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International spillovers of quantitative easing

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International spillovers of quantitative easing

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Abstract

This paper develops a two-country model with asset market segmentation to investigate the effects of quantitative easing implemented by the major central banks on a typical small open economy that follows independent monetary policy. The model is able to replicate the key empirical facts on emerging countries' response to large scale asset purchases conducted abroad, including inflow of capital to local sovereign bond markets and an increase in international co-movement of term premia. According to our simulations, quantitative easing abroad boosts domestic demand in the small economy, but undermines its international competitiveness and depresses aggregate output, at least in the short run. This is in contrast to conventional monetary easing in the large economy, which has positive spillovers to output in other countries. We also find that limiting these spillovers might require policies that affect directly international capital flows, like imposing capital controls or mimicking quantitative easing abroad by purchasing local long-term bonds.

JEL: E44, E52, F41

Keywords: quantitative easing, international spillovers, bond market segmentation, term premia

Non-technical summary

Following the financial turmoil in the second half of 2008 and after decreasing their short-term interest rates close to zero, the major central banks, notably the Federal Reserve, the European Central Bank and the Bank of England, implemented several rounds of non-standard policy measures. These measures included substantial purchases of long-term assets which led to a reduction in duration risk, and hence to a fall in the term premium and long term interest rates. It is believed that these actions, often referred to as quantitative easing, contributed to a revival in economic activity in countries pursuing them.

However, given the importance of monetary policy in big countries for global financial cycles, the scale of asset purchases provoked a heated debate on their impact on other economies. On the one hand, improved economic conditions in countries engaged in asset purchases stimulate their demand for imports. Also, the induced world-wide compression of long-term yields supports spending in other economies. On the other hand, this effect can be offset by exchange rate appreciation associated with increased capital inflows to countries not undertaking quantitative easing.

In this paper we contribute to this debate by proposing a general equilibrium model that helps understand and quantitatively analyze international spillovers of long-term asset purchase programs pursued in the major economies, and in particular capital flows that this type of unconventional policy generates. The model consists of two countries: (i) large, that is calibrated to a conglomerate of three big economies whose central banks engaged in long-term asset purchases during the last decade, namely the United States, the United Kingdom and the euro area, and (ii) small, calibrated to Poland, i.e. a typical small open economy pursuing independent monetary policy and deeply integrated with the rest of the world. Importantly, apart from standard features of DSGE models such as price stickiness, we use a segmented asset markets framework. In our setup, agents can trade long-term bonds issued by the two governments so that changes in their supply trigger portfolio adjustments, which lead to international capital flows and have real effects on both countries.

We next use this model to simulate quantitative easing in the large economy. We find that the model is able to replicate the salient features of the data. In particular, apart from stimulating economic activity in the large economy, it generates an inflow of foreign capital to the small economy's sovereign bond market that matches the observed one very well. Furthermore, the model implies very strong comovement of term premia in the two regions during the period of quantitative easing, but not necessarily in normal times, which is also in line with the empirical evidence. Thus, quantitative easing in the large economy impacts the small economy via all three major channels

discussed both in the policy debate and academic literature.

A lower term premium in the large economy induces its investors to search for yield abroad. As a consequence, the share of non-residents in the small economy's long-term bond market increases significantly. The inflow of foreign capital into the small economy's bond market is accompanied by a large drop in the domestic term premium. In this way the program is expansionary as lower long-term interest rates stimulate both consumption and investments. Improved demand in the large economy also supports small economy's exports. At the same time, however, the inflow of foreign capital into the small economy leads to persistent appreciation of its real exchange rate, which undermines its international price competitiveness and depresses economic activity in the short run. Overall, according to our simulations, the unfavorable channels prevail, leading to a drop in small economy's output. To the extent that capital flows finance productive investment, the decrease in GDP could be short-lived and followed by longer-lasting recovery.

This is in contrast to the effects of conventional monetary easing abroad, which positively affects the small economy's GDP. In this case, the reaction of long-term bond yields and term premia in both regions is small and aggregate demand in the small economy actually falls due to unfavorable balance sheet effects (the value of foreign bond holdings by small country's agents, expressed in local currency, decreases) and domestic monetary policy tightening. As in the case of quantitative easing, expansion in foreign demand stimulates the small economy's exports while appreciation of the exchange rate deteriorates the price competitiveness of the small economy. However, this time the magnitude of the latter is much smaller since capital inflows to other economies are substantially less volatile when the major central banks reduce their short-term interest rates. Thus, from our model's perspective, the differences between the two forms of monetary accommodation are related to the size of international capital movements they induce.

