta_{t+1}^k) < 1$ ,  $\frac{\partial(\Gamma_t^{\mathcal{J}})^k}{\partial\alpha^k} > \frac{\partial(\Gamma_t^{\mathcal{W}})^k}{\partial\alpha^k}$ . Therefore, as wage stickiness  $\alpha^k$  increases,  $(\Gamma_t^{\mathcal{J}})^k / (\Gamma_t^{\mathcal{W}})^k$  increases, which decreases the effective bargaining power of workers  $H_t^k$ . In the limiting case of flexible wages, i.e.  $\alpha^k = 0$ , I obtain  $(\Gamma_t^{\mathcal{J}})^k / (\Gamma_t^{\mathcal{W}})^k = 1$  and  $H_t^k = \eta^k$ . So, an increase in wage rigidity  $\alpha^k$  leads to a decrease in the effective bargaining power of workers  $H_t^k$  because workers have a shorter horizon and therefore are more impatient.

Secondly, I explore the effect of wage stickiness  $\alpha^k$  on other labour market variables through the effective bargaining power  $H_t^k$ . Taking the derivative of the SAMTANK-SW job creation condition (1.12) with respect to  $H_t^k$  gives:

$$\frac{\partial \frac{\kappa}{q(\theta_t^k)}}{\partial H_t^k} = -(\mu_t A_t - b) - (1 - \gamma^k)\mathbb{E}_t \left[ \Lambda_{t,t+1}^k p(\theta_{t+1}^k) \frac{\partial \frac{\kappa}{q(\theta_{t+1}^k)}}{\partial H_t^k} \right]$$

which is the effect of a change in effective bargaining power  $H_t^k$  on the expected cost of posting vacancies  $\frac{\kappa}{q(\theta_t^k)}$ . This effect is negative asymptotically. So, when  $\alpha^k$  increases and  $H_t^k$  decreases, the expected cost of posting vacancies  $\frac{\kappa}{q(\theta_t^k)}$  increases. Intuitively, wage stickiness adds more friction in the labour market and thus

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increases the expected cost of posting vacancies. As  $\kappa$  is constant, this leads to a decrease in the probability of filling a vacancy  $q(\theta_t^k)$ . I rewrite the probability of filling a vacancy  $q(\theta_t^k)$  and finding a job  $p(\theta_t^k)$  as:

$$q(\theta_t^k) = \psi_t^k \theta_t^{-(1-\zeta)} \quad \text{and} \quad p(\theta_t^k) = \psi_t^k \theta_t^\zeta.$$

where the two expressions share the matching efficiency parameter  $\psi_t^k$  which fluctuates with output by definition. Then, a decrease in  $q(\theta_t^k)$  leads to an increase in the labour market tightness  $\theta_t^k$ . This increase in labour market tightness in turn leads to an increase in the probability of finding a job  $p(\theta_t^k)$  which intuitively makes sense. When  $p(\theta_t^k)$  increases a multiplier effect starts because it amplifies the gap between  $(\Gamma_t^J)^k$  and  $(\Gamma_t^W)^k$ . This effect drives the effective bargaining power  $H_t^k$  further down. The increase in the labour market tightness  $\theta_t^k = \frac{v_t^k}{u_t^k}$  implies that vacancies  $v_t^k$  increase and unemployment rate  $u_t^k$  decreases. Therefore, the employment rate  $n_t^k$  increases. Altogether, wage rigidities amplify the variables in the labour market by creating more friction for firms when hiring workers.

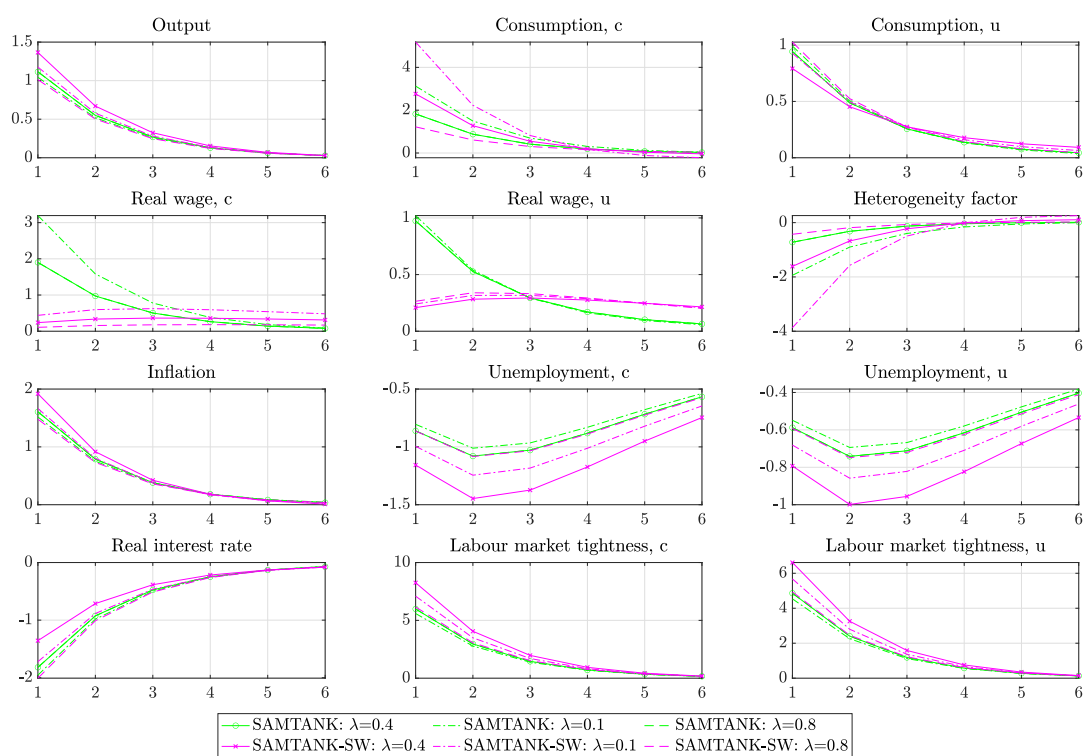
### A.4 Robustness checks

To verify the models' robustness I conduct sensitivity analyses by changing parameters in the model. First, I conduct robustness checks with the key parameter, the fraction of constrained households  $\lambda$ . The baseline models consider  $\lambda = 0.4$  and I take  $\lambda = 0.1$  and  $\lambda = 0.8$  as robustness checks. The results are in Figure A.1. I perform the checks only for the SAMTANK with sticky wages. Even though the new IRFs depart from the baseline case, implications for the transmission channels are qualitatively similar. I observe that the share of constrained households  $\lambda$  affects the transmission of monetary policy to consumption inequality considerably, mostly through the responses of constrained households. The consumption, wages, and unemployment IRFs of unconstrained households are much less sensitive. The wage and unemployment responses of constrained households reflect that when  $\lambda = 0.1$ , the upwards pressure on the labour

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market tightness is higher than when  $\lambda = 0.8$ . So, both the income composition channel and the earnings heterogeneity channel increase the consumption of the constrained when  $\lambda$  is smaller, which leads to a bigger decrease in the consumption inequality. This result enhances the conclusion by researchers such as Lenza and Slacalek (2021) and Ampudia et al. (2018) who empirically deduce that the lowest part of the income distribution of the population account for a big share of the transmission of monetary policy to inequality.

**Figure A.1:** Robustness check with different fractions of constrained households

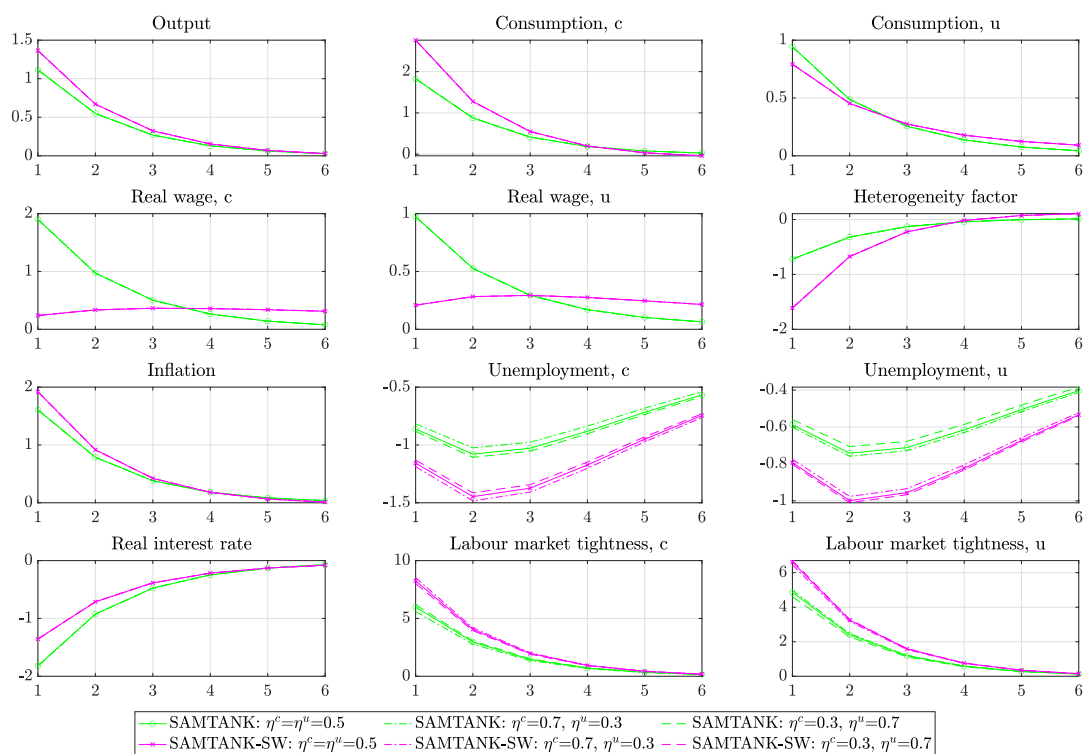


Note: The IRFs are in response to a 1% expansionary monetary policy shock. The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

Below I present more robustness checks and summary of their results from changing other parameters. I conclude that these checks also do not change the results qualitatively.

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**Figure A.2:** Robustness check with different bargaining powers of households



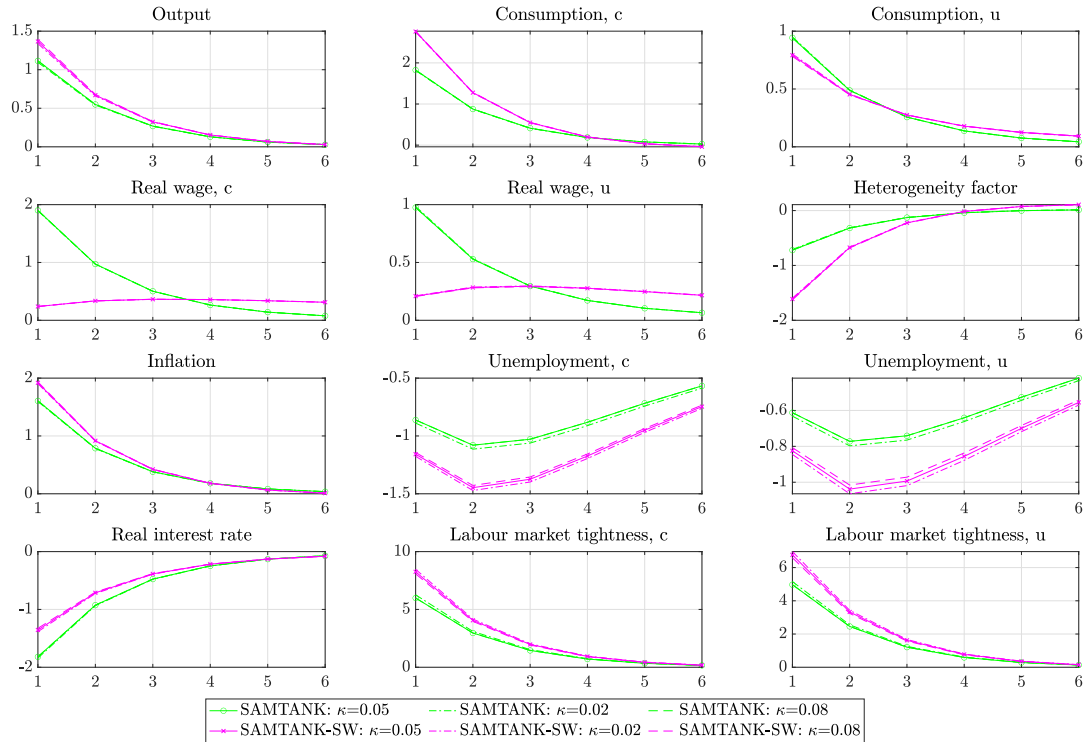
Note: The IRFs are in response to a 1% expansionary monetary policy shock. The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

### Summary of results with different bargaining powers of households

- Main variables like output, inflation, and the heterogeneity factor are robust against changes to the bargaining power of households.
- The changes affect labour market variables like unemployment slightly and predictably: The decrease in unemployment dampens when the bargaining power is higher for a household compared to the baseline case, and vice versa.

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**Figure A.3: Robustness check with different vacancy posting costs**



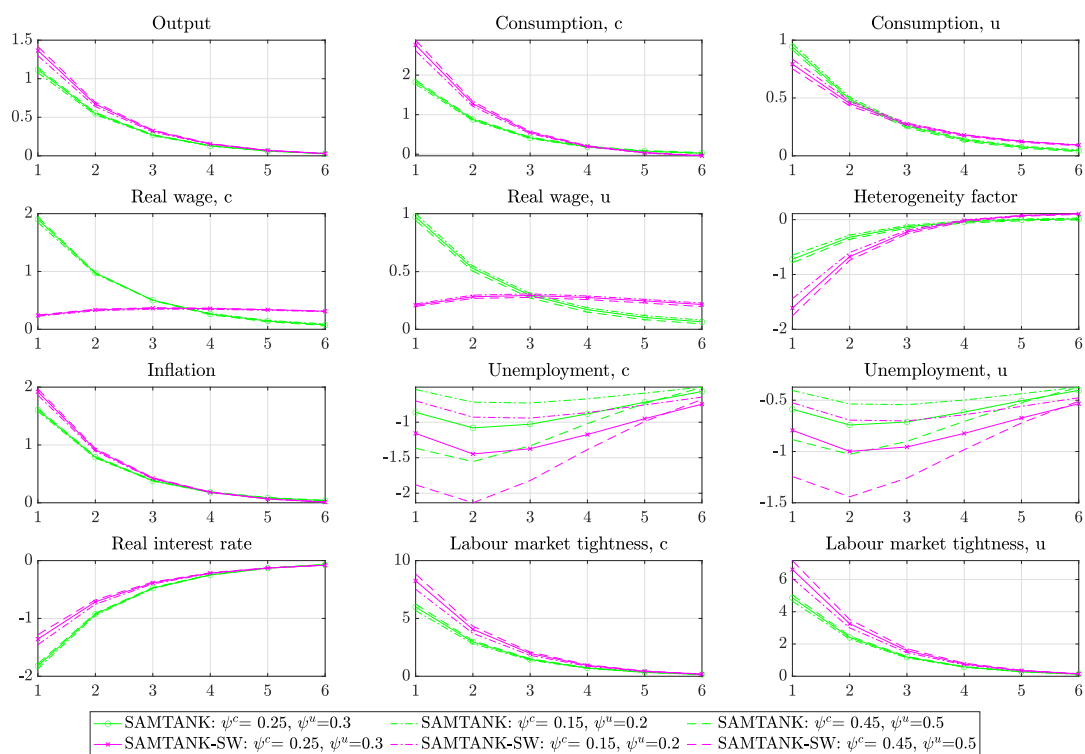
Note: The IRFs are in response to a 1% expansionary monetary policy shock. The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

### Summary of results with different vacancy posting costs

- Model results are robust against changes to different vacancy posing costs.

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**Figure A.4:** Robustness check with different steady-state matching efficiencies



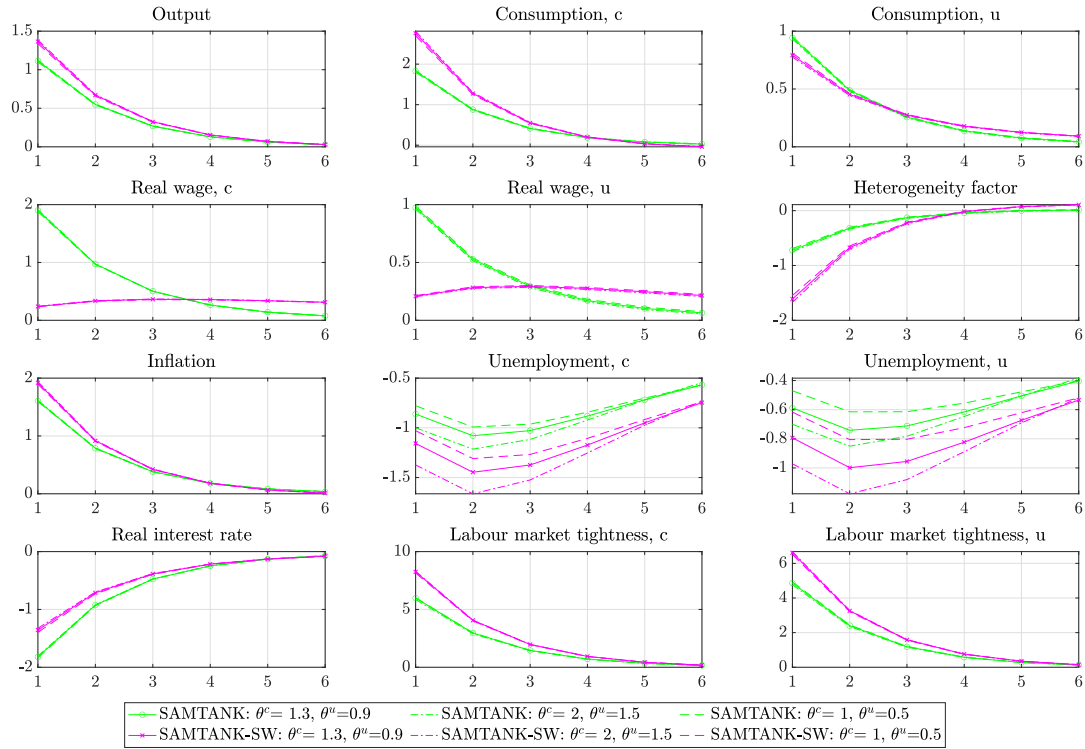
Note: The IRFs are in response to a 1% expansionary monetary policy shock. The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

### Summary of results with different steady-state matching efficiencies

- Main variables like output, inflation, and the heterogeneity factor are robust against changes to steady-state matching efficiency levels.
- The changes affect labour market variables like unemployment predictably: The decrease in unemployment dampens when the steady-state matching efficiency is lower for a household compared to the baseline case, and vice versa.

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**Figure A.5:** Robustness check with different steady-state labour market tightness levels



Note: The IRFs are in response to a 1% expansionary monetary policy shock. The x-axis is in quarters and the y-axis is in percentages. Inflation and real interest rate are annualised.

### Summary of results with different steady-state labour market tightness levels

- Main variables like output, inflation, and the heterogeneity factor are robust against changes to steady-state labour market tightness levels.
- The changes affect labour market variables like unemployment predictably: The decrease in unemployment dampens when the steady-state labour market tightness is lower for a household compared to the baseline case, and vice versa.

# Chapter 2

## To Cap or Not to Cap? Energy Crises in a Currency Union

**Abstract** During the recent energy crisis some Euro Area countries introduced price caps on energy, while others did not, leading to about 30 percentage points higher energy inflation in uncapped countries. This paper investigates the trade-offs policymakers face with energy price caps in a two-country currency union model with shared energy supply. The cooperative, optimal outcome is for neither country to impose a price cap, since the cap is a costly market distortion. However, capping allows a country to avoid a crisis at the cost of negative spillovers on the uncapped country, characterized by high inflation and lower output. The quantitative model with non-homothetic preferences and substitutability of energy sources shows that the cost of the price cap exceeds the cost of such spillovers, explaining why some countries capped prices while others did not. Moreover, I show that the spillovers from price caps contributed to about 10 (0.5) percentage points of energy (headline) inflation in the uncapped Euro Area countries in 2022. Targeted transfers, an alternative policy to the price cap, is a cheaper and more effective way to boost consumption of the poor without creating divergence within the union.

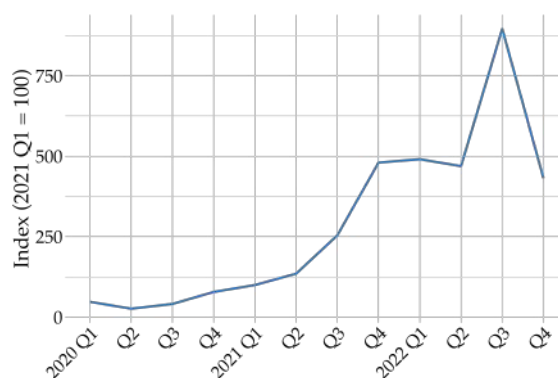
**Keywords** energy crisis, energy price cap, monetary union, international spillovers

**JEL codes** E31, E63, F45, Q41

## 2.1 Introduction

The Euro Area, and Europe as a whole, experienced a large energy crisis in 2022. Energy prices began rising in mid-2021 and soared in 2022 after the Russian invasion of Ukraine, as shown in Figure 2.1. The increase in energy prices triggered energy price cap decisions from many, but not all governments. This paper investigates the effects of an energy price cap in a subset of countries in a currency union during an energy crisis, focusing on international spillovers and policy trade-offs of the price cap.

**Figure 2.1:** Natural gas price in Europe



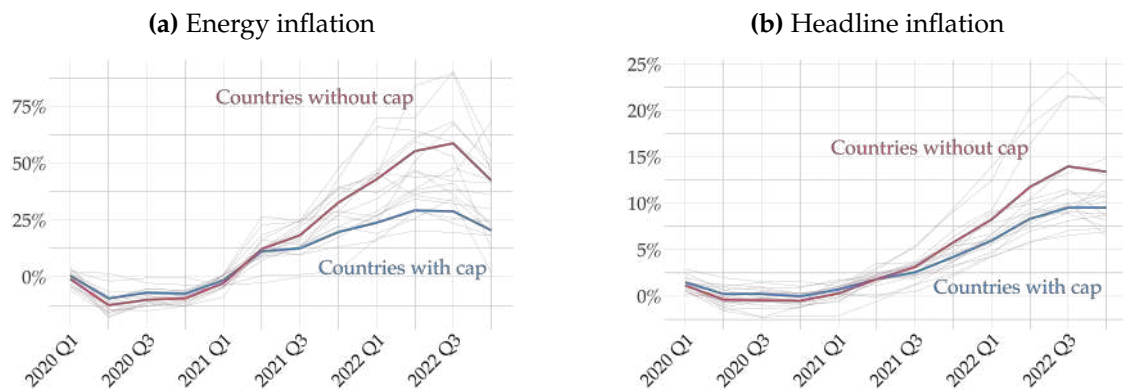
*Notes:* The price index of the Title Transfer Facility (TTF) gas in the Netherlands. Most price setters use this price as the reference price and gas contracts are indexed to this price, the TTF price index is the standard gas price benchmark for Europe (Rogge, 2024).<sup>1</sup> For longer time series, see Figure B.4 in Appendix B.3. Data source: IMF Data (2024).

Inflation rates in uncapped countries were considerably higher than in capped countries, as shown in Figure 2.2. In 2022, France and Germany, among others, decided to impose an energy price cap, whereas other countries including The Netherlands and Italy did not. The energy inflation in countries without an energy price cap was about 30 percentage points higher than in the capped countries in 2022Q3, and for headline inflation the difference was about 5 percentage points. Figure B.5 in Appendix B.3 shows that the divergence of both energy and headline inflation in 2022 was at an unprecedented magnitude since the start of the Euro Area.

<sup>1</sup>Moreover, gas prices drive wholesale electricity prices as the highest marginal cost of energy production, so they are a good indicator for energy/electricity price movements (Pescatori & Steurmer, 2022).

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**Figure 2.2:** Inflation in the Euro Area 2020 – 2022



*Notes:* Annualized energy and headline inflation rates in the Euro Area. Source: Eurostat. Countries with an energy price cap in 2022 are Austria, Estonia, France, Germany, Luxembourg, Malta, Portugal, Slovakia, Slovenia, Spain. Countries without are Belgium, Cyprus, Finland, Greece, Ireland, Italy, Latvia, Lithuania, The Netherlands. Bold lines are weighted averages for each group.

The paper uses a two-country currency union model with a shared energy supply to investigate the trade-offs of an energy price cap. In the absence of price caps, an adverse energy supply shock not only reduces energy consumption, but also acts as a cost-push shock to an economy: a decline in the exogenous supply of energy depresses output while increasing inflation. The assumption of an exogenous energy supply reflects the high dependency of Europe on Russian gas before 2022 (Pescatori & Steurmer, 2022; Moll et al., 2023). Since the shock is essentially a relative price shock, it is a standard result in New Keynesian frameworks that it acts like a cost-push shock.

First, I find that capping the energy price allows a country to avoid the crisis while imposing negative spillovers on the uncapped country, causing divergence within the currency union. I define the energy price cap as a policy that fixes energy price. The government then pays the difference between the actual price of energy and its retail price. This setup is somewhat stylized, because in reality most governments imposed a price cap that was less strict. However, this assumption is not overly restrictive, as the strictness of the price cap shifts the overall level of responses but does not alter the underlying mechanisms.

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With the price cap, a country does not suffer from the energy supply shock: output does not suffer a fall and inflation does not soar. Moreover, households can maintain their energy consumption. On the contrary, the uncapped country experiences a larger cost-push shock compared to the case of no price caps in the entire union, and also a larger decline in energy consumption. A crucial assumption behind these spillovers is the shared energy supply between the capped and uncapped countries, as is the case in Europe for Russian gas. During the adverse energy supply shock the capped country's energy consumption does not decrease because the price does not change. Then, the energy supply available in the uncapped country declines even more, which causes an even higher (energy) inflation and a lower welfare.

Second, the paper demonstrates that for policymakers facing the decision – to cap or not to cap – there is a trade-off between the cost of the price cap and the cost of the spillovers. I analyze the welfare implications of energy price caps in the two-country model, in which each country faces two policy decisions at the onset of an energy supply shock. The optimal, cooperative outcome occurs when both countries refrain from imposing a price cap. This outcome avoids market distortions, as energy prices reflect true scarcity during the crisis. However, because of the lack of cooperation between countries within the union, each country has an incentive to deviate from the cooperative strategy: if one country does not impose an energy price cap, the other country has an incentive to impose one to avoid the energy crisis as described above.

If one country imposes a price cap, should the other country follow suit? On one hand, imposing the price cap leads to inefficiencies and high costs, as artificially low prices in both countries encourage excessive energy consumption despite scarcity. On the other hand, not imposing the cap means bearing the negative spillovers from the first country's cap, which is also costly. In the quantitative model the cost of imposing the price cap are larger than the cost of these negative spillovers. Hence, the outcome of a static decision game is a price cap in one of the two countries, even though the cooperative strategy is

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for neither of the countries to impose the cap. This result explains why in reality some countries capped the energy price while others did not.

The key assumptions to this result are the type of household preferences and the substitutability of the energy source that is shared between the countries: they both affect the magnitude of the negative spillovers experienced by the uncapped country. The non-homothetic preferences are as in Boppart (2014): households spend a higher share of their income on energy when their income is low, which means they dislike reducing their energy consumption. These type of preferences are common in literature handling necessity goods like energy and food (Blanco & Diz, 2021; Olivi et al., 2023). Non-homothetic preferences amplify the negative spillovers, which results in costs from spillovers exceeding the costs of implementing the price cap depending on the substitutability of the energy source.

Endogenous energy production dampens the spillovers and explains why a country might prefer to bear the negative spillovers from the price cap as an uncapped country rather than imposing a price cap themselves. During the European energy crisis in 2022, the elasticity of substitution between gas, subjected to the exogenous supply shock, and non-gas energy was crucial, since the total energy consumption per capita did not decrease (Energy Institute, 2024). In the quantitative model, I estimate this elasticity of substitution and find that with the estimated parameters the cost of bearing the spillovers is smaller than the cost of implementing a price cap.

Third, I provide counterfactual exercises of price cap policies in Europe in 2022. I perform a historical shock decomposition of the energy and headline inflation rates in which the energy price cap is one of the shocks. I find that the energy price cap contributed to 10 percentage points of energy inflation and 0.5 percentage points to headline inflation in the uncapped countries in 2022. Moreover, the inflation rates in the capped countries would not have been much higher without the energy price cap, reinforcing the model result that the cooperative, optimal outcome involves no price caps.

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Last, I introduce a version of the model with hand-to-mouth households to compare the energy price cap to targeted transfers as an alternative policy measure. Shielding low-income households from rising energy costs was a key priority for many governments (Sgaravatti et al., 2023). I show that targeted transfers are a cheaper and more effective way to boost the consumption of the poor during an energy crisis. Moreover, because targeted transfers do not distort the energy market in the union, they do not cause large spillovers nor divergence within the union.

The contributions of this paper are both general, on international policy coordination, and specific to the European energy crisis in 2022: first, I show that in a decision game of two countries and two cap options, the degree of non-homotheticity and the substitutability of the shared energy source determines the magnitude of the spillovers, and hence the incentives for policymakers to implement the price cap. Second, I quantify the model by estimating it with European data. I confirm the general result that the negative spillovers from the capped to uncapped country are much larger than the benefits the capped country experiences by implementing the cap.

**Related Literature.** This paper contributes to two strands of the literature. First, it builds onto the vast literature on monetary and fiscal policy in a currency union. R. M. W. J. Beetsma et al. (2001), R. M. Beetsma and Jensen (2005), Galí and Monacelli (2008), Ferrero (2009), and Hjortsoe (2016) are pioneers of this strand of literature and explore the optimal joint conduct of monetary and fiscal policy as stabilization tools under asymmetric shocks. Other authors like Anderson (2007) and Keen and Konrad (2013) focus on strategic interactions of regulatory policies, like taxes, trade policies, and industrial regulation. Later, papers on this topic consider long-term coordination, with the sovereign debt crises in mind (Trichet, 2013; Chang, 2015). In this paper, I introduce a new dimension of integration: a shared energy supply. I analyze the international coordination in energy price cap policies during a union-wide energy shock. The analysis

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focuses on the determinants of the magnitude of the cap's spillovers, and finds that fiscal coordination between countries is favorable. However, I show that countries do not always have the incentives to cooperate.

Second, this paper contributes to the rapidly expanding literature on energy crises. This paper is closest to Bayer et al. (2023), who also evaluate different fiscal responses to an energy shock in a currency union. They compare two types of energy price caps and the trade-off between stabilization of the domestic economy and costly spillovers abroad. Auclert et al. (2023) and Chan et al. (2024) study the macroeconomic effects of an energy price shock and look at the coordination of fiscal policies and optimal monetary policy, respectively. Moreover, Erceg et al. (2024) and Glocker and Wegmüller (2024) study the effectiveness of fiscal policies, including energy subsidies, in stabilizing inflation. This paper analyzes the trade-offs and the spillovers of the energy price cap in an international setting. I approach the topic with a novel angle: I adopt a tractable, game-theoretic approach to determine the cooperative energy price cap policy as well as the equilibrium that arises when countries have their own incentives.

The rest of this paper is organized as follows: Section 2.2 outlines the model with non-homothetic preferences, the price cap setup, and the model calibration. Section 2.3 discusses the results of the baseline model, including the magnitude of the spillovers. I also analyze the trade-offs between headline and core-inflation targeting. Then, in Section 2.4 I estimate the substitutability between the shared energy source (gas) and domestically produced energy (non-gas) and show that the costs of implementing a price cap are larger than the costs of bearing the negative spillovers. I also quantify the contribution of the energy price cap to (energy) inflation in 2022. Lastly, in Section 2.5 I investigate targeted transfers by adding hand-to-mouth households to the model. Section 2.6 concludes.

### 2.2 Model

The model considers a currency union with two countries, Home and Foreign  $\{H, F\}$ , and incomplete financial markets. The relative size of the Home country is  $\Theta \in (0, 1)$  and hence of the Foreign is  $1 - \Theta$ . Time is discrete and indexed by  $t \in \{0, \dots\}$ . Both countries are inhabited by households, firms and a fiscal authority. There is one central bank setting monetary policy for the entire currency union.

Energy supply to the union is exogenous which follows from the high dependency of Europe on imported energy (Eurostat, 2023a). The energy market clears with a single price for the whole union reflecting the well-integrated energy market in Europe (Pescatori & Steurmer, 2022). When there is an energy price cap, the government pays for the difference between the actual price of energy and the retail price of energy. This setup for the energy market is similar to the one introduced by Bayer et al. (2023).

Households consume energy as part of their consumption basket. Households have non-homothetic preferences for energy, which ensure that they consume a higher expenditure share of energy when their income decreases. Firms in both countries produce tradable goods under monopolistic competition, using energy and labor as inputs. The law of one price holds for those goods and there is home bias.

Since the Home and Foreign country are symmetric, I explain only the Home-side of the union, unless otherwise stated. Foreign variables are denoted with an \*. Appendix B.1 provides a more detailed description of the model, including a list of relevant equilibrium conditions and the steady state.

This model includes non-homothetic preferences but not the substitutability of different energy sources. This version of the model is useful for understanding the core intuition and mechanics before introducing the substitutability of energy sources. In Section 2.4 I complete the model by adding domestic energy production and allowing for substitutability of the exogenous source of energy (gas) and domestically produced energy (non-gas).

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### 2.2.1 Households

#### 2.2.1.1 Preferences

Households derive utility from two types of goods: energy goods,  $E_t^h$ , and non-energy, other goods,  $C_{Ot}$ . Preferences of the households are non-homothetic as introduced by Boppart (2014). In this specification of preferences, the total nominal expenditure of the household, defined as  $exp_t = P_{Et}E_t^h + P_{Ot}C_{Ot}$ , matters for the share of expenditure spent on energy and the other goods.  $P_{Et}$  and  $P_{Ot}$  are prices for energy and other goods respectively. The indirect utility function of the representative household with non-homothetic preferences is:<sup>2</sup>

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} - 1 \right] \right\} \quad (2.1)$$

where  $\alpha_E > 0$  is the share of energy consumption in the steady state and  $\beta$  is the discount factor.  $\varepsilon_1$  governs the expenditure elasticity of demand: when  $\varepsilon_1 > 0$ , the expenditure elasticity of demand is strictly smaller than unity for energy and larger than unity for other goods. So, when total nominal expenditure, or total income available for consumption, decreases, the demand for energy decreases less than proportionally with income and the demand for other goods decreases more than proportionally.  $\varepsilon_2$  controls the elasticity of substitution between energy and other goods. In steady state, the elasticity of substitution between energy and other goods is  $\bar{\sigma} = 1 - \varepsilon_2 - \frac{\alpha_E}{1 - \alpha_E}(\varepsilon_2 - \varepsilon_1)$ .<sup>34</sup>

**Relative demand between energy and other goods.** The relative demand for energy and other goods obtained using Roy's identity reads as:<sup>5</sup>

$$C_{Ot} = \frac{1 - \alpha_E \varpi_t}{\alpha_E \varpi_t} \frac{P_{Et}}{P_{Ot}} E_t^h \quad (2.2)$$

<sup>2</sup>An indirect utility function  $v(p, exp)$  expresses the household's maximal attainable utility when faced with vector  $p$  of goods prices and an amount of expenditure  $exp$ . In general, a direct utility counterpart of this indirect utility function does not exist.

<sup>3</sup>See Lemma 3 in Boppart (2014) for the derivation and Appendix B.1.4 for the steady state.

<sup>4</sup>Another commonly used non-homothetic preference specification is the Stone-Geary preferences, with which the consumer derives utility from consumption that exceeds the subsistence level. Under Stone-Geary preferences the expenditure share of energy does not increase after a price increase. Since in practice the household energy expenditure share increased in Europe in 2022, I chose to use the preferences from Boppart (2014) (OECD, 2023; European Commission, 2024).

<sup>5</sup>See Appendix B.1 for a detailed derivation of the first order conditions.

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where

$$\varpi_t = \left( \frac{P_{Ot}}{exp_t} \right)^{\varepsilon_1} \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} \quad (2.3)$$

is the energy expenditure share wedge. This wedge increases when the total expenditure decreases or when the price of energy increases, both relative to the price of the other goods. Consequently, the consumption demand is non-homothetic in income since the share of expenditure on energy,  $\alpha_E \varpi_t$ , increases when the household becomes poorer. When  $\varepsilon_1 = \varepsilon_2 = 0$ , Eq. (2.2) simplifies to  $C_{Ot} = \frac{1-\alpha_E}{\alpha_E} \frac{P_{Et}}{P_{Ot}} E_t^h$ , which is the standard Cobb-Douglas result. In this case, the expenditure elasticity for both types of goods are equal to unity. Section 2.3.2.4 discusses the case under preferences with Constant Elasticity of Substitution (CES).