This conclusion is supported by the simulated policy interventions undertaken in the small economy: pegging the exchange rate, imposing capital controls, and engaging in a bond purchase program targeted at domestic assets. Fixing the nominal exchange rate does not prevent inflow of foreign capital and hence only slightly delays the loss of international competitiveness. The remaining two policies, in turn, prove to be successful in eliminating negative spillovers of quantitative easing abroad as they address directly the associated capital inflows.

Two caveats to our results should be born in mind, however. Firstly, quantitative easing spillovers do not need to be uniform accross countries since they may be dependent on factors that are hard to include in our framework, such as institutions that may impact risk premia behavior. Secondly, we abstract from non-productive investment and macroeconomic imbalances (credit

booms, asset bubbles) that might emerge in a small economy following the substantial inflow of capital. Their presence could enhance the response of GDP in the short run at the cost of a downturn in the medium term.

To sum up, our main finding is that the international spillovers of conventional and unconventional monetary policy can be very different, and in particular the impact of the latter on other countries' output is likely to be negative. Our results thus offer support for concerns expressed by some policy makers about possibly negative international spillovers of non-standard measures adopted by the major central banks.

1 Introduction

Following the financial turmoil in the second half of 2008 and after decreasing their short-term interest rates close to zero, the major central banks, notably the Federal Reserve, the European Central Bank and the Bank of England, implemented several rounds of non-standard policy measures. These measures included purchases of long-term assets, the scale of which was unprecedented in the modern economic history. Figure 1 offers one way of documenting this process by showing that asset purchases in the United States, the United Kingdom and the euro area substantially lowered the share of long-term government bonds in total supply of consolidated public sector liabilities: by mid-2016 this share had decreased by nearly 10 percentage points as compared with 2009.

The primary goal of these operations, popularly referred to as quantitative easing, was to reduce long-term interest rates and overcome the ongoing slump in economic activity. However, given the importance of monetary policy in the countries that implemented these programs for global financial cycles (as documented e.g. by Rey, 2013), the scale of asset purchases provoked a heated debate among policymakers on their net benefits to other economies. Some of them were expressing concerns about excessive currency appreciation in small open economies (SOEs) and possible imbalances in emerging markets, see e.g. Rajan (2016), and a speech by Per Jansson invoked in Bluwstein and Canova (2016). Others were stressing a favorable impact of quantitative easing on global demand, see e.g. Blanchard (2016), and speeches by Ben Bernanke and Mario Draghi quoted by Bhattarai et al. (2015) and Falagiarda et al. (2015).

The existing empirical evidence provides fairly strong support for the positive impact of quantitative easing on financial markets. A number of papers have confirmed a significant reduction of long-term yields in the economies that engaged in asset purchase programs, especially in the US economy, see e.g. Gagnon et al. (2011), Joyce et al. (2011), D'Amico et al. (2012), Baumeister and Benati (2013), Kiley (2014). On the other hand, Neely (2015), Fratzscher et al. (2013), Ahmed and Zlate (2014), Lim and Mohapatra (2016) and Tillmann (2016) all stress that quantitative easing by the Federal Reserve resulted in procyclical capital inflows into emerging markets and appreciation of their exchange rates. Falagiarda et al. (2015) find similar effects of the ECB non-standard monetary policy measures on Central and Eastern European countries that are tightly integrated with the euro area.

To illustrate the magnitude of capital inflows to sovereign bond markets in SOEs, we plot in Figure 2 the share of non-resident investors holdings in the outstanding bonds issued by emerg-

ing market governments (in their currencies). Since 2009, this share has increased by about 15 percentage points. Naturally, flows of this type and scale have affected the prices of long-term bonds issued by the recipient countries. As Figure 3 strikingly reveals, the comovement between the term premium on 10-year US treasuries and 10-year bonds issued by the governments of SOEs has significantly increased since 2009. It is important to note that this capital inflow into emerging market sovereign bond markets was not matched by offsetting capital outflows. We demonstrate it in Figure 4, which shows that during the period of quantitative easing the net foreign portfolio assets position of SOEs significantly deteriorated, and its value relative to GDP is still about 8% below the 2008 level. A similar picture emerges if we consider all net financial flows summarized by the evolution of the international investment position.

Overall, the existing evidence suggests that, while there are strong reasons to believe that the reaction of financial markets to unconventional monetary policy contributed to revival in economic activity in countries pursuing quantitative easing, the net effect on other countries' output is not clear. On the one hand, improved economic conditions in countries engaged in asset purchases stimulate their demand for imports. Moreover, the induced world-wide compression of long-term yields should support spending in SOEs. On the other hand, this favorable impact can be offset by the exchange rate appreciation associated with increased capital inflows. Bhattarai et al. (2015) offer some support for the hypothesis that the net effect of quantitative easing pursued by major economies on output in other economies does not need to be positive. Using a VAR analysis, they fail to detect a significantly positive impact of the Fed non-standard measures on GDP in emerging markets, and some of their specifications actually suggest negative effects.

In this paper we contribute to this debate by proposing a model that helps us understand and quantitatively analyze international spillovers of long-term asset purchase programs pursued in the major economies, and in particular the capital flows that this type of unconventional policy generates. We build on the segmented asset markets framework considered by Andres et al. (2004), and more recently further developed by Chen et al. (2012). Our main modeling extension is to formulate this environment in an open economy, two-country setup. In the model we propose, agents can trade long-term bonds issued by the two governments so that changes in their supply trigger portfolio adjustments that have real effects on both economies.[1] Importantly, as recently advocated by Passari and Rey (2015), we define financial linkages in terms of gross rather than net international positions in assets.

[1] Bartocci et al. (2017) use a similar framework to study asset purchases by the ECB. However, they do not allow for international trade in long-term bonds, which is the key transmission mechanism in our model.

We calibrate the two-country model to Poland, a typical small open economy pursuing independent monetary policy and deeply integrated with the rest of the world, and a conglomerate of three big economies whose central banks engaged in long-term asset purchases during the last decade, namely the United States, the United Kingdom and the euro area. We next use this model to simulate the quantitative easing in the large economies. We find that the model is able to replicate the salient features of the data discussed above. In particular, it generates an inflow of foreign capital to the small economy's sovereign bond market that matches the data very well. In line with what we show in Figure 3, the model also implies very strong comovement of term premia in the two regions during the period of quantitative easing, but not necessarily in normal times.

According to our model-based simulations, quantitative easing abroad boosts domestic demand in the small economy, but strongly undermines its international competitiveness and depresses economic activity as measured with GDP, at least in the short run. This is in contrast to the effects of conventional monetary easing abroad, which positively affects the small economy's output. Our model is hence consistent with the empirical findings on conventional monetary policy spillovers (Mackowiak, 2007; Banerjee et al., 2016; Dedola et al., 2017) and unconventional ones (Bhattarai et al., 2015). From the model's perspective, the differences between these two forms of monetary accommodation are related to the size of international capital movements they induce. For a given magnitude of impact on the large economy's output, central bank asset purchases generate much larger inflow of non-residents into sovereign bond markets of other countries, resulting in a much sharper appreciation of their real exchange rate. In this sense, our model-based predictions support the concerns raised e.g. by Rajan (2016) about the impact of quantitative easing in advanced countries on emerging economies. We also show that limiting the negative impact of unconventional monetary policy spillovers requires interventions that directly address the associated financial flows, like taxing capital inflows or purchasing small economy's long-term bonds. This outcome is consistent with Blanchard (2016), who argues in favor of capital controls and calls for international coordination of large scale asset purchases.

The closest paper to ours is the recent work by Alpanda and Kabaca (2017), who develop a two-country model with portfolio balance effects to investigate international spillovers of large scale asset purchases in the US. Similarly to ours, their model predicts an inflow of capital into the markets for long-term bonds issued by other economies. Its magnitude, however, is much smaller. Moreover, their simulations feature offsetting flows of capital, and in particular a massive increase in short-term US bond holdings by the rest of the world. As a result, the net inflow of capital to countries not engaged in quantitative easing is moderate, their trade balance does not deteriorate

much, and its negative effect on output is easily dwarfed by a boost in domestic demand driven by compression of local long-term yields, even though their reaction is relatively weak. In contrast, our model generates bigger and arguably more realistic net capital flows following quantitative easing abroad, and their negative effect on the domestic economy's international competitiveness is strong enough to result in a fall in its output. More broadly, our paper is hence related to the recent literature highlighting the role of exchange rate adjustments and international financial flows, including the beggar-thy-neighbor effects, during the period of extremely low global interest rates (see e.g. Caballero et al., 2015; Eggertsson et al., 2016; Cook and Devereux, 2016).