**Relative demand between Home and Foreign goods.** The consumption of non-energy goods is a composite index, bundling consumption of Home-produced goods  $C_{Ht}$  and Foreign-produced goods  $C_{Ft}$ :

$$C_{Ot} = \left[ (1 - \alpha_I)^{1/\gamma} (C_{Ht})^{(\gamma-1)/\gamma} + (\alpha_I)^{1/\gamma} (C_{Ft})^{(\gamma-1)/\gamma} \right]^{\gamma/(\gamma-1)} \quad (2.4)$$

where  $\alpha_I \in (0, 1)$  is the share of imported goods in the consumption basket and  $\gamma$  is the elasticity of substitution between Home and Foreign goods. Since the preferences between Home and Foreign-produced goods are homothetic, the intratemporal consumption demand between Home and Foreign goods are standard:

$$\frac{C_{Ht}}{C_{Ft}} = \frac{1 - \alpha_I}{\alpha_I} \left( \frac{P_{Ht}}{P_{Ft}} \right)^{-\gamma} \quad (2.5)$$

where  $P_{Ht}$  and  $P_{Ft}$  are the price indices of Home and Foreign goods respectively. The aggregate expenditure on other consumption is then:

$$\int_0^1 P_{Ht}(i) C_{Ht}(i) di + \int_0^1 P_{Ft}(i) C_{Ft}(i) di = P_{Ht} C_{Ht} + P_{Ft} C_{Ft} = P_{Ot} C_{Ot} \quad (2.6)$$

where  $P_{Ot}$  is the aggregate price index for non-energy goods:

$$P_{Ot} = \left[ (1 - \alpha_I) P_{Ht}^{1-\gamma} + \alpha_I P_{Ft}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \quad (2.7)$$

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### 2.2.1.2 Intertemporal choices

The representative household makes intertemporal choices since it can trade in one-period bonds  $B_t$  with gross interest rate  $R_t$ . The household's income sources are from labor  $N_t$  for a nominal wage  $W_t$  per unit and from profits of domestic firms,  $D_t$ , and energy sellers,  $D_t^E$ .<sup>6</sup> The nominal budget constraint of the households is the following:

$$exp_t = P_{Et}E_t^h + P_{Ot}C_{Ot} = W_tN_t + D_t + D_t^E + R_{t-1}B_{t-1}^h - B_t^h - HC_t - T_t \quad (2.8)$$

where  $HC_t = \frac{\bar{\nu}}{2}(B_t^h - \bar{B}^h)^2$  are the portfolio adjustment costs of the household and  $T_t$  lump-sum taxes. The government uses those taxes to finance energy price caps. When the household maximizes their utility function (2.1) subject to the constraint, the Euler equation becomes:

$$\left( \frac{\mathbb{E}_t[exp_{t+1}]}{exp_t} \right)^{1-\varepsilon_1} = \beta \frac{R_t}{1 + P_t \tilde{\nu}(b_t^h - \bar{b}^h)} \mathbb{E}_t \left[ \left( \frac{1}{\Pi_{O,t+1}} \right)^{\varepsilon_1} \right] \quad (2.9)$$

where  $b_t^h = \frac{B_t^h}{P_t}$  denotes real bond holdings and  $\Pi_{Ot} = \frac{P_{Ot}}{P_{O,t-1}}$  gross inflation of the other goods.  $P_t$  is the aggregate price index, explained below. Households supply labor inelastically, such that  $N_t = \bar{N} \forall t$ . In Section 2.3.2.4, I briefly discuss the results under elastic labor supply.

### 2.2.2 Firms

**Final good producer.** The final good firms produce the final consumption good,  $Y_t$ , using intermediate goods,  $Y_t(i)$ , according to:

$$Y_t = \left[ \int_0^1 Y_t(i)^{(1-\epsilon)/\epsilon} di \right]^{\epsilon/(1-\epsilon)} \quad (2.10)$$

where  $Y_t(i)$  is the output of the intermediate firm  $i$  and  $\epsilon$  the elasticity of substitution between different varieties of the intermediate good. The firms produce in a competitive market and maximize profits given by  $P_t Y_t - \int_0^1 P_t(i) Y_t(i) di$ . The

<sup>6</sup>As in Bayer et al. (2023), households earn profits determined by deviations from steady state when selling energy.

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first-order condition to the maximization problem gives the demand function of the intermediate good  $i$ :

$$Y_t(i) = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} Y_t \quad (2.11)$$

and the price of the final good  $Y_t$ :

$$P_{Ht} = \left[ \int_0^1 P_{Ht}(i)^{-(1-\epsilon)} \right]^{1-\epsilon} \quad (2.12)$$

where  $P_{Ht}(i)$  is the price of the intermediate good  $i$ .

**Intermediate good producers.** The country has a continuum of  $i \in [0, 1]$  firms who produce the (non-energy) other goods under monopolistic competition. They use both labor  $N_t$  and energy  $E_t^f$  as production inputs in their Constant Elasticity of Substitution (CES) production function:

$$Y_t(i) = A_t \left[ (\alpha^f)^{1/\theta^f} (E_t^f(i))^{(\theta^f-1)/\theta^f} + (1-\alpha^f)^{1/\theta^f} (N_t(i))^{(\theta^f-1)/\theta^f} \right]^{\theta^f/(\theta^f-1)} \quad (2.13)$$

where  $\alpha^f$  is the share of energy used in production and  $\theta^f$  is the elasticity of substitution between input factors energy and labor.  $A_t$  is the total factor productivity which follows an AR(1) shock process. The firms face adjustment costs à la Rotemberg (1982), so their profit maximization problem is:<sup>7</sup>

$$\max_{P_{Ht}(i), N_t(i)} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta \left[ \frac{P_{Ht}(i)}{P_{Ht}} Y_t(i) - \frac{W_t}{P_{Ht}} N_t(i) - P_{Et} E_t^f(i) - Y_t FC_t \right] \quad (2.14)$$

subject to

$$\text{demand curve } Y_t(i) = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} Y_t \quad (2.15)$$

$$\text{price adjustment costs } FC_t(i) = \frac{\xi}{2} \left( \frac{P_{Ht}(i)}{P_{H,t-1}(i)} - 1 \right)^2 \quad (2.16)$$

where  $\xi$  governs the level of price adjustment costs.

The first-order condition with respect to  $P_{Ht}(i)$  leads to the standard New Keynesian Philips Curve (NKPC). See Appendix B.1 for detailed derivations. As

<sup>7</sup>Since energy is an exogenous supplied good, Rotemberg (1982) and Calvo (1983) pricing are identical up to first order, unlike conventional two-sector models.

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in Aoki (2001), the relative price of energy shows up as a shift of the NKPC, like a cost-push shock, when re-writing the NKPC in terms of headline inflation.

Since all intermediate goods are identical,  $P_{Ht}(i) = P_{Ht}$  and  $N_t(i) = N_t$ . Aggregate firm's profits reads:

$$D_t = P_{Ht}Y_t(1 - FC_t) - W_tN_t - P_{Et}E_t^f \quad (2.17)$$

### 2.2.3 Monetary policy

The monetary authority targets the headline inflation of the two countries, Home and Foreign, with a Taylor rule set accordingly to their respective size. So, the Taylor rule for the nominal interest rate  $R_t$  is:

$$R_t = \frac{1}{\beta} \left( \frac{\Pi_t^W}{\bar{\Pi}^W} \right)^{\phi_\pi} \exp(\nu_t) \quad (2.18)$$

where superscript  $W$  indicates a union-wide variable, defined as:

$$\Pi_t^W = (\Pi_t)^\Theta (\Pi_t^*)^{1-\Theta} \quad (2.19)$$

The monetary authority only targets inflation, and no output gap, reflecting the European Central Bank's price stability mandate. The inflation that the central bank targets is:

$$\Pi_t = (\Pi_{Et})^{\alpha_E} (\Pi_{Ot})^{1-\alpha_E} \quad (2.20)$$

which corresponds to the Consumer Price Index (CPI), or headline inflation in common literature and data sources. The price level follows from the inflation term  $\Pi_t = P_t/P_{t-1}$ .<sup>8</sup>

### 2.2.4 Fiscal policy: The energy price cap

If the Home country introduces a cap on energy prices, the fiscal policy and the government budget constraint of the country become relevant. With an energy price cap in the Home country, the effective energy price becomes:

$$P_{Et}^{eff} = \begin{cases} \bar{P}_E & \text{with cap and } P_{Et} > \bar{P}_E \\ P_{Et} & \text{otherwise} \end{cases} \quad (2.21)$$

<sup>8</sup>The main results are robust to changing the central bank's target from CPI to core inflation. In Section 2.3.2.3 I discuss the implications of core targeting on inflation rates.

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Hence, under the cap, the effective price for energy for the households and firms is equal to the steady state price of energy,  $\bar{P}_E$ . Consequently, when the fiscal authority introduces the price cap, the price of energy in households' and firms' equilibrium conditions is given by the effective price of energy  $P_{Et}^{eff} = \bar{P}_E$ .<sup>9</sup> The government runs a balanced budget and finances the cap by a lump-sum tax, such that the government budget constraint reads:

$$COST_t(E_t^h + E_t^f) = T_t \quad (2.22)$$

where  $COST_t = P_{Et} - \bar{P}_E$  denotes the cost of the cap per unit of energy for the government. Ricardian Equivalence holds in this model because consumption does not respond to changes in future expected taxes and government spending. Later, I introduce hand-to-mouth agents to the model as an extension in which case Ricardian Equivalence does not hold.

### 2.2.5 Equilibrium

The equilibrium of this economy is characterized by a sequence of prices  $\{W_t, W_t^*, P_{Ht}, P_{Ft}, P_{Et}\}$  and allocations  $\{E_t^h, E_t^{h*}, C_{Ht}, C_{Ft}, C_{Ht}^*, C_{Ft}^*, N_t, N_t^*, E_t^f, E_t^{f*}, b_t^h, b_t^{h*}\}$  such that the goods market is cleared for both Home and Foreign-produced goods, the energy market is cleared, the assets are in zero net supply between the countries, and the labor market is cleared in both countries. The full list of equilibrium conditions are in Appendix B.1.3.

#### 2.2.5.1 Goods market clearing

The goods market clears for the Home country when the production in that country is equal to the demand for consumption goods produced in that country. Hence, the market clearing condition includes the demand for Home-produced

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<sup>9</sup>The results are robust to changing the price cap target from both household and firms to just households.

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goods in the Foreign country:

$$Y_t = C_{Ht} + C_{Ht}^* + HC_t + FC_t \quad (2.23)$$

$$= (1 - \alpha_I) \left( \frac{P_{Ht}}{P_{Ot}} \right)^{-\gamma} C_{Ot} + \alpha_I^* \left( \frac{P_{Ht}}{P_{Ot}^*} \right)^{-\gamma} C_{Ot}^* + HC_t + FC_t \quad (2.24)$$

where  $C_{Ht}^*$  is the consumption of Home-produced goods in Foreign, and  $C_{Ot}^*$  is the consumption of other goods (both Home and Foreign-produced) in Foreign.

### 2.2.5.2 Energy market clearing.

The energy market is fully integrated across the two countries in the union. As in Bayer et al. (2023), I model the supply of energy  $E_t$  as exogenous. So, the supply of energy does not respond to price movements and the price of energy has to adjust for the market to clear. The energy market clears when the demand for energy by households and firms from both countries equals the exogenous supply:

$$E_t = E_t^h + E_t^f + E_t^{h*} + E_t^{f*} \quad (2.25)$$

### 2.2.5.3 Current account and the dynamics of net foreign assets

I derive the dynamics of net foreign assets, and hence the current account, by consolidating households' and firms resource constraints, (2.8) and (2.17):

$$B_t^h - B_{t-1}^h = r_{t-1} B_{t-1}^h + P_{Ht} Y_t (1 - FC_t) - P_{Ot} C_{Ot} - HC_t \quad (2.26)$$

where  $r_t = R_t - 1$  is the net nominal interest rate set by the monetary authority. Since the right-hand side of the equation is the current account I can express the above equation as the following:

$$CA_t = b_t^h - b_{t-1}^h \quad (2.27)$$

$$CA_t = r_{t-1} b_{t-1}^h + \frac{P_{Ht}}{P_t} Y_t (1 - FC_t) - \frac{P_{Ot}}{P_t} C_{Ot} - \frac{1}{P_t} HC_t \quad (2.28)$$

where  $b_t^h = \frac{B_t^h}{P_t}$  is real bond holdings. Since the union is a closed economy, to ensure mutual consistency of current accounts  $CA_t = -CA_t^*$  needs to hold. Moreover, the assets are in zero net supply between countries.

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### 2.2.6 Calibration

The model is calibrated at quarterly frequency. In the extended model, I perform a Bayesian estimation of some of the model parameters. Table 2.1 provides an overview of the baseline calibration values. The countries are identical except for their relative sizes.

**Table 2.1:** Baseline calibration of parameters

<i>Parameter</i>	<i>Description</i>	<i>Value</i>
<b>Households</b>		
$\alpha_I$	Share of imports in consumption	0.25
$\alpha_E$	Share of energy in consumption	0.066
$\gamma$	Elasticity of substitution between Home and Foreign goods	6
$\epsilon$	Elasticity of substitution within goods	9
$\epsilon_1$	Non-homotheticity parameter	1
$\epsilon_2$	Non-homotheticity parameter	0.77
$\tilde{\nu}$	Adjustment cost for bonds	0.001
$\beta$	Discount factor	0.99
<b>Firms</b>		
$\alpha^f$	Share of energy in production	0.011
$\theta^f$	Elasticity of substitution between energy and labor	0.2
$\xi$	Price-adjustment cost	15.84
<b>Monetary policy</b>		
$\phi_\pi$	Taylor-coefficient on inflation	1.5
$\alpha^{CB}$	Share of energy for central bank's consideration	0.066
<b>Currency union</b>		
$\Theta$	Relative GDP size Home country (with cap)	0.68

On the household side, Eurostat (2023b) reports that in 2022, the share of internationally traded goods and services relative to GDP was 25%. Hence, the share of imports in consumption,  $\alpha_I$ , is 0.25. The share of energy in total consumption expenditure is on average 6.6%, so I set  $\alpha_E$  as 0.066.<sup>10</sup> The elasticity of substitution within different varieties of Home and Foreign,  $\epsilon$ , is 9, in line with standard literature. The adjustment cost for bond-holdings,  $\tilde{\nu}$ , is 0.001, to match the canonical work by Schmitt-Grohé and Uribe (2003). The discount factor  $\beta$  is 0.99 as is standard in the literature. I perform a data matching exercise at the end of the subsection to calibrate the non-homotheticity parameters  $\epsilon_1$  and  $\epsilon_2$ .

For the firms, I set the share of energy in production,  $\alpha^f$ , to 1.1% to target the steady-state energy expenditure of the industry as share of total produc-

<sup>10</sup>Eurostat data, online data code: hbs\_str\_t223.

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tion value of 1%.<sup>11</sup> The elasticity of substitution of energy and labor,  $\theta^f$ , is 0.2, following Bayer et al. (2023) and Bachmann et al. (2024).<sup>12</sup> I calibrate the Rotemberg (1982) price-adjustment cost parameter,  $\xi$ , such that the slope of the New Keynesian Philips Curve matches that of the Calvo (1983) price rigidities for the Calvo parameter 0.5. This value implies an expected price duration of two quarters, which is more frequent than standard, to reflect the fast change in prices in 2022. The corresponding price-adjustment cost parameter is  $\xi = [(\epsilon - 1)0.5]/[(1 - 0.5)(1 - 0.5\beta)] \approx 15.84$

Monetary policy follows a standard Taylor (1993) rule, with the coefficient on inflation  $\phi_\pi$  as 1.5. The monetary authority targets headline inflation, following the official target of the European Central Bank (ECB, 2021).<sup>13</sup>

To obtain the relative size of the two countries, I calculate the GDP ratio of countries that introduced a cap in 2022 and that did not introduce a cap in 2022.<sup>14</sup> Since the sum of GDPs of countries with an energy price cap in 2022 was about 68% of the total of countries in the Euro Area, I set the size of the Home country  $\Theta = 0.68$ .<sup>15</sup>

**Non-homotheticity parameters.** For the calibration of the non-homotheticity parameters  $\varepsilon_1$  and  $\varepsilon_2$ , I conduct a data matching exercise. I take the gas inflation

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<sup>11</sup>I calculate the steady-state energy expenditure as share of total production value with data from Rademaekers et al. (2020) and Eurostat data (online data code: sbs\_sc\_ovw). The sectors included are selected manufacturing sectors, wholesale and retail trade, accommodation and restaurants, and information and communication, and the countries included are the 27 European Union members in 2020.

<sup>12</sup>Bachmann et al. (2024) show that when other production inputs are constant, the own-price elasticity maps directly to the elasticity of substitution. They estimate the own-price elasticity of energy to range from  $-0.15$  to  $-0.20$ .

<sup>13</sup>Moreover, the press releases of the ECB monetary policy decisions between June 2022 and September 2023, when the ECB kept increasing interest rates, often mention energy prices as one of the key drivers of upwards pressures for inflation. The decision reports mention headline inflation figures to indicate how far the economy is off the 2% target (European Central Bank, 2024).

<sup>14</sup>Euro Area countries with an energy price cap in 2022: Austria, Estonia, France, Germany, Luxembourg, Malta, Portugal, Slovakia, Slovenia, Spain. Euro Area countries without an energy price cap in 2022: Belgium, Cyprus, Finland, Greece, Ireland, Italy, Latvia, Lithuania, The Netherlands. Croatia joined the Euro Area in 2023 and therefore excluded from the analysis in this paper.

<sup>15</sup>The results are robust against a calibration with equal-sized countries, so  $\Theta = 0.5$ .

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data for France and the Netherlands from Eurostat from 2019 to 2022, and feed it into the model as perfect foresight energy price shocks, as shown Figure 2.3.<sup>16</sup> At the peak in 2022Q3, the Netherlands experienced a gas price inflation of about 30% in quarterly rates (over 90% in annual rates). France, on the other hand, imposed a price cap on gas inflation which barely exceeded 10% in quarterly rates (about 30% in annual rates). The gas consumption data reflect the policies: in the Netherlands, the gas consumption decreased about 15 percentage points more than in France. I conduct a parameter search for  $\varepsilon_1$  and  $\varepsilon_2$ , imposing  $0 \leq \varepsilon_1 \leq 1$  and  $0 \leq \varepsilon_2 \leq 1$  to minimize the Mean Squared Error (MSE) between the energy consumption from the model in which I feed in the gas inflation data, and the realized gas consumption in 2020Q3 to 2022Q4 for both countries.<sup>17</sup> The results give  $\varepsilon_1 = 1$  and  $\varepsilon_2 = 0.77$ , which implies an elasticity of substitution between energy and other goods of 0.25 in steady state, which is in line with other literature on energy shocks like Bayer et al. (2023) and Chan et al. (2024). I set the elasticity of substitution between Home and Foreign goods,  $\gamma$ , to 6, the upper bound of standard literature (P. Benigno, 2009), since the data exercise gives the lowest error under this calibration.

**Shock specification.** In the numerical analyses in the following sections, I shock the model with an adverse energy supply shock of 15% that lasts for six quarters. In this way, I capture the decline in the supply of Russian gas in summer 2022 and the expectations of governments that the shock would last until spring 2023. More concretely, in July 2022 the European Union member states agreed to a gas

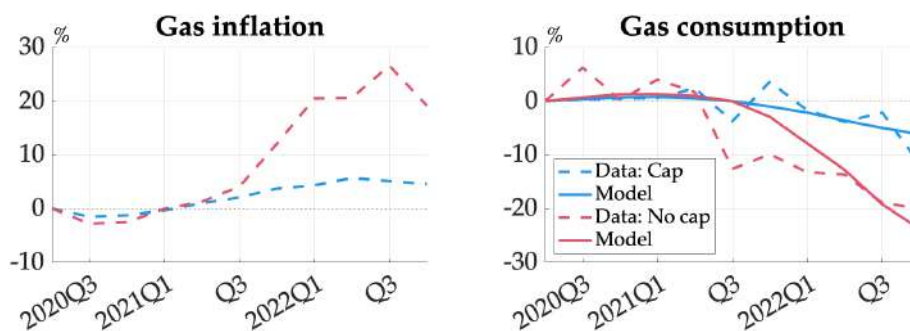
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<sup>16</sup>I manipulate the data from Eurostat (online data code: `prc_hicp_manr`) to obtain quarterly rates. I use the observations from 2020Q3 to 2021Q3 to compute the steady state to express all data in deviations from steady state. France and the Netherlands are one of the most extreme cases of inflation divergence within the Euro Area. The countries are relatively close geographically and socio-economically, which make them good candidates for this data exercise. Including all countries in the Euro Area makes this exercise less clear cut, since idiosyncrasies, like proximity to Ukraine or Russia, affect the price dynamics in different ways than this reduced form exercise can handle. In the Bayesian estimation of the extended model, I include all countries in the Euro Area.

<sup>17</sup>The data is from Eurostat (online data code: `nrg_c_gas`). With population data (intrapolated for the quarters), I obtain the gas consumption per capita. I seasonally adjust the data using X-13ARIMA-SEATS in R before taking quarterly data points and steady-state deviations from steady state.

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**Figure 2.3:** Data exercise to calibrate the non-homotheticity parameters



*Notes:* The left panel shows the gas inflation of France (cap) and the Netherlands (no cap). I feed this data into the model and find the parameters  $\epsilon_1$  and  $\epsilon_2$  that minimize the Mean Squared Error (MSE) between the gas consumption data (right panel, dotted) and the model-implied gas consumption (solid). Sources for data: Eurostat.

consumption reduction target of 15% between August 2022 and March 2023, and another extension until March 2024, to prepare for possible supply disruptions (European Commission, 2023). Moreover, most countries introduced energy price caps lasting four to nine quarters in 2022.

### 2.3 Results

In this section, I conduct a series of simulations with the dynamic model to investigate the effect of an adverse energy supply shock on a currency union. First, I show how an adverse energy supply shock affects the economy in absence of price caps. The shock causes an increase in the price of energy, and a cost-push shock in the economy. Second, I take the scenario of the Euro Area in 2022, and impose an energy price cap in the bigger country in the union. I find that the capped country can avoid most of the crisis, while the uncapped country experiences a cost-push shock double the size. The size of such negative spillovers depend on the degree of non-homotheticity of energy and affect policy decisions. Moreover, I discuss the consequences of headline and core targeting and the trade-offs they impose.

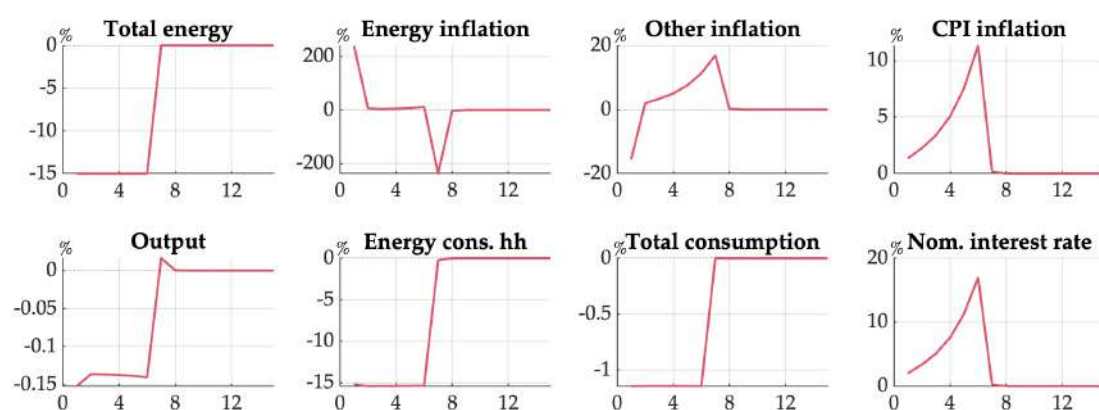
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### 2.3.1 Energy crisis without energy caps

The shock is a 15% shock to the energy supply of the currency union and lasts six quarters. Since there are no energy price caps in either country and the countries are otherwise symmetric, the responses for the two countries are the same. Hence, the results in Figure 2.4 show one response per variable.

The adverse energy supply shock pushes up on the energy inflation. The recessionary shock decreases inflation for other goods on impact. In the later periods, the other goods inflation increases since energy is one of the production inputs. Consumer Price Index (CPI) inflation, or headline inflation, is a weighted average of energy inflation and other goods inflation, and hence peaks when other goods inflation is highest. Production and consumption of other goods decrease as a consequence of the energy supply declining.<sup>18</sup> Energy consumption by households decreases by about the same amount as the shock. Since the energy shock increases CPI inflation while depressing output, the shock acts as a cost-push shock. The monetary authority conducts contractionary policy to dampen inflationary pressures, and returns to steady state together with CPI inflation.

**Figure 2.4:** Responses to an adverse energy supply shock | No caps



*Notes:* Impulse responses to a 15% decline in energy supply. Preferences are non-homothetic. Output is equal to the output gap. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

<sup>18</sup>Shown in the Output panel, since output is the production of other goods, which is equal to the consumption of other goods.

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### 2.3.2 Energy crisis with one cap and one no-cap country

Now consider the case in which the the larger country introduces a price cap on the energy price, such that the retail energy price stays constant. Figure 2.5 shows the impulse responses for the economy when households have non-homothetic preferences. When the energy supply decreases by 15%, the bigger country (blue solid lines) introduces an energy price cap which costs about 2.5% of the annual GDP for the government. In the uncapped country (red dotted lines) the adverse energy supply shock is essentially doubled compared to the case without any price caps, since the capped country's share of the shock spills over.

In the capped country the economy avoids most of the energy crisis. Because their energy prices do not increase, households in this country have more purchasing power than households in the uncapped country. Therefore, they consume more of the other goods produced in their own country, but also more of the ones produced in the uncapped country. Moreover, the other goods inflation responses show that the goods from the uncapped country have become relatively cheaper because of the large recession in that country. Hence, total consumption in the capped country increases.

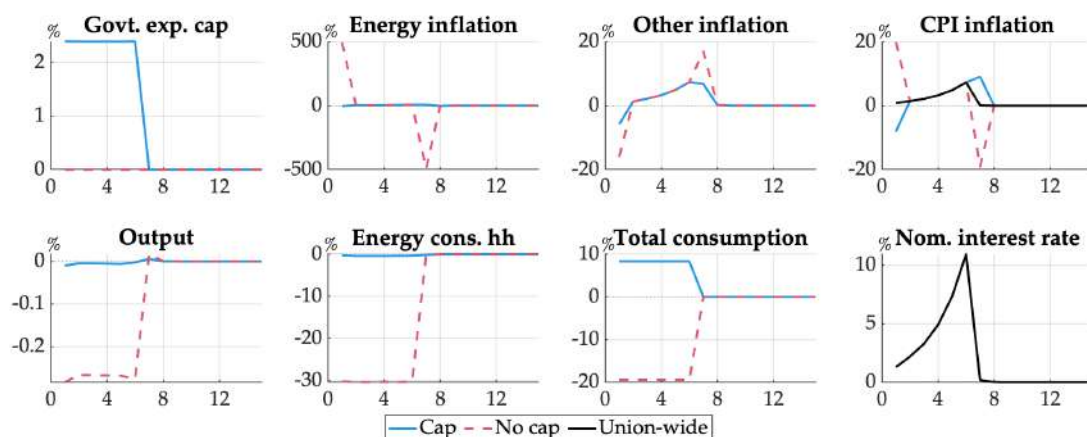
In the country without the cap the energy price increase doubles compared to the previous case without any caps. The energy scarcity is more severe due to the capped country not reducing their energy consumption. Since the capped country does not decrease their energy consumption, energy is an even scarcer good in the uncapped country. The adverse energy supply shock causes households in this country to reduce their energy consumption by twice as much relative to the case when the other country also did not introduce the energy price cap. The energy supply shock is essentially double the size in the uncapped country. Crucially, the other inflation fluctuations in both countries imply a terms-of-trade depreciation for the uncapped country, because their other inflation decreases more than the one in the capped country. Since the terms of trade depreciates for the uncapped country, their purchasing power decreases. Imports become more expensive and exports to the households in the capped country increases, which

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decreases total consumption in the uncapped country drastically.<sup>19</sup> Despite the increased demand from the capped country for goods produced in the uncapped country, the output in the uncapped country decreases due to the large energy supply shock.

The common monetary policy adopts a less contractionary stance than when neither of the countries implemented the energy price cap, in Figure 2.4. The central bank targets the weighted-average headline inflation in its Taylor rule, which is the black line in the CPI inflation graph in Figure 2.5. Since the inflation rates of the capped and uncapped countries peak at different times, the weighted-average inflation does not increase as much as in the case without any price caps, which causes a milder response from the central bank.

**Figure 2.5:** Responses to an adverse energy supply shock | Cap vs. no cap



*Notes:* Impulse responses to a 15% decline in energy supply. Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. Output is equal to the output gap. Government expenditure on the price cap (Govt. exp. cap) is the cost of the cap as a share of annual total output of the country (GDP). The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

### 2.3.2.1 Energy crisis with energy price caps

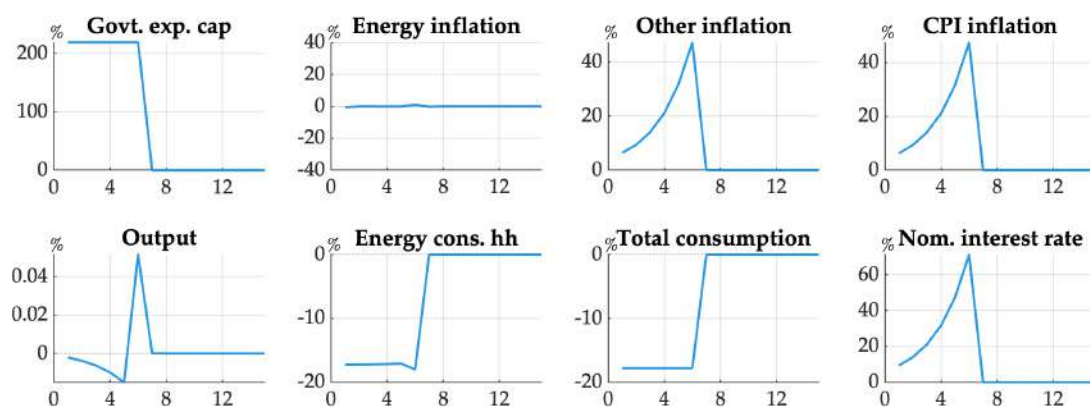
Figure 2.6 shows the responses when both countries impose an energy price cap. In this case, the price of energy stays constant in the entire union. Because

<sup>19</sup>This result is similar to the terms-of-trade externality by for example Corsetti and Pesenti (2001), in which an expansionary fiscal policy causes a terms-of-trade appreciation for the country, hurting trading partners.

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of the distorted price, consumers try to maintain their energy and other goods consumption. However, since the supply of energy is exogenous, the supply side of the economy cannot increase its production accordingly. Hence, there is high pressure on other goods inflation as well as the actual price of energy. Because the government pays the difference between the actual and retail price of energy, the price cap becomes a large cost for the government and ultimately for the consumers. Combined with the high other goods inflation, such high costs cause a big decline in the total consumption of the households.

**Figure 2.6:** Responses to an adverse energy supply shock | Caps



*Notes:* Impulse responses to a 15% decline in energy supply and a price cap in both countries. Preferences are non-homothetic. Output is equal to the output gap. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

### 2.3.2.2 Implications for policy decisions and welfare

In this subsection, I analyze the welfare implications for each combination of policy strategies (cap and no cap, for both countries) and show the decision game is a classic Prisoner's Dilemma.

**Policy outcomes under symmetric price cap policy.** Table 2.2 summarizes the welfare results in a two-by-two matrix. The relevant metric is the consumption

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equivalent welfare gains and losses relative to the steady state of the economy.<sup>20</sup> First, focus on the cells on the diagonal where the policies are symmetric (cap-cap and no cap-no cap), which is the symmetric benchmark. Since the currency union is a closed economy, the symmetric benchmark is equivalent to the closed economy case. In this closed economy case, the adverse energy supply shock causes a welfare loss of 0.1% without an energy price cap and 1% with the cap.

With an energy price cap in the entire union the welfare losses are a tenfold bigger. As discussed, such a scenario is detrimental for household consumption since the demand distortions under the price cap increases the fiscal cost for the government to finance the cap, ultimately born by households, and the inflation of other goods. The consumption equivalent welfare loss is 1% when both countries introduce an energy price cap.

**Table 2.2:** Welfare gains/losses after energy supply shock

		Non-homothetic preferences	
		1/3 of union	
		Cap	No cap
2/3 of union	Cap	(-1.0, -1.0)	(0.5, -1.1)
	No cap	(-1.1, 0.4)	(-0.1, -0.1)

*Notes:* Welfare gains and losses after a 15% energy supply shock. Preferences are non-homothetic. The gains and losses are in terms of the consumption equivalent relative to the steady state. The circles are around the preferred policy choices (Cap or No cap) for the countries.

**Policy outcomes under asymmetric price cap policy.** When the countries do not have to cooperate, is the non-distortionary no-cap strategy still the Nash equilibrium? As the circles around the welfare values indicate in Table 2.2, the cooperative case is not the Nash equilibrium. Instead, as in the classic Prisoner's Dilemma, the non-cooperative decision, imposing the price cap, is the dominant strategy for both fiscal authorities.

<sup>20</sup>For the consumption equivalent, I find  $\chi$  which satisfies:

$$\mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Rt}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Rt}} \right)^{\varepsilon_2} - 1 \right] \right\} = \sum_{t=0}^{\infty} \beta^t \frac{1}{\varepsilon_1} \{ [\overline{exp}(1 + \chi)]^{\varepsilon_1} - 1 \} \quad (2.29)$$

So,  $\chi$  is the fraction of total expenditure, i.e. total consumption, that the household would be willing to forgo in the economy in steady state (right-hand side) to live in the economy with the energy supply shock, as evaluated by the left-hand side of the equation.

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First, *given 1/3 of the union does not impose an energy price cap*, does the rest, 2/3 of the union, have an incentive to deviate from the no-cap strategy? If they keep to the no-cap strategy, the union is in the cooperative case, in which both countries experience a welfare loss of 1%. However, the country representing 2/3 of the union has an incentive to deviate to the cap policy, which improves the welfare in that country (0.5%) at the expense of the no-cap country (-1.1%). This result is a summary of the impulse responses in Figure 2.5, with large spillovers from the capped to the uncapped country.

Second, *given 2/3 of the union imposes an energy price cap*, does the rest, 1/3 of the union, also have an incentive to impose the price cap? The large, negative spillovers are very costly for the uncapped country; they cause a welfare loss of 1.1%. Hence, the country has an incentive to also impose the price cap, even though both countries imposing the cap causes a welfare loss of 1%. The loss is relatively big because when both countries implement an energy price cap, the cost for the cap spirals upwards: the only benefit from the price cap emerges from creating spillovers to the other country, which is not possible when both countries impose the cap.

The above argument also applies when the small and large countries switch: for both countries, it is better to impose the energy price cap when the other does, despite the large cost of the distortion, rather than bearing the negative spillovers.<sup>21</sup> Hence, imposing an energy price cap is the dominant strategy for both countries, leading to a Prisoner's Dilemma: both countries can gain from cooperating, but it is not rational to do so.

The Prisoner's Dilemma as the Nash equilibrium does not reflect the choices that policymakers made in reality. In the next section I introduce substitutability between energy sources, which is an important feature in energy crises, and show that the model achieves the Nash equilibria in which one country imposes an energy price cap and the other country does not.

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<sup>21</sup>The externalities are smaller when the smaller country implements the energy price cap. However, not small enough to break symmetry in the preferred strategies in Table 2.2.

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**Policy outcomes under homothetic preferences.** How much do these results depend on the non-homotheticity of energy? Here, I illustrate that the above results are highly dependent on the degree of non-homotheticity. The welfare table for homothetic preferences is in Table 2.3. The degree of non-homotheticity does not affect the values on the diagonal of the symmetric cap policies. Again, the non-cooperative case when both countries impose a cap are much worse (−1%) than in the cooperative case without any caps (−0.1%) due to the market-distorting price cap.

**Table 2.3:** Welfare gains/losses after energy supply shock

		Homothetic preferences	
		1/3 of union	
2/3 of union	%	Cap	No cap
	Cap		(−1.0, −1.0)
No cap		(−0.3, 0.0)	(−0.1, −0.1)

*Notes:* Welfare gains and losses after a 15% energy supply shock. Preferences are homothetic (Cobb-Douglas). The gains and losses are in terms of the consumption equivalent relative to the steady state. The circles are around the preferred policy choices (Cap or No cap) for the countries.

However, non-homotheticity of preferences affects the magnitude of the spillovers significantly. Under the homothetic case, the externalities of the price cap are not as large, because energy is not a necessity. Hence, when the counterpart country implements a cap, the welfare losses associated with negative spillovers are not as large: −0.4% when the larger country imposes a cap and −0.3% when the smaller country imposes a cap. So, implementing the price cap is not worth the cost when the other country also has the cap. Thus, with homothetic preferences, there are two Nash equilibria, in which one country implements a price cap and the other does not. Although this reflects what occurred in reality, the assumption that energy is not a necessity is unrealistic. Instead of relying on homothetic preferences to dampen spillovers, I show in the next section that introducing substitutability between energy sources can achieve the same effect, leading to the desired outcome.

Recall that parameters  $\varepsilon_1$  and  $\varepsilon_2$  govern the degree of non-homotheticity of energy. Welfare outcomes under the baseline calibration with non-homothetic

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preferences,  $\varepsilon_1 = \varepsilon_2 = 0.77$ , are in Table 2.2: one Nash equilibrium which is a price cap in both countries. Welfare outcomes in the homothetic case,  $\varepsilon_1 = \varepsilon_2 = 0$ , are in Table 2.3: two Nash equilibria for differing cap policies. The magnitude of the spillovers are crucial in determining the size of the negative spillovers to the uncapped country and depend on the degree of non-homotheticity. The value for  $\varepsilon_1$  and  $\varepsilon_2$  for which the smaller country is indifferent about imposing a cap or not, when the bigger country has imposed a cap, is  $\varepsilon_1 = \varepsilon_2 = 0.72$ .

### 2.3.2.3 Implications for the central bank: Headline vs. core inflation targeting

In this subsection, I explore the different implications for the monetary authority when targeting Consumer Price Index (CPI) inflation, i.e. headline inflation, or other goods inflation, i.e. core inflation.<sup>22</sup> I show that there is a trade-off between stabilizing different inflation rates. However, since the relative inflation rates between the capped and uncapped country are similar in either targeting regime, the magnitude of the spillovers do not change much.

In the baseline analysis, the monetary authority targets headline inflation in its Taylor rule. In that case, Figure 2.5 shows that the monetary authority conducts contractionary monetary policy to stabilize union-wide headline inflation, which is the weighted average of the headline inflation rates of the two countries. However, under headline inflation targeting, there are large fluctuations in the core sector in both countries, but worse for the uncapped country. On top of the adverse energy supply shock, a contractionary monetary policy worsens the cost-push shock in the core sector of the economies.

Figure 2.7 present the responses of the interest rates and inflation rates with a central bank that targets core inflation in its Taylor rule. The figure shows that the central bank conducts expansionary policy in this case. Because the adverse energy supply shock is a cost-push shock to the core-goods sector, a central bank that targets core-goods inflation decreases its rates to stabilize the

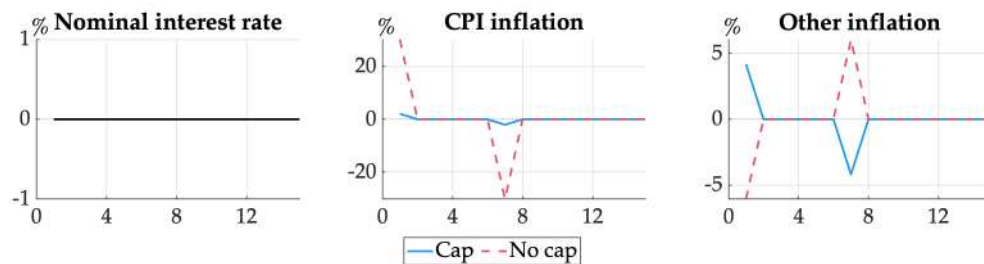
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<sup>22</sup>In the literature, core inflation refers to CPI inflation excluding food and energy inflation. Since my model does not have food inflation, I refer to CPI inflation excluding energy inflation as core inflation.

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fluctuations in that sector. As expected, the expansionary monetary policy comes at the cost of a higher headline inflation.

**Figure 2.7:** Responses to an adverse supply shock | Core inflation targeting



*Notes:* Impulse responses to a 15% decline in energy supply under core inflation targeting. Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

All in all, a central bank with a target for other goods inflation should conduct relatively expansionary policy during an energy crisis with heterogeneous cap policies. When the target is for headline inflation, a more contractionary monetary policy mitigates the inflationary pressures from the high energy inflation in the uncapped country, reducing the headline inflation fluctuations. In Figure B.6 in Appendix B.3 I display the rest of the impulse responses, which show that for the magnitude of the spillovers, the targeting regime does not matter. This result arises because the relative inflation rates between the capped and uncapped country, which matters for the spillovers, is similar regardless of the targeting regime.

### 2.3.2.4 Robustness checks under alternative model specifications

In this section I conduct robustness checks with alternative assumptions of the model: elastic labor supply, flexible prices, flexible exchange rates, and preferences with Constant Elasticity of Substitution (CES). Most alternative model specifications confirm the robustness of the main results.

Elastic labor supply dampens the negative spillovers, which gives result to a welfare table that is in-between the non-homothetic and homothetic case. To

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allow for hours worked to adjust in the model, I implement an ad-hoc approach to elastic labor supply by incorporating a labor disutility term into the utility function, deviating from the preferences outlined by Boppart (2014).<sup>23</sup> Figure B.8 and Table B.1 in Appendix B.3.1 present the results for this alternative specification.

The impulse responses in Figure B.8 imply that elastic labor supply does not change the inflation dynamics of the two countries. However, because firms can now increase their production by employing more labor, the output responses are different to the baseline case. As discussed earlier, due to the increased demand in purchasing power of households in the capped country, they import more goods from the uncapped country. Contrary to the baseline case, the firms in the uncapped country now scale up their production by hiring more labor, which is beneficial for households in the uncapped country. Those households do not decrease their consumption as much as in the baseline case because of the increased labor demand. Accordingly, Table B.1 shows that the costs of implementing a cap are higher than the cost of bearing the spillovers as the uncapped country, which is a similar result to the homothetic case.<sup>24</sup>

Under flexible prices the main results under the asymmetric price cap policies and the welfare table are robust. The results are in Appendix B.3.2. While the spillovers under asymmetric price cap policies are similar to the sticky price case, the symmetric cases shows some differences. Specifically, output does not decline following the energy supply shock, since price flexibility allows for efficient adjustments. Firms can adjust prices immediately, enabling the economy to absorb the shock without reducing output.

<sup>23</sup>The utility function with labor disutility is:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Rt}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Rt}} \right)^{\varepsilon_2} - 1 \right] - \chi \frac{N_t^{1+\varphi}}{1+\varphi} \right\} \quad (2.30)$$

where  $\chi$  is the disutility of labor and  $1/\varphi$  the Frisch labor elasticity. The calibration is  $\chi = \varphi = 1$ , as is standard in the literature.

<sup>24</sup>In the reverse case, when the smaller country imposes the price cap and the bigger country does not, the positive effect on welfare from increased labor demand is not big enough to outweigh the costs of implementing the price cap.

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The tables and figures in Appendix B.3.2, B.3.3, and B.3.4 show the results for the last two alternative assumptions, flexible exchange rates and CES preferences. Even though the impulse responses are somewhat different, the welfare table is the same as under the baseline case. This result confirms that the crucial assumption to the mechanism is the shared energy supply, not the shared monetary authority. Moreover, CES preferences dampen the overall effect of the energy supply shock and the price cap spillovers on the economy, because the expenditure share of energy remains constant and energy is not a necessity good.

### 2.4 Endogenous energy production

So far, the analysis uses the model which only has an exogenous source of energy. This setup is valuable for understanding the core intuition and mechanics, as well as investigating the dynamics of the economies and their spillovers. However, during the European energy crisis in 2022 total energy consumption per capita did not decrease. When the supply of gas fell, other energy sources substituted out for gas, such that total energy consumption stayed roughly constant (Energy Institute, 2024). Therefore, to estimate the model, I add a domestic energy production sector to both countries. There is still an exogenous supply of gas which the two countries in the union share.

With the extended model, I first perform a Bayesian estimation of the parameters. Then, I revisit the mechanism and the incentives about whether to cap or not. I show that the domestic production of energy dampens the negative spillovers of the energy price cap, such that Nash equilibria, with one capped and one uncapped country, matches the reality in 2022. Moreover, I demonstrate with a historical shock decomposition that the energy price cap contributed to 40% of energy inflation and 20% of CPI inflation in 2022Q3 in the uncapped countries.

#### 2.4.1 Energy sector and energy market clearing in the model

To make sure there is a substitute for the exogenous supply of gas, I add energy firms to both countries in the union. Unless otherwise stated, all other equations

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in the model stay unchanged from the baseline specification.

Energy firms only use labor,  $N_{Et}$ , as their input in their production  $Y_{Et}$ :

$$Y_{Et} = A_{Et} N_{Et}^{\eta} \quad (2.31)$$

where  $A_{Et}$  is the total factor technology in the energy sector.  $\eta$  determines the share of profits from total revenue. The production function uses a diminishing-return technology, as in Ferrero and Seneca (2019), to match the oligopolies in the energy sector.

The representative energy producer takes the wages as given. I assume that the energy firms sell any quantity of energy at the prevailing price. This assumption reflects the findings by Zakeri et al. (2022) who find that the European electricity prices depend highly on natural gas prices. The energy firm's problem is

$$\max_{N_{Et}} P_{Et} Y_{Et} - W_t N_{Et} \quad (2.32)$$

subject to the production function (2.31). The first-order conditions are in Appendix B.1.5.

**Energy market clearing.** Energy supply comes from the exogenous, union-wide gas supply  $GAS_t^W$  and the domestically produced energy. Hence, the market clearing conditions for energy are:

$$E_t^h + E_t^f = \left[ (1 - \alpha_G)^{1/\zeta} (Y_{Et})^{(\zeta-1)/\zeta} + \alpha_G^{1/\zeta} (GAS_t)^{(\zeta-1)/\zeta} \right]^{\zeta/(\zeta-1)} \quad (2.33)$$

$$E_t^{h*} + E_t^{f*} = \left[ (1 - \alpha_G^*)^{1/\zeta} (Y_{Et}^*)^{(\zeta-1)/\zeta} + \alpha_G^{*1/\zeta} (GAS_t^*)^{(\zeta-1)/\zeta} \right]^{\zeta/(\zeta-1)} \quad (2.34)$$

$$GAS_t + GAS_t^* = GAS_t^W \quad (2.35)$$

where  $\alpha_G$  is the share of gas in energy use and  $\zeta$  governs the substitutability of gas and other energy.

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### 2.4.2 Calibration and estimation of the parameters

In the model with domestic energy production, there are a few extra parameters to consider. Moreover, since the goal is to estimate the contributions of the energy price cap, I divert from the symmetric setup and calibrate some extra parameters differently for the capped and uncapped countries when there is distinguishing data. I calibrate the share of gas in energy use,  $\alpha_G$  and  $\alpha_G^*$ , the steady-state productivity of the energy sector,  $\bar{A}_E$ , and the share of profits,  $\eta$ , with data and matching targets. For the non-homotheticity parameters,  $\varepsilon_1$ ,  $\varepsilon_1^*$ ,  $\varepsilon_2$  and  $\varepsilon_2^*$ , and the elasticity of substitution between gas and non-gas energy,  $\zeta$  and  $\zeta^*$ , I use Bayesian estimation.

#### 2.4.2.1 Calibration

For the share of gas in energy use,  $\alpha_G$  and  $\alpha_G^*$ , I use the Harmonized Index of Consumer Prices (HICP) item weights from Eurostat and set them to 0.18 and 0.22 respectively for the capped and uncapped countries.<sup>25</sup> Even though the data for estimation starts a decade earlier than 2022, I group the countries already into capped and uncapped countries, referring to the energy price cap policy in 2022. To set the steady-state productivity of the energy sector,  $\bar{A}_E$ , and the share of profits,  $\eta$ , I match the following targets: the share of workers in the energy sector of 3.66% in Europe<sup>26</sup> and the relative price of energy and other goods of 1, as in the baseline model. The values that match the targets are  $\eta = 0.19$  and  $\bar{A}_E = 0.17$ . These parameters are symmetric across the countries. Table 2.4 provides a summary.

#### 2.4.2.2 Estimation

I estimate the non-homotheticity parameters,  $\varepsilon_1 = \varepsilon_2$ , and the elasticity of substitution between gas and non-gas energy,  $\zeta$  and  $\zeta^*$ . Here, I outline the method

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<sup>25</sup>Eurostat data, online data code: `prc_hicp_inw`. I take the weighted average according to Eurostat's country weights (data code: `prc_hicp_cow`) when calculating the values for capped and uncapped countries. The categorization of capped and uncapped countries is in Footnote 14.

<sup>26</sup>Own calculations from the World Energy Employment report in 2022 by the International Energy Agency (IEA, 2022) and Eurostat data.

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**Table 2.4:** Extra parameters in model with domestic energy production

<i>Parameter</i>	<i>Description</i>	<i>Value</i>
$\alpha_G$	Share of gas in energy, "Cap"	0.18
$\alpha_G^*$	Share of gas in energy, "No cap"	0.22
$\eta$	Share of profits for energy firms	0.19
$A_E$	Steady-state productivity energy sector	0.17
$\varepsilon_1$	Non-homotheticity parameter	0.25
$\varepsilon_2$	Non-homotheticity parameter	0.25
$\zeta$	Elasticity of substitution between gas and non-gas energy, "Cap"	14.88
$\zeta^*$	Elasticity of substitution between gas and non-gas energy, "No cap"	34.89

*Notes:* Calibration of the extra parameters in the model with energy production. All other variables are the same as in the baseline case as in Table 2.1.

used and steps taken for Bayesian estimation and present the outcome.

I use the Bayesian estimation techniques programmed in Dynare (Adjemian et al., 2024). I include the following shocks and measurement errors in the model: total factor productivity (TFP) shocks for other goods and energy sector, demand shocks, cost-push shocks in the other goods sector, shocks to gas supply, monetary policy shock, and measurement errors for energy consumption and energy inflation. Those shocks and measurement errors are separate for the two countries in the union, except for the monetary policy shock and the energy inflation measurement error.<sup>27</sup>

First, I compute the mode of the posterior distribution with the Monte-Carlo based optimization routine. Second, the Metropolis-Hastings algorithm evaluates the marginal likelihood of the model and produces the posterior distributions of the parameters. This method closely follows the Bayesian estimation approach in Smets and Wouters (2007). More details on the estimation method are in Appendix B.2.

**Prior distributions.** I only estimate the parameters which have no direct counterpart in the data or a sensible target to match. The non-homotheticity parameter  $\varepsilon_1 = \varepsilon_2$  is bounded by zero and one.<sup>28</sup> Hence, I use the Beta distribution as the

<sup>27</sup>I add the measurement error for energy inflation with a tight prior to avoid stochastic singularity.

<sup>28</sup>I estimate with  $\varepsilon_1 = \varepsilon_1^* = \varepsilon_2 = \varepsilon_2^*$ . First, I assume that the "Cap" and "No cap" do not differ in their non-homotheticity to energy. Since the data series is not too long and the "Cap" and "No cap"-blocks only arose in 2022, I assume, as in the baseline calibration, that the countries are symmetric. The only exception I make is the elasticity of substitution between gas and non-gas, as

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prior distribution. The prior mean is set to 0.77, the calibration value from the data exercise in the baseline model. For the elasticity of substitution between gas and non-gas energy,  $\zeta$  and  $\zeta^*$ , I use the Gamma distribution as the prior distribution. I set the prior mean to 2 with a loose standard error. Following Krause et al. (2008), all shock processes follow an AR(1) process. The prior means of all AR-coefficient parameters are 0.9 and the standard deviations are 0.01. The AR-coefficients are bounded by one and zero, so they follow a Beta distribution. The standard deviations follow an Inverse-gamma distribution.

**Data.** I use the following data series from 2008Q1 to 2019Q4 in the Bayesian estimation:<sup>29</sup> Energy inflation, gas inflation, CPI inflation, energy consumption, gas consumption, output, and the nominal interest rate. Since the union has an integrated energy market, and therefore also gas market, there is one energy and gas inflation rate each for the entire union. Moreover, since the model implies a shared supply of gas, the gas consumption is the same as well. All data are from Eurostat Data. I seasonally adjust the data and detrend them to get the cyclical component. More details are in Appendix B.2.

**Estimation results.** Table 2.5 presents the results of the Bayesian estimation. The non-homotheticity parameters,  $\varepsilon_1$ , and therefore also  $\varepsilon_1^*$ ,  $\varepsilon_2$ , and  $\varepsilon_2^*$ , are 0.27.<sup>30</sup> Moreover, the substitutability of gas and non-gas energy,  $\zeta$  and  $\zeta^*$ , are 15.21 and 35.31 respectively. Interestingly, the country-bloc that in 2022 implements an energy price cap have a much lower elasticity of substitution between gas and non-gas energy. This policy decision seems to make sense given the relatively low

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explained in this paragraph. Second, I set  $\varepsilon_1 = \varepsilon_2$  to keep tractability. When  $\varepsilon_1 = \varepsilon_2$  the elasticity of substitution between energy and other goods is  $1 - \varepsilon_2$ .

<sup>29</sup>I deliberately omit the COVID-19 pandemic year to keep the observables stable. For the estimation of the shocks later, I cannot avoid the pandemic year. The sample starts in 2008Q1 due to data availability.

<sup>30</sup>The estimated non-homotheticity values, 0.27, are substantially lower than the values from the data exercise in the baseline model, 0.77. A couple reasons to explain this difference: in the baseline model, the parameter captures the non-homotheticity of gas, whereas the extended model covers all energy. Moreover, the sample period of the data exercise was very short, 2020Q3 – 2022Q4, and not overlapping with the sample period of the estimation exercise. Despite the difference, the results of the extended model does not change qualitatively when I set the non-homotheticity parameter to 0.77 instead of 0.27.

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ability to substitute away from gas. The parameters are well-identified because I use both gas and energy inflation rates and gas and energy consumption for the estimation.<sup>31</sup> The posterior distributions plots and some more details about the estimation results are in Appendix B.2.

**Table 2.5:** Priors and posteriors

Parameter	Prior dist.	Prior mean	Prior std.	Post. mean	Post. std.	90% HPD interval
$\varepsilon_1$	Gamma	0.8	0.1	0.27	0.07	[0.165,0.380]
$\zeta$	Beta	2	1	15.21	1.86	[12.190,18.265]
$\zeta^*$	Beta	2	1	35.31	3.31	[29.981,40.802]

*Notes:* The prior distribution, mean, standard deviation, posterior mean and standard deviation, and the Highest Posterior Density (HPD) interval of the Bayesian estimation.

### 2.4.3 Results

In this subsection, I first show the simulation results of the extended model with parameter values from the calibration and the estimation, as summarized in Table 2.4. I show that domestic energy production dampens the effect of the gas supply shock on the economy. Consequently, the negative spillovers are also smaller, which leads the costs of implementing the price cap exceeding the costs of bearing the spillovers. Then, I conduct a historical shock decomposition to quantify the contribution of the energy price cap in 2022 to the energy and CPI inflation levels in both the capped and uncapped countries.

#### 2.4.3.1 Simulation results

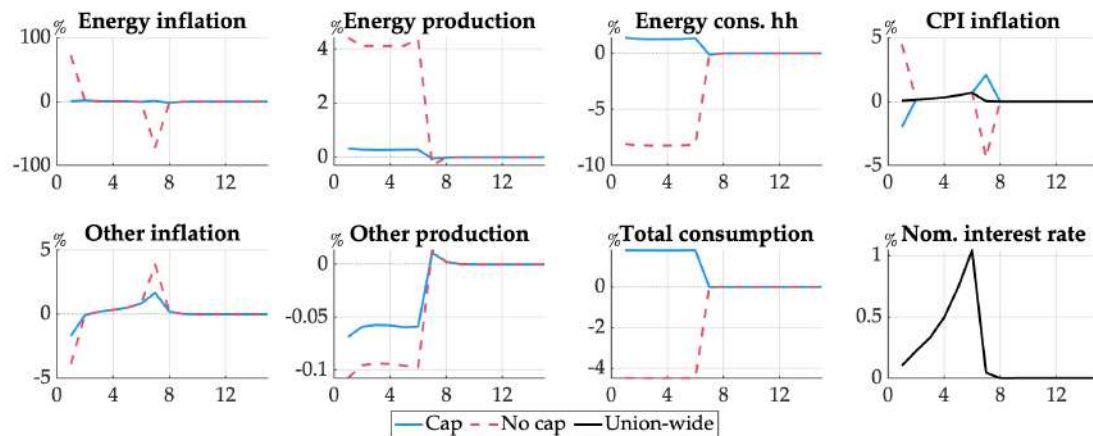
Figure 2.8 shows the impulse responses to an adverse energy supply shock when one country implements an energy price cap, with the model that allows for domestic energy production. The energy production in the uncapped country dampens the negative spillovers from the capped to the uncapped country substantially. For example, energy consumption for the households only decreases by about 10% compared to about 20% in the case without energy production

<sup>31</sup>Since gas inflation/consumption is a fraction of energy inflation/consumption, the data implies inflation/consumption of non-gas energy.

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in Figure 2.5. The response of CPI inflation, about 3% on impact, is also much lower than the 20% in the previous case.

**Figure 2.8:** Responses to an adverse gas supply shock | Energy production



*Notes:* Impulse responses to a 15% decline in gas supply, in a model with energy production. Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

The welfare outcomes for the combinations of price cap strategies are in Table 2.6. Because the energy sector dampens the effect of the exogenous gas supply shock, the loss from the gas supply shock is 0.02% instead of 0.1% in the baseline case, when there are no price cap policies in place. Moreover, when both countries impose a price cap, in the baseline case the losses rose to 1%. The domestic energy production dampens this effect to a loss of 0.3%, implying that the actual price of energy, and therefore the cost for the government to implement the cap, does not rise as high as in the baseline case. Importantly, Table 2.6 shows that imposing a price cap is not the dominant strategy as it was in the baseline case in Table 2.2. Under the extended model there are two Nash equilibria in which one country imposes the price cap and the other country does not, explaining the reality in 2022. Because the energy sector dampens the negative spillovers of the energy price cap, imposing the cap when the opponent country also has one is not worth the cost.

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Table 2.6 also displays the union-wide welfare losses, outside of the parentheses in case of differing cap policies. The union-wide welfare loss is biggest when both countries impose the energy price cap, 0.5%, because the cost of imposing the cap is high for the government, and there is no other country to spillover to. The cooperative outcome when there are no price caps in the entire union has the smallest union-wide welfare loss,  $-0.03\%$ , compared to the weighted averages  $-0.03\%$  (with higher precision) and  $-0.07\%$ , when one of the countries impose the price cap. So, the Nash equilibria are not the optimal outcome for union-wide welfare, even if they benefit the bigger country.

**Table 2.6:** Welfare gains/losses after gas supply shock

		Model with domestic energy production	
		1/3 of union	
		Cap	No cap
2/3 of union	Cap	$(-0.5, -0.5)$	$(0.1, -0.3); -0.03$
	No cap	$(-0.3, 0.1); -0.2$	$(-0.03, -0.03)$

*Notes:* Welfare gains and losses after a 15% gas supply shock, in a model with energy production. Preferences are non-homothetic. The gains and losses are in terms of the consumption equivalent relative to the steady state. The circles are around the preferred policy choices (Cap or No cap) for the countries. The values outside the parentheses are weighted averages, i.e. union-wide welfare.

To understand the forces behind the welfare gains and losses, I decompose the loss value  $-0.3$  of the uncapped 1/3 of the union in Table 2.7. The welfare loss of the uncapped country when the countries sharing a gas supply are in a currency union (iii), is, with higher precision,  $-0.26$ . By computing the welfare losses in the cases of (i) two autarkies sharing a gas supply and (ii) two trading countries not in a currency union sharing a gas supply, the Table decomposes the total welfare loss of the uncapped country into three components: loss coming from energy price distortions, loss coming from the terms-of-trade effect, and the loss coming from being in a currency union.

Table 2.7 shows that the welfare loss coming from the terms-of-trade effect is the largest. Energy price distortions, though they affect the inflation rates, do not seem to have a big contribution to the welfare losses. Lastly, being in a

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currency union does not seem to affect the welfare losses too much, as expected from the robustness checks in Appendix B.3.3.

**Table 2.7:** Decomposition of the welfare loss for uncapped country

%	<b>(i) Autarkies</b> ( $\alpha_I = 0$ , indep. CBs)	<b>(ii) Trade partners</b> ( $\alpha_I = 0.25$ , indep. CBs)	<b>(iii) In union</b> ( $\alpha_I = 0.25$ , one CB)
Energy price	-0.03	-0.03	-0.03
Terms of trade	-	-0.23	-0.23
Currency union	-	-	+0
<b>Total loss</b>	<b>-0.03</b>	<b>-0.26</b>	<b>-0.26</b>

*Notes:* Decomposition of the welfare loss of the uncapped country after a 15% gas supply shock, in a model with energy production. Preferences are non-homothetic. The losses are in terms of the consumption equivalent relative to the steady state. The first column indicates the welfare loss in the case in which the countries are autarkies, i.e. do not trade ( $\alpha_I = 0$ ) and have independent central banks. The second column relaxes the no-trading assumption ( $\alpha_I = 0.25$ ) but still assumes independent central banks. The third column is the full model, with countries trading and in a currency union.

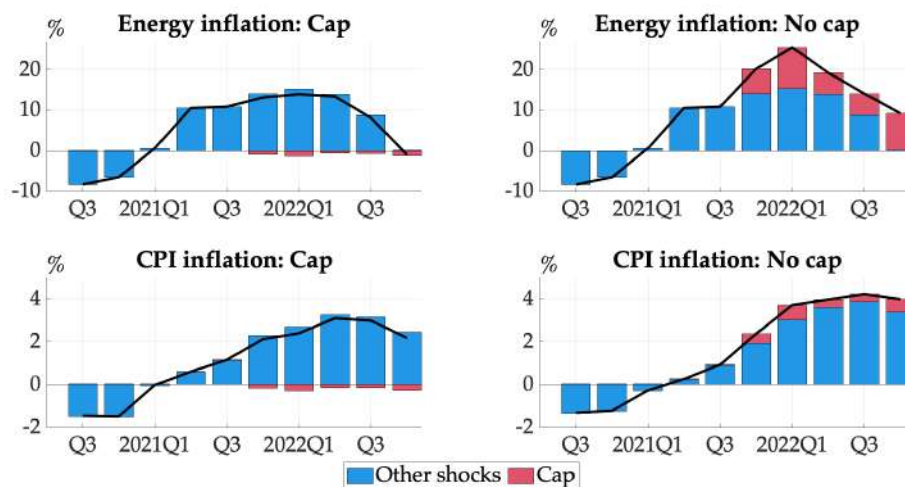
### 2.4.3.2 Historical shock decomposition

Using the calibrated and estimated values in Table 2.4, I perform a historical shock decomposition for the period 2008Q1–2022Q4. Again, I use the Bayesian estimation techniques in Dynare (Adjemian et al., 2024). I use the same shock processes and data series as described for the estimation of the parameters. I add the energy price cap as an additional shock. As before, all shocks follow an AR(1) process and I estimate the coefficients for the shock in the same way as before. After the estimation of the shock processes, I perform a historical shock decomposition. More details on the data and estimation method are in Appendix B.2.

The historical shock decomposition decomposes the fluctuations in the data series into the contributions from the shocks. The results are in Figure 2.9. I group all shocks but the energy price cap in one (blue bars) and keep the contributions from the cap separate (red bars). The top-right graph in Figure 2.9 shows that the energy price cap contributed to about 10 percentage points of energy inflation in the uncapped countries in 2022. In the last quarter of 2022, the price cap was responsible for virtually all of energy inflation in the uncapped countries. Even

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**Figure 2.9:** Historical shock decomposition | Contributions from the energy price cap



*Notes:* Historical shock decomposition of the annual inflation rates in deviations from the sample mean. “Other shocks” consist of total factor productivity (TFP) shocks for other goods and energy sector, demand shocks, cost-push shocks in the other goods sector, shocks to gas supply, monetary policy shock, and measurement errors for energy consumption and energy inflation. Those shocks and measurement errors are separate for the two countries in the union, except for the monetary policy shock. Mean energy inflation is 2.15% and 2.72% for capped and no-cap countries respectively. Mean CPI inflation is 1.42% and 1.46% for capped and no-cap countries respectively. The red bars indicate the contributions from the energy price cap, whereas the blue bars aggregate all other shocks. More details are in Appendix B.2.

though the spillovers that the price cap created were large, the top-left graph shows that in the countries with the cap the energy inflation would not have been much higher without it. If there were no energy price caps, the burden of the gas supply shocks would have been shared equally in the union. The partial substitution to non-gas energy mitigates the upward pressure on energy inflation across the entire union.

Similarly, the bottom graphs show that there were negative spillovers of the price cap to the uncapped countries, the upward pressure on CPI inflation: the price cap contributed to about 0.5 percentage points of CPI inflation in the uncapped countries, depending on the quarter. Moreover, the contribution increasing CPI inflation in the uncapped countries was a lot larger than the cap’s contribution lowering inflation in the capped countries.

## 2.5 TANK results

In this section I compare the energy price cap with targeted transfers. Most national governments conducted transfers to vulnerable groups in 2022, since the energy crisis affected them the most (Sgaravatti et al., 2023). To create heterogeneity within households, I add poor hand-to-mouth to the model with domestic energy production. A targeted transfer is a transfer to just those hand-to-mouth households. Since labor income is the only source for hand-to-mouth households and hence an important model feature, this version of the model includes elastic labor supply as discussed in Section 2.3.2.4. Therefore, the model becomes a Two-Agent New Keynesian (TANK) model.

The TANK version of the model does not alter in the transmission mechanism and the spillovers of the price cap and the aggregate welfare results discussed in the previous sections hold. An interesting aspect of the TANK model is its potential for evaluating the effects of targeted policies, such as the transfer program, on different household groups: I compare a country-wide energy price cap (to all households and firms) to a targeted transfer to the hand-to-mouth households. Since low-income, hand-to-mouth households spend a larger share of their income on energy, an adverse energy supply shock is particularly burdensome for them (Bayer et al., 2023). I find that with much lower cost for the government, the targeted transfers achieve more favorable results in terms of boosting consumption for the poor. Moreover, since the transfer does not distort the energy market, there is barely any divergence within the union even if only one country implements the transfers.

### 2.5.1 Adding hand-to-mouth households to the model

In the two-agent version of the model, there are financially constrained households who represent share  $\lambda \in [0, 1]$  of the population, and unconstrained households who are share  $1 - \lambda$ . Financially constrained households have no access to the one-period bonds. Moreover, they earn no profits from firms nor

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the energy sellers. The budget constraints of the constrained and unconstrained households are respectively:

$$exp_t^c = P_{Et}e_t^{h,c} + P_{Rt}c_{Rt}^c = W_t n_t^c + P_t \tau_t^c + \mathcal{T} - T_t^c \quad (2.36)$$

$$exp_t^u = P_{Et}e_t^{h,u} + P_{Rt}c_{Rt}^u \quad (2.37)$$

$$= W_t n_t^u + \frac{1-\delta}{1-\lambda} D_t + \frac{1}{1-\lambda} D_t^E + R_{t-1} \frac{B_{t-1}}{1-\lambda} - \frac{B_t}{1-\lambda} - HC_t + P_{Rt} \tau_t^u - T_t^u \quad (2.38)$$

where superscript  $c$  refers to variables belonging to constrained households and  $u$  to unconstrained ones.  $\tau_t$  are redistributive transfers from the government explained below.  $\mathcal{T}$  is a steady-state transfer from the constrained to unconstrained, to make sure their consumption is equal in steady state. The preferences are the same for both households and include the disutility for labor supply as in 2.3.2.4.

I aggregate energy and other goods consumption and labor as:

$$\lambda e_t^{h,c} + (1-\lambda)e_t^{h,u} = E_t^h \quad (2.39)$$

$$\lambda c_{Rt}^c + (1-\lambda)c_{Rt}^u = C_{Rt} \quad (2.40)$$

$$\lambda n_t^c + (1-\lambda)n_t^u = N_t \quad (2.41)$$

Labor supply of constrained and unconstrained households are therefore identical to the firms.

Following Debortoli and Galí (2018) and Komatsu (2023), the fiscal authority redistributes the taxed profits from firms  $D_t$  as transfers to the constrained households,  $\tau_t^c$ , and unconstrained households,  $\tau_t^u$ , according to the rules:

$$\tau_t^c = (1-\tau_0)\delta D_t \quad (2.42)$$

$$\tau_t^u = \left(1 + \frac{\tau_0 \lambda}{1-\lambda}\right) \delta D_t \quad (2.43)$$

where  $\delta$  is the tax rate on firms' profits, where  $\tau_0$  indicates how much of the profits go to (un)constrained households, using  $\lambda \tau_t^c + (1-\lambda)\tau_t^u = \delta D_t$ . So, when  $\tau_0$  is equal to unity, all profits go back to the unconstrained households.

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**Calibration.** The Household Finance and Consumption Survey (HFCS, 2022) collects household-level data in the Eurozone and estimate that credit-constrained households make up around 5-10% of the population. Hence, in the TANK version, the share of hand-to-mouth households,  $\lambda$ , is 0.1.<sup>32</sup> For the redistribution of taxed firms' profits, I set the tax rate on firm's profits at  $\delta = 0.215$ , which was the average corporate tax rate in 2022 of European OECD countries (Bray, 2023). The redistribution rule,  $\tau$ , is equal to unity, such that all profits go to unconstrained households. All other calibration values are identical to the baseline model and the model with domestic energy production.

**Consumption response decomposition.** In the next subsection I investigate the consumption responses of constrained and unconstrained households in detail. Hence, I perform an impulse response decomposition by rearranging the log-linearized equations. Hatted variables indicate log-linear deviations from steady state.

For constrained households, take total consumption as a sum of energy consumption and other goods consumption:

$$\hat{c}_t^c = \frac{\bar{e}^c}{\bar{c}^c} \hat{e}_t^c + \frac{\bar{c}_R^c}{\bar{c}^c} \hat{c}_{Rt}^c \quad (2.44)$$

Using the choice between energy and other goods, Eq. (2.2), the definition of the energy expenditure wedge, Eq. (2.3), and their budget constraint, Eq. (2.36), I decompose the consumption of the constrained households:

$$\hat{c}_t^c = \underbrace{\mathbf{A}^c \hat{e}_t^c + \mathbf{B} \hat{p}_t^{rel,ER}}_{\text{energy consumption}} + \underbrace{\mathbf{C} \hat{w}_t}_{\text{real wage}} - \underbrace{\mathbf{D} \hat{t}_t}_{\text{taxes}} \quad (2.45)$$

where  $\mathbf{A}^c = \frac{1}{\bar{c}^c} (\bar{e}^c + \bar{c}_R^c)$ ,  $\mathbf{B} = \frac{\bar{c}_R^c}{\bar{c}^c} \left[ 1 + \frac{1}{1-\alpha_E} \left( \frac{1}{exp} \varepsilon_1 \bar{W} \bar{N} \alpha_E - \varepsilon_2 \right) \right]$ ,

$\mathbf{C} = \frac{\bar{c}_R^c}{\bar{c}^c} \frac{1}{(1-\alpha_E)exp} \varepsilon_1 \bar{W} \bar{N}$ , and  $\mathbf{D} = \frac{\bar{c}_R^c}{\bar{c}^c} \frac{1}{(1-\alpha_E)exp} \varepsilon_1 \lambda$ .

---

<sup>32</sup>5-10% is the share of so-called "poor" hand-to-mouth households. When including the share of "wealthy" hand-to-mouth households, who own illiquid assets, the share of hand-to-mouth households rises to about 30%.

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Analogously for unconstrained households, decompose total consumption using the choice between energy and other goods, Eq. (2.2), the definition of the energy expenditure wedge, Eq. (2.3):

$$\hat{c}_t^u = \underbrace{\mathbf{A}^u \hat{c}_t^u + \mathbf{E} \hat{p}_t^{rel, ER}}_{\text{energy consumption}} + \underbrace{\mathbf{F} e \hat{x} p_t}_{\text{consumption smoothing}} \quad (2.46)$$

where  $\mathbf{A}^u = \frac{1}{\bar{c}^u} (\bar{c}^u + \bar{c}_R^u)$ ,  $\mathbf{E} = \frac{\bar{c}_R^u}{\bar{c}^u} \left(1 - \frac{1}{1-\alpha_E} \varepsilon_2\right)$ , and  $\mathbf{F} = \frac{\bar{c}_R^u}{\bar{c}^u} \frac{1}{1-\alpha_E} \varepsilon_1$ . I call the last term “consumption smoothing”, since the Euler equation (2.9) determines the total nominal expenditures of the unconstrained household,  $e \hat{x} p_t$ .

### 2.5.2 Results: Price cap vs. targeted transfers

The TANK impulse responses after an adverse gas supply shock with one capped and one uncapped country are quantitatively and qualitatively similar to the representative agent model in Figure 2.8.<sup>33</sup> So, the analysis of the macroeconomic responses and welfare in the previous section still applies to the TANK model.

To investigate the consumption responses for constrained and unconstrained in detail, I decompose the consumption responses for the constrained and unconstrained as in Eq. (2.45) and (2.46). The results are in Figure 2.10. For the uncapped country, I decompose the aggregate consumption response into contributions from constrained and unconstrained households.

In the capped country, the consumption of the unconstrained increases, whereas the consumption of the constrained decreases. The unconstrained households increase their consumption both by increasing their energy consumption and from consumption smoothing. Recall the mechanism through which households benefit from the energy price cap in the baseline model: households increase their consumption because they consume cheap goods from the uncapped country, i.e. the capped country consumes more than it produces. This mechanism is *intertemporal*, since the capped country temporarily runs a current account deficit and borrows from abroad while the energy shock takes place. In the two-agent version, only unconstrained households make

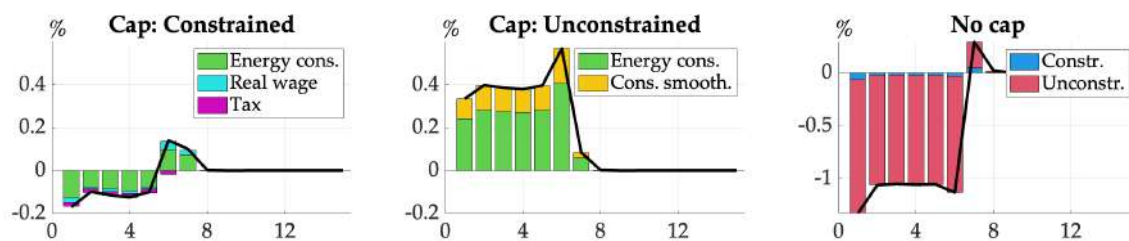
<sup>33</sup>The responses for the TANK model are in Figure B.7 in Appendix B.3.

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*intertemporal* decisions. Hence, unconstrained households can increase their consumption, whereas constrained households cannot.

The rightmost graph displays the large spillovers from the capped to uncapped country, similar to previous versions of the model. Because the price cap distorts the energy market in the union, it creates spillovers to the uncapped country. Next, I analyze whether targeted transfers are more effective in helping poorer, constrained households, and whether they create less distortions and spillovers.