The rest of this paper is structured as follows. Section two presents the model and section three discusses its calibration. The main results and robustness checks are covered in section four. Section five concludes.

2 Model

We develop a two-country DSGE model where agents can trade long- and short-term government bonds issued by the two governments. The world population is normalized to unity and the relative size of the domestic (small) economy is $\omega \in (0; 0.5)$. Each country is populated by two types of households, as well as final and intermediate goods producers that supply domestic and foreign markets. The government in each country controls the short-term interest rate, exogenous spending and the supply of long- and short-term bonds, both issued in local currency.

Similarly to Andres et al. (2004) and others who followed their modeling approach (e.g. Chen et al., 2012; Kiley, 2014; Alpanda and Kabaca, 2017), we introduce market segmentation between short- and long-term bonds in a parsimonious way. It allows us to analyze the impact of quantitative easing on macrovariables without modeling imperfect asset substitutability in detail.

As the model structure is largely symmetric, in what follows we focus on the problems faced by agents populating the domestic (small) economy, and discuss those related to foreign agents only when they are distinct. We also adopt a standard convention of indicating variables related to the foreign economy with an asterisk. A full list of equations defining the equilibrium in our model can be found in the Appendix.

2.1 Households

There are two types of households in our model, which we call restricted and unrestricted, and which we index with $j = \{r, u\}$. The mass of restricted households is $\omega_r \in (0; 1)$ and that of

unrestricted agents is $1 - \omega_r$ so that the measure of households in the economy is normalized to unity.

Household types differ in two ways. First, they are distinguished by their access to bond markets. Restricted households trade only in long-term bonds, reflecting the observation that in the real world some agents hold mostly long-term assets (e.g. pension funds). Unrestricted households, in turn, conduct transactions in long-term bonds, both foreign and domestic, as well as in short-term bonds issued by their own country. Second, while trading in long-term bonds, unrestricted households have to pay transaction costs, whereas restricted households do not bear such expenses. As argued by Chen et al. (2012), since the latter type of agents specialize in trading only in long-term bonds and their investment horizon is likely to be longer, their transaction costs are believed to be minor.

The introduction of segmented markets and transaction costs limits the arbitrage between short and long-term bonds. As a result, fluctuations in transaction costs have effects on real activity since, by impacting yields on long-term bonds, they affect intertemporal consumption allocation of restricted households who trade only in this type of assets. However, these frictions do not directly influence the stochastic discount factor of unrestricted households since it is determined by the short-term interest rates.

2.1.1 Households in the small economy

Restricted agents in the small economy have access only to domestic long-term bonds, while unrestricted households can additionally trade in domestic short-term bonds and foreign long-term bonds. Both types of households rent their labor services to firms at the nominal wage rate W_t, receive dividends from monopolistically competitive firms D_t^j and pay lump sum taxes T_t^j.

A representative household of type j maximizes her lifetime utility that depends on consumption c_t^j and labor effort n_t^j

$$U_t^j = E_t \sum_{s=0}^{\infty} \beta_j^s \exp\{\varepsilon_{t+s}^d\} \left[\frac{(c_{t+s}^j)^{1-\sigma}}{1-\sigma} - \frac{(n_{t+s}^j)^{1+\varphi}}{1+\varphi} \right] \tag{1}$$

where ε_t^d is the preference shock, $\beta_j \in (0;1)$ is the subjective discount factor, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution and φ is the inverse of the Frisch elasticity of labor supply.

Following Woodford (2001), we model long-term bonds as perpetuities that pay an exponentially decaying coupon κ^s every period $s+1$ ($s \geq 0$) after the issuance, where $\kappa \in (0;1]$. Then the

current price of a bond issued s periods ago is related to the price of currently issued bonds with $P_{L-s,t} = \kappa^s P_{L,t}$. This allows us to write the budget constraint of restricted households as (see Chen et al., 2012)

$$P_t c_t^r + P_{L,t} B_{H,L,t}^r + T_t^r = P_{L,t} R_{L,t} B_{H,L,t-1}^r + W_t n_t^r + D_t^r \tag{2}$$

where P_t is the aggregate price level, $B_{H,L,t}^r$ denotes bonds issued by the domestic government and held by domestic restricted households, and $R_{L,t} \equiv P_{L,t}^{-1} + \kappa$ is the gross yield to maturity on these bonds.