**Figure 2.10:** Consumption response decomposition | Cap and no cap



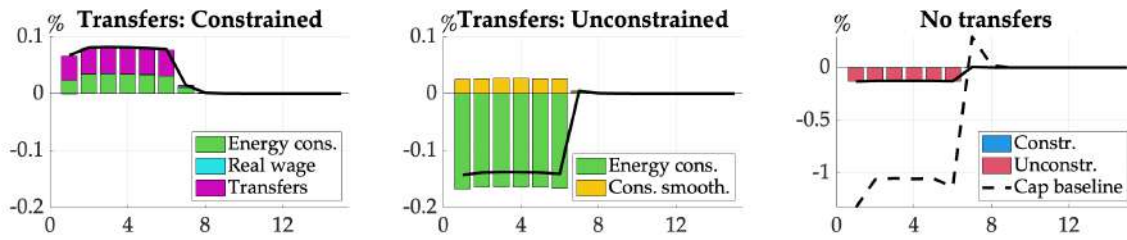
*Notes:* Impulse responses to a 15% decline in energy supply (black lines) and the decomposition of the responses (colored bars). Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (left two panels) and the smaller country, of size  $1 - \Theta$  does not (rightmost panel). The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

**Targeted transfers.** For easy comparison with the price cap, I set the targeted transfers to the same per person government expenditure, but only for the constrained households. Since they are 10% of the population, the specified targeted transfer only costs 10% of the cost of the price cap. The consumption responses are in Figure 2.11. The left graph shows that the targeted transfers are effective in increasing the constrained household's consumption, while not lowering the consumption of the unconstrained too much. Moreover, the spillovers to the country without transfers substantially smaller than under the cap.

The responses of some other macroeconomic variables for both the country with and without transfers are in Figure 2.12. Because transfers do not distort the integrated energy market in the currency union, they do not create much divergence within the union. The inflation response is significantly milder than in the case with price caps. So, together with the absence of divergence, the

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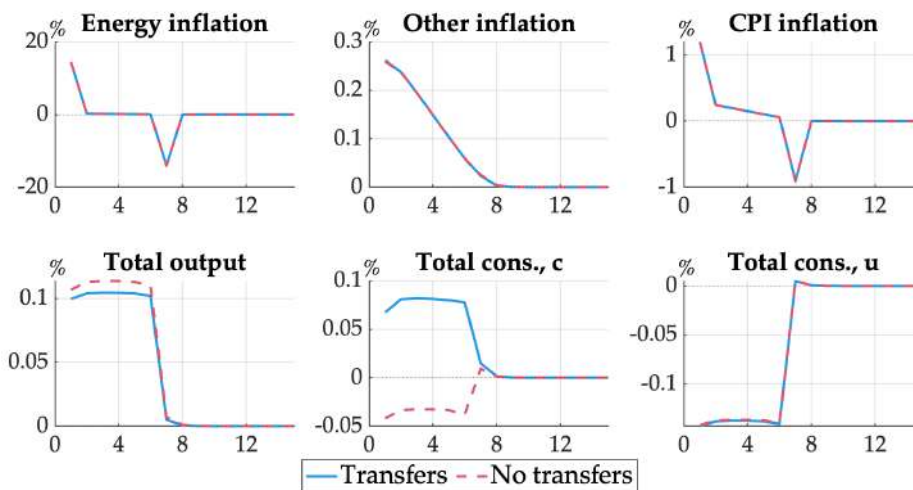
**Figure 2.11:** Consumption response decomposition | Transfers and no transfers



*Notes:* Impulse responses to a 15% decline in energy supply (black lines) and the decomposition of the responses (colored bars). Preferences are non-homothetic. The bigger country, of size  $\Theta$  conducts targeted transfers to the constrained households (left two panels) and the smaller country, of size  $1 - \Theta$  does not (rightmost panel). The dashed line indicates the baseline scenario with the energy price cap. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

transfers are more preferable for the common central bank when stabilizing the inflation rates across the union. Moreover, the spillover in terms of consumption are also substantially lower than with the price cap.

**Figure 2.12:** Responses to an adverse energy shock | Transfers vs. no transfers



*Notes:* Impulse responses to a 15% decline in energy supply. Preferences are non-homothetic. The bigger country, of size  $\Theta$  conducts targeted transfers to the constrained (*c*) households (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). *u* stands for the unconstrained households. Output is equal to the output gap. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

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### **2.5.3 Discussion: A debt-financed energy price cap in a non-Ricardian monetary union**

Contrary to the baseline model, Ricardian Equivalence does not hold in the TANK version of the model. If a country finances its cost of implementing the price cap through debt, being part of a monetary union prevents that country to fully benefit from the cap.

Considering the case of a two-country monetary union with one capped and one uncapped country, the capped country can limit the surge in inflation rates, whereas the uncapped country cannot. Since the countries are in a monetary union, the interest rates set by the central bank are too high for the capped country while too low for the uncapped country. Assuming the capped country financed its cap implementation costs through debt, the country faces debt-servicing costs higher than desired due to not having its own monetary policy. I intend to explore this idea in greater depth in future work.

## **2.6 Conclusion**

This paper investigates the trade-offs of imposing an energy price cap during an energy crisis, based on the Euro Area energy crisis in 2022. I introduce a shared energy supply as an additional dimension of integration to a New Keynesian currency union model with two countries and rationalize the decisions that policymakers made in 2022. An adverse energy supply shock causes high energy inflation and a cost-push shock in the non-energy, core sector. I show that the cooperative policy is to refrain from introducing price caps. However, for an individual country it is welfare improving to impose a price cap, if the other country does not: the capped country avoids the crisis while the uncapped country experiences a supply shock of twice the magnitude.

The magnitude of those spillovers determine the preferred policy decisions – To cap or not to cap? On the one hand, a price cap ensures that households can maintain energy consumption levels. On the other hand, a cap is a cost to the government, and therefore ultimately the households. When one country

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imposes a price cap, the uncapped country incurs negative spillovers. So, there is a trade-off between paying for the cap and the paying for the negative spillovers. The magnitude of the spillovers depend on the non-homotheticity of preferences and the substitutability of energy sources. The quantitative model with both ingredients show that the cost of funding the price cap exceeds the costs of bearing negative spillovers. This result explains why some Euro Area countries did not introduce a price cap in 2022, while others did.

Moreover, I perform some counterfactual exercises. First, I use a historical shock decomposition to examine what energy and headline inflation would have been in the Euro Area in 2022 if none of the countries imposed an energy price cap. I find that the energy price cap contributed to about 10 percentage points to energy inflation and 0.5 percentage points to headline inflation in 2022. Second, I compare the energy price cap with targeted transfers and show that targeted transfers to those households is cheaper and more effective in boosting consumption of the poor. In addition, because the transfers do not distort the energy price, there is no divergence within the union.

# Appendices to Chapter 2

## B.1 Model

In this section, I expand on the Household and Firm's side of the model. The market clearing, monetary and fiscal policy parts are as described in the main text.

### B.1.1 Households

#### B.1.1.1 Preferences

Indirect utility function with non-homothetic preferences as in Boppart (2014):<sup>34</sup>

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} - 1 \right] \right\} \quad (\text{B.1})$$

where  $0 \leq \varepsilon_1 \leq \varepsilon_2 < 1$  and  $\alpha_E > 0$ . The utility assumes an inelastic labor supply and a per-period utility of the form  $v = \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} - 1 \right]$ .  $exp_t$  is the total nominal expenditure of the household on Energy and non-energy (Rest) goods, defined as  $exp_t = P_{Et}E_t^h + P_{Ot}C_{Ot}$ .

**Choice between energy and non-energy other goods.** Marshallian demand functions obtained with Roy's identity:

$$E_t^h = - \frac{\partial v / \partial P_{Et}}{\partial v / \partial exp_t} = \frac{\alpha_E \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2 - 1}}{\left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1 - 1}} \quad (\text{B.2})$$

$$C_{Ot} = - \frac{\partial v / \partial P_{Ot}}{\partial v / \partial exp_t} = \frac{\left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1} - \alpha_E \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2}}{\left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1 - 1}} \quad (\text{B.3})$$

<sup>34</sup>Indirect utility function  $v(p, exp)$ : household's maximal attainable utility when faced with vector  $p$  of goods prices and an amount of expenditure  $exp$ .  $v(p, exp) = u(x(p, exp))$ . Recall Roy's identity:

$$E^h = - \frac{\partial v / \partial P_E}{\partial v / \partial exp} \quad c_O = - \frac{\partial v / \partial P_O}{\partial v / \partial exp}$$

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Rearrange to express  $C_{Ot}$  in terms of  $E_t^h$  to get relative demand:<sup>35</sup>

$$C_{Ot} = \frac{\left(\frac{exp_t}{P_{Ot}}\right)^{\varepsilon_1} - \alpha_E \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2}}{\left(\frac{exp_t}{P_{Ot}}\right)^{\varepsilon_1 - 1}} = \frac{1 - \alpha_E \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2}}{\frac{P_{Ot}}{exp_t}} = \frac{1 - \alpha_E \varpi_t}{\frac{P_{Ot}}{exp_t}} \quad (\text{B.8})$$

$$= \frac{1 - \alpha_E \varpi_t}{\alpha_E \varpi_t} \frac{P_{Et}}{P_{Ot}} E_t^h \quad (\text{B.9})$$

where

$$\varpi_t = \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2} \quad (\text{B.10})$$

is the energy expenditure share wedge. When  $\varepsilon_1 = \varepsilon_2 = 0$  (Cobb-Douglas case), then  $C_{Ot} = \frac{1 - \alpha_E}{\alpha_E} \frac{P_{Et}}{P_{Ot}} E_t^h$ . Define relative total expenditure as:

$$exp_t^{rel} \equiv \frac{exp_t}{P_{Ot}} = \frac{P_{Et}}{P_{Ot}} E_t^h + C_{Ot} \quad (\text{B.11})$$

**Choice between Home and Foreign goods.** The non-energy goods are bundled in a composite index:

$$C_{Ot} = \left[ (1 - \alpha_I)^{1/\gamma} (C_{Ht})^{(\gamma-1)/\gamma} + (\alpha_I)^{1/\gamma} (C_{Ft})^{(\gamma-1)/\gamma} \right]^{\gamma/(\gamma-1)} \quad (\text{B.12})$$

where  $\alpha_I \in (0, 1)$  is the share of imported goods in the consumption basket and  $\gamma$  is the elasticity of substitution between Home and Foreign goods.  $C_{Ht}, C_{Ft}$  are consumption indices of  $H$ -produced and  $F$ -produced goods respectively:

$$C_{Ht} \equiv \left[ \int_0^1 C_{Ht}(i)^{(\varepsilon-1)/\varepsilon} di \right]^{\varepsilon/(\varepsilon-1)} \quad C_{Ft} \equiv \left[ \int_0^1 C_{Ft}(i)^{(\varepsilon-1)/\varepsilon} di \right]^{\varepsilon/(\varepsilon-1)} \quad (\text{B.13})$$

<sup>35</sup> Another way to rearrange the Marshallian demands:

$$E_t^h = \alpha_E \frac{exp_t}{P_{Et}} \varpi_t = \alpha_E \frac{exp_t}{P_{Et}} \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2} \quad (\text{B.4})$$

$$C_{Ot} = \frac{exp_t}{P_{Ot}} (1 - \alpha_E \varpi_t) = \frac{exp_t}{P_{Ot}} \left[ 1 - \alpha_E \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2} \right] \quad (\text{B.5})$$

- With  $\varepsilon_1 > 0$ , the expenditure elasticity of demand is positive, but strictly smaller than unity for energy and larger than unity for Rest. With  $\varepsilon_1 = 0$ , they are both equal to unity.
- The expenditure elasticity of demand for energy is  $1 - \varepsilon_1$ .

The expenditure shares of the two types of goods are:

$$\eta_{Et} = \frac{P_{Et} E_t^h}{exp_t} = \alpha_E \varpi_t = \alpha_E \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2} \quad (\text{B.6})$$

$$\eta_{Ot} = \frac{P_{Ot} C_{Ot}}{exp_t} = 1 - \alpha_E \varpi_t = 1 - \alpha_E \left(\frac{P_{Ot}}{exp_t}\right)^{\varepsilon_1} \left(\frac{P_{Et}}{P_{Ot}}\right)^{\varepsilon_2} \quad (\text{B.7})$$

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where  $\epsilon$  is the elasticity of substitution between different varieties within Home and Foreign goods. The intratemporal consumption choice between different varieties of  $H$ -produced and  $F$ -produced non-energy goods is:<sup>36</sup>

$$C_{Ht}(i) = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} C_{Ht} \quad C_{Ft}(i) = \left( \frac{P_{Ft}(i)}{P_{Ft}} \right)^{-\epsilon} C_{Ft} \quad (\text{B.16})$$

where  $P_{Ht}, P_{Ft}$  are indices of prices of  $H$ -produced and  $F$ -produced goods respectively:

$$P_{Ht} \equiv \left( \int_0^1 P_{Ht}(i)^{1-\epsilon} di \right)^{1/(1-\epsilon)} \quad P_{Ft} \equiv \left( \int_0^1 P_{Ft}(i)^{1-\epsilon} di \right)^{1/(1-\epsilon)} \quad (\text{B.17})$$

From Eq. (B.16) and (B.17), aggregate expenditure on  $H$ -produced and  $F$ -produced goods respectively:

$$\int_0^1 P_{Ht}(i) C_{Ht}(i) di = P_{Ht} C_{Ht} \quad \int_0^1 P_{Ft}(i) C_{Ft}(i) di = P_{Ft} C_{Ft} \quad (\text{B.18})$$

Intratemporal consumption choice between  $H$ -produced and  $F$ -produced goods bundle:<sup>37</sup>

$$C_{Ht} = (1 - \alpha_I) \left( \frac{P_{Ht}}{P_{Ot}} \right)^{-\gamma} C_{Ot} \quad C_{Ft} = \alpha_I \left( \frac{P_{Ft}}{P_{Ot}} \right)^{-\gamma} C_{Ot} \quad (\text{B.19})$$

where  $P_{Ot}$  is the aggregate price index for non-energy goods:

$$P_{Ot} = \left[ (1 - \alpha_I) P_{Ht}^{1-\gamma} + \alpha_I P_{Ft}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \quad (\text{B.20})$$

Combining the intratemporal consumption choice between Home and Foreign goods, I get:

$$\frac{C_{Ht}}{C_{Ft}} = \frac{1 - \alpha_I}{\alpha_I} \left( \frac{P_{Ht}}{P_{Ft}} \right)^{-\gamma} \quad (\text{B.21})$$

<sup>36</sup>Solutions to the following problems:

$$\min_{C_{Ht}(i)} \int_0^1 P_{Ht}(i) C_{Ht}(i) di \quad \text{s.t.} \quad \left[ \int_0^1 C_{Ht}(i)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}} \geq C_{Ht} \quad (\text{B.14})$$

$$\min_{C_{Ft}(i)} \int_0^1 P_{Ft}(i) C_{Ft}(i) di \quad \text{s.t.} \quad \left[ \int_0^1 C_{Ft}(i)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}} \geq C_{Ft} \quad (\text{B.15})$$

<sup>37</sup>Solution to the following problem:

$$\min_{C_{Ht}, C_{Ft}} P_{Ht} C_{Ht} + P_{Ft} C_{Ft} \quad \text{s.t.} \quad \left[ (1 - \alpha)^{\frac{1}{\gamma}} C_{Ht}^{\frac{\gamma-1}{\gamma}} + \alpha^{\frac{1}{\gamma}} C_{Ft}^{\frac{\gamma-1}{\gamma}} \right]^{\frac{\gamma}{\gamma-1}} \geq C_{Ot}$$

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From Eq. (B.19) and (B.20), aggregate expenditure on non-energy consumption is:

$$\int_0^1 P_{Ht}(i)C_{Ht}(i)di + \int_0^1 P_{Ft}(i)C_{Ft}(i)di = P_{Ht}C_{Ht} + P_{Ft}C_{Ft} = P_{Ot}C_{Ot} \quad (\text{B.22})$$

### B.1.1.2 Intertemporal consumption choices and labor supply

Nominal budget constraint:

$$exp_t = P_{Et}E_t^h + P_{Ot}C_{Ot} = W_tN_t + D_t + D_t^E + R_{t-1}B_{t-1} - B_t - HC_t - T_t \quad (\text{B.23})$$

where  $D_t$  is the nominal profit paid by the domestic firms to the representative domestic household and  $D_t^E$  the profits from the energy sellers given by:

$$D_t^E = \frac{P_{Et}}{\bar{P}_E} (E_t^h + E_t^f) \quad (\text{B.24})$$

$HC_t$  are the portfolio adjustment costs of the household:

$$HC_t = \frac{\tilde{\nu}}{2}(B_t - \bar{B})^2 \quad (\text{B.25})$$

where  $B_t$  is nominal bond holdings of the household.  $T_t$  are lump-sum taxes for the government to finance the energy price cap.

$$\begin{aligned} \mathcal{L} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{\varepsilon_1} \left[ \left( \frac{exp_t}{P_{Ot}} \right)^{\varepsilon_1} - 1 \right] - \frac{\alpha_E}{\varepsilon_2} \left[ \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} - 1 \right] \right. \\ \left. + \lambda_t \left[ W_tN_t + D_t + D_t^E + R_{t-1}B_{t-1} - B_t - HC_t - exp_t \right] \right\} \quad (\text{B.26}) \end{aligned}$$

$$\frac{\partial \mathcal{L}}{\partial exp_t} : exp_t^{\varepsilon_1-1} P_{Ot}^{-\varepsilon_1} - \lambda_t = 0 \quad (\text{B.27})$$

$$\frac{\partial \mathcal{L}}{\partial B_t} : \lambda_t = \beta R_t \mathbb{E}_t[\lambda_{t+1}] \quad (\text{B.28})$$

Euler equation:

$$\left( \frac{\mathbb{E}_t[exp_{t+1}]}{exp_t} \right)^{1-\varepsilon_1} = \beta \frac{R_t}{1 + P_t \tilde{\nu}(b_t - \bar{b})} \mathbb{E}_t \left[ \left( \frac{1}{\Pi_{O,t+1}} \right)^{\varepsilon_1} \right] \quad (\text{B.29})$$

where  $b_t = \frac{B_t}{P_t}$  is real bond holdings and  $\Pi_{Ot} = \frac{P_{Ot}}{P_{O,t-1}}$  is gross inflation. Inelastic labor means  $N_t = \bar{N}$ .

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### B.1.2 Firms

There is monopolistic competition among intermediate firms producing the other consumption goods. They face adjustment costs à la Rotemberg (1982).

#### Cost minimization

$$\min_{N_t(i), E_t^f(i)} W_t N_t(i) + P_{Et} E_t^f(i) \quad (\text{B.30})$$

$$\text{s.t. demand curve } Y_t(i) = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} Y_t \quad (\text{B.31})$$

$$\text{production function } Y_t(i) = A_t \left[ (\alpha^f)^{1/\theta^f} (E_t^f(i))^{(\theta^f-1)/\theta^f} + (1-\alpha^f)^{1/\theta^f} (N_t(i))^{(\theta^f-1)/\theta^f} \right]^{\theta^f/(\theta^f-1)} \quad (\text{B.32})$$

First order condition w.r.t.  $N_t(i)$  and  $E_t^f(i)$ :<sup>38</sup>

$$W_t = (1 - \alpha^f)^{1/\theta^f} \mu_t^{nom} \left( \frac{Y_t(i)}{N_t(i)} \right)^{1/\theta^f} A_t^{(\theta^f-1)/\theta^f} \quad (\text{B.33})$$

$$P_{Et} = (\alpha^f)^{1/\theta^f} \mu_t^{nom} \left( \frac{Y_t(i)}{E_t^f(i)} \right)^{1/\theta^f} A_t^{(\theta^f-1)/\theta^f} \quad (\text{B.34})$$

Combining these equations, we get that the relative price of the production inputs determine the trade-off between them:

$$\frac{E_t^f(i)}{N_t(i)} = \frac{\alpha^f}{1 - \alpha^f} \left( \frac{P_{Et}}{W_t} \right)^{-\theta^f} \quad (\text{B.35})$$

The total factor productivity:

$$\ln(A_t) \equiv a_t = \rho_a a_{t-1} + \varepsilon_t^a \quad (\text{B.36})$$

#### Price setting

$$\max_{P_{Ht}(i), N_t(i)} \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{t+1} \left[ \frac{P_{Ht}(i)}{P_{Ht}} Y_t(i) - \frac{W_t}{P_{Ht}} N_t(i) - P_{Et} E_t^f(i) - Y_t FC_t \right] \quad (\text{B.37})$$

$$\text{s.t. demand curve } Y_t(i) = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} Y_t \quad (\text{B.38})$$

$$\text{price adjustment costs } FC_t(i) = \frac{\xi}{2} \left( \frac{P_{Ht}(i)}{P_{H,t-1}(i)} - 1 \right)^2 \quad (\text{B.39})$$

<sup>38</sup>The Lagrange multiplier on the demand curve  $\mu_t^{nom}$  is the nominal marginal cost.

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where  $\Lambda_{t+1} = \beta \left( \frac{C_{t+1}}{C_t} \right)^{-\sigma}$  is the stochastic discount factor and  $\int_0^1 P_{Ht}(i) = P_{Ht}$  the average price of  $H$  goods. First order condition w.r.t.  $P_{Ht}(i)$  is:<sup>39</sup>

$$(1 - \epsilon) \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)^{-\epsilon} \frac{1}{P_{Ht}} Y_t(i) - \xi \left( \frac{P_{Ht}(i)}{P_{H,t-1}(i)} - 1 \right) \frac{1}{P_{H,t-1}(i)} Y_t(i) + \mu_t \epsilon P_{Ht}(i)^{-\epsilon-1} \left( \frac{1}{P_{Ht}} \right)^{-\epsilon} Y_t(i) + \mathbb{E}_t \left[ \Lambda_{t+1} \xi \left( \frac{P_{H,t+1}(i)}{P_{Ht}(i)} - 1 \right) Y_{t+1}(i) \left( \frac{P_{H,t+1}(i)}{P_{Ht}(i)^2} \right) \right] = 0 \quad (\text{B.40})$$

Imposing the symmetric equilibrium conditions  $P_{Ht}(i) = P_{Ht}$  and  $Y_t(i) = Y_t$ , derive the New Keynesian Philips Curve (NKPC):

$$(1 - \epsilon) - \xi (\Pi_{Ht} - 1) \Pi_{Ht} + \mu_t \epsilon + \beta \mathbb{E}_t \left[ \xi (\Pi_{H,t+1} - 1) \Pi_{H,t+1} \frac{Y_{t+1}}{Y_t} \right] = 0 \quad (\text{B.41})$$

where  $\Pi_{Ht} = \left( \frac{P_{Ht}(i)}{P_{Ht}} \right)$  is inflation of the Home-produced good.

Aggregate price adjustment costs:

$$FC_t = \int_0^1 FC_t(i) di \quad (\text{B.42})$$

Aggregate nominal profits:

$$D_t = P_{Ht} Y_t (1 - FC_t) - W_t N_t - P_{Et} E_t^f \quad (\text{B.43})$$

### B.1.3 Summary of model equations

Relative prices

$$P_{Ot} = \left[ (1 - \alpha_I) P_{Ht}^{1-\gamma} + \alpha_I P_{Ft}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \quad (\text{B.44})$$

$$P_{Ot}^* = \left[ \alpha_I^* P_{Ht}^{1-\gamma} + (1 - \alpha_I^*) P_{Ft}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \quad (\text{B.45})$$

$$P_t = \alpha_E \log P_{Et} + (1 - \alpha_E) \log P_{Ot} \quad (\text{B.46})$$

$$P_t^* = \alpha_E \log P_{Et}^* + (1 - \alpha_E) \log P_{Ot}^* \quad (\text{B.47})$$

$$S_t = \frac{P_{Ft}}{P_{Ht}} \quad (\text{B.48})$$

$$P_t^{rel,EO} = \frac{P_{Et}}{P_{Ot}} \quad (\text{B.49})$$

$$P_t^{rel,EO*} = \frac{P_{Et}^*}{P_{Ot}^*} \quad (\text{B.50})$$

$$P_{Et} = P_{Et}^* \quad (\text{B.51})$$

<sup>39</sup>The Lagrange multiplier on the demand curve  $\mu_t$  is the real marginal cost.

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### Households.

$$C_t = E_t^h + C_{Ot} \quad (\text{B.52})$$

$$C_t^* = E_t^{h*} + C_{Ot}^* \quad (\text{B.53})$$

$$C_{Ot} = \left[ (1 - \alpha_I)^{1/\gamma} (C_{Ht})^{(\gamma-1)/\gamma} + (\alpha_I)^{1/\gamma} (C_{Ft})^{(\gamma-1)/\gamma} \right]^{\gamma/(\gamma-1)} \quad (\text{B.54})$$

$$C_{Ot}^* = \left[ (1 - \alpha_I^*)^{1/\gamma} (C_{Ft}^*)^{(\gamma-1)/\gamma} + (\alpha_I^*)^{1/\gamma} (C_{Ht}^*)^{(\gamma-1)/\gamma} \right]^{\gamma/(\gamma-1)} \quad (\text{B.55})$$

$$\frac{C_{Ht}}{C_{Ft}} = \frac{1 - \alpha_I}{\alpha_I} \left( \frac{P_{Ht}}{P_{Ft}} \right)^{-\gamma} = \frac{1 - \alpha_I}{\alpha_I} S_t^\gamma \quad (\text{B.56})$$

$$\frac{C_{Ht}^*}{C_{Ft}^*} = \frac{1 - \alpha_I^*}{\alpha_I^*} \left( \frac{P_{Ht}}{P_{Ft}} \right)^{-\gamma} = \frac{1 - \alpha_I^*}{\alpha_I^*} S_t^\gamma \quad (\text{B.57})$$

$$C_{Ot} = \frac{[1 - \alpha_E \varpi_t]}{\alpha_E \varpi_t} P_t^{rel,EO} E_t^h \quad (\text{B.58})$$

$$C_{Ot}^* = \frac{[1 - \alpha_E \varpi_t^*]}{\alpha_E \varpi_t^*} P_t^{rel,EO*} E_t^{h*} \quad (\text{B.59})$$

$$\varpi_t = \left( \frac{P_{Ot}}{exp_t} \right)^{\varepsilon_1} \left( \frac{P_{Et}}{P_{Ot}} \right)^{\varepsilon_2} = (exp_t^{rel})^{-\varepsilon_1} (P_t^{rel,EO})^{\varepsilon_2} \quad (\text{B.60})$$

$$\varpi_t^* = \left( \frac{P_{Ot}^*}{exp_t^*} \right)^{\varepsilon_1} \left( \frac{P_{Et}^*}{P_{Ot}^*} \right)^{\varepsilon_2} = (exp_t^{rel*})^{-\varepsilon_1} (P_t^{rel,EO*})^{\varepsilon_2} \quad (\text{B.61})$$

$$exp_t^{rel} = P_t^{rel,EO} E_t^h + C_{Ot} \quad (\text{B.62})$$

$$exp_t^{rel*} = P_t^{rel,EO*} E_t^{h*} + C_{Ot}^* \quad (\text{B.63})$$

$$N_t = \bar{N} \quad (\text{B.64})$$

$$N_t^* = \bar{N} \quad (\text{B.65})$$

$$\left( \frac{\mathbb{E}_t [exp_{t+1}^{rel}]}{exp_t^{rel}} \right)^{1-\varepsilon_1} = \beta \frac{R_t}{1 + P_{Ot} \tilde{\nu}(b_t - \bar{b})} \mathbb{E}_t \left[ \Pi_{O,t+1}^{-1} \right] \quad (\text{B.66})$$

$$\left( \frac{\mathbb{E}_t [exp_{t+1}^{rel*}]}{exp_t^{rel*}} \right)^{1-\varepsilon_1} = \beta \frac{R_t}{1 + P_{Ot}^* \tilde{\nu}(b_t^* - \bar{b})} \mathbb{E}_t \left[ \left( \Pi_{O,t+1}^* \right)^{-1} \right] \quad (\text{B.67})$$

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### Firms.

$$Y_t = A_t \left[ (\alpha^f)^{1/\theta^f} (E_t^f)^{(\theta^f-1)/\theta^f} + (1-\alpha^f)^{1/\theta^f} (N_t)^{(\theta^f-1)/\theta^f} \right]^{\theta^f/(\theta^f-1)} \quad (\text{B.68})$$

$$Y_t^* = A_t^* \left[ (\alpha^f)^{1/\theta^f} (E_t^{f*})^{(\theta^f-1)/\theta^f} + (1-\alpha^f)^{1/\theta^f} (N_t^*)^{(\theta^f-1)/\theta^f} \right]^{\theta^f/(\theta^f-1)} \quad (\text{B.69})$$

$$\ln(A_t) \equiv \hat{a}_t = \rho_a \hat{a}_{t-1} + \varepsilon_t^a \quad (\text{B.70})$$

$$\ln(A_t^*) \equiv \hat{a}_t^* = \rho_a \hat{a}_{t-1}^* + \varepsilon_t^{a*} \quad (\text{B.71})$$

$$\frac{W_t}{P_t} = (1-\alpha^f)^{1/\theta^f} \mu_t \left( \frac{Y_t}{N_t} \right)^{1/\theta^f} A_t^{(\theta^f-1)/\theta^f} \quad (\text{B.72})$$

$$\frac{W_t^*}{P_t^*} = (1-\alpha^f)^{1/\theta^f} \mu_t^* \left( \frac{Y_t^*}{N_t^*} \right)^{1/\theta^f} (A_t^*)^{(\theta^f-1)/\theta^f} \quad (\text{B.73})$$

$$\frac{P_{Et}}{P_t} = (\alpha^f)^{1/\theta^f} \mu_t \left( \frac{Y_t}{E_t^f} \right)^{1/\theta^f} A_t^{(\theta^f-1)/\theta^f} \quad (\text{B.74})$$

$$\frac{P_{Et}^*}{P_t^*} = (\alpha^f)^{1/\theta^f} \mu_t^* \left( \frac{Y_t^*}{E_t^{f*}} \right)^{1/\theta^f} (A_t^*)^{(\theta^f-1)/\theta^f} \quad (\text{B.75})$$

$$(\Pi_{Ht} - 1) \Pi_{Ht} = \frac{\epsilon}{\xi} (\mu_t - \bar{\mu}) + \beta \mathbb{E}_t \left[ (\Pi_{H,t+1} - 1) \Pi_{H,t+1} \frac{Y_{t+1}}{Y_t} \right] \quad (\text{B.76})$$

$$(\Pi_{Ft} - 1) \Pi_{Ft} = \frac{\epsilon}{\xi} (\mu_t^* - \bar{\mu}) + \beta \mathbb{E}_t \left[ (\Pi_{F,t+1} - 1) \Pi_{F,t+1} \frac{Y_{t+1}^*}{Y_t^*} \right] \quad (\text{B.77})$$

### Goods market clearing.

$$Y_t = (1-\alpha_I) (P_{Ht}^{rel})^{-\theta} C_{Ht} + \alpha_I (P_{Ht}^{rel*})^{-\theta} C_{Ht}^* + AC_t + FC_t + T_t \quad (\text{B.78})$$

$$Y_t^* = \alpha_I (P_{Ft}^{rel})^{-\theta} C_{Ft} + (1-\alpha_I) (P_{Ft}^{rel*})^{-\theta} C_{Ft}^* + AC_t^* + FC_t^* \quad (\text{B.79})$$

### Energy market clearing.

$$E_t = E_t^h + E_t^{h*} + E_t^f + E_t^{f*} \quad (\text{B.80})$$

$$E_t = E_{t-1}^{\rho_e} \bar{E}^{1-\rho_e} \exp(\varepsilon_t^e) \quad (\text{B.81})$$

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### Bonds market clearing.

$$CA_t = r_{t-1}b_{t-1}^h + P_{Ht}Y_t(1 - FC_t) - P_{Ot}C_{Ot} - HC_t \quad (\text{B.82})$$

$$CA_t^* = r_{t-1}b_{t-1}^{h*} + P_{Ft}Y_t^*(1 - FC_t^*) - P_{Ot}^*C_{Ot}^* - HC_t^* \quad (\text{B.83})$$

$$(CA_t)^\Theta = - (CA_t^*)^{1-\Theta} \quad (\text{B.84})$$

$$(b_t^h)^\Theta = - (b_t^{h*})^{1-\Theta} \quad (\text{B.85})$$

### Monetary policy.

$$R_t = \frac{1}{\beta} \left( \frac{\Pi_t^W}{\bar{\Pi}^W} \right)^{\phi_\pi} \left( \frac{Y_t^W}{\bar{Y}_t^W} \right)^{\phi_y} \exp(\nu_t) \quad (\text{B.86})$$

$$\nu_t = \rho^\nu \nu_{t-1} + \varepsilon_t^\nu \quad (\text{B.87})$$

### Fiscal policy.

$$P_{Et}^{eff} = P_{Et} - CAP_t \quad (\text{B.88})$$

$$CAP_t = P_{Et} - \bar{P}_E \quad (\text{B.89})$$

$$CAP_t(E_t^h + E_t^f) = T_t \quad (\text{B.90})$$

$$CAP_t^{exp} = \frac{CAP_t(E_t^h + E_t^f)}{Y_t} \quad (\text{B.91})$$

## B.1.4 Steady state

This section characterizes the steady state of the Home economy. The Foreign economy is identical. In steady state, the prices are constant. Hence, the inflation rates are all equal to unity.

$$\bar{\Pi} = 1 \quad (\text{B.92})$$

$$\bar{\Pi}_E = 1 \quad (\text{B.93})$$

$$\bar{\Pi}_O = 1 \quad (\text{B.94})$$

I take  $\bar{P}_O = 1$  as the numeraire. With the below calculations, I get the exogenous level of energy  $\bar{E}$  which sets the steady-state price of energy also equal to unity, so  $\bar{P}_E = 1$ .

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**Demand side.** Taking the Euler equation in steady state, I can express the steady state nominal interest rate as a function of the discount factor:

$$\bar{R} = \frac{1}{\beta} \quad (\text{B.95})$$

Moreover, I assume that the energy expenditure wedge  $\varpi_t$  is unity in steady state, so that the expenditure shares of energy and the other consumption goods are the same as in the benchmark Cobb-Douglas case:

$$\bar{\varpi} = 1 \quad (\text{B.96})$$

Then, since prices are equal to unity in steady state, I obtain that steady-state total expenditure of the household from the food expenditure wedge equation:

$$e\bar{x}p = \bar{\varpi}^{1/\varepsilon_1} \quad (\text{B.97})$$

From the Marshallian demands from Footnote 35, derive the steady-state values for energy and other goods consumption:

$$\bar{E}^h = \alpha_E e\bar{x}p \bar{\varpi} \quad (\text{B.98})$$

$$\bar{C}_O = (1 - \alpha_E \bar{\varpi}) e\bar{x}p \quad (\text{B.99})$$

Then, from the goods market clearing condition, get the steady-state output value:

$$Y = (1 - \alpha_I) \bar{C}_O + \alpha_I^* \bar{C}_O^* \quad (\text{B.100})$$

**Supply side.** From the price-setting equation of the firms, get the steady-state real marginal cost:

$$\bar{\mu} = \frac{\epsilon - 1}{\epsilon} \quad (\text{B.101})$$

Since  $\exp(\bar{a})$  scales the economy, I set the total factor productivity  $\bar{a}$  such that  $\exp(\bar{a}) = 1$ :

$$\bar{a} = 0 \quad (\text{B.102})$$

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From the energy demand equation of the firms, get the steady-state value for the firms' energy use:

$$\bar{E}^f = \alpha^f (\bar{\mu})^{\theta^f} \bar{Y} \quad (\text{B.103})$$

Then, from the production function, obtain the steady-state value for labor:

$$\bar{N} = \left[ \frac{Y - (\alpha^f)^{1/\theta^f} (\bar{E}^f)^{(\theta^f-1)/\theta^f}}{(1 - \alpha^f)^{1/\theta^f}} \right]^{(\theta^f)/(\theta^f-1)} \quad (\text{B.104})$$

Using the steady-state values for labor, output and marginal cost, get the real wage:

$$\bar{W}^{real} = (1 - \alpha^f)^{1/\theta^f} \bar{\mu} \left( \frac{\bar{Y}}{\bar{N}} \right)^{1/\theta^f} \quad (\text{B.105})$$

The profits in steady state are:

$$\bar{D} = Y - \bar{W}^{real} \bar{N} - \bar{E}^f \quad (\text{B.106})$$

**Check supply and demand side are consistent.** From the budget constraint of the household, check that the following equation holds:

$$e\bar{x}p = \bar{W}^{real} \bar{N} + \bar{D} + \bar{E}^h + \bar{E}^f \quad (\text{B.107})$$

For the two-agent version, check that the aggregate budget constraint (constrained and unconstrained household holds combined) holds:

$$e\bar{x}p = \bar{W} \bar{N} + (1 - \delta) \bar{D} + \bar{E}^h + \bar{E}^f + \lambda \tau_t^c + (1 - \lambda) \tau_t^u \quad (\text{B.108})$$

### B.1.5 Domestic energy production sector

The oligopolistic energy firm's problem is

$$\max_{N_{Et}} P_{Et} Y_{Et} - W_t N_{Et} \quad (\text{B.109})$$

$$\text{s.t. production function } Y_{Et} = A_{Et} N_{Et}^\eta \quad (\text{B.110})$$

The first-order condition gives rise to the labor demand:

$$N_{Et} = \left( \eta A_{Et} \frac{P_{Et}}{W_t} \right)^{\frac{1}{1-\eta}}, \quad (\text{B.111})$$

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which determines the energy production:

$$Y_{Et} = A_{Et}^{\frac{1}{1-\eta}} \left( \eta \frac{P_{Et}}{W_t} \right)^{\frac{\eta}{1-\eta}} \quad (\text{B.112})$$

and the profits of the energy firm:

$$D_{Et} = (1 - \eta) P_{Et} Y_{Et} \quad (\text{B.113})$$

### B.2 Bayesian estimation: Details on data used and results

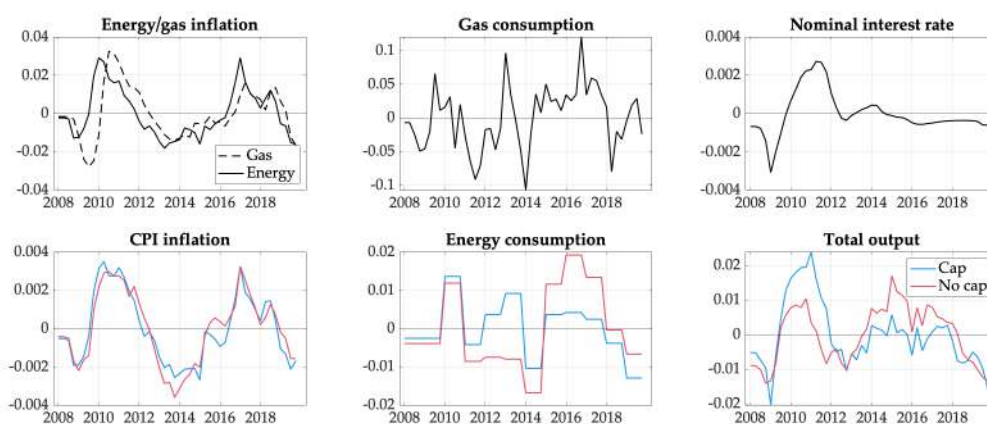
In this section, I describe and present the data used for Bayesian estimation. For the first estimation, to estimate the parameters, I use data from before the COVID-19 pandemic, so 2008Q1 – 2019Q4. For the second estimation, to perform a historic shock decomposition of the shock, I use data up to 2022Q4. I seasonally adjust the all data series with X-13ARIMA-SEATS. When the data is monthly, I transform the data to get quarterly equivalents. To get the aggregates for “Cap” and “No cap” countries, I take weighted averages with country weights from Eurostat Data. Finally, I detrend the data with the one-sided Hodrick-Prescott filter and demean the series to match the model variables.