Unrestricted households additionally have access to domestic short-term bonds and long-term bonds issued by the foreign government. Whenever they trade in long-term bonds, unrestricted households are required to pay transaction costs. Their budget constraint can be written as

$$\begin{aligned} P_t c_t^u + B_{H,t}^u + (1+\zeta_{H,t}) P_{L,t} B_{H,L,t}^u + (1+\zeta_{F,t}) S_t P_{L,t}^* B_{F,L,t}^u + T_t^u = \\ R_{t-1} B_{t-1}^u + P_{L,t} R_{L,t} B_{H,L,t-1}^u + S_t P_{L,t} (1+\Gamma_{t-1}) R_{L,t}^* B_{F,L,t-1}^u + W_t n_t^u + D_t^u + \Xi_t^u \end{aligned} \tag{3}$$

where R_t is the short-term interest rate controlled by the domestic monetary authority, S_t is the nominal exchange rate expressed as the home currency price of one unit of foreign currency, B_t^u and $B_{H,L,t}^u$ stand for short and long-term domestic bond holdings, while $B_{F,L,t}^u$ denotes holdings of bonds issued by the foreign government, the price and yield to maturity of which are $P_{L,t}^*$ and $R_{L,t}^*$, respectively.

Unrestricted households are subject to the following three types of transaction costs, all of which are external to an individual household (i.e. depend on aggregate positions) and rebated back in a lump sum fashion as Ξ_t^u. Two of these costs are related to transactions in long-term bonds and are given by

$$\frac{1+\zeta_{h,t}}{1+\zeta_h} = \left(\frac{P_{L,t} b_{h,L,t}^u}{P_L b_{h,L}^u} \right)^{\xi_h} \tag{4}$$

for $h = \{H, F\}$, where $\xi_h > 0$, $b_{H,L,t}^u \equiv B_{H,L,t}^u / P_t$, $b_{F,L,t}^u \equiv B_{F,L,t}^u / P_t^*$, and variables without time subscripts indicate their steady state values. The third transaction cost is a standard country premium as in Schmitt-Grohe and Uribe (2003), which we introduce only to make the model stationary

$$1 + \Gamma_t = \exp\left\{ -\xi(a_t - a) + \varepsilon_t^\Gamma \right\} \tag{5}$$

where ξ is a small positive number, ε_t^Γ is the country risk premium shock, and a_t is the ratio of

domestic economy's net foreign assets to output defined as

$$a_t = \frac{(1-\omega_r)(B^u_{H,t} + S_t B^u_{F,t} + P_{L,t} B^u_{H,L,t} + S_t P^*_{L,t} B^u_{F,L,t}) + \omega_r P_{L,t} B^r_{H,L,t} - B^g_{H,t} - P_{L,t} B^g_{H,L,t}}{P_t y_t} \quad (6)$$

where $B^g_{H,t}$ and $B^g_{H,L,t}$ stand for the supply of domestic short and long-term bonds controlled by the local government, while y_t is the economy-wide output that we define later.

2.1.2 Households in the large economy

Households in the large (foreign) economy are modeled analogously, except that restricted agents trade in both domestic and foreign long-term bonds. We allow them to hold small economy's assets relying on two pieces of evidence. First, OECD data on foreign investment by pension funds indicates that a substantial portion of their assets is allocated in foreign debt securities.[2] Secondly, we draw on anecdotal evidence suggesting that yield-seeking pension funds are increasingly interested in acquiring emerging market fixed-income securities (see e.g. Fixsen, 2016).[3]

The budget constraint of restricted households in the large economy can be written as

$$\begin{aligned} P^*_t c^{r*}_t + P^*_{L,t} B^{r*}_{F,L,t} + (1+\Gamma^{r*}_t)\frac{P_{L,t}}{S_t} B^{r*}_{H,L,t} + T^{r*}_t = \\ P^*_{L,t} R^*_{L,t} B^{r*}_{F,L,t-1} + \frac{P_{L,t}}{S_t} R_{L,t} B^{r*}_{H,L,t-1} + W^*_t n^{r*}_t + D^{r*}_t + \Xi^{r*}_t \end{aligned} \quad (7)$$

where Γ^{r*}_t is an external adjustment cost given by

$$1 + \Gamma^{r*}_t = \exp\left\{\xi^*_r \left(\frac{P_{L,t} B^{r*}_{H,L,t}}{S_t P^*_{L,t} B^{r*}_{F,L,t}} - \kappa^{r*}\right)\right\} \quad (8)$$

and rebated back as Ξ^{r*}_t, where $\kappa^{r*} > 0$ is the steady state proportion of restricted households' holdings of bonds issued by the small and large economies. This adjustment cost is introduced only to make the steady state portfolio problem of restricted households in the large economy determinate, and we parameterize it such that it does not affect the model dynamics, i.e. by setting ξ^*_r to a very low positive number.

[2] See Figure 9 in OECD (2015).

[3] It is important to note that the assumed asymmetry in the model structure does not have any significant impact on our results, i.e. they are very similar if we allow also the home restricted agents to hold both domestic and foreign long-term bonds.

2.2 Firms

To introduce price stickiness and imperfect substitution between domestic and imported goods, we consider three stages of production. At the final stage, perfectly competitive final goods producers combine homogeneous home-made goods $y_{H,t}$ and imported goods $y_{F,t}$ according to the following technology

$$\tilde{y}_t = \left(\eta^{\frac{1}{\nu}} y_{H,t}^{\frac{\nu-1}{\nu}} + (1-\eta)^{\frac{1}{\nu}} y_{F,t}^{\frac{\nu-1}{\nu}} \right)^{\frac{\nu}{\nu-1}} \tag{9}$$

where $\eta \in (0;1)$ is the home-bias parameter and $\nu > 0$ is the elasticity of substitution between domestic and imported goods.

At the previous production stage homogeneous goods are produced by perfectly competitive aggregators according to

$$y_{h,t} = \left(\int_0^1 y_{h,t}(i)^{\frac{1}{\mu}} di \right)^{\mu} \tag{10}$$

for $h = \{H, F\}$, where $\mu > 1$ controls the degree of substitution between intermediate inputs $y_{h,t}(i)$.

Intermediate inputs are produced by monopolistically competitive firms indexed by i that operate a linear production function in local labor

$$y_{H,t}(i) + y^*_{H,t}(i) = \exp\{\varepsilon^z_t\} n_t(i) - \phi \tag{11}$$

where ε^z_t is the productivity shock and ϕ is the fixed cost of production. These firms set their prices in the buyer's currency, separately for the domestic market and exports, in a staggered fashion that is similar to the Calvo scheme. More specifically, every period a firm operating in the domestic economy faces a fixed probability θ_H of price reoptimization for the domestic market and probability θ^*_H of price reset for exports. Firms that cannot reoptimize index their prices to steady state CPI inflation.

We assume that firms using local labor are owned by local restricted and unrestricted households in a proportion equal to their shares in population. The problem of reoptimizing firms is hence to maximize

$$E_t \sum_{s=0}^{\infty} (\theta_H)^s \Lambda_{t+s} \left(P_{H,t}(i) \pi^s - \frac{W_{t+s}}{\exp\{\varepsilon^z_{t+s}\}} \right) y_{H,t+s}(i) \tag{12}$$

$$E_t \sum_{s=0}^{\infty} (\theta^*_H)^s \Lambda_{t+s} \left(S_{t+s} P^*_{H,t}(i) (\pi^*)^s - \frac{W_{t+s}}{\exp\{\varepsilon^z_{t+s}\}} \right) y^*_{H,t+s}(i) \tag{13}$$

where $\Lambda_{t+s} \equiv P^{-1}_{t+s}[\omega_r \beta^s_r (c^r_t)^{-\sigma} + (1-\omega_r)\beta^s_u (c^u_t)^{-\sigma}]$ is the stochastic discount factor for nominal payoffs that is consistent with the assumed firm ownership structure, $P_{H,t}(i)$ is the price set by

intermediate producer i for the domestic market, $P^*_{H,t}(i)$ is the price set for the foreign market, while $\pi_t \equiv P_t/P_{t-1}$ and $\pi^*_t \equiv P^*_t/P^*_{t-1}$ are the domestic and foreign inflation rates for final goods. This maximization problem is subject to the demand schedules consistent with aggregators' optimization sketched above.

2.3 Government

The monetary authority follows a Taylor-like feedback rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\gamma_r} \left[\left(\frac{\pi_t}{\pi}\right)^{\gamma_\pi} \left(\frac{y_t}{y}\right)^{\gamma_y}\right]^{1-\gamma_r} \exp\{\varepsilon^r_t\} \tag{14}$$

where ε^r_t is the monetary policy shock, $\gamma_r \in (0;1)$ controls the degree of interest rate smoothing, while γ_π and γ_y control, respectively, the degree of interest rate response to deviations of inflation from the target and to the output gap.