**Pre-pandemic data for estimating parameters.** The data used for the estimation parameters are in Figure B.1.<sup>40</sup> Since the price cap policy only took place in 2022, the energy and gas inflation in the union is the same across countries. Using gas consumption as a common variable avoids stochastic singularity. Since I assume that the countries in the union share one supply of gas, when the gas price is the same across countries the gas consumption also needs to be the same. Nominal interest is the rate that the European Central Bank sets. Energy consumption is yearly data. Hence, I allow for measurement errors in the model to capture quarterly fluctuations.

<sup>40</sup>Data sources: Energy, gas, and CPI inflation (Eurostat, `prc_hicp_manr`), gas consumption (Eurostat, `nrg_cb_gasm`), nominal interest rate (Eurostat, `irt_st_q`), total output (Eurostat, `namq_10_pc`), energy consumption (Our World in Data, Per capita primary energy consumption by source). When data are not per capita and they need to be, I use intrapolated population data (Eurostat, `demo_pjan`) to transform them to per capita variables.

## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

**Figure B.1:** Data used for estimation of parameters



*Notes:* Plot of the Euro Area data used in the Bayesian estimation of the parameters. For the lower panels I separate the Euro Area countries into “Cap” and “No cap” countries, according to whether countries imposed an energy cap in 2022 or not. See Figure 2.2 for details.

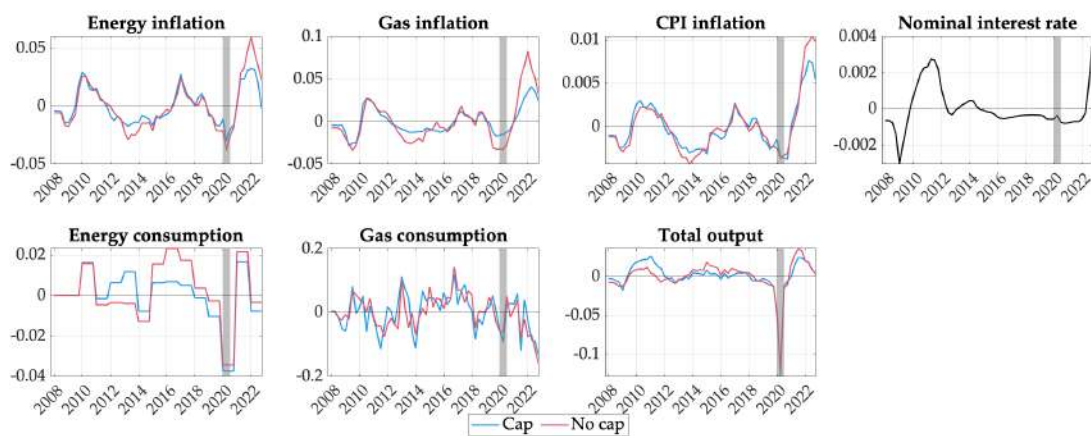
**Data for historical shock decomposition.** The data used for the historical shock decomposition are in Figure B.2. The data sources are identical to those for the pre-pandemic data. However, since I detrend the data over a slightly longer sample, the values are somewhat different. Moreover, I only let the energy and gas inflation diverge in 2022. Before 2022, I take the weighted average of the two blocs, since there are no price caps in place. Figure B.2 shows that the energy and gas inflation rates moved very closely between “Cap” and “No cap” countries before 2022.

**Estimation method.** I use the Bayesian estimation approach built in Dynare Adjemian et al. (2024). For the estimation of the parameters, I use a slice optimizer to find the mode of the posterior distribution.<sup>41</sup> Then, the Metropolis-Hastings algorithm evaluates the marginal likelihood of the model and produces the posterior distributions. I use one million replications for each chain of the algorithm and four parallel chains. I check that the Monte Carlo Markov Chain converges and that the posterior chain for each parameter is stable. The posterior plots are in Figure B.3. For the historical shock decomposition, I use the `shock_decomposition`-command in Dynare, which uses the Kalman

<sup>41</sup>Option 5 of the `mode_compute`-option in the `estimation`-command in Dynare.

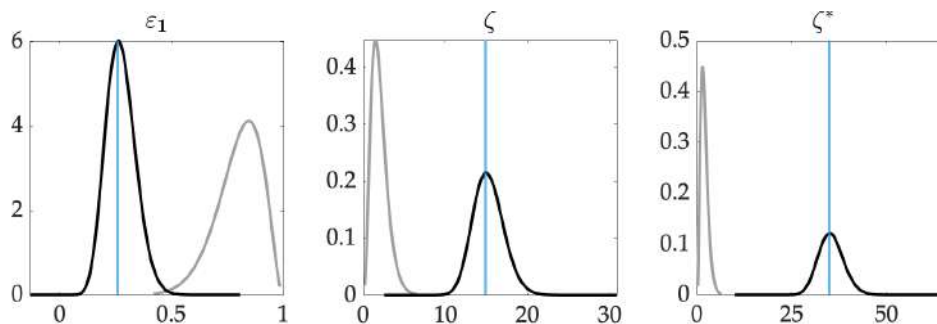
## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

**Figure B.2:** Data used for historical shock decomposition



*Notes:* Plot of the data used in the historical shock decomposition. I separate the Euro Area countries into “Cap” and “No cap” countries, according to whether countries imposed an energy cap in 2022 or not. See Figure 2.2 for details. Grey-shaded area are 2020Q1 and Q2, the quarters most affected by the COVID-19 pandemic.

**Figure B.3:** Prior and posterior distributions



*Notes:* Plot of the prior distribution (gray) and the posterior distribution (black). The vertical blue line indicates the posterior mode. The y-axis displays the density of the distributions.

smoother to decompose the historical fluctuations of the variables into contributions from each shock.

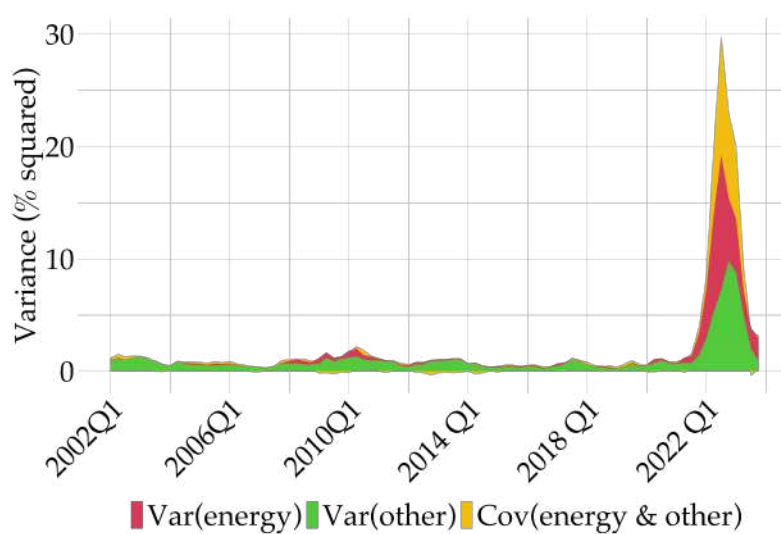
### B.3 Additional figures

**Figure B.4:** Natural gas price in Europe



*Notes:* The price index of the Title Transfer Facility (TTF) gas in the Netherlands. Data source: IMF Data (2024).

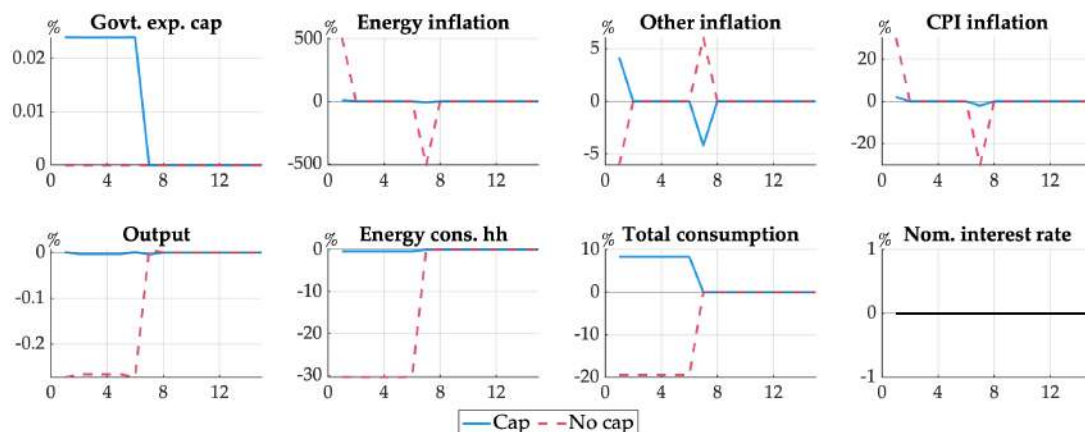
**Figure B.5:** Decomposition of the variance of headline inflation



*Notes:* The headline inflation in country  $i$  in quarter  $t$  is  $\Pi_{it} = (1 - \alpha_{it}^E)\Pi_{it}^O + \alpha_{it}^E\Pi_{it}^E$  where  $\alpha^{ENG}$  is the share of energy in the consumption basket,  $\Pi_{it}^E$  and  $\Pi_{it}^O$  energy and other goods inflation. The variance decomposition is across countries for each quarter, so  $Var_t(\Pi_{it}) = Var_t[(1 - \alpha_{it}^E)\Pi_{it}^O + \alpha_{it}^E\Pi_{it}^E]$ . Data source: Eurostat.

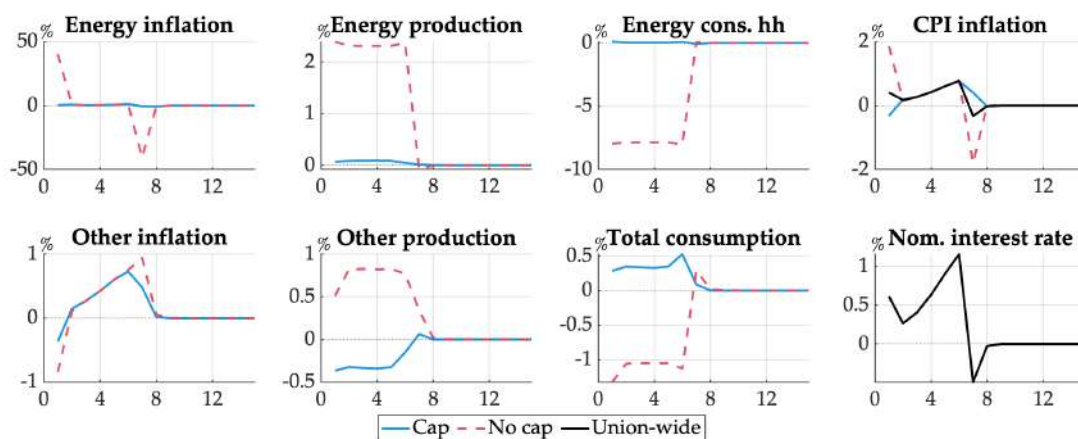
## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

**Figure B.6:** Responses to an adverse energy supply shock | Cap vs. no cap under core-inflation targeting



*Notes:* Impulse responses to a 15% decline in energy supply, in a model in which the central bank targets other inflation (core inflation). Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

**Figure B.7:** Responses to an adverse energy supply shock | Cap vs. no cap with TANK

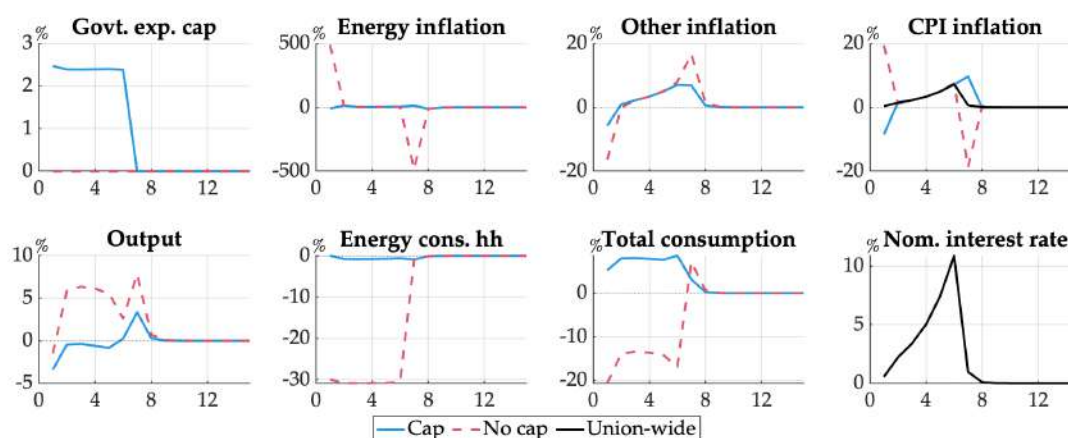


*Notes:* Impulse responses to a 15% decline in energy supply, in the two-agent version of the model. Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

### B.3.1 Results under elastic labor supply

**Figure B.8:** Responses to an adverse energy supply shock | Cap vs. no cap with elastic labor supply



*Notes:* Impulse responses to a 15% decline in energy supply, in a model with elastic labor supply. Preferences are non-homothetic. The bigger country, of size  $\Theta$  imposes a price cap on the energy price (blue, solid) and the smaller country, of size  $1 - \Theta$  does not (red, dashed). The black solid lines show the union-wide variables. Output is equal to the output gap. Government expenditure on the price cap (Govt. exp. cap) is the cost of the cap as a share of annual total output of the country (GDP). The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

**Table B.1:** Welfare gains/losses after energy supply shock

(a) Baseline

(b) Elastic labor supply

	%	1/3 of union	
		Cap	No cap
2/3	Cap	(-1.04, -1.04)	(0.49, -1.08)
	No cap	(-1.08, 0.42)	(-0.05, -0.05)

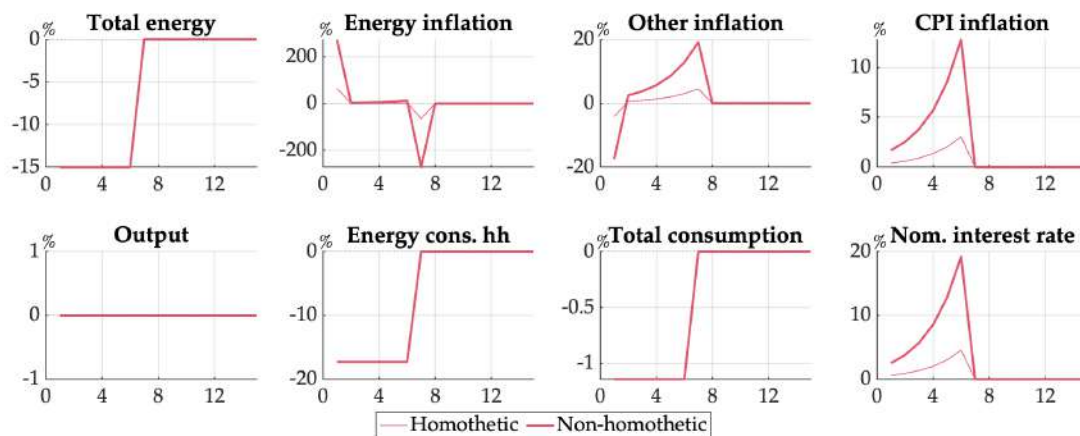
	%	1/3 of union	
		Cap	No cap
2/3	Cap	(-0.86, -0.86)	(0.40, -0.72)
	No cap	(-0.97, 0.53)	(-0.03, -0.03)

*Notes:* Welfare gains and losses after a 15% energy supply shock, in a model with elastic labor supply. The gains and losses are in terms of the consumption equivalent relative to the steady state. The circles are around the preferred policy choices (Cap or No cap) for the countries.

## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

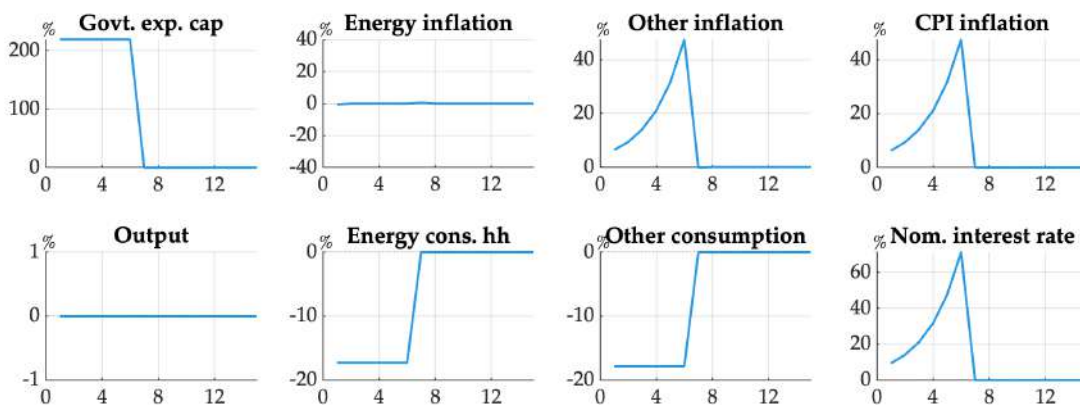
### B.3.2 Results under flexible prices

**Figure B.9:** Responses to an adverse energy supply shock | No price caps with flexible prices



*Notes:* See Figure B.8. Impulse responses to a 15% decline in energy supply, in a model with flexible prices.

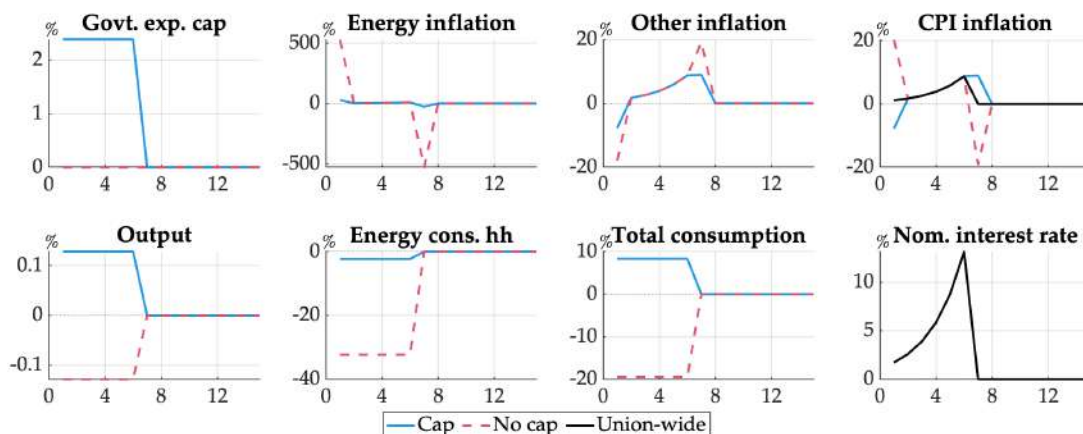
**Figure B.10:** Responses to an adverse energy supply shock | Price caps with flexible prices



*Notes:* See Figure B.8. Impulse responses to a 15% decline in energy supply, in a model with flexible prices.

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**Figure B.11:** Responses to an adverse energy supply shock | Cap vs. no cap with flexible prices



Notes: See Figure B.8. Impulse responses to a 15% decline in energy supply, in a model with flexible prices.

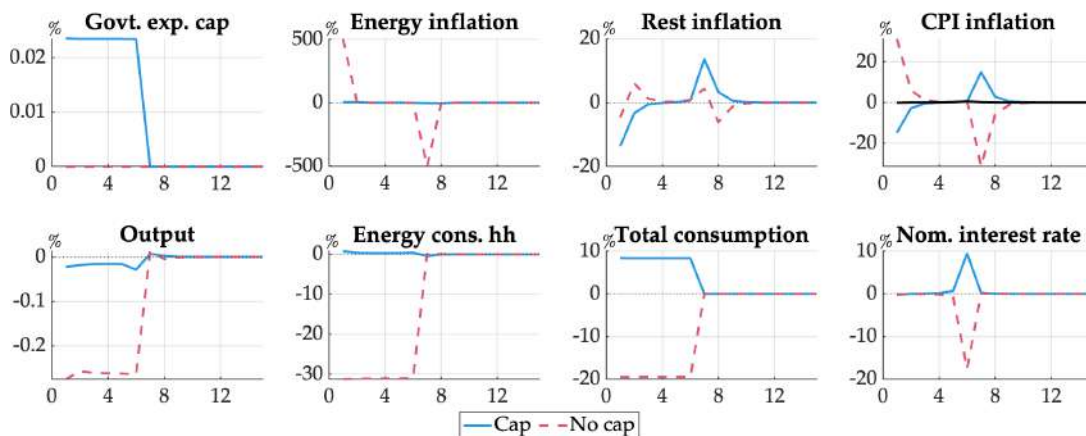
**Table B.2:** Welfare gains/losses after energy supply shock

		(a) Baseline		(b) Flexible prices	
		1/3 of union		1/3 of union	
		Cap	No cap	Cap	No cap
2/3	Cap	(-1.04, -1.04)	(0.49, -1.08)	(-1.04, -1.04)	(0.49, -1.08)
	No cap	(-1.08, 0.42)	(-0.05, -0.05)	(-1.08, 0.42)	(-0.05, -0.05)

Notes: See Table B.1. Welfare gains and losses after a 15% energy supply shock, in a model with flexible prices.

### B.3.3 Results under flexible exchange rates

**Figure B.12:** Responses to an adverse energy supply shock | Cap vs. no cap in world with flexible nominal exchange rates



Notes: See Figure B.8. Impulse responses to a 15% decline in energy supply, in a model with flexible nominal exchange rates.

## 2. To Cap or Not to Cap? Energy Crises in a Currency Union

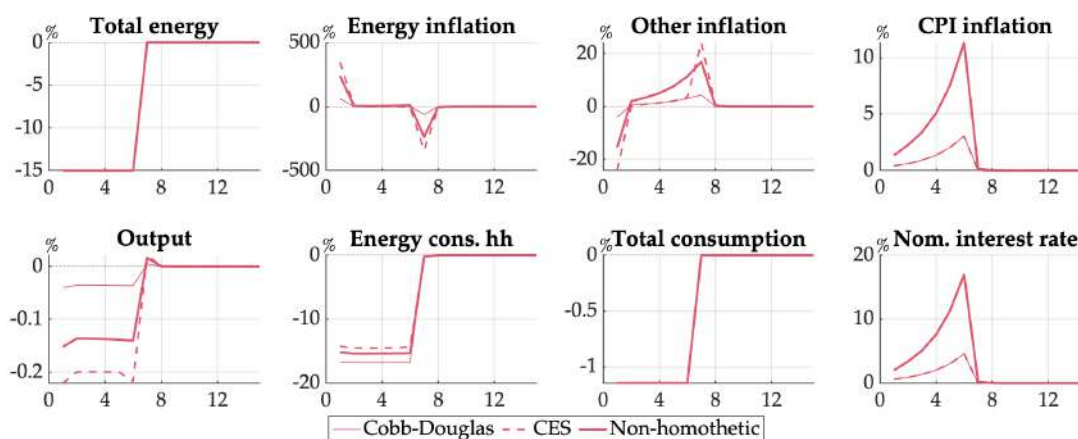
**Table B.3:** Welfare gains/losses after energy supply shock

(a) Baseline			(b) Flexible nominal exchange rate			
%	1/3 of union		%	1/3 of union		
	Cap	No cap		Cap	No cap	
2/3	Cap	(-1.04, -1.04)	(0.49, -1.08)	Cap	(-1.04, -1.04)	(0.49, -1.08)
	No cap	(-1.08, 0.42)	(-0.05, -0.05)	No cap	(-1.07, 0.42)	(-0.05, -0.05)

Notes: See Table B.1. Welfare gains and losses after a 15% energy supply shock, in a model with flexible nominal exchange rates.

### B.3.4 Results under CES preferences

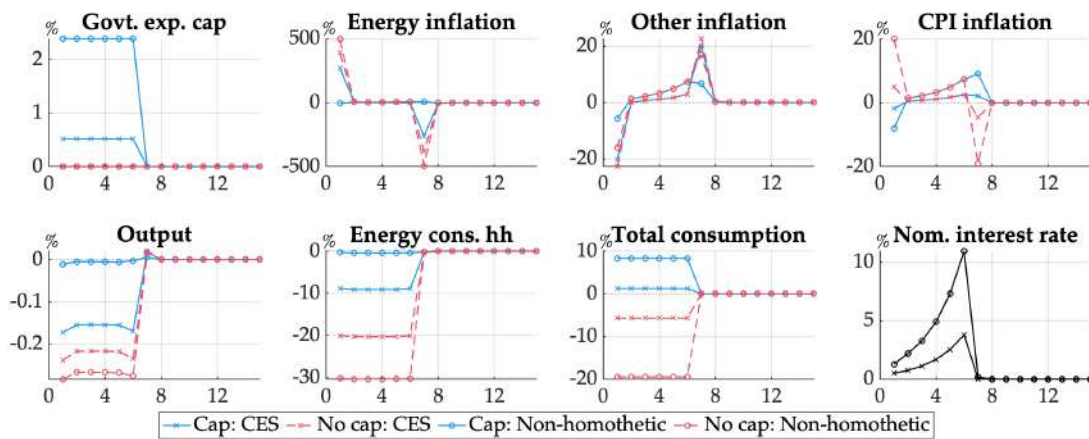
**Figure B.13:** Responses to an adverse energy supply shock | No caps with CES preferences



Notes: Impulse responses to a 15% decline in energy supply. The graph compares three types of preferences: Cobb-Douglas (solid, thin), Constant Elasticity of Substitution (CES) (dashed), and non-homothetic preferences (solid, bold). Output is equal to the output gap. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

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**Figure B.14:** Responses to an adverse energy supply shock | Cap vs. no cap with CES preferences



*Notes:* See Figure B.8. Impulse responses to a 15% decline in energy supply, in a model with CES preferences.

# Chapter 3

## Monetary and Exchange Rate Policies Under Diagnostic Expectations<sup>\*</sup>

**Abstract** What is the optimal degree of exchange rate stabilization in an open economy? We revisit this classic question by introducing Diagnostic Expectations (DE) into a standard New Keynesian small open-economy model. DE is a departure from the Rational Expectations hypothesis which, through an overreaction of agents' beliefs, generates additional endogenous macroeconomic volatility. As a first pass at disciplining the model with data, we find that the inclusion of DE can help resolve key empirical exchange rate puzzles identified in the literature such as the exchange rate disconnect and forward premium puzzles. In terms of optimal monetary policy, we find that the model with DE can alter the welfare rankings of selected exchange rate regimes established in earlier studies. In particular, under reasonable assumptions regarding the strength of DE, simulations suggest that an exchange rate peg could be welfare superior to a policy that targets consumer price index (CPI) inflation. Importantly, extreme model parameterizations are not needed to justify exchange rate stabilization.

**Keywords** small open economy, diagnostic expectations, optimal monetary policy

**JEL codes** E52, F41, D84

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<sup>\*</sup>Joint work with Lahcen Bounader, Selim Elekdag, and Luis-Felipe Zanna. The views expressed in this paper are those of the author(s) and do not necessarily represent the views of the IMF, its Executive Board, or IMF management.

## 3.1 Introduction

The optimal degree of exchange rate stabilization is a perennial topic of debate within academic and policy circles alike. Under strong assumptions which facilitate analytical results, a classic study by Galí and Monacelli (2005) shows how the monetary policy implications of an open economy are similar to a closed-economy model, without a role for exchange rate stabilization. In contrast, the subsequent literature has relaxed these restrictive assumptions and demonstrated that optimal monetary policy could result in the stabilization of the exchange rate.<sup>1</sup>

In this paper, we investigate the implications of relaxing the assumption of Rational Expectations in the context of optimal monetary policy for a small open economy. Motivated by a vast literature that rejects the pure form of the Rational Expectations Hypothesis, we introduce Diagnostic Expectations (Bordalo et al., 2018), a departure from Rational Expectations (RE) which allows for an overreaction of beliefs—and hence greater endogenous macroeconomic volatility—in an otherwise standard small open-economy model.

Recent research shows that a macroeconomic model with Diagnostic Expectations (DE) can better capture empirically relevant macroeconomic dynamics relative to closed-economy RE models (see, for example, Bianchi et al. (2024), Bounader and Elekdag (2024), and L’Huillier et al. (2024)). Moreover, the DE framework is a simple, parsimonious, and microfounded deviation from RE that is immune to the Lucas critique. The framework incorporates overreaction to news, which the psychology and experimental economics literature present as a plausible and an empirically validated framework of belief formation (e.g., Bordalo et al. (2018)).

By introducing DE into an otherwise standard small, open-economy New Keynesian model, this paper presents two key sets of results. First, our model with DE can help resolve two longstanding empirical puzzles, which, as noted by

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<sup>1</sup>See for example, Engel (2014) or, more recently, Itskhoki and Mukhin (2023).

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Obstfeld and Rogoff (2000), are a part of a literature focusing on the disconnect between exchange rate movements and the fluctuations of key macroeconomic variables. Regarding the first puzzle, because DE endogenously generates greater volatility relative to the RE model, especially for the nominal exchange rate, our model holds promise in terms of addressing the Meese and Rogoff (1983) puzzle, or the exchange rate disconnect puzzle, which states that the nominal exchange rate follows a random-walk-like process. As for the second puzzle, the incorporation of DE helps our model better match the empirical Fama (1984) regressions, thus addressing the uncovered interest parity violations found in the data, and thereby helping in the resolution of the forward premium puzzle. Even though these empirical exercises represent a first pass at disciplining our augmented model with the data, the fact that the model with DE can help address these puzzles is reassuring.

Second, in terms of loss-minimizing monetary policy, we find that the model with DE can alter the welfare rankings of selected exchange rate regimes established in earlier studies. In particular, even in the open-economy context, previous papers have argued that an inward-looking policy of targeting (domestic) inflation is optimal. However, these studies abstract from the terms-of-trade externality which refers to the incentive for policymakers to influence the terms of trade to their advantage: When domestic prices increase, the relative price of imported goods decrease, resulting in a terms-of-trade improvement. If domestic and foreign goods are close substitutes, households can consume more imported goods (expenditure switching), without necessarily increasing labor effort, thereby improving welfare. At the same time, expenditure switching is associated with greater trade balance and output fluctuations. Under DE, however, given the greater volatility of exchange rates, it could be desirable to stabilize the exchange rate (and thereby output). More specifically, model simulations suggest that an exchange rate peg could be welfare superior relative to a policy that targets consumer price index (CPI) inflation. Importantly, extreme model parameterizations are not needed to justify exchange rate stabilization.

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Finally, by optimizing over simple rules, we find that DE strengthen the exchange rate channel of monetary policy through fluctuations in the UIP and hence the central bank should react less to CPI inflation under DE.

**Diagnostic Expectations** Diagnostic Expectations (DE) is a departure from the Rational Expectations (RE) hypothesis which, through an overreaction of agents' beliefs, generates additional endogenous macroeconomic volatility. DE is based on the representative heuristic by Tversky and Kahneman (1983): "An attribute is representative of a class if it is very diagnostic; that is, the relative frequency of this attribute is much higher in that class than in the relevant reference class". They state that an individual often assesses likelihood by representativeness. A simple example, taken from Bordalo et al. (2018), illustrates this claim: Consider an individual guessing the hair color ( $X$ ) of an individual given data,  $D = Irish$ . The individual is likely to overestimate the probability of an Irish person having red hair, because having red hair is representative for the Irish. That is, relative to the rest of the world, the Irish have a higher likelihood of having red hair.<sup>2</sup>

Bordalo et al. (2018) then derive the following tractable formalization of this idea:

$$E^\theta[\text{red hair}|Irish] = E[\text{red hair}|Irish] + \theta (E[\text{red hair}|Irish] - E[\text{red hair}|World])$$

where  $E^\theta$  is the DE operator, while  $E$  is the RE operator;  $\theta$  indicates the strength of the DE (note that with  $\theta = 0$  we revert to RE). This parameter,  $\theta$ , over weights the difference between the likelihood of Irish versus non-Irish people having red hair—that is, representativeness—when individuals form their beliefs.

Bordalo et al. (2018) introduce this idea of DE into the field of macroeconomics and finance, as an alternative to RE. They give multiple examples of economic

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<sup>2</sup>Consider a numerical example based on Gennaioli et al. (2010). Assume the probability of  $X = red$  is 10 percent and 2 percent when  $D = Irish$  and  $D = Not Irish$ , respectively. Despite the low chance of occurrence, after receiving data  $D = Irish$ , red hair color becomes representative (and, indeed, is associated with the highest likelihood ratio among hair colors). This notion of representativeness causes the agents to therefore overestimate the incidence of red hair color. This is because the true probability of occurrence (consistent with the rational expectations hypothesis) is distorted by the likelihood ratio (where  $X = red|D = Irish$  is divided by  $X = red|D = Not Irish$ ).

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agents acting under DE in the real world, for example, by showing how forecast errors by investors are predictable, instead of random. Of note, economic agents overreact to news under DE, which, owing to greater volatility, can play an important role in business cycle fluctuations. Below, in the section that presents the model, we explain how we incorporate DE into our New Keynesian small open-economy model, based on the work of Bianchi et al. (2024) as well as L’Huillier et al. (2024) who show how this type of expectation formation can be integrated into close-economy New Keynesian frameworks.

**Literature review** Our paper represents a synthesis of three strands of the literature: (i) optimal monetary policy in the open economy, (ii) exchange rate puzzles, and (iii) departures from the Rational Expectations (RE) hypothesis. The first strand investigates optimal monetary policy in open-economy settings. Clarida et al. (2001) and Galí and Monacelli (2005) show that, under certain (restrictive) assumptions, the monetary policy implications of an open economy are similar to a closed-economy environment. These papers suggest that a policymaker in an open economy should follow a purely inward-looking policy and respond only to domestic price fluctuations, such that there is no scope for exchange rate stabilization. More generally, however, when these parametric restrictions are relaxed, the optimal policy implication for the open economy is no longer isomorphic to its closed-economy counterpart. Then, movements in the nominal and real exchange rates, and hence the terms of trade, start playing a role in the welfare of the economy: As explained previously, the terms-of-trade externality arises.<sup>3</sup> Furthermore, De Paoli (2009a) emphasizes how the role of alternative asset market structures, and the degree of substitutability between domestic and foreign goods can affect optimal monetary policy. For instance, the complete markets framework of Galí and Monacelli (2005) argues for the stabilization of the domestic inflation rate. In contrast, under incomplete international financial markets, De Paoli (2009a) finds that in some cases optimal

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<sup>3</sup>See Obstfeld and Rogoff (1998), Corsetti and Pesenti (2001), Tille (2001), and G. Benigno and Benigno (2003) on the “terms-of-trade externality” and welfare in an open economy.

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monetary policy prescribes the stabilization of the exchange rate.<sup>4</sup> Likewise, Devereux and Engel (2003) argue that once the assumption of the law of one price is relaxed, optimal monetary policy leads to a fixed exchange rate.<sup>5</sup> More generally, although there is recognition that different modelling assumptions could alter the ensuing policy implications, only a handful of papers depart from the RE hypothesis, as discussed below.

The second strand of literature that this paper contributes towards tries to account for the main exchange rate puzzles observed in the data, but which are at odds with standard open-economy models. As summarized in Itskhoki and Mukhin (2021), the puzzles include the Meese and Rogoff (1983) disconnect puzzle and the forward premium puzzle (Fama, 1984), also known as the uncovered interest parity (UIP) puzzle.<sup>6</sup> Building on an expansive set of studies, Itskhoki and Mukhin (2021) propose an international real business cycle model with RE, but augmented with, *inter alia*, financial frictions, resulting in equilibrium UIP deviations due to limits to arbitrage. Their model reproduces the exchange rate disconnect observed in the data.

The third strand of the literature introduces departures from the RE hypothesis to help explain major exchange rate puzzles mentioned above (Devereux & Engel, 2002; Gourinchas & Tornell, 2004; Chakraborty & Evans, 2008; Du et al., 2021; Kolasa et al., 2022; Candian & De Leo, 2023). We build on these studies by

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<sup>4</sup>See also papers investigating two-country models, including to assess the role of policy coordination, such as Obstfeld and Rogoff (1995) and Corsetti and Pesenti (2001, 2005), and more recently, Rabitsch (2012).

<sup>5</sup>Other studies that also explore welfare and monetary policy include Sutherland (2005), Elekdag and Tchakarov (2007), and P. Benigno (2009). See Corsetti et al. (2011) for a literature review and Corsetti et al. (2010) for a thorough analysis as part of a handbook. More recent papers include Senay and Sutherland (2016), Bergin and Corsetti (2023), and Corsetti et al. (2023).