The fiscal authority sets exogenous spending on final goods $g_t \equiv g\exp\{\varepsilon^g_t\}$, where ε^g_t is the government spending shock, and finances it with lump sum taxes levied on domestic households $T_t \equiv \omega_r T^r_t + (1-\omega_r)T^u_t$ and with net debt issuance. We assume that both types of households pay the same amount of taxes in per capita terms so that $T^r_t = T^u_t = T_t$. The government budget constraint is

$$B^g_{H,t} + P_{L,t}B^g_{H,L,t} + T_t = R_{t-1}B^g_{H,t-1} + P_{L,t}R_{L,t}B^g_{H,L,t-1} + P_t g_t \tag{15}$$

and the market value of total (short and long-term) government debt is

$$B^g_t = B^g_{H,t} + P_{L,t}B^g_{H,L,t} \tag{16}$$

The government of the small country keeps the real market value of debt $b^g_t \equiv B^g_t/P_t$ and its composition $\frac{B^g_{H,t}}{P_{L,t}B^g_{H,L,t}}$ constant. Total real debt of the large country b^{g*}_t is also fixed, but its composition may change according to the following rule

$$\frac{P^*_{L,t}b^{g*}_{F,L,t}}{P^*_L b^{g*}_{F,L}} = \left(\frac{P^*_{L,t-1}b^{g*}_{F,L,t-1}}{P^*_L b^{g*}_{F,L}}\right)^{\gamma^*_L} \exp\{\varepsilon^{L*}_t\} \tag{17}$$

where $\gamma^*_L > 0$ is a smoothing parameter and ε^{L*}_t is the quantitative easing shock.

2.4 Goods market clearing

We impose a set of market clearing conditions. Equilibrium on the goods market requires

$$\tilde{y}_t = \omega_r c_t^r + (1-\omega_r) c_t^u + g_t \tag{18}$$

and

$$y_t \equiv y_{H,t}\Delta_{H,t} + \frac{1-\omega}{\omega} y^*_{H,t}\Delta^*_{H,t} = \exp\{\varepsilon_t^z\} n_t - \phi \tag{19}$$

where $n_t \equiv \omega_r n_t^r + (1-\omega_r) n_t^u$ is aggregate labor input, y_t defines aggregate output while

$$\Delta_{H,t} = \int_0^1 \left(\frac{P_{H,t}(i)}{P_{H,t}}\right)^{\frac{\mu}{1-\mu}} di \tag{20}$$

$$\Delta^*_{H,t} = \int_0^1 \left(\frac{P^*_{H,t}(i)}{P^*_{H,t}}\right)^{\frac{\mu^*}{1-\mu^*}} di \tag{21}$$

are the measures of price dispersion resulting from staggered pricing by intermediate goods producing firms.

Given our assumptions on market segmentation, the market clearing conditions for domestic bonds are

$$(1-\omega_r) B^u_{H,t} = B^g_{H,t} \tag{22}$$

$$\omega_r B^r_{H,L,t} + (1-\omega_r) B^u_{H,L,t} + \frac{1-\omega}{\omega}\omega_r^* B^{r*}_{H,L,t} + \frac{1-\omega}{\omega}(1-\omega_r^*) B^{u*}_{H,L,t} = B^g_{H,L,t} \tag{23}$$

Using these market clearing conditions together with the budget constraints of the households and government, as well as the zero-profit condition of the final goods producers and aggregators, we obtain the following law of motion for the small economy's net foreign assets position $A_t \equiv a_t P_t y_t$

$$A_t = R^*_{L,t}\frac{S_t}{S_{t-1}}\frac{P^*_{L,t}}{P^*_{L,t-1}} A^+_{t-1} - R_{L,t}\frac{P_{L,t}}{P_{L,t-1}} A^-_{t-1} + NX_t \tag{24}$$

where

$$A^+_t = (1-\omega_r) S_t P^*_{L,t} B^u_{F,L,t} \tag{25}$$

$$A^-_t = \frac{1-\omega}{\omega} P_{L,t}\left((1-\omega_r^*) B^{u*}_{H,L,t} + \omega_r^* B^{r*}_{H,L,t}\right) \tag{26}$$

$$NX_t = \frac{1-\omega}{\omega} S_t P^*_{H,t} y^*_{H,t} - P_{F,t} y_{F,t} \tag{27}$$

are, respectively, small economy's gross foreign assets, gross foreign liabilities and net exports.