<sup>6</sup>Itskhoki and Mukhin (2021) consider several puzzles, including two we consider in this paper: The first the Meese and Rogoff (1983) puzzle where the nominal exchange rate follows a random-walk-like process which is not correlated with macroeconomic fundamentals (see also Engel and West (2005)). Moreover, the exchange rate is significantly more volatile than macroeconomic aggregates such as consumption, output, and, for instance, inflation. The second puzzle is the forward premium puzzle (Fama, 1984), or the violation of the uncovered interest rate parity (UIP): Cross-currency interest rate differentials are not balanced out by expected depreciations, and instead predict exchange rate appreciations, albeit with a very low R-squared, resulting in positive expected returns on currency carry trades. See also McCallum (1994) and Engel (1996).

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introducing DE based on the more recent work by Bordalo et al. (2018). Tversky and Kahneman (1983)'s idea of representativeness, which induces people to overestimate the probability of outcomes that are relatively more likely considering recently observed data, is key to this model of expectations. Good news does not only increase the true likelihood of good future outcomes, but also causes beliefs to overweight such outcomes. In this way, DE give rise to overreaction by agents: They are too optimistic after goods news, and too pessimistic after bad news. Bordalo et al. (2018), Bianchi et al. (2024), L'Huillier et al. (2024), and Selim Elekdag (2025) provide additional empirical evidence supporting DE.<sup>7</sup>

Our paper contributes to these strands of the literature along three dimensions: First, to our knowledge, this paper is the first that introduces DE into an open-economy framework, including to assess the implications for optimal monetary and exchange rate policy. This is a noteworthy contribution because DE is a simple, transparent, and portable departure from the RE hypothesis. At the same time, DE nests RE. In particular, RE can be recovered by simply setting the key parameter that determines the strength of DE,  $\theta$ , to zero. Bianchi et al. (2024) and L'Huillier et al. (2024) develop techniques to introduce DE into New Keynesian models. As noted above, there is also ample empirical evidence supporting the inclusion of such expectations into otherwise traditional closed-economy macroeconomic and macrofinancial models. Second, as an initial attempt at confronting our model with data, we assess how the inclusion of DE can address key empirical exchange puzzles identified in the literature. Our small, open-economy DE model can help resolve the exchange rate disconnect and Fama (1984) puzzles, including because of the associated increase in endogenous exchange rate (and, therefore, macroeconomic) volatility. Third, we investigate the implications of DE for optimal monetary policy. We find that DE can alter the welfare rankings

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<sup>7</sup>Diagnostic Expectations can also explain other macroeconomic fluctuations. Bordalo et al. (2018) use DE to explain several features of credit cycles and macroeconomic volatility in the spirit of Minsky (1977). Bordalo et al. (2021) use this form of expectations to explain stock market bubbles, Bordalo et al. (2019) to explain stock returns, d'Arienzo (2020) to explain bond yields, and Favero et al. (2023) to explain bond pricing. More recently, Bounader and Elekdag (2024) show how DE can worsen the inflation-output volatility trade-off confronting policymakers and provide evidence that targeting house price growth could result in welfare gains.

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of selected exchange rate regimes. For instance, under reasonable assumptions regarding the strength of DE, simulations suggest that an exchange rate peg could be welfare superior relative to a policy that targets consumer price index (CPI) inflation. Hence, we do not need extreme model parameterizations (which determine the strength of DE or the degree of substitutability between foreign and domestic goods) to justify exchange rate stabilization.

## 3.2 Model

We consider a standard small open economy with a representative household, a continuum of firms, and a monetary authority.<sup>8</sup> Both the household and the firms have DE, which affects the canonical equations of the standard model. We assume incomplete financial markets. We assume that the equilibrium outcomes of the small open economy (country  $H$ ) do not affect the rest of the world (country  $F$ ), but that the opposite is not true. Foreign variables have an asterisk (e.g.,  $X^*$ ).  $E_t^\theta$  is the expectations operator for DE. The full list of equilibrium conditions is in Appendix C.1.

### 3.2.1 Households

The representative households maximize their lifetime utility

$$U(C_t, N_t) + E_t^\theta \left[ \sum_{s=1}^{\infty} \beta^{t+s} U(C_{t+s}, N_{t+s}) \right] \quad (3.1)$$

where the per-period utility function is  $U(C_t, N_t) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi}$ ;  $N_t$  is the labor per period and  $\beta$  is the discount factor;  $\sigma$  and  $\varphi$  are the elasticity of intertemporal substitution and the Frisch elasticity of labor supply.  $C_t$  is a composite consumption index defined by:

$$C_t \equiv \left[ (1-\alpha)^{\frac{1}{\eta}} C_{H,t}^{\frac{\eta-1}{\eta}} + \alpha^{\frac{1}{\eta}} C_{F,t}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \quad (3.2)$$

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<sup>8</sup>Our model builds on the frameworks of Galí and Monacelli (2005) and Clarida et al. (2001).

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where  $C_{H,t}$  and  $C_{F,t}$  are an index of consumption of domestic and foreign goods, given by the Constant Elasticity of Substitution (CES) functions:

$$C_{H,t} \equiv \left( \int_0^1 C_{H,t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}} \quad C_{F,t} \equiv \left( \int_0^1 C_{F,t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}} \quad (3.3)$$

$C_{i,t}(j)$  is the quantity of good  $j$  from country  $i$ .  $\eta$  is the elasticity of substitution between domestic and foreign goods, whereas  $\epsilon$  is the elasticity of substitution between the different varieties produced in the same country.  $\alpha$  is the share of imports in the household's consumption basket and thus the degree of openness to trade. After computing the expenditure minimization problems for the intra-temporal choice between varieties and goods bundles, we can express the consumer price index (CPI) as:

$$P_t = \left[ (1 - \alpha)P_{H,t}^{1-\eta} + \alpha P_{F,t}^{1-\eta} \right]^{\frac{1}{1-\eta}} \quad (3.4)$$

Then, we can rewrite the total expenditure on consumption for the household as:

$$\int_0^1 P_{H,t}(j)C_{H,t}(j)dj + \int_0^1 P_{F,t}(j)C_{F,t}(j)di = P_{H,t}C_{H,t} + P_{F,t}C_{F,t} = P_t C_t \quad (3.5)$$

The nominal budget constraint of the representative household in period  $t$  is:

$$P_t C_t + B_{H,t-1} + \mathcal{E}_t B_{F,t-1} = \frac{B_{H,t}}{(1 + i_t)} + \frac{\mathcal{E}_t B_{F,t}}{(1 + i_t^*)\psi_t(\cdot)} + W_t N_t + D_t - P_t T_t \quad (3.6)$$

where  $D_t$  are firms' profits and  $T_t$  taxes.  $B_{H,t}$  and  $B_{F,t}$  are the domestic- and foreign-currency-denominated nominal bonds and  $i_t$  and  $i_t^*$  their respective interest rates.  $\mathcal{E}_t$  is the nominal exchange rate, i.e., the price of foreign country's currency in terms of domestic currency.  $\psi_t(\cdot)$  is the cost from international borrowings, increasing in the aggregate level of real foreign debt:  $\psi_t'(\cdot) > 0$ . Assume a zero steady-state risk premium by setting  $\psi(\overline{B}_F) = 1$ . Households produce all goods and share the revenues from production in equal proportions. As in De Paoli (2009a), since there is no idiosyncratic risk amongst domestic households, and foreign households only trade in foreign-currency-denominated bonds, households do not trade domestic-currency denominated bonds in equilibrium. Hence, defining the intermediation cost over the foreign

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currency bond is sufficient to pin down the overall steady state of the net foreign assets position. More specifically, we define the debt-elastic interest premium as  $\psi_t(\cdot) = e^{\frac{\psi_b}{\bar{Y}} \left( \frac{\varepsilon_t^{BF,t}}{P_t} - \bar{B}_F \right)}$ .<sup>9</sup>

Maximizing the utility function subject to the budget constraint, we get the following first-order conditions:

$$\frac{W_t}{P_t} = C_t^\sigma N_t^\varphi \quad (3.7)$$

$$\frac{C_t^{-\sigma}}{P_t} = (1 + i_t) \beta E_t^\theta \left[ \frac{C_{t+1}^{-\sigma}}{P_{t+1}} \right] \quad (3.8)$$

$$\frac{C_t^{-\sigma} \mathcal{E}_t}{P_t} = (1 + i_t^*) \psi_t(\cdot) \beta E_t^\theta \left[ \frac{C_{t+1}^{-\sigma}}{P_{t+1}} \mathcal{E}_{t+1} \right] \quad (3.9)$$

The last two equations, the Euler equations for home and foreign bonds, must equal each other for no arbitrage. The uncovered interest parity (UIP) arises from here, as described in Section 3.2.4.

#### 3.2.2 Some identities: Domestic inflation, CPI inflation, real exchange rate, and the terms of trade

Here, we define some terms that are key to the analysis in small open economy models. We define the terms of trade as the relative price of the domestic and foreign good and write down its log-linear form:

$$S_t \equiv \frac{P_{F,t}}{P_{H,t}} \Rightarrow \hat{s}_t = \hat{p}_{F,t} - \hat{p}_{H,t} \quad (3.10)$$

A hatted variable indicates the percentage deviations from its steady state:  $\hat{x}_t = \frac{x_t - \bar{x}}{\bar{x}}$ . With the above definition, we express the CPI equation (3.4) in terms of the terms of trade:

$$\hat{p}_t \equiv (1 - \alpha) \hat{p}_{H,t} + \alpha \hat{p}_{F,t} = \hat{p}_{H,t} + \alpha \hat{s}_t \quad (3.11)$$

Taking first differences, we get an expression for the CPI inflation:

$$\hat{\pi}_t = \hat{\pi}_{H,t} + \alpha \Delta \hat{s}_t \quad (3.12)$$

<sup>9</sup>See Schmitt-Grohé and Uribe (2003). Note that also in the steady state, we assume  $\bar{Y} = 1$  (See Appendix C.1).

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where  $\hat{\pi}_{H,t} \equiv \hat{p}_{H,t} - \hat{p}_{H,t-1}$  is the domestic inflation and  $\Delta$  a difference operator such that  $\Delta x_t = x_t - x_{t-1}$ . The greater the openness to trade  $\alpha$ , the more the changes in the terms of trade affect the CPI inflation. We assume that the law of one price (LOOP) holds:

$$P_{H,t} = \mathcal{E}_t P_{H,t}^* \Rightarrow \hat{p}_{H,t} = \hat{e}_t + \hat{p}_{H,t}^* \quad (3.13)$$

$$P_{F,t} = \mathcal{E}_t P_{F,t}^* \Rightarrow \hat{p}_{F,t} = \hat{e}_t + \hat{p}_{F,t}^* = \hat{e}_t + \hat{p}^* \quad (3.14)$$

Combining the above result with the terms of trade definition and assuming the foreign inflation is constant, we can define the nominal appreciation/depreciation as:

$$\Delta \hat{e}_t = \Delta \hat{s}_t + \hat{\pi}_{H,t} \quad (3.15)$$

Finally, we define the real exchange rate as:

$$Q_t \equiv \frac{\mathcal{E}_t P_t^*}{P_t} \Rightarrow \hat{q}_t = \hat{e}_t + \hat{p}_t^* - \hat{p}_t = (1 - \alpha) \hat{s}_t \quad (3.16)$$

For the last equation in the log-linearization, we use the definitions described above. The real exchange rate and the terms of trade are linked by the degree of openness  $\alpha$ .

#### 3.2.3 Diagnostic Expectations and its linearization

This technical subsection is a brief overview on Diagnostic Expectations (DE), and how we deal with the DE operator  $E_t^\theta$  in the remainder of this paper. We now apply the same logic of the representative heuristic as described in the introduction to belief formation in a dynamic macroeconomic context. Building onto the example in the introduction, replace  $X = \text{hair color}$  by a random variable one period ahead,  $x_{t+1}$ , and  $D = \text{Irish}$  by the realization of that variable in the current period,  $x_t$ , with which agents form the expectation  $E_t[x_{t+1}]$ . We can measure the representativeness of the realization of  $x_t$  by using the data until  $t - 1$  as the reference group. As shown in Bordalo et al. (2018), the following tractable formula follows:

$$E_t^\theta[x_{t+1}] = E_t[x_{t+1}] + \theta (E_t[x_{t+1}] - E_{t-1}[x_{t+1}]) \quad (3.17)$$

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So, for example, if after observing  $x_t$ , an individual expects a higher  $x_{t+1}$  than they did before, they over-weight that news when forming expectations. We can interpret the representativeness in an economic model as a surprise term:

$$E_t^\theta[x_{t+1}] = E_t[x_{t+1}] + \theta \underbrace{(E_t[x_{t+1}] - E_{t-1}[x_{t+1}])}_{\text{surprise at } t \text{ regarding the expectation of } x_{t+1}} \quad (3.18)$$

$$= E_t[x_{t+1}] + \theta \xi_{t+1}^x \quad (3.19)$$

With some abuse of notation, we define  $\xi_{t+1}^x$  as the surprise associated with the expectation of  $x_{t+1}$  after receiving news at time  $t$ . In other words, it is the effect of today's news on tomorrow's expectations. The DE parameter  $\theta$  determines how strong the agents react to the surprise term. When  $\theta = 0$ , and the agents do not overreact to news, and the diagnostic expectation operator is identical to the RE operator. For variables at time  $t$ , we have:

$$E_t^\theta[x_t] = E_t[x_t] + \theta \underbrace{(E_t[x_t] - E_{t-1}[x_t])}_{\text{surprise at } t \text{ regarding the expectation of } x_t} \quad (3.20)$$

$$= E_t[x_t] + \theta \xi_t^x \quad (3.21)$$

Now,  $\xi_t^x$  is the surprise on  $x_t$  from news at time  $t$ . In other words, it is the effect of today's news on the realization of  $x$ .<sup>10</sup> In this equation, the DE operator is notably different from the RE operator. Whereas under RE case, we have  $E_t[x_t] = x_t$ , in the DE case,  $E_t^\theta[x_t] = x_t + \theta \xi_t^x \neq x_t$ . Therefore, when working with DE, one needs to be careful with taking terms outside of the expectation operator.<sup>11</sup>

<sup>10</sup>Note that the surprise is the outcome of the time needed (in this case one period) to revise expectations. Put differently, the surprise term dissipates after one period. See Bianchi et al. (2024) and Bounader and Elekdag (2024) for cases where the revision periods are longer (the case of "distant memory").

<sup>11</sup>Note also, that DE has the property of strong additivity (see, L'Huillier et al. (2024)):

$$E_t^\theta[x_{t+r} + y_{t+s}] = E_t^\theta[x_{t+r}] + E_t^\theta[y_{t+s}], r, s \geq 0 \quad (3.22)$$

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#### 3.2.4 Uncovered interest parity under Diagnostic Expectations

DE has important implications, especially for the uncovered interest parity (UIP) condition. Rearranging the Euler equation of home bonds (3.8) and taking into consideration the properties of the DE operator mentioned in the previous subsection yields the following:<sup>12</sup>

$$\frac{1}{\pi_t} C_t^{-\sigma} = (1 + i_t) \beta E_t \left[ \frac{C_{t+1}^{-\sigma}}{\pi_{t+1}} \frac{1}{\pi_t} \right] \quad (3.24)$$

In log-linear deviations from steady state, and working out the DE, we get:

$$\sigma \left( E_t [\hat{c}_{t+1}] + \theta \xi_{t+1}^c - \hat{c}_t \right) = \hat{i}_t - \left[ E_t [\hat{\pi}_{t+1}] + \theta \left( \xi_{t+1}^\pi + \xi_t^\pi \right) \right] \quad (3.25)$$

Here, we see that the DE play a role through two channels: First, there is a wedge between expected consumption and current consumption,  $\theta \xi_{t+1}^c$ , which amplifies the reaction of current consumption,  $\hat{c}_t$ , to the expected consumption,  $E_t [\hat{c}_{t+1}]$ . Second, there are two surprise terms  $\xi_{t+1}^\pi$  and  $\xi_t^\pi$  that accompany expected inflation,  $E_t [\hat{\pi}_{t+1}]$ . These surprise terms make the representative household overreact when there is news on expected and realized inflation, and accordingly affect the (ex-ante) real interest rate. We rearrange the Euler equation of the foreign bonds as:

$$\frac{1}{\pi_t} C_t^{-\sigma} = \frac{(1 + i_t^*)}{\mathcal{E}_t} \mathcal{E}_{t-1} \psi_t(\cdot) \beta E_t^\theta \left[ \frac{C_{t+1}^{-\sigma}}{\pi_{t+1}} \frac{1}{\pi_t} \frac{\mathcal{E}_{t+1}}{\mathcal{E}_t} \frac{\mathcal{E}_t}{\mathcal{E}_{t-1}} \right] \quad (3.26)$$

In log-linear deviations from steady state and working out the DE, we get:

$$\sigma \left( E_t [\hat{c}_{t+1}] + \theta \xi_{t+1}^c - \hat{c}_t \right) = \hat{i}_t^* + \psi_b \hat{b}_t - \left[ E_t [\hat{\pi}_{t+1}] + \theta \left( \xi_{t+1}^\pi + \xi_t^\pi \right) \right] + \left[ E_t [\Delta \hat{e}_{t+1}] + \theta \left( \xi_{t+1}^{\Delta e} + \xi_t^{\Delta e} \right) \right] \quad (3.27)$$

where  $b_t = \left( \frac{\mathcal{E}_t B_{F,t}}{P_t} - \overline{B_F} \right) / \overline{Y}$  is the foreign bond holdings in real terms. We define the deviation as a fraction of steady-state output instead of bonds, so that we can analyze the case when steady-state bond holdings are zero.

<sup>12</sup>Multiply both sides of the equations by  $P_{t-1}$ , and multiply the righthand-side with  $P_t/P_t$ . So, for the first Euler equation we get:

$$\frac{C_t^{-\sigma}}{P_t} P_{t-1} = (1 + i_t) \beta E_t \left[ \frac{C_{t+1}^{-\sigma}}{P_{t+1}} \frac{P_t}{P_t} P_{t-1} \right] \Rightarrow \frac{1}{\pi_t} C_t^{-\sigma} = (1 + i_t) \beta E_t \left[ \frac{C_{t+1}^{-\sigma}}{\pi_{t+1}} \frac{1}{\pi_t} \right] \quad (3.23)$$

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We attain the uncovered interest parity (UIP) condition by combining the home and foreign bond Euler equations:

$$\hat{r}_t = \hat{r}_t^* + \psi_b \hat{b}_t + E_t[\Delta \hat{e}_{t+1}] + \theta (\xi_{t+1}^{\Delta e} + \xi_t^{\Delta e}) \quad (3.28)$$

When  $\theta = 0$ , the above equation reverts to the standard uncovered interest parity  $\hat{r}_t = \hat{r}_t^* + \psi_b \hat{b}_t + E_t[\Delta \hat{e}_{t+1}]$ . Importantly, and central to the paper, note that DE creates a wedge between the home and foreign interest rate, which increases exchange rate volatility as we show in the later sections.

#### 3.2.4.1 Firms

There is a continuum of firms  $j \in [0, 1]$  in the small open economy and each firm produces a differentiated good  $j$ . Monopolistic competition ensures that the firms are profit-maximizing. The profit function of firm  $j$  is:

$$\begin{aligned} D_t(j) = & \frac{P_{H,t}(j)}{P_{H,t}} Y_t - \frac{W_t}{P_{H,t}} N_t(j) - \frac{\psi_p}{2} \left( \frac{P_{H,t}(j)}{P_{H,t-1}(j)} - 1 \right)^2 Y_t \\ & + E_t^\theta \sum_{s=1}^{\infty} \Lambda_{t+s+1} \left[ \frac{P_{H,t+s}(j)}{P_{H,t+s}} Y_{t+s+1}(j) - \frac{W_{t+s}}{P_{H,t+s}} N_{t+s}(j) \right. \\ & \left. - \frac{\psi_p}{2} \left( \frac{P_{H,t+s}(j)}{P_{H,t+s-1}(j)} - 1 \right)^2 Y_{t+s} \right] \end{aligned} \quad (3.29)$$

where  $\Lambda_{t+1} = \beta \left( \frac{C_{t+1}}{C_t} \right)^{-\sigma}$  is the stochastic discount factor.  $\psi_p$  is the Rotemberg (1982) adjustment cost parameter. The firm maximizes its profits,  $D_t(j)$ , subject to the production function  $Y_t(j) = A_t N_t(j)$  and the demand function  $Y_t(j) = \left( \frac{P_{H,t}(j)}{P_{H,t}} \right)^{-\epsilon} Y_t$ . Taking the first-order condition with respect to  $P_{H,t}(j)$  and imposing the symmetric equilibrium conditions we get the New Keynesian Philips Curve in terms of marginal cost  $\hat{\mu}_t$ :

$$\hat{\pi}_{H,t} = \beta E_t[\hat{\pi}_{H,t+1}] + \frac{\epsilon}{\psi_p \mathcal{M}} \hat{\mu}_t + \hat{u}_t \quad (3.30)$$

$$= \beta \left( E_t[\hat{\pi}_{H,t+1}] + \theta \xi_{t+1}^\pi \right) + \frac{\epsilon}{\psi_p \mathcal{M}} \hat{\mu}_t + \hat{u}_t \quad (3.31)$$

where  $\mathcal{M} = \frac{\epsilon}{\epsilon-1}$  is the price mark-up under flexible prices and  $\hat{u}_t$  is the cost-push shock. The DE amplify the reaction of firms at time  $t$  on the news they receive

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about  $t + 1$ . As we show in later sections, this amplification mechanism is key in the transmission of shocks to the economy. The first-order condition with respect to  $N_t(j)$  is  $\frac{W_t}{P_t} \frac{P_t}{P_{H,t}} = \mu_t A_t$ .

#### 3.2.4.2 Monetary and fiscal policy

Monetary policy follows a Taylor rule of the form:

$$1 + i_t = \beta \left( \frac{\pi_t}{\bar{\pi}} \right)^{\phi_\pi} \left( \frac{\pi_{t,H}}{\bar{\pi}_H} \right)^{\phi_{\pi,H}} \left( \frac{Y_t}{Y_t^n} \right)^{\phi_y} \left( \frac{\mathcal{E}_t}{\mathcal{E}_{t-1}} \right)^{\phi_\mathcal{E}} \exp(\nu_t) \quad (3.32)$$

Here,  $\psi_\pi$ ,  $\psi_{\pi_H}$ ,  $\phi_y$ , and  $\phi_\mathcal{E}$  are the weights the monetary policy authority places on CPI inflation, domestic inflation, output gap, and the change in the nominal exchange rate, respectively. Variants of three main regimes will be considered: (i) CPI inflation targeting rule (CITR) with  $\phi_\pi > 0$ , (ii) domestic inflation targeting rule (DITR) with  $\phi_{\pi_H} > 0$ , and a fixed exchange rate regime (PEG) with  $\phi_\mathcal{E} \rightarrow \infty$ .

The budget constraint of the fiscal authority balances its income and revenues:

$$P_t G_t = P_t T_t + \frac{B_{H,t}}{1 + i_t} - B_{H,t-1} \quad (3.33)$$

#### 3.2.4.3 Market clearing

Each firm in the small open economy clears its goods in the market:

$$Y_t(j) = C_{H,t}(j) + C_{H,t}^*(j) + \frac{\psi_p}{2} \left( \frac{P_{H,t}(j)}{P_{H,t-1}(j)} - 1 \right)^2 Y_t(j) + G_t(j) \quad (3.34)$$

Using the demand equations and substituting the definition of aggregate domestic output  $Y_t \equiv \left[ \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}}$ , we can express the aggregate output in terms of trade, the real exchange rate, domestic consumption, and exogenous variables:<sup>13</sup>

$$Y_t = \left[ (1 - \alpha) + \alpha S_t^{1-\eta} \right]^{\frac{1}{1-\eta}} \left[ (1 - \alpha) C_t + \alpha Q_t^\eta C_t^* \right] + \frac{\psi_p}{2} \left( \frac{P_{H,t}}{P_{H,t-1}} - 1 \right)^2 Y_t + G_t \quad (3.35)$$

where we make use of  $\frac{P_t}{P_{H,t}} \equiv \left[ (1 - \alpha) + \alpha S_t^{1-\eta} \right]^{\frac{1}{1-\eta}}$ .

<sup>13</sup>We assume that the government expenditure bundle aggregates in the same way as the household's consumption bundle.

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#### 3.2.4.4 Trade balance

When the international financial markets are incomplete and the small open-economy households hold foreign bonds, the trade balance determines the evolution of foreign-debt holdings. To calculate the trade balance, we consolidate the household's budget constraint (3.6), the government's budget constraint (3.33), and the aggregate nominal profits by the firms,  $D_t = P_{H,t}Y_t - W_tN_t - P_tY_t\frac{\psi_p}{2}(\pi_{H,t-1})^2$ :

$$P_{H,t}Y_t - P_tC_t + P_tG_t - \frac{\psi_p}{2}(\pi_{H,t} - \bar{\pi}_H)^2P_{H,t}Y_t = \mathcal{E}_tB_{F,t-1} - \frac{\mathcal{E}_tB_{Ft}}{(1 + i_t^*)\psi(\cdot)} \quad (3.36)$$

We then write the trade balance as:

$$TB_t = \frac{P_{H,t}}{P_t}Y_t - C_t + G_t - \frac{\psi_p}{2}(\pi_{H,t} - \bar{\pi}_H)^2\frac{P_{H,t}}{P_t}Y_t \quad (3.37)$$

where the trade balance pins down the evolution of net foreign debt:

$$TB_t = \frac{\mathcal{E}_tB_{F,t-1}}{P_{t-1}}\frac{1}{\pi_t} - \frac{1}{(1 + i_t^*)\psi(\cdot)}\frac{\mathcal{E}_tB_{Ft}}{P_t} \quad (3.38)$$

## 3.3 Quantitative analysis

### 3.3.1 Calibration

This section presents the baseline calibration of the parameters in the model described above. We take most parameters from the standard New Keynesian literature. We consider alternative values of some parameters for welfare implications in the next section. The summary of the parameterization is in Table 3.1.

#### 3.3.1.1 Preferences

As is common in the literature, we assume the subjective discount factor  $\beta$  to be 0.99, which implies an annual risk-free rate of return of 4 percent in the steady state. We consider the elasticity of intertemporal substitution  $\sigma$  to be 0.5, and in the baseline case we set the elasticity of substitution between home and foreign goods  $\eta$  equal to unity. Following the literature, the Frisch elasticity of labor supply  $1/\varphi$  is 0.33 and the elasticity of substitution between the different varieties  $\epsilon$  is equal to 6.

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#### 3.3.1.2 Production

To match the Rotemberg-pricing in our model to the Calvo one, we set the price-adjustment cost parameter  $\psi_p$  such that the slope of the New Keynesian Philips Curve (NKPC) matches the slope of the NKPC under the Calvo parameter 0.75. This calibration implies that prices have an expected price duration of four quarters. The corresponding Rotemberg-adjustment cost parameter is  $\psi_p = [(\epsilon - 1)0.75]/[(1 - 0.75)(1 - 0.75\beta)] \approx 58.25$ . The elasticity of substitution between the different varieties determines the steady-state mark-up  $\mathcal{M} = \epsilon/(\epsilon - 1) = 1.125$ , which is in-between the two benchmark cases that Galí and Monacelli (2005) consider.

#### 3.3.1.3 Open-economy parameters

A key parameter in open-economy models, the openness parameter  $\alpha$ , is 0.4, which is also the share of imports in the household's consumption basket. The calibration matches both the literature on small open economies and empirical evidence. Since our model considers the incomplete financial markets case, we have a debt-elastic interest rate. The debt-elasticity parameter  $\psi_b$  is set to 0.01, following P. Benigno (2009).

#### 3.3.1.4 Monetary policy and persistence of shocks

In the baseline case, monetary policy follows a Taylor rule with the coefficients on (current) CPI and domestic inflation ( $\phi_\pi$  or  $\phi_{\pi_H}$ ) set at 1.5, along with a coefficient of 0.125 on the output gap ( $\phi_y$ ). We simulate the exchange rate peg ("PEG") by setting  $\phi_e = 100,000$ . With the exception of the monetary policy (which is set at 0.5 as is common in the literature), the persistence of all other shocks is set to 0.9, unless otherwise specified. We consider alternative shock processes in the welfare analysis, explained in the respective sections.

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#### 3.3.1.5 Diagnostic Expectations parameter

In the baseline case, we use the Diagnostic Expectations (DE) parameter  $\theta = 1$ . This calibration is broadly consistent with the papers Bianchi et al. (2024) as well as L’Huillier et al. (2024). Likewise, Selim Elekdag (2025) estimate a small open economy model with DE and find values of  $\theta$  encompassing values ranging from 0.59–1.96, as standard in the DE literature. We also show in the next section that this calibration does well in resolving some of the exchange rate puzzles. We consider alternative values for  $\theta$  in the welfare analysis.

**Table 3.1:** Calibration of parameters

<i>Parameter</i>	<i>Description</i>	<i>Value</i>
$\beta$	Discount factor	0.99
$\sigma$	Elasticity of intertemporal substitution	0.5
$\eta$	Elasticity of substitution between home and foreign goods	1
$\varphi$	Inverse Frisch elasticity of labor supply	3
$\epsilon$	Elasticity of substitution between different varieties	6
$\psi_p$	Rotemberg-adjustment cost parameter	58.25
$\alpha$	Trade openness	0.4
$\psi_b$	Debt-elasticity parameter	0.01
$\phi_\pi$	Taylor-coefficient on inflation	1.5
$\phi_y$	Taylor-coefficient on output gap	0.125
$\theta$	Diagnostic Expectations parameter	1

Source: Authors’ calculations.

#### 3.3.2 Properties: Amplification mechanism and puzzles

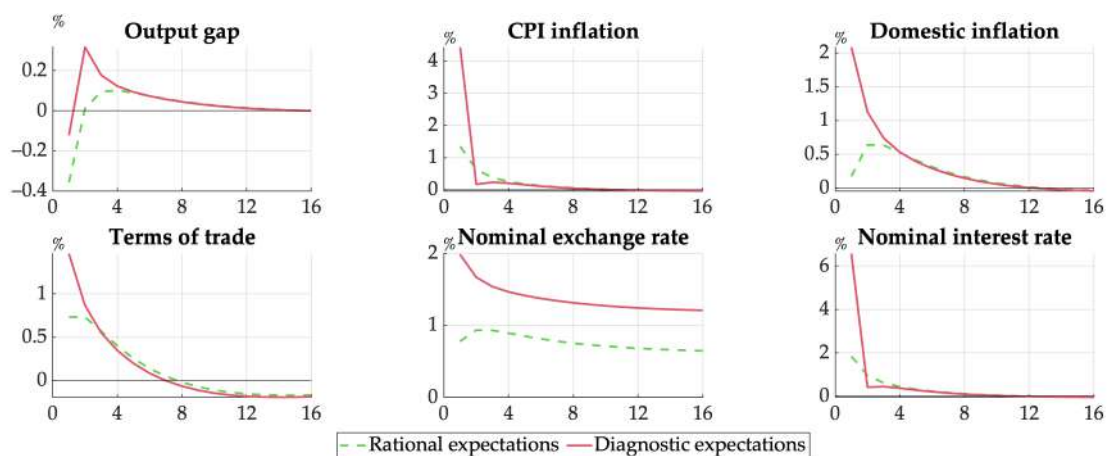
In this section, we present the properties of the small open-economy model with incomplete financial markets and DE. Firstly, we show the impulse responses functions of the model with DE, comparing it to the RE counterpart. Here, we confirm that the DE induce an amplification in the responses. Secondly, we present the relevant moments of the model to demonstrate that DE can help resolve some puzzles related to the exchange rate literature. In this literature, uncovered interest parity (UIP) shocks are key, so we use the foreign interest rate shock in the analysis in this section. We present the impulse responses of other types of shocks in Appendix C.2.

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#### 3.3.2.1 Amplification of responses after a foreign interest rate shock

We use a 1 percentage point foreign interest rate increase, a contractionary monetary policy shock in the foreign country, to illustrate the amplification mechanism in the model with DE. This will be useful, including because in the next subsection, we use the same shock to assess the model's ability to help resolve selected exchange rate puzzles. The central bank uses the Taylor rule targeting consumer price index (CPI) inflation and the output gap.

**Figure 3.1:** Responses to a foreign interest rate shock



*Source:* Authors' calculations. *Notes:* Impulse responses to a 1 percentage point foreign interest rate increase. The Taylor rule targets CPI inflation with  $\phi_\pi = 1.5$  and output gap with  $\phi_y = 0.125$ . The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized. Inflation and interest rates are annualized.

In Figure 3.1, we display the impulse responses of the home economy in response to the foreign interest rate shock. We start with the analysis of the RE case, the green dashed line, and then compare it to the DE case, the red solid line. With RE, when the foreign interest rate shock hits the economy, the nominal exchange rate depreciates in line with the UIP condition. Two channels are at work here. First, the nominal depreciation results in a real exchange rate depreciation (and a deterioration in the terms of trade). Through the expenditure switching mechanism (which boosts relatively cheaper exports and reduces imports), the trade balance improves. Second, given the law of one price—which implies full exchange rate pass-through—the nominal exchange rate depreciation

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results in higher import prices and thus an increase in CPI inflation. Because the central bank targets CPI inflation, a contractionary monetary policy stance ensues. Higher nominal rates translate into higher real interest rates thereby suppressing consumption (the expenditure reduction mechanism). The net effect of the trade balance surplus and decline in consumption is an initial decline in output. As CPI inflation reverts to target, the policy stance loosens, and supports the economic recovery.

Under DE, the depreciation of the nominal exchange rate is striking. In particular, the initial spike is driven by endogenous amplification associated with exchange rate surprises in the UIP equation with DE (recall equation (3.28)). Accordingly, this results in a more pronounced real exchange rate depreciation and improvement in the trade balance. At the same time, full exchange rate pass-through brings about a sharper rise in import prices, and therefore a spike in headline inflation. The central bank tightens aggressively in an effort to preserve price stability which results in an abrupt increase in real interest rates, yielding a sharp decline in consumption. With DE, the overall effect is now a smaller decline in output (which is accompanied by an increase in domestic inflation). In summary, the impact of shifts in international relative prices on the economy are significantly stronger owing to amplified exchange rate volatility under DE.

#### 3.3.2.2 Tackling exchange rate puzzles

As a first pass at disciplining the model with data, we assess how the inclusion of DE into an otherwise standard small open-economy model can shed light on two longstanding empirical exchange rate puzzles: the forward premium and exchange rate disconnect puzzles. Using foreign interest rates shocks for the simulations, we contrast the performance of the RE and DE versions of the model with the empirical moments taken directly from Itskhoki and Mukhin (2021).

The model with DE helps resolve the forward premium puzzle (Itskhoki & Mukhin, 2021). In terms of context, the forward premium puzzle states that the UIP condition does not hold in the data. Specifically, when the domestic interest

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rate rises, under UIP, the domestic currency depreciates to equate the returns of holding home and foreign bond. However, the data do not support this model-based prediction. In particular, after a depreciation, empirically, domestic bonds tend to nevertheless offer higher returns. We use the Fama (1984) regression to assess the validity of UIP under various assumption of expectations formation:

$$E_t[\Delta\hat{e}_{t+1}] = \beta_0 + \beta_1 (\hat{i}_t - \hat{i}_t^*) + \epsilon_t \quad (3.39)$$

When the UIP holds, the equation should return  $\beta_1 = 1$ , but empirical estimates suggest that  $\beta_1 = 0$ , or even  $\beta_1 < 0$  (Itskhoki & Mukhin, 2021). The data also suggest that the R-squared of this regression is close to zero, indicating that the interest rate differentials do not explain much of the variation in the nominal exchange rate. As we present in the penultimate column in Table 3.2, our baseline DE model with  $\theta = 1$  matches the regression coefficient and R-squared in the data much better than the RE counterpart. In particular, while the RE model suggests a coefficient of 0.84 with an R-squared of unity, under DE (with  $\theta = 1$ ), these estimates are  $-0.21$  and  $0.21$ , respectively—and significantly more in line with the data.<sup>14</sup>

**Table 3.2:** Summary of statistics

Statistic	Data	RE ( $\theta = 0$ )	DE ( $\theta = 0.5$ )	DE ( $\theta = 1$ )	DE ( $\theta = 1.5$ )
UIP puzzle					
Fama $\beta_1$	$< 0$	0.84***	0.24***	$-0.21$ ***	$-0.36$ ***
Fama $R^2$	0.02	0.98	0.25	0.21	0.60
Disconnect puzzle					
$corr(\Delta\hat{e}_t, \Delta\hat{e}_{t+1})$	0.00	0.45	0.06	$-0.14$	$-0.23$
$\sigma(\Delta e)/\sigma(\Delta y)$	5.20	1.95	2.01	3.04	4.04
$\sigma(\Delta e)/\sigma(\Delta c)$	6.30	0.62	0.59	0.73	1.36

*Source:* Authors' calculations. The values in column "Data" are from Itskhoki and Mukhin (2021). *Notes:* Results of the Fama (1984) regression and correlations of macroeconomic variables under a 1 percentage point increase in foreign interest rates, using 500 simulations. "\*\*\*" denotes statistical significance at the 1 percent level.

The second puzzle considered is the Meese and Rogoff (1983) puzzle, or the exchange rate disconnect puzzle, as is commonly referred to in literature.

<sup>14</sup>We generate these results with a 1 percentage point foreign interest rate shock to the domestic economy (using 500 simulations).

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This puzzle states that the nominal exchange rate follows a random-walk-like process and is an order of magnitude more volatile than other macroeconomic variables. As in Itskhoki and Mukhin (2021), we assess model performance by setting the discount factor,  $\beta \approx 1$ , and shock persistence,  $\rho \approx 1$ . Therefore, if the nominal exchange rate follows a random-walk-like process, we should get  $\text{corr}(\Delta\hat{e}_t, \Delta\hat{e}_{t+1}) \approx 0$ . We can see in Table 3.2 that our baseline case, with  $\theta = 1$ , gets closer to the data when compared to the RE case. In terms of disconnect between the nominal exchange rate and real variables, a parametrization of  $\theta = 1.5$  is most promising in terms of better matching the volatility ratios in the data. In summary, this initial empirical assessment of the model with DE is encouraging, since it demonstrates the potential DE models have in terms of better capturing salient data patterns.

#### 3.3.3 Welfare evaluations

The objective of this section is to assess how DE affect optimal monetary policy in a small open economy. Our research question is as follows: under DE, is there scope for exchange rate stabilization in an otherwise standard New Keynesian small open economy model? To address this question, in this section, we compute the welfare function for the small open economy with incomplete markets and interpret the results using impulse response functions and the welfare rankings of selected monetary policy regimes. Notably, we show how the elasticity of substitution between home and foreign goods  $\eta$  and the diagnostics expectations parameter  $\theta$  affect the welfare rankings.

##### 3.3.3.1 Welfare objective function

In this section, we present the objective function of the welfare-maximizing social planner, the loss function of the small-open economy. We express the welfare as the second-order Taylor expansion of the household utility function

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in the following form:

$$\begin{aligned} \mathcal{L}_t = E_0 \sum_{t=0}^{\infty} \beta^t & \left( \frac{1}{2} L_{yy} \hat{y}_t^2 + \frac{1}{2} L_{\pi\pi} \hat{\pi}_{Ht}^2 + \frac{1}{2} L_{qq} \hat{q}_t^2 + L_{yq} \hat{y}_t \hat{q}_t + L_{ya} \hat{y}_t \hat{a}_t + L_{yu} \hat{y}_t \hat{u}_t \right. \\ & \left. + L_{yg} \hat{y}_t \hat{g}_t + L_{yc^*} \hat{y}_t \hat{c}_t^* + L_{qa} \hat{q}_t \hat{a}_t + L_{qu} \hat{q}_t \hat{u}_t + L_{qg} \hat{q}_t \hat{g}_t + L_{qc^*} \hat{q}_t \hat{c}_t^* \right) + t.i.p. + O(\cdot) \end{aligned} \quad (3.40)$$

where all coefficients, in the form of  $L_{xx}$  and  $L_{xz}$ , depend on the structural parameters of the model, as shown in Appendix C.3. We commit to presenting the loss function in linear-quadratic terms only, such that the minimization problem is accurate to second order.<sup>15</sup> This method requires substituting out the linear terms in the initial approximation of the loss function with second-order approximations of the key equilibrium conditions. De Paoli (2009b) follows a similar approach. See Appendix C.3 for more details.

#### 3.3.3.2 Impulse responses under different monetary policy regimes under the cost-push shock

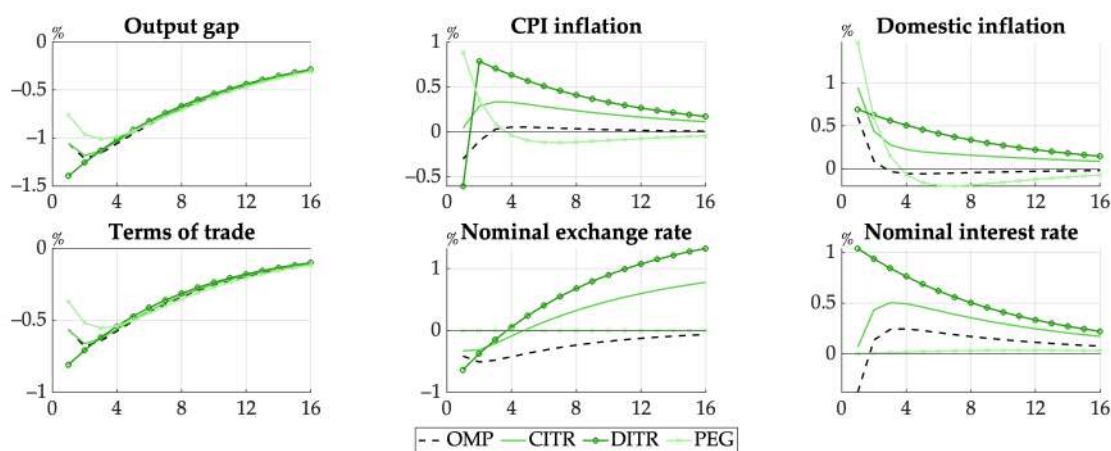
A key goal of this paper is to evaluate the welfare implications of the model under different policy regimes and parametrizations regarding the strength of DE and the substitutability of home and foreign goods. To gain insights into the model, we first investigate the dynamic responses of key macroeconomic variables to a cost-push shock, shown in Figure 3.2 assuming RE. Because the implications of the cost-push shock differs depending on monetary policy, we initially consider three regimes in line with earlier studies, captured by simple policy rules: (i) a domestic inflation-based interest rate rule (DITR), (ii) a consumer price index (CPI) inflation-based interest rate rule (CITR), and (iii) an exchange rate peg (PEG).<sup>16</sup> We contrast each of these with optimal monetary policy (OMP) under commitment, by minimizing the welfare objective function derived above. After reviewing the case under RE, we consider the implications of introducing DE.

<sup>15</sup>In the closed-economy case or in a complete-markets small-open economy, this method is common in the literature.

<sup>16</sup>The coefficient for inflation in the interest rule for the DITR and CITR are 1.5 and the coefficient for output gap is 0.

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**Figure 3.2:** Responses to a cost-push shock, rational expectations



Source: Authors' calculations. Notes: Impulse responses to a 0.22 percentage point cost-push shock under rational expectations. The selected monetary policy rules are optimal monetary policy (OMP), CPI inflation Taylor rule (CITR), domestic inflation Taylor rule (DITR) and the exchange rate peg (PEG). The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized. Inflation and interest rates are annualized.

Starting with the DITR case, the cost-push shock causes a spike in domestic inflation, which induces a monetary contraction. Given constant foreign interest rates, the uncovered interest parity (UIP) condition implies an initial nominal appreciation, followed by expectations of a future depreciation as reflected in the response of the nominal exchange rate. In turn, the real exchange rate appreciates (and likewise, the terms of trade improves), which renders imports prices cheaper, owing to full exchange rate pass-through, and therefore suppresses CPI inflation.<sup>17</sup> The combined effect of higher nominal rates and lower CPI inflation raises the real interest rate which suppresses consumption and output (and accordingly labor effort).<sup>18</sup> However, via the terms-of-trade improvement, expenditure switching can offset some of the decline in consumption. By encouraging the consumption of foreign goods as a substitute for home goods, the terms-of-trade improvement can improve welfare as households can maintain consumption levels despite a decrease in labor effort. Nevertheless, the greater consumption of foreign goods comes at the cost of a deterioration in the trade balance and

<sup>17</sup>Recall that the law of one price assumption implies a full exchange-rate pass-through.

<sup>18</sup>Given the constancy of the natural rate of output, the output is equivalent to the output gap.

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a larger decrease in domestic output. Recall that the degree of substitutability between home and foreign goods, summarized by the intra-temporal elasticity of substitution  $\eta$ , determines the strengths of the expenditure switching channel.

Under optimal monetary policy (OMP), in response to the cost-push shock, agents anticipate a future monetary policy tightening, which tempers expected domestic inflation, and therefore results in lower current domestic inflation. This more favorable policy trade-off allows for a monetary loosening. Indeed, in line with familiar result from closed-economy models (for example, Woodford (2003)), the initial rise in domestic inflation is followed by a (mild) deflationary episode which is consistent with inflation dynamics under price-level targeting. Under OMP, the lower (real) policy rate is also associated with a milder decline in consumption and output and the real exchange rate appreciation (and terms-of-trade improvement) is smaller relative to the DITR case.

In the baseline assumption of incomplete financial markets, the dynamics associated with inflation-based interest rate rule (CITR) resembles the OMP case. For instance, the nominal and real interest rates decline on impact, in part because the appreciation of the real exchange rate helps with the desired stabilization of CPI inflation given the assumption of full exchange rate pass through. Similarities of the policy response along with those of international relative prices underpin the virtual overlap of the consumption and output profiles in the OMP and CITR cases.

Under the PEG, the commitment to exchange rate stabilization implies a nearly constant nominal interest rate, resulting in a more muted terms of trade (and thus real exchange rate) response.<sup>19</sup> In turn, the relative decline in consumption and output is milder when compared to the other regimes, but at the cost of higher (domestic) inflation.

In Figure 3.3, we introduce DE to the analysis. A key difference is that the impact of the cost-push shock is generally more pronounced as would be expected

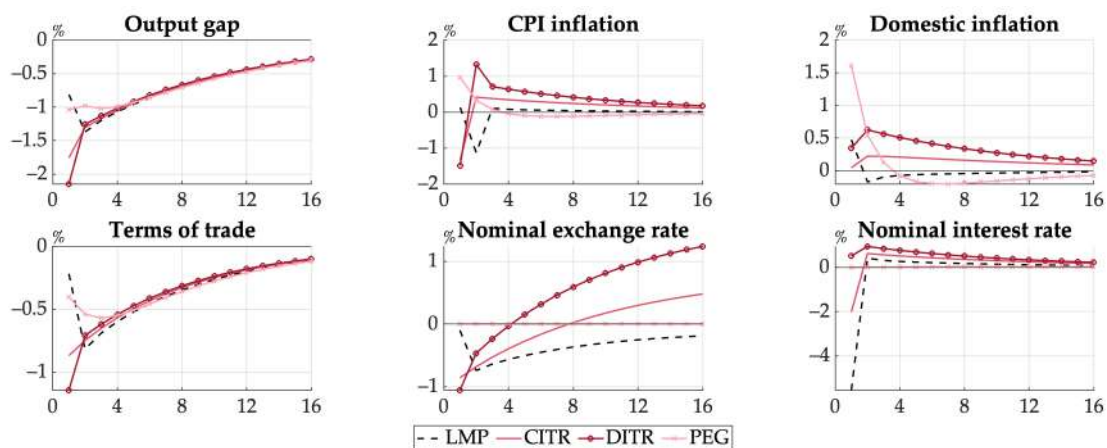
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<sup>19</sup>While hard to discern, the nominal interest rate does increase. Note also that given our baseline calibration, the net foreign asset position has negligible effects on interest rates.

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given that agents overreact to incoming news (shocks) under this type of belief formation. Several observations are worthy to emphasize.

**Figure 3.3:** Responses to a cost-push shock, diagnostic expectations



*Source:* Authors' calculations. *Notes:* Impulse responses to a 0.22 percentage point cost-push shock under diagnostic expectations. The selected monetary policy rules are loss-minimizing policy (LMP), CPI inflation Taylor rule (CITR), domestic inflation Taylor rule (DITR) and the exchange rate peg (PEG). The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

With DE, we define the monetary policy that minimizes the loss function as loss-minimizing policy (LMP).<sup>20</sup> Under DE, LMP results in a slightly shallower recession relative to the RE case. This appears to be counterintuitive, but hinges on the assumption of optimal monetary policy under commitment and the role of expectations. Indeed, LMP under DE results in a stronger expected decline in domestic inflation (owing to the role of the domestic inflation surprise terms, recall equation (3.31)). Again, here we have the analog of the price-level targeting dynamic from closed-economy models, but in an enhanced manifestation. In fact, we see a mild deflation in the context of domestic prices. This results in lower current inflation, and as a result, allows for a greater monetary loosening (and therefore a milder decline in output).

More generally, the sharp responses upon shock impact under DE are because agents revise their expectations after one period (that is, the effect of the DE

<sup>20</sup>We refer to the policy as “loss-minimizing” rather than “optimal” because defining optimal monetary policy under DE requires taking a stance on how the social planner accounts for DE, which is beyond the scope of this paper.

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surprises dissipate after one period). A case in point is the dynamic of the nominal exchange rate. In conjunction with the tighter policy stance in the DITR regime, under DE we see a sharper nominal (and real) exchange rate appreciation, a dynamic which is amplified by the exchange rate surprise terms in the UIP condition. The strengthened exchange rate channel under DE results in a real appreciation that tightens monetary conditions. The CITR regime bear semblance to LMP, but with less policy accommodation.

By contrast, under PEG, while (domestic) inflation is more volatile, but the contraction in economic activity is less severe relative to LMP. Does this finding foreshadow a role for exchange rate stabilization under DE? To address this question, we explore the welfare implications of selected monetary policy regimes under alternative calibrations below.

#### 3.3.3.3 Welfare ranking of different monetary policy regimes

Table 3.3 presents the welfare losses of the three simple rules considered above. In addition to the baseline RE case, we present the results of selected values of  $\theta$ , which determine the strength of DE. Given its role in underpinning the terms-of-trade externality, we also consider various values of  $\eta$ , the elasticity of substitution between home and foreign goods. As above, we apply cost-push shocks to the economy and compute the welfare loss from the welfare objective function 3.40.

**Table 3.3:** Welfare losses for selected monetary policy rules, only cost-push shocks

	Rational			Diagnostic ( $\theta = 0.5$ )			Diagnostic ( $\theta = 1$ )			Diagnostic ( $\theta = 1.5$ )		
	DITR	CITR	PEG	DITR	CITR	PEG	DITR	CITR	PEG	DITR	CITR	PEG
$\eta = 1$	0.0803	<b>0.0797</b>	0.0802	0.0818	<b>0.0803</b>	0.0807	0.0853	0.0834	<b>0.0812</b>	0.0932	0.1185	<b>0.0817</b>
$\eta = 2$	0.1266	0.1258	<b>0.1255</b>	0.1286	0.1269	<b>0.1260</b>	0.1335	0.1308	<b>0.1267</b>	0.1463	0.1659	<b>0.1276</b>
$\eta = 3$	0.1396	0.1389	<b>0.1383</b>	0.1416	0.1401	<b>0.1389</b>	0.1466	0.1438	<b>0.1397</b>	0.1611	0.1753	<b>0.1407</b>
$\eta = 4$	0.1460	0.1453	<b>0.1447</b>	0.1478	0.1465	<b>0.1452</b>	0.1527	0.1500	<b>0.1460</b>	0.1683	0.1791	<b>0.1471</b>
$\eta = 5$	0.1497	0.1492	<b>0.1485</b>	0.1515	0.1503	<b>0.1490</b>	0.1561	0.1536	<b>0.1499</b>	0.1725	0.1811	<b>0.1509</b>
$\eta = 6$	0.1522	0.1517	<b>0.1511</b>	0.1539	0.1528	<b>0.1516</b>	0.1583	0.1559	<b>0.1524</b>	0.1753	0.1823	<b>0.1534</b>
$\eta = 7$	0.1540	0.1536	<b>0.1529</b>	0.1555	0.1546	<b>0.1534</b>	0.1598	0.1576	<b>0.1542</b>	0.1772	0.1830	<b>0.1552</b>

*Source:* Authors' calculations. *Notes:* Welfare losses for selected monetary policy rules. The selected rules are: CPI inflation Taylor rule (CITR), domestic inflation Taylor rule (DITR) and the exchange rate peg (PEG). The standard deviations of the cost-push shock is 0.0013 and the persistence is 0.99 as in De Paoli (2009b). Entries are percentage units of steady-state consumption.

Under rational expectations and the baseline calibration  $\eta = 1$ , the CITR is welfare superior to the PEG (and the DITR). As we increase the value of  $\eta$

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to 2, we see that the welfare ranking switches from CITR to the PEG. To help understand the intuition behind the switch in regime rankings, we examine the impulse response of a cost-push shock under two different calibrations of the intra-temporal elasticity of substitution,  $\eta$ , in Figure 3.4. Recall that a value of  $\eta > 1$  implies that home and foreign goods are substitutes. Indeed, if home and foreign goods are close substitutes, an improvement in the terms of trade can induce agents to consume more imported goods via the expenditure switching effect. These agents are better off because they can reduce labor effort without a corresponding fall in their consumption levels. Hence, policymakers may try to affect the terms of trade to optimally improve welfare.

In Figure 3.4, we compare the baseline value of  $\eta = 1$  under RE where the CITR is welfare superior to the PEG, with the case when  $\eta = 6$  where the PEG is more desirable.<sup>21</sup> We also include the optimal monetary policy (OMP) associated with each calibration. Under the baseline calibration ( $\eta = 1$ ), the responses under CITR are more similar to OMP relative to the PEG. In particular, the response of the terms of trade under the CITR virtually overlaps with that of the OMP. Hence it is not surprising that the CITR is welfare superior to the PEG in this case. However, with  $\eta = 6$ , the responses of the PEG track those of optimal monetary policy relatively more closely. Recall that with  $\eta = 6$ , a smaller change in the terms of trade can facilitate expenditure switching. Indeed, the PEG is more desirable because the smaller change in the terms of trade is sufficient to maintain consumption levels (by inducing a greater consumption of foreign goods given  $\eta = 6$ ) with a more limited impact on output (including because the trade balance deteriorates relatively less). At this calibration, greater output stabilization comes at a cost of higher (domestic) inflation, nonetheless, the PEG seems to strike a good balance between these two key competing policy objectives.

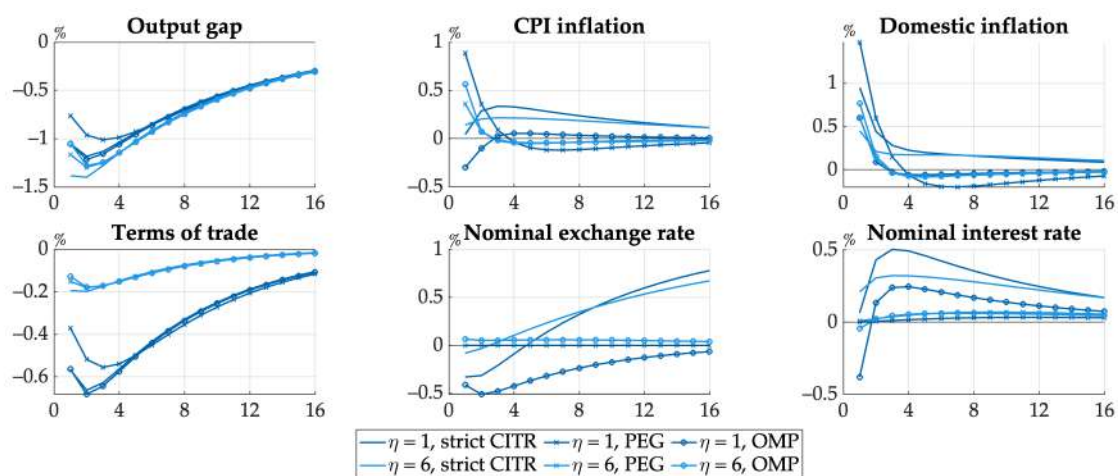
Now consider DE, which has implications for the welfare rankings. For the baseline case of  $\eta = 1$ , contrasting RE ( $\theta = 0$ ) with DE ( $\theta > 0$ ), the welfare losses

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<sup>21</sup>To make the contrasts clear, we use  $\eta = 6$  instead of  $\eta = 2$  where the change happens. Moreover, we use a strict CITR in this case for the same reason. For the DE case, Figure C.3 in the Appendix.

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**Figure 3.4:** Responses to a cost-push shock under different  $\eta$ , rational expectations



*Source:* Authors' calculations. *Notes:* Impulse responses to a 0.22 percentage point cost-push shock under rational expectations. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized.

generally increase because DE increases macroeconomic volatility. Moreover, we show in section 3.3.2.2 that DE amplifies the volatility of the exchange rate. This channel has important implications for the welfare rankings: Given the higher volatility of the exchange rate under DE (e.g.,  $\theta = 1$ ) relative to the RE case, lower values of  $\eta$  (e.g.,  $\eta = 1$ ) can result in a sufficient degree of expenditure switching leading to a change in the welfare rankings. So, for reasonable values of  $\theta$  (including based on empirical estimates), exchange rate stabilization is welfare superior for broad range of values for the parameter  $\eta$ .

Now, let us consider a combination of technology shocks and foreign output shocks, as in Galí and Monacelli (2005). The results for the combination of shocks, and then the shocks individually are in Table 3.4. The results for the combination of shocks, as displayed in the top panel, are qualitatively similar to the result under the cost-push shocks: Higher elasticity of substitution parameters  $\eta$  and higher DE parameters  $\theta$  induce the loss-minimizing policy to switch from CITR to PEG.

Studying the shocks individually, as in the lower panels of Table 3.4, we find that the technology shocks drive the main result in the upper panel. Again, the

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**Table 3.4:** Policy rules with lowest welfare loss, under technology shocks and foreign demand shocks

	Rational	Diagnostic expectations		
		$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$
$\eta = 1$	CITR	CITR	CITR	PEG
$\eta = 2$	CITR	CITR	CITR	PEG
$\eta = 3$	CITR	CITR	CITR	PEG
$\eta = 4$	CITR	CITR	CITR	PEG
$\eta = 5$	CITR	CITR	CITR	PEG
$\eta = 6$	CITR	CITR	CITR	PEG
$\eta = 7$	CITR	CITR	PEG	PEG

**(a)** Combination of technology and foreign demand shocks as in Galí and Monacelli (2005)

	Rational	Diagnostic expectations				Rational	Diagnostic expectations		
		$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$			$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$
$\eta = 1$	CITR	CITR	CITR	PEG	$\eta = 1$	DITR	CITR	CITR	DITR
$\eta = 2$	CITR	CITR	CITR	PEG	$\eta = 2$	DITR	DITR	CITR	DITR
$\eta = 3$	CITR	CITR	CITR	PEG	$\eta = 3$	DITR	DITR	CITR	DITR
$\eta = 4$	CITR	CITR	CITR	PEG	$\eta = 4$	DITR	DITR	DITR	DITR
$\eta = 5$	CITR	CITR	PEG	PEG	$\eta = 5$	DITR	DITR	DITR	DITR
$\eta = 6$	CITR	CITR	PEG	PEG	$\eta = 6$	DITR	DITR	DITR	DITR
$\eta = 7$	CITR	CITR	PEG	PEG	$\eta = 7$	DITR	DITR	DITR	DITR

**(b)** Technology shocks only

**(c)** Foreign demand shocks only

*Source:* Authors' calculations. *Notes:* Policy rules associated with the highest welfare. The selected rules are: CPI inflation Taylor rule (CITR), domestic inflation Taylor rule (DITR) and the exchange rate peg (PEG). For CITR and DITR, the weight on inflation in the Taylor Rule is 1.5. The standard deviations of the technology shocks, and foreign demand shocks are 0.0071 and 0.0078 respectively, and their persistence parameters are 0.66 and 0.86 respectively. The correlation of shocks is 0.3. See Galí and Monacelli (2005) for more details.

mechanism under the technology shocks is similar to that of the cost-push shock. The foreign demand shocks however, have a different mechanism: Since foreign demand shocks affect the availability of foreign goods in the home economy, stabilizing the wedge in the UIP through the PEG does not help stabilizing the rest of the economy. Hence, the DITR dominates in most cases.

In Table 3.6 in the Appendix we show that government spending shocks and foreign interest rate shocks also have the same mechanism to the cost-push shock and the technology shock, where the ranking switches by increasing  $\eta$  and  $\theta$ . Finally, we use a combination of shocks introduced by De Paoli (2009a) and show that the welfare results follow from the results of the individual shocks.

#### 3.3.4 Simple monetary policy rules

We now investigate how the central bank can best minimize the loss function (3.40) when the preferred monetary policy regime is CITR. We use the benchmark

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calibration of  $\eta = 1$  and shocks à la Galí and Monacelli (2005). Table 3.4 shows that for this case, CITER is the loss-minimizing monetary policy regime under rational expectations and two levels of DE ( $\theta = 0.5$  and  $\theta = 1$ ). To find the parameter values for CITER that the central bank should follow to minimize welfare losses, we consider the general Taylor rule (3.32) and optimize over its coefficients on the CPI inflation,  $\phi_\pi$ , and output gap,  $\phi_y$ . The results are in Table 3.5.

**Table 3.5:** Loss-minimizing parameter values and volatilities

	RE ( $\theta = 0$ )	DE ( $\theta = 0.5$ )	DE ( $\theta = 1$ )
$\phi_\pi$	5.41	3.26	2.58
$\phi_y$	0.00	0.00	0.00
$\sigma_\pi$	0.0002	0.0004	0.0008
$\sigma_y$	0.0047	0.0049	0.0053
$\sigma_q$	0.0037	0.0038	0.0039

*Source:* Authors' calculations. *Notes:* Values for  $\phi_\pi$  and  $\phi_y$  that minimize the welfare loss when the economy is propagated with shocks as in Galí and Monacelli (2005).  $\sigma_x$  is the standard deviation of variable  $x$ .

Table 3.5 shows that the central bank should not put any weight on the output gap in the Taylor rule when they minimize the welfare loss. Moreover, we find that the higher the DE parameter  $\theta$ , the lower the weight should be on CPI inflation. In other words, the central bank should react less to CPI inflation fluctuations in the model with DE. DE enhance the exchange rate channel and enforce the interest rate channel of monetary policy: For example, when the central bank increases its interest rate, appreciation in the exchange rate puts downward pressure on the output gap and CPI inflation, and enforces the contractionary monetary policy. DE strengthens these fluctuations in the exchange rate through the UIP and hence reduces the burden on monetary policy.

## 3.4 Conclusion

In this paper we revisit the classic debate on the optimal degree of exchange rate stabilization in an open economy. We do it with a twist, however. In particular, we introduce Diagnostic Expectations (DE) into an otherwise standard New Keynesian small open economy framework. DE differ from the standard presumption

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of Rational Expectations (RE) whereby an overreaction of agents' beliefs generates an additional mechanism of endogenous macroeconomic volatility. Motivated by the failure of the pure RE hypothesis, DE have been incorporated into closed-economy models where it has been empirically validated. Of note, DE are a simple, transparent, and portable alternative to RE, and we contribute to existing research by being the first to incorporate this type of belief formation in a small open economy model to conduct a rigorous comparison of exchange rate regimes.

This paper also contributes to the previous studies in two other important ways. First, our small, open-economy model with DE can help resolve the longstanding exchange rate disconnect and forward premium puzzles, including because of the greater degree of associated macroeconomic volatility. The resolution of these two key exchange rate puzzles identified in earlier research is reassuring, including because it serves as an initial empirical assessment of our model.

Second, in terms of loss-minimizing monetary policy, we find that the incorporation of DE alters the welfare rankings of selected exchange rate regimes. Specifically, when the strength of DE is calibrated in line with empirical estimates, simulations suggest that an exchange rate peg could be welfare superior relative to a policy that targets consumer price index (CPI) inflation. Extreme model parameterizations are not needed to justify the stabilization of the exchange rate. Moreover, optimization of simple rules suggest that the central bank should react less to CPI inflation when accounting for DE, since DE enhances the exchange rate channel of monetary policy. In terms of future research, the model could be extended by adding additional nominal and real rigidities to facilitate estimation, including to provide robust estimates of the diagnosticity parameter in open-economy contexts.

# Appendices to Chapter 3

## C.1 Equilibrium conditions and the steady state

### C.1.1 Equilibrium conditions

Labor supply equation [ $\hat{w}_t^{real}$ ]

$$\hat{w}_t^{real} = \sigma \hat{c}_t + \varphi \hat{n}_t \quad (\text{A.1})$$

Euler equation [ $\hat{c}_t$ ]

$$\sigma(E_t[\hat{c}_{t+1}] + \theta \xi_{t+1}^c - \hat{c}_t) = \hat{i}_t - (E_t[\hat{\pi}_{t+1}] + \theta \xi_{t+1}^\pi + \theta \xi_t^\pi) \quad (\text{A.2})$$

CPI inflation [ $\hat{\pi}_t$ ]

$$\hat{\pi}_t = \hat{\pi}_{H,t} + \alpha \Delta \hat{s}_t \quad (\text{A.3})$$

Real exchange rate [ $\hat{q}_t$ ]

$$\hat{q}_t = (1 - \alpha) \hat{s}_t \quad (\text{A.4})$$

Nominal appreciation/depreciation [ $\hat{s}_t$ ]

$$\Delta \hat{e}_t = \Delta \hat{s}_t + \hat{\pi}_{H,t} \quad (\text{A.5})$$

Uncovered interest parity [ $\Delta \hat{e}_t$ ]

$$\hat{i}_t = \hat{i}_t^* + \psi_b \hat{b}_t + (E_t[\Delta \hat{e}_{t+1}] + \theta \xi_{t+1}^{\Delta e} + \theta \xi_t^{\Delta e}) \quad (\text{A.6})$$

Production function [ $\hat{n}_t$ ]

$$\hat{y}_t = \hat{n}_t + \hat{a}_t \quad (\text{A.7})$$

New Keynesian Phillips Curve [ $\hat{\pi}_{H,t}$ ]

$$\hat{\pi}_{H,t} = \beta (E_t[\hat{\pi}_{H,t+1}] + \theta \xi_{t+1}^{\pi H}) + \frac{\epsilon}{\psi_p \mathcal{M}} \hat{\mu}_t + \hat{u}_t \quad (\text{A.8})$$

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Marginal cost/labor demand [ $\hat{\mu}_t$ ]

$$\hat{w}_t^{real} = \hat{a}_t + \hat{\mu}_t - \alpha \hat{s}_t \quad (\text{A.9})$$

Market clearing [ $\hat{y}_t$ ]

$$\hat{y}_t = \frac{\bar{c}}{\bar{y}} \{(1 - \alpha)\hat{c}_t + \alpha[\eta(2 - \alpha)\hat{s}_t + \hat{y}_t^*]\} + \hat{g}_t \quad (\text{A.10})$$

Trade balance [ $\hat{tb}_t$ ]

$$\hat{tb}_t = \hat{y}_t - \frac{\bar{c}}{\bar{y}}\hat{c}_t + \alpha\hat{s}_t - \hat{g}_t \quad (\text{A.11})$$

Interest rate rule [ $\hat{l}_t$ ]

$$\hat{l}_t = \phi_\pi \hat{\pi}_t + \phi_y \tilde{y}_t + \hat{\nu}_t \quad (\text{A.12})$$

Output gap [ $\tilde{y}_t$ ]

$$\tilde{y}_t = \hat{y}_t - \hat{y}_t^n \quad (\text{A.13})$$

Evolution of foreign debt [ $\hat{b}_t$ ]

$$\hat{tb}_t = \hat{b}_{t-1} - \beta \hat{b}_t \quad (\text{A.14})$$

#### Shock processes

Total factor productivity [ $\hat{a}_t$ ]

$$\hat{a}_t = \rho_a \hat{a}_{t-1} + \varepsilon_t^a \quad (\text{A.15})$$

Cost-push shock [ $\hat{u}_t$ ]

$$\hat{u}_t = \rho_u \hat{u}_{t-1} + \varepsilon_t^u \quad (\text{A.16})$$

Government spending shock [ $\hat{g}_t$ ]

$$\hat{g}_t = \rho_g \hat{g}_{t-1} + \varepsilon_t^g \quad (\text{A.17})$$

Monetary policy shock [ $\hat{\nu}_t$ ]

$$\hat{\nu}_t = \rho_\nu \hat{\nu}_{t-1} + \varepsilon_t^\nu \quad (\text{A.18})$$

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Foreign demand shock  $[\hat{y}_t^*]$

$$\hat{y}_t^* = \rho_y \hat{y}_{t-1}^* + \varepsilon_t^{y^*} \quad (\text{A.19})$$

Foreign interest rate shock  $[\hat{r}_t^*]$

$$\hat{r}_t^* = \rho_r \hat{r}_{t-1}^* + \varepsilon_t^{r^*} \quad (\text{A.20})$$

#### Flexible price equilibrium

Natural output  $[\hat{y}_t^n]$

$$\hat{y}_t^n = \frac{\bar{c}}{\bar{y}} \{(1 - \alpha) \hat{c}_t^n + \alpha [\eta(2 - \alpha) \hat{s}_t^n + \hat{y}_t^*]\} + \hat{g}_t \quad (\text{A.21})$$

Natural consumption  $[\hat{c}_t^n]$ <sup>22</sup>

$$\sigma \hat{c}_t^n + \varphi y_t^n + \alpha \hat{s}_t = (1 + \varphi) \hat{a}_t \quad (\text{A.22})$$

Natural trade balance  $[\hat{b}_t^n]$

$$\hat{t}b_t^n = \hat{y}_t^n - \frac{\bar{c}}{\bar{y}} \hat{c}_t^n + \alpha \hat{s}_t^n - \hat{g}_t \quad (\text{A.23})$$

Natural foreign assets  $[\hat{b}_t^n]$

$$\hat{t}b_t^n = \hat{b}_{t-1}^n - \beta \hat{b}_t^n \quad (\text{A.24})$$

Natural real exchange rate  $[\hat{q}_t^n]$ <sup>23</sup>

$$\sigma \left( E_t[c_{t+1}^n] + \theta \xi_{t+1}^c - \hat{c}_t^n \right) = \hat{r}_t + \psi_b \hat{b}_t^n + E_t[\hat{q}_{t+1}^n] - \hat{q}_t^n + \theta \left( \xi_{t+1}^{\Delta q} + \xi_t^{\Delta q} \right) \quad (\text{A.25})$$

Natural terms of trade  $[\hat{s}_t^n]$

$$\hat{s}_t^n = \frac{\hat{q}_t^n}{1 - \alpha} \quad (\text{A.26})$$

<sup>22</sup>From the firm's problem, setting mark-ups equal to zero.

<sup>23</sup>From combining the UIP condition in real terms and the Euler equation.

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#### C.1.2 Steady state

We assume that the relative price between home and foreign goods is unity in steady state:

$$\bar{S} = 1 \quad (\text{A.27})$$

It follows that the real exchange rate is also unity in steady state:

$$\bar{Q} = 1 \quad (\text{A.28})$$

Combining the labor supply, marginal cost, and production function, we get the steady-state total factor productivity:

$$\bar{A} = \left( \frac{1 - \nu}{\bar{\mu}} \right)^{\frac{1}{1+\varphi}} \bar{Y}^*{}^{\frac{\sigma+\varphi}{1+\varphi}} \quad (\text{A.29})$$

where  $\bar{\mu} = \frac{\epsilon-1}{\epsilon}$ , obtained from the firm's first-order condition in steady state, and  $\nu$  is the employment subsidy that ensures an efficient steady state. We assume for simplicity that  $\bar{Y} = \bar{Y}^* = \bar{C}^* = 1$ .

## C.2 Impulse responses under different financial markets

In this Appendix, we compare impulse responses of the model in the paper, a small open economy model with incomplete financial markets, with the responses under complete markets. For the incomplete markets case, we show both the rational and DE cases. We strengthen our understanding on DE and show how and why the model results differ from classical responses.

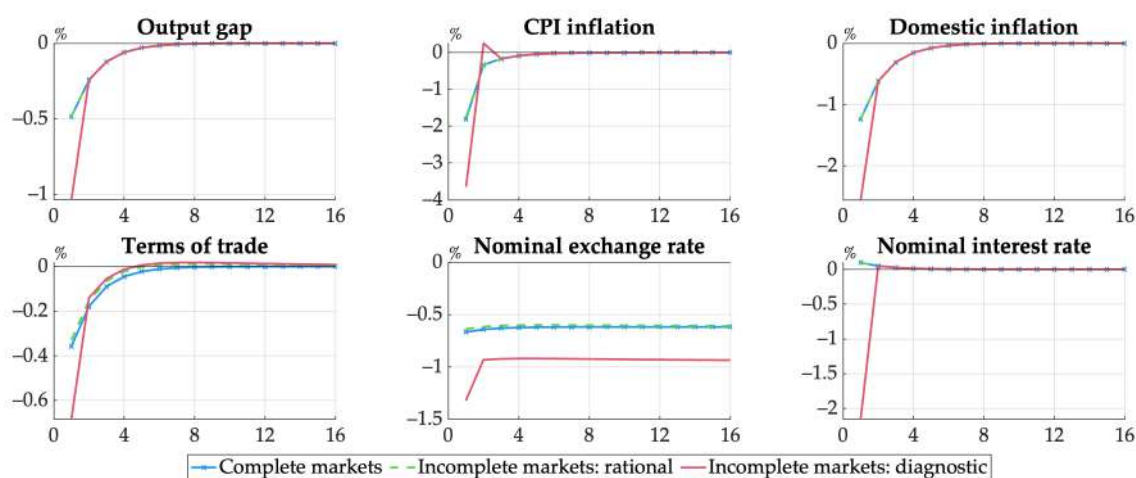
### C.2.1 Monetary policy shock

This subsection shows that our small open economy model can replicate the results in Galí (2015). We consider the case of a 1 percentage point contractionary monetary policy shock. The impulse responses are in Figure C.1. The monetary policy rule in this exercise is a Taylor rule that targets domestic inflation and

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output gap. The crossed blue lines are the responses for the complete markets case, which match the results in Galí (2015). We can see that the incomplete markets case, the dashed green line, closely follows the complete markets case, since the debt elasticity parameter  $\psi_b$  is low in the baseline calibration. As in the results shown in the main text, DE introduce an amplification of impulse responses, as the red solid lines show.

**Figure C.1:** Responses to a monetary policy shock



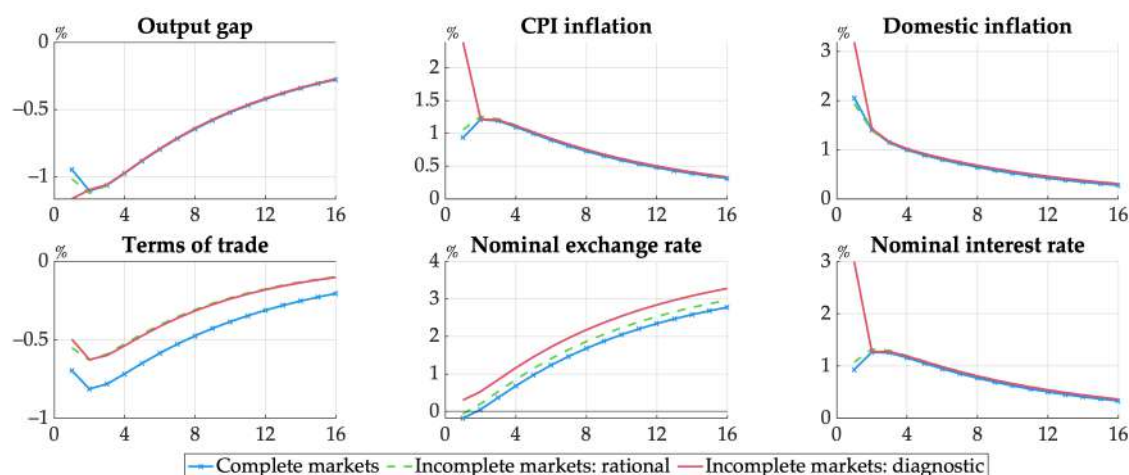
*Source:* Authors' calculations. *Notes:* Impulse responses to a 1 percentage point increase in domestic interest rates. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized. Inflation and interest rates are annualized.

Interestingly, the nominal interest rate decreases after the contractionary monetary policy shock, which is the result of the following amplification mechanism: When the nominal interest rate increases from the shock, the home currency appreciates through the uncovered interest condition. From the surprise terms of the DE in the UIP condition (3.28), this appreciation overshoots the appreciation for the RE case. Consequently, in the DE case, imports become cheaper and domestic firms also decrease their prices. Moreover, from the terms-of-trade externality, output decreases more under DE. The decrease in domestic inflation, together with the strong decrease in output, feeds back into the Taylor rule and decreases the nominal interest rate on impact.

### C.2.2 Cost-push shock

To show the implications of DE, we present the impulse responses after a 0.22 percent cost-push shock in Figure C.2. We calibrate the shock such that the response of output for the RE case is about 1 percent. The responses of the complete markets case and the incomplete markets case with RE are similar and are in line with the literature. As in the closed economy case, a positive cost-push increases domestic inflation. This rise in domestic inflation pushes the CPI upwards and the output gap downwards. Given the larger weight on CPI inflation, nominal interest rate increases after the shock. Since the economy is open to international trade, the shock induces a real appreciation of the exchange rate, which combined with the terms-of-trade externality, aggravated the economic contraction. We show in the welfare analysis that when the elasticity of substitution between home and foreign goods are higher, this real exchange rate appreciation matters for the welfare of households.

Figure C.2: Responses to a cost-push shock



Source: Authors' calculations. Notes: Impulse responses to a 0.22 percentage point cost-push shock. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized. Inflation and interest rates are annualized.

The impulse responses of the DE economy are like the RE counterparts, but with amplified dynamics. First, because the responses of output and consumption intensify from the surprise terms in the consumption Euler equation (3.25), the

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responses of output and consumption are bigger under DE. Second, the real appreciation, and hence the terms-of-trade externality, are also more severe, from the surprise terms in the UIP condition (3.28). Third, the response of domestic inflation amplifies from the surprise term in the NKPC (3.31), which also augments the response of CPI inflation. Hence, under DE, the monetary authority needs to react stronger to shocks than under RE.

## C.3 Derivation of the loss function

In this section, we present the derivation of the loss function. The utility function is:

$$\mathcal{U}(C_t, N_t) = U(C_t) - V(N_t) \quad (\text{A.30})$$

where

$$U(C_t) = \frac{C_t^{1-\sigma}}{1-\sigma} \quad \text{and} \quad V(N_t) = \frac{N_t^{1+\varphi}}{1+\varphi} \quad (\text{A.31})$$

We can find the per-period deviation of utility from steady state using:

$$\bar{\mathcal{U}} - \mathcal{U}_t = [V(N_t) - V(\bar{N})] - [U(C_t) - U(\bar{C})] \quad (\text{A.32})$$

To take the second-order approximation, use  $\frac{X_t - \bar{X}}{\bar{X}} \cong \hat{x}_t + \frac{1}{2}\hat{x}_t^2$  with  $\hat{x}_t = \log\left(\frac{X_t}{\bar{X}}\right)$ .

Then, we can express the components of the utility function as:

$$V(N_t) - V(\bar{N}) = \bar{V}_N \bar{N} \left( \hat{n}_t + \frac{1+\varphi}{2} \hat{n}_t^2 \right) + t.i.p. + O(\cdot) \quad (\text{A.33})$$

$$U(C_t) - U(\bar{C}) = \bar{U}_C \bar{C} \left( \hat{c}_t + \frac{1-\sigma}{2} \hat{c}_t^2 \right) + t.i.p. + O(\cdot) \quad (\text{A.34})$$

where we simplify notation with  $V_N = \frac{\partial V(N)}{\partial N}$  and  $U_C = \frac{\partial U(C)}{\partial C}$ . *t.i.p.* stands for “terms independent of policy”. Using the second-order expansion of the market clearing condition (3.35) and of the aggregate price index (3.4), rewrite the consumption utility component as:

$$\begin{aligned} U(C_t) - U(\bar{C}) = & \bar{U}_C \bar{C} \phi \left\{ \hat{y}_t - \alpha\eta(\phi+1)\hat{q}_t + \frac{1-\sigma\phi}{2}\hat{y}_t^2 - \frac{\psi_p}{2}\hat{\pi}_{Ht}^2 \right. \\ & - \frac{1}{2}\alpha\eta \left[ 1 + \phi - \zeta + \sigma\alpha\eta\phi(1+\phi)^2 \right] \hat{q}_t^2 - \alpha\eta\phi[1-\sigma(\phi+1)]\hat{y}_t\hat{q}_t + \sigma\hat{y}_t\hat{q}_t + \sigma\alpha\phi\hat{y}_t\hat{c}_t^* \\ & \left. - \sigma\alpha\eta(\phi+1)\hat{q}_t\hat{q}_t - \alpha\eta[\sigma\alpha\phi(\phi+1)+1]\hat{q}_t\hat{c}_t^2 - \frac{\hat{q}_t}{\phi} - \alpha\hat{c}_t^* \right\} + t.i.p. + O(\cdot) \quad (\text{A.35}) \end{aligned}$$

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where  $\phi = (1 - \alpha)^{-1}$  and  $\zeta = \eta\phi^2 + \alpha(\eta - 1)\phi^2 - (\eta - 1)$ . Using the log-linear production function (A.7), rewrite the labor disutility component as:

$$V(N_t) - V(\bar{N}) = \overline{MU_C C} \hat{y}_t + \frac{\overline{MU_C C}(1 + \varphi)}{2} \hat{y}_t^2 - \overline{MU_C C}(1 + \varphi) \hat{y}_t \hat{a}_t + t.i.p. + O(\cdot) \quad (\text{A.36})$$

where  $\bar{M} = -\frac{\overline{U_{NN}}}{\overline{U_C C}}$ . Combine the two components to rewrite the loss as:<sup>24</sup>

$$\begin{aligned} L_t &= \frac{V(N_t) - V(\bar{N}) - [V(C_t) - V(\bar{C})]}{\overline{U_C C}} \\ &= (\bar{M} - \phi) \hat{y}_t + \alpha\eta\phi(\phi + 1) \hat{q}_t + \frac{\bar{M}(1 + \varphi) - \phi(1 - \sigma\phi)}{2} \hat{y}_t^2 + \phi \frac{\psi_p}{2} \hat{\pi}_{Ht}^2 \\ &+ \frac{1}{2} \alpha\eta\phi [1 + \phi - \zeta + \sigma\alpha\phi(1 + \phi)^2] \hat{q}_t^2 + \alpha\eta\phi^2 [1 - \sigma(\phi + 1)] \hat{y}_t \hat{q}_t - \bar{M}(1 + \varphi) \hat{y}_t \hat{a}_t - \sigma\phi \hat{y}_t \hat{g}_t \\ &- \sigma\alpha\phi^2 \hat{y}_t \hat{c}_t^* + \sigma\alpha\eta\phi(\phi + 1) \hat{q}_t \hat{g}_t + \alpha\eta\phi [\sigma\alpha\phi(\phi + 1) + 1] \hat{q}_t \hat{c}_t^* + \hat{g}_t + \alpha\phi \hat{c}_t^* + t.i.p. + O(\cdot) \end{aligned} \quad (\text{A.38})$$

We need to get rid of the linear terms  $\hat{y}_t$  and  $\hat{q}_t$ . Before we do that, rewrite the above equation as:

$$\begin{aligned} \mathcal{L}_t &= -\frac{U_0}{\overline{U_C C}} = \sum_{t=0}^{\infty} \beta^t \left\{ (\bar{M} - \phi) \hat{y}_t + \alpha\eta\phi(\phi + 1) \hat{q}_t + \frac{\bar{M}(1 + \varphi) - \phi(1 - \sigma\phi)}{2} \hat{y}_t^2 \right. \\ &+ \phi \frac{\psi_p}{2} \hat{\pi}_{Ht}^2 + \frac{1}{2} \alpha\eta\phi [1 + \phi - \zeta + \sigma\alpha\phi(1 + \phi)^2] \hat{q}_t^2 + \alpha\eta\phi^2 [1 - \sigma(\phi + 1)] \hat{y}_t \hat{q}_t \\ &- \bar{M}(1 + \varphi) \hat{y}_t \hat{a}_t - \sigma\phi \hat{y}_t \hat{g}_t - \sigma\alpha\phi^2 \hat{y}_t \hat{c}_t^* + \sigma\alpha\eta\phi(\phi + 1) \hat{q}_t \hat{g}_t + \\ &\left. \alpha\eta\phi [\sigma\alpha\phi(\phi + 1) + 1] \hat{q}_t \hat{c}_t^* + \hat{g}_t + \alpha\phi \hat{c}_t^* \right\} + t.i.p. + O(\cdot) \end{aligned} \quad (\text{A.39})$$

We proceed to remove the terms  $(\bar{M} - \phi) \hat{y}_t + \alpha\eta\phi(\phi + 1) \hat{q}_t$  by taking second-order approximations of the equilibrium conditions.

First, rewrite the New Keynesian Philips Curve (NKPC) as:

$$(\Pi_{Ht} - \Pi) \Pi_{Ht} = \beta E_t [D_t (\Pi_{H,t+1} - \Pi) \Pi_{H,t+1}] + \frac{\epsilon}{\psi_p} \left( mc_t - \frac{\epsilon - 1}{\epsilon} \right) \quad (\text{A.40})$$

<sup>24</sup>Note that if  $\alpha = 0 \Rightarrow \bar{M} = 1 \wedge \phi = 1$ . The loss function becomes:

$$L_t = \frac{\varphi + \sigma}{2} \hat{y}_t^2 + \frac{\psi_p}{2} \hat{\pi}_{Ht}^2 - (1 + \varphi) \hat{y}_t \hat{a}_t - \sigma \hat{y}_t \hat{g}_t + \hat{g}_t \quad (\text{A.37})$$

which equals the corresponding loss function in a closed economy.

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where  $D_t = \frac{P_{H,t+1}Y_{t+1}}{P_{Ht}Y_t} \left(\frac{C_{t+1}}{C_t}\right)^{-\sigma}$  and  $m_{C_t} = (1 - \nu) \frac{\mu_t Y_t^\varphi}{A_t^{1+\varphi} P_{Ht} C_t^{-\sigma}}$ , and take the second-order approximation:

$$\begin{aligned}
\hat{\pi}_{Ht} + \frac{3}{2}\hat{\pi}_{Ht}^2 &= \beta \left( E_t[\hat{\pi}_{Ht}] + \frac{3}{2}E_t[\hat{\pi}_{Ht}^2] \right) + K(\sigma\phi + \varphi) \left( \hat{y}_t + \frac{1}{2}\hat{y}_t^2 \right) \\
&\quad K\alpha\phi[1 - \sigma\eta(\phi + 1)] \left( \hat{q}_t + \frac{1}{2}\hat{q}_t^2 \right) - \frac{K\sigma\phi\psi_p}{2}\hat{\pi}_{Ht}^2 + \frac{Km_Y}{2}\hat{y}_t^2 + \frac{Km_{QQ}}{2}\hat{q}_t^2 \\
&\quad + Km_{YQ}\hat{y}_t\hat{q}_t - Km_{YA}\hat{y}_t\hat{a}_t + Km_{Yu}\hat{y}_t\hat{u}_t - Km_{YG}\hat{y}_t\hat{g}_t - Km_{YC^*}\hat{y}_t\hat{c}_t^* - Km_{QA}\hat{q}_t\hat{a}_t \\
&\quad + Km_{Qu}\hat{q}_t\hat{u}_t - Km_{QG}\hat{q}_t\hat{g}_t + Km_{QC^*}\hat{q}_t\hat{c}_t^* \\
&\quad + \beta(\sigma\phi - 1) (\hat{y}_t - E_t[\hat{y}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] + \beta\alpha\phi[1 - \sigma\eta(\phi + 1)] (\hat{q}_t - E_t[\hat{q}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] \\
&\quad - \beta\sigma (\hat{g}_t - E_t[\hat{g}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] - \beta\sigma\alpha\phi (\hat{c}_t^* - E_t[\hat{c}_{t+1}^*]) E_t[\hat{\pi}_{H,t+1}] + t.i.p. + O(\cdot)
\end{aligned} \tag{A.41}$$

where  $K = \frac{\epsilon-1}{\psi_p}$  and  $m_X$  are the coefficients taken from the second-order approximation of  $m_{C_t}$ :

$$m_Y = \sigma(\sigma - 1)\phi^2 + \varphi(\varphi - 1) + 2\varphi\sigma\phi \tag{A.42}$$

$$m_Q = \alpha\phi[\sigma\eta\zeta + \sigma(\sigma - 1)\alpha\phi\eta^2(\phi + 1)^2 - \eta\phi + 2\alpha\phi - 2\sigma\alpha\eta\phi(\phi + 1)] \tag{A.43}$$

$$m_{YQ} = \alpha\phi[\sigma\eta\phi + \sigma(\sigma - 1)\eta\phi(\phi + 1) + \varphi\sigma\eta(\phi + 1) - \sigma\phi - \varphi] \tag{A.44}$$

$$m_{YA} = (1 + \varphi)(\sigma\phi + \varphi) \quad m_{Yu} = \sigma\phi + \varphi \quad m_{YG} = \sigma[\varphi + (\sigma - 1)\phi] \tag{A.45}$$

$$m_{YC^*} = \sigma\alpha\phi[(\sigma - 1)\phi + \varphi] \quad m_{QA} = (1 + \varphi)\alpha\phi[1 - \sigma\eta(\phi + 1)] \tag{A.46}$$

$$m_{Qu} = \alpha\phi[1 - \sigma\eta(\phi + 1)] \quad m_{QG} = \sigma\alpha\phi[1 - (\sigma - 1)\eta(\phi + 1)] \tag{A.47}$$

$$m_{QC^*} = \sigma\alpha\phi[(\sigma - 1)\alpha\eta\phi(\phi + 1) - \eta - \alpha\phi] \tag{A.48}$$

Rewrite the second-order approximation of the NKPC (A.41) in the following format:

$$V_t = I_t + \beta E_t[V_{t+1}] + t.i.p. + O(\cdot) \tag{A.49}$$

where  $V_t = \hat{\pi}_{Ht} + \frac{3}{2}\hat{\pi}_{Ht}^2$  and  $I_t = K(\sigma\phi + \varphi) \left( \hat{y}_t + \frac{1}{2}\hat{y}_t^2 \right) + K\alpha\phi[1 - \sigma\eta(\phi + 1)] \left( \hat{q}_t + \frac{1}{2}\hat{q}_t^2 \right) \dots$

Iterate backward to get:

$$V_0 = E_0 \sum_{t=0}^{\infty} \beta^t I_t + t.i.p. + O(\cdot) \tag{A.50}$$

If  $\pi_0 = \bar{\pi}$ , then  $V_0 = 0$ . So,  $V_0$  is also t.i.p. and we can rewrite as:

$$E_0 \sum_{t=0}^{\infty} \beta^t I_t + t.i.p. + O(\cdot) = 0 \tag{A.51}$$

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$$\begin{aligned}
E_0 \sum_{t=0}^{\infty} \beta^t (n_y \hat{y}_t + n_q \hat{q}_t) &= -\frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t (n_y + Km_Y) \hat{y}_t^2 - \frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t (n_q + Km_{QQ}) \hat{q}_t^2 \\
&+ \frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t K \sigma \phi \psi_p \hat{\pi}_{Ht}^2 - E_0 \sum_{t=0}^{\infty} \beta^t Km_Y \hat{y}_t \hat{q}_t + E_0 \sum_{t=0}^{\infty} \beta^t Km_{YA} \hat{y}_t \hat{a}_t \\
&+ E_0 \sum_{t=0}^{\infty} \beta^t Km_{Yu} \hat{y}_t \hat{u}_t - E_0 \sum_{t=0}^{\infty} \beta^t Km_{YG} \hat{y}_t \hat{g}_t - E_0 \sum_{t=0}^{\infty} \beta^t Km_{YC^*} \hat{y}_t \hat{c}_t^* \\
&\quad - E_0 \sum_{t=0}^{\infty} \beta^t Km_{QA} \hat{q}_t \hat{a}_t + E_0 \sum_{t=0}^{\infty} \beta^t Km_{Qu} \hat{q}_t \hat{u}_t \\
&\quad - E_0 \sum_{t=0}^{\infty} \beta^t Km_{QG} \hat{q}_t \hat{g}_t + E_0 \sum_{t=0}^{\infty} \beta^t Km_{QC^*} \hat{q}_t \hat{c}_t^* \\
&\quad + \beta E_0 \sum_{t=0}^{\infty} \beta^t (\sigma \phi - 1) (\hat{y}_t - E_t[\hat{y}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] \\
&\quad + \beta E_0 \sum_{t=0}^{\infty} \beta^t \alpha \phi [1 - \sigma \eta (\phi + 1)] (\hat{q}_t - E_t[\hat{q}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] \\
&\quad \quad - \beta E_0 \sum_{t=0}^{\infty} \beta^t \sigma (\hat{g}_t - E_t[\hat{g}_{t+1}]) E_t[\hat{\pi}_{H,t+1}] \\
&\quad \quad - \beta E_0 \sum_{t=0}^{\infty} \beta^t \sigma \alpha \phi (\hat{c}_t^* - E_t[\hat{c}_{t+1}^*]) E_t[\hat{\pi}_{H,t+1}] + t.i.p. + O(\cdot) \quad (\text{A.52})
\end{aligned}$$

where  $n_y = K(\sigma \phi + \varphi)$  and  $n_q = K\alpha \phi [1 - \sigma \eta (\phi + 1)]$ . Use the first-order approximation of  $m_{ct}$  and the second-order approximation of  $D_t$  to express the last four terms, with the format  $\beta E_0 \sum_{t=0}^{\infty} \beta^t (\dots) (\hat{x}_t - E_t[\hat{x}_{t+1}]) E_t[\hat{\pi}_{H,t+1}]$ , in terms of  $\hat{y}_t^2, \hat{q}_t^2, \hat{y}_t \hat{q}_t, \hat{y}_t \hat{a}_t, \hat{y}_t \hat{u}_t$ , etc. Then, we can rewrite the above expression as:

$$\begin{aligned}
E_0 \sum_{t=0}^{\infty} \beta^t (n_y \hat{y}_t + n_q \hat{q}_t) &= \frac{1}{2} K_{yy} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t^2 + \frac{1}{2} K_{\pi\pi} E_0 \sum_{t=0}^{\infty} \beta^t \hat{\pi}_{Ht}^2 + \frac{1}{2} K_{qq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t^2 \\
&+ k_{yq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{q}_t + k_{ya} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{a}_t + k_{yu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{u}_t + k_{yg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{g}_t \\
&+ k_{yc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{c}_t^* + k_{qa} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{a}_t + k_{qu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{u}_t + k_{qg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{g}_t \\
&\quad - k_{qc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{c}_t^* + t.i.p. + O(\cdot) \quad (\text{A.53})
\end{aligned}$$

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where

$$k_{yy} = 2(2\phi - 1)n_y - (n_y + Km_Y) \quad k_{\pi\pi} = K\sigma\phi\psi_p \quad (\text{A.54})$$

$$k_{qq} = 2\alpha\phi[1 - \sigma\eta(\phi + 1)]n_q - (n_q + Km_{QQ}) \quad (\text{A.55})$$

$$k_{yq} = (\sigma\phi - 1)n_q + \alpha\phi[1 - \sigma\eta(\phi + 1)]n_y - Km_{YQ} \quad (\text{A.56})$$

$$k_{ya} = Km_{YA} - (\sigma\phi - 1)K(1 + \varphi) \quad k_{yu} = (\sigma\phi - 1)K - Km_{Yu} \quad (\text{A.57})$$

$$k_{yg} = Km_{YG} - (\sigma\phi - 1)K\sigma - \sigma n_y \quad (\text{A.58})$$

$$k_{qc^*} = Km_{YC^*} - (\sigma\phi - 1)K\sigma\alpha\phi - \sigma\alpha\phi n_y \quad (\text{A.59})$$

$$k_{qu} = \alpha\phi[1 - \sigma\eta(\phi + 1)]K - Km_{Qu} \quad (\text{A.60})$$

$$k_{qg} = Km_{QG} - \sigma n_q - \alpha\phi[1 - \sigma\eta(\phi + 1)]K\sigma \quad (\text{A.61})$$

$$k_{qc^*} = Km_{QC^*} + \sigma\alpha\phi n_q + \alpha^2\phi^2[1 - \sigma\eta(\phi + 1)]K\sigma \quad (\text{A.62})$$

Second, we take the second-order approximation of the resource constraint of the economy, the trade balance equation (3.36). Rewrite the equation as:

$$E_0 \sum_{t=0}^{\infty} \beta^t V_{t+1} = V_t + C_t^{1-\sigma} + C_t^{-\sigma} G_t - \frac{P_{Ht}}{P_t} C_t^{-\sigma} Y_t + \frac{\psi_p}{2} (\pi_{Ht} - 1)^2 \frac{P_{Ht}}{P_t} C_t^{-\sigma} Y_t \quad (\text{A.63})$$

where  $V_t = \frac{\varepsilon_t P_{t-1}}{P_t \varepsilon_{t-1}} b_{F,t-1}$ .  $V_0 = 0$  since at steady state the above equation is 0. Hence, we can rewrite the second-order approximation in a similar fashion to the NKPC:

$$\begin{aligned} E_0 \sum_{t=0}^{\infty} \beta^t (d_y \hat{y}_t + d_q \hat{q}_t) &= \frac{1}{2} (d_{yy} - d_y) E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t^2 - \frac{1}{2} (d_q + d_{qq}) E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t^2 \\ &\quad - \frac{1}{2} d_{\pi\pi} E_0 \sum_{t=0}^{\infty} \beta^t \hat{\pi}_{Ht}^2 - d_{yq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{q}_t - d_{yg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{g}_t \\ &\quad - d_{yc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{c}_t^* - d_{qg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{g}_t - d_{qc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{c}_t^* + t.i.p. + O(\cdot) \end{aligned} \quad (\text{A.64})$$

where

$$d_y = 1 - \phi \quad d_q = \alpha\phi[\eta(\phi + 1) - \eta] \quad d_{\pi\pi} = (\phi - 1)\psi_p \quad (\text{A.65})$$

$$d_{yy} = 2\sigma\phi(1 - \phi) \quad d_{qq} = \alpha\eta\phi \{ \phi - \zeta + 2\sigma\alpha\phi(\phi + 1)[\eta(\phi + 1) - 1] \} \quad (\text{A.66})$$

$$d_{yq} = \alpha\phi \{ \eta\phi - 1 - \sigma[\phi[\eta(\phi + 1) - 1] - \eta(\phi + 1)(1 - \phi)] \} \quad (\text{A.67})$$

$$d_{yg} = \sigma(1 - \phi) \quad d_{yc^*} = \sigma\alpha\phi \quad d_{qg} = \sigma\alpha\phi[\eta(\phi + 1) - 1] \quad (\text{A.68})$$

$$d_{qc^*} = \alpha\phi \{ \eta + \sigma\alpha\phi[2\eta(\phi + 1) - 1] \} \quad (\text{A.69})$$

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Now, we have two second-order approximations, (A.53) and (A.64), of the following form:

$$n_y E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t + n_q E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t = RHS_n \quad (A.70)$$

$$d_y E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t + d_q E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t = RHS_d \quad (A.71)$$

where the  $RHS_x$  contain the quadratic terms of equation (A.53) and (A.64) respectively. In matrix form, the above two equations present as:

$$\begin{bmatrix} n_y & n_q \\ d_y & d_q \end{bmatrix} \begin{bmatrix} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \\ E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \end{bmatrix} = \begin{bmatrix} RHS_n \\ RHS_d \end{bmatrix} \quad (A.72)$$

which we rewrite as:

$$\begin{bmatrix} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \\ E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \end{bmatrix} = [n_y d_q - n_q d_y]^{-1} \begin{bmatrix} d_q & -n_q \\ -d_y & n_y \end{bmatrix} \begin{bmatrix} RHS_n \\ RHS_d \end{bmatrix} \quad (A.73)$$

So, we can present the two equations as:

$$E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t = \Gamma d_q RHS_n - \Gamma n_q RHS_d \quad (A.74)$$

$$E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t = \Gamma n_y RHS_d - \Gamma d_y RHS_n \quad (A.75)$$

where  $\Gamma = [n_y d_q - n_q d_y]^{-1}$ . Writing out the two equations, we find:

$$\begin{aligned} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t &= \frac{1}{2} y_{yy} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t^2 + \frac{1}{2} y_{\pi\pi} E_0 \sum_{t=0}^{\infty} \beta^t \hat{\pi}_{Ht}^2 + \frac{1}{2} y_{qq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t^2 \\ &+ y_{yq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{q}_t + y_{ya} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{a}_t + y_{yu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{u}_t + y_{yg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{g}_t \\ &+ y_{yc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{c}_t^* + y_{qa} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{a}_t + y_{qu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{u}_t + y_{qg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{g}_t \\ &+ y_{qc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{c}_t^* + t.i.p. + O(\cdot) \quad (A.76) \end{aligned}$$

and

$$\begin{aligned} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t &= \frac{1}{2} q_{yy} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t^2 - \frac{1}{2} q_{\pi\pi} E_0 \sum_{t=0}^{\infty} \beta^t \hat{\pi}_{Ht}^2 - \frac{1}{2} q_{qq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t^2 \\ &- q_{yq} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{q}_t - q_{ya} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{a}_t - q_{yu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{u}_t - q_{yg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{g}_t \\ &- q_{yc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t \hat{c}_t^* - q_{qa} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{a}_t - q_{qu} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{u}_t - q_{qg} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{g}_t \\ &- q_{qc^*} E_0 \sum_{t=0}^{\infty} \beta^t \hat{q}_t \hat{c}_t^* + t.i.p. + O(\cdot) \quad (A.77) \end{aligned}$$

### 3. Monetary and Exchange Rate Policies Under Diagnostic Expectations

where

$$y_{yy} = \Gamma [d_q k_{yy} - n_q (d_y y - d_y)] \quad y_{\pi\pi} = \Gamma (d_q k_{\pi\pi} + n_q d_{\pi\pi}) \quad (\text{A.78})$$

$$y_{qq} = \Gamma [d_q k_{qq} + n_q (d_q + d_{qq})] \quad y_{yq} = \Gamma (d_q k_{yq} + n_q d_{yq}) \quad y_{ya} = \Gamma d_q k_{ya} \quad (\text{A.79})$$

$$y_{yu} = \Gamma d_q k_{yu} \quad y_{yg} = \Gamma (d_q k_{yg} + n_q d_{yg}) \quad y_{yc^*} = \Gamma (d_q k_{yc^*} + n_q d_{yc^*}) \quad (\text{A.80})$$

$$y_{qa} = \Gamma d_q k_{qa} \quad y_{qu} = \Gamma d_q k_{qu} \quad y_{qg} = \Gamma (d_q k_{qg} + n_q d_{qg}) \quad (\text{A.81})$$

$$y_{qc^*} = \Gamma (n_q d_{qc^*} - d_q k_{qc^*}) \quad (\text{A.82})$$

and

$$q_{yy} = \Gamma [n_y (d_y y - d_y) - d_y k_{yy}] \quad q_{\pi\pi} = \Gamma (n_y d_{\pi\pi} + d_y k_{\pi\pi}) \quad (\text{A.83})$$

$$q_{qq} = \Gamma [n_y (d_q + d_{qq}) + d_y k_{qq}] \quad q_{qa} = \Gamma (n_y d_{yq} + d_y k_{yq}) \quad q_{ya} = \Gamma d_y k_{ya} \quad (\text{A.84})$$

$$q_{yu} = \Gamma d_y k_{yu} \quad q_{yg} = \Gamma (n_y d_{yg} + d_y k_{yg}) \quad q_{yc^*} = \Gamma (n_y d_{yc^*} + d_y k_{yc^*}) \quad (\text{A.85})$$

$$q_{qa} = \Gamma d_y k_{qa} \quad q_{qu} = \Gamma d_y k_{qu} \quad q_{qg} = \Gamma (n_y d_{qg} + d_y k_{qg}) \quad (\text{A.86})$$

$$q_{qc^*} = \Gamma (n_y d_{qc^*} - d_y k_{qc^*}) \quad (\text{A.87})$$

Go back to the loss function (A.38) and rewrite as:

$$\begin{aligned} \mathcal{L}_t = E_0 \sum_{t=0}^{\infty} \beta^t L_t = E_0 \sum_{t=0}^{\infty} \beta^t & \left( U_y \hat{y}_t + U_q \hat{q}_t + \frac{U_{yy}}{2} \hat{y}_t^2 + \frac{U_{\pi\pi}}{2} \hat{\pi}_{Ht}^2 + \frac{U_{qq}}{2} \hat{q}_t^2 + U_{yq} \hat{y}_t \hat{q}_t \right. \\ & \left. - U_{ya} \hat{y}_t \hat{a}_t - U_{yg} \hat{y}_t \hat{g}_t - U_{yc^*} \hat{y}_t \hat{c}_t^* + U_{qg} \hat{q}_t \hat{g}_t + U_{qg} \hat{q}_t \hat{g}_t + U_{qc^*} \hat{q}_t \hat{c}_t^* \right) + t.i.p. + O(\cdot) \end{aligned} \quad (\text{A.88})$$

where

$$U_y = \bar{M} - \phi \quad U_q = \alpha \eta \phi (\phi + 1) \quad U_{yy} = \bar{M} (1 + \varphi) - \phi (1 - \sigma \phi) \quad (\text{A.89})$$

$$U_{\pi\pi} = \phi \psi_p \quad U_{qq} = \alpha \eta \phi [1 + \phi - \zeta + \alpha \eta \phi (1 + \phi)^2 \sigma] \quad (\text{A.90})$$

$$U_{yq} = \alpha \eta \phi^2 [1 - \sigma (\phi + 1)] \quad U_{ya} = \bar{M} (1 + \varphi) \quad U_{yg} = \sigma \phi \quad (\text{A.91})$$

$$U_{yc^*} = \sigma \alpha \phi^2 \quad U_{qg} = \sigma \alpha \eta \phi (\phi + 1) \quad U_{qc^*} = \alpha \eta \phi [\sigma \alpha \phi (\phi + 1) + 1] \quad (\text{A.92})$$

Combine equation (A.76) and (A.77) with the loss function to get rid of the linear terms and obtain the quadratic loss function:

$$\begin{aligned} \mathcal{L}_t = E_0 \sum_{t=0}^{\infty} \beta^t & \left( \frac{1}{2} L_{yy} \hat{y}_t^2 + \frac{1}{2} L_{\pi\pi} \hat{\pi}_{Ht}^2 + \frac{1}{2} L_{qq} \hat{q}_t^2 + L_{yq} \hat{y}_t \hat{q}_t + L_{ya} \hat{y}_t \hat{a}_t + L_{yu} \hat{y}_t \hat{u}_t \right. \\ & \left. + L_{yg} \hat{y}_t \hat{g}_t + L_{yc^*} \hat{y}_t \hat{c}_t^* + L_{qa} \hat{q}_t \hat{a}_t + L_{qu} \hat{q}_t \hat{u}_t + L_{qg} \hat{q}_t \hat{g}_t + L_{qc^*} \hat{q}_t \hat{c}_t^* \right) + t.i.p. + O(\cdot) \end{aligned} \quad (\text{A.93})$$

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where

$$L_{yy} = U_y y_{yy} + U_q q_{yy} + U_{yy} \quad L_{\pi\pi} = U_y y_{\pi\pi} - U_q q_{\pi\pi} + U_{\pi\pi} \quad (\text{A.94})$$

$$L_{qq} = U_y y_{qq} U_q q_{qq} + U_{qq} \quad L_{yq} = U_y y_{yq} - U_q q_{yq} + U_{yq} \quad (\text{A.95})$$

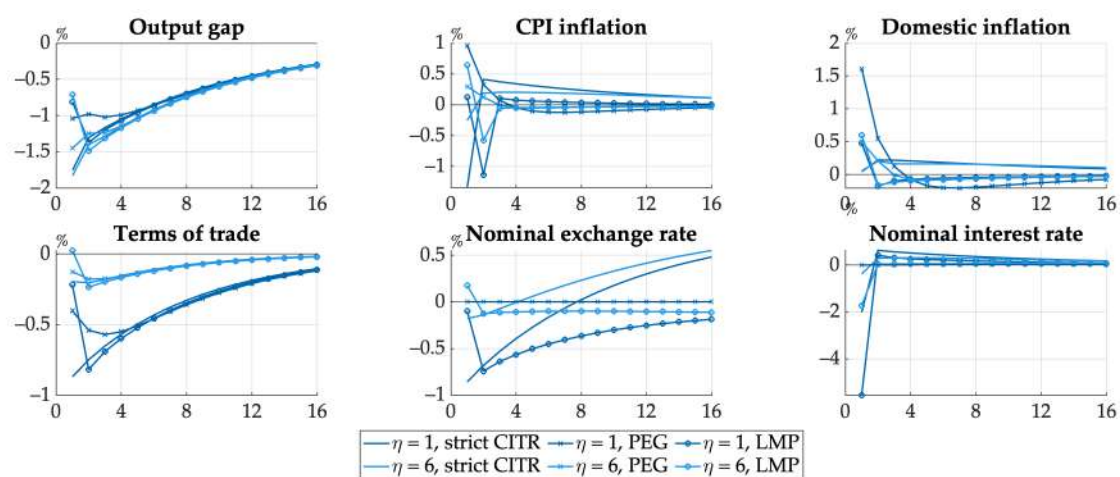
$$L_{ya} = U_y y_{ya} - U_q q_{ya} - U_{ya} \quad L_{yu} = U_y y_{yu} - U_q q_{yu} \quad (\text{A.96})$$

$$L_{qu} = U_y y_{qu} - U_q q_{qu} \quad L_{qg} = U_y y_{qg} + U_q q_{qg} + U_{qg} \quad (\text{A.97})$$

$$L_{qc^*} = U_y y_{qc^*} + U_q q_{qc^*} + U_{qc^*} \quad (\text{A.98})$$

## C.4 Additional figures

Figure C.3: Responses to a cost-push shock under different  $\eta$ , diagnostic expectations



Source: Authors' calculations. Notes: Impulse responses to a 0.22 percentage point cost-push shock under diagnostic expectations. The y-axis is in terms of percentage deviations from steady state. The x-axis is in quarters. Inflation and interest rates are annualized. Inflation and interest rates are annualized.

### 3. Monetary and Exchange Rate Policies Under Diagnostic Expectations

**Table 3.6:** Policy rules with lowest welfare loss under various shocks

	Rational	Diagnostic		
		$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$
$\eta = 1$	CITR	CITR	CITR	PEG
$\eta = 2$	CITR	CITR	CITR	PEG
$\eta = 3$	CITR	CITR	CITR	PEG
$\eta = 4$	CITR	CITR	CITR	PEG
$\eta = 5$	DITR	CITR	CITR	PEG
$\eta = 6$	DITR	CITR	CITR	PEG
$\eta = 7$	DITR	CITR	CITR	PEG

**(a)** Combination of various shocks as in De Paoli (2009a)

	Rational	Diagnostic		
		$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$
$\eta = 1$	CITR	CITR	CITR	PEG
$\eta = 2$	CITR	CITR	CITR	PEG
$\eta = 3$	CITR	CITR	CITR	PEG
$\eta = 4$	CITR	CITR	CITR	PEG
$\eta = 5$	CITR	CITR	CITR	PEG
$\eta = 6$	CITR	CITR	CITR	PEG
$\eta = 7$	DITR	CITR	CITR	PEG

**(b)** Government spending shocks only

	Rational	Diagnostic		
		$\theta = 0.5$	$\theta = 1$	$\theta = 1.5$
$\eta = 1$	DITR	DITR	DITR	DITR
$\eta = 2$	DITR	DITR	DITR	DITR
$\eta = 3$	DITR	DITR	PEG	PEG
$\eta = 4$	PEG	PEG	PEG	PEG
$\eta = 5$	PEG	PEG	PEG	PEG
$\eta = 6$	PEG	PEG	PEG	PEG
$\eta = 7$	PEG	PEG	PEG	PEG

**(c)** Foreign interest rate shocks only

*Source:* Authors' calculations. *Notes:* Policy rules associated with the highest welfare. The selected rules are: CPI inflation Taylor rule (CITR), domestic inflation Taylor rule (DITR) and the exchange rate peg (PEG). For CITR and DITR, the weight on inflation in the Taylor Rule is 1.5. For the shocks as in De Paoli (2009a), the standard deviations of the technology shocks, government spending shocks, cost-push shocks, and foreign demand shocks are 0.0071, 0.0062, 0.0013, and 0.0129 respectively, and their persistence parameters are 0.66, 0.66, 0.94, 0.99 respectively. The shocks are uncorrelated. The government spending shocks are the same as in P. Benigno (2009). The standard deviation and persistence of the foreign interest rate shock are 0.0018 and 0.84 following Lubik and Schorfheide (2005).

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