2.5 Term premium

As in Chen et al. (2012), we define the term premium on long-term bonds as

$$TP_t = R_{L,t} - R_{L,t}^{EH} \tag{28}$$

where $R_{L,t}^{EH}$ is the counterfactual yield to maturity on a long-term bond in the absence of transaction costs, which we price using unrestricted households' stochastic discount factor, and κ^{EH} is such that this counterfactual bond has the same steady state duration D_L as the actual bond, i.e. the following must hold

$$D_L = \frac{R_L}{R_L - \kappa} = \frac{R_L^{EH}}{R_L^{EH} - \kappa^{EH}} \tag{29}$$

As shown by Chen et al. (2012), the term premium can be approximated up to first order as the discounted sum of expected values of transaction costs $\xi_{H,t}$ associated with trade in domestic long-term bonds

$$TP_t \approx D_L^{-1} \sum_{s=0}^{\infty} \left(\frac{D_L - 1}{D_L} \right)^s E_t \xi_{H,t+s} \tag{30}$$

Hence, fluctuations in the term premium essentially reflect the current and planned portfolio rebalancing decisions made by unrestricted agents.

2.6 Exogenous shocks

The key driving force in our model are exogenous shifts in the composition of public debt in the large economy ε_t^{L*}. The model also features a set of standard shocks used in open economy DSGE models. These are the country pairs of shocks to productivity (ε_t^z and ε_t^{z*}), time preferences (ε_t^d and ε_t^{d*}), government spending (ε_t^g and ε_t^{g*}) and monetary policy (ε_t^r and ε_t^{r*}), as well as country risk premium (ε_t^Γ). All shocks are modeled as independent first-order autoregressions, except for monetary and quantitative easing shocks that we assume to be i.i.d.

3 Calibration

We calibrate our two-country model to Poland and a block of three big economies that engaged in quantitative easing during the last decade, namely the United States, the United Kingdom and the euro area (BIG3 henceforth). We set the parameters to match some key steady state proportions

observed in the data or take them from the previous literature. Table 1 shows the calibrated parameter values while Table 2 presents the targeted steady state ratios. The time period is one quarter.

If we measure the country size with GDP in current US dollars, the relative size of the small economy ω is 0.014. The home bias parameter η is calibrated at 0.75 to capture the average share of imports in the Polish GDP, corrected for the import content of exports estimated by the OECD. The elasticity of substitution between domestically produced goods and imports is set to 3, which can be seen as a compromise between the micro and macro estimates found in the literature.

In our model the key transmission channel of international policy spillovers relies on gross bond holdings and their adjustment. Hence, the crucial part of our calibration concerns the steady state composition of the bond portfolios held by agents in the small and large economy. Our targets for these proportions are based on the averages observed over the period 2004-2015, which are calculated by combining several data sources. The shares of sovereign bonds in quarterly GDP in Poland and in BIG3 are calibrated to 1.25 and 2.65, respectively. These values are derived using the nominal value of government debt securities reported by Eurostat (for Poland) and by the World Bank in its Quarterly Public Sector Debt Database (for BIG3).[4] These databases also allow us to distinguish between long- and short-term bonds, where we follow Chen et al. (2012) and treat sovereign debt securities that mature in one year or less as short-term bonds. For BIG3, the latter category also includes money holdings since these are very close substitutes of short-term safe debt securities when the policy rate is close to zero. This gives the share of long-term bonds in total sovereign bonds of 0.71 in Poland and 0.63 for BIG3. The steady state share of resident holdings in total long-term bonds issued by the small economy is set to 0.76, which is in line with data published by the Polish Ministry of Finance. The ratio of foreign bonds to total bonds held by small economy's agents is calibrated at 0.05, reflecting average portfolio investment in foreign bonds by Polish residents according to the International Investment Position statistics published by the Polish central bank. Finally, we assume that the share of small economy's bonds in the long-term bond portfolio held by foreign households is the same for their two types, which pins down the value of κ^{r*} at 0.0018.

Another important group of parameters determine the degree of market segmentation and sensitivity of transaction costs, and hence the term premia, to adjustments in agents' portfolios. While calibrating these parameters, we rely heavily on Chen et al. (2012), but later verify that our simu-

[4] In the World Bank database the time series on debt securities for Poland are only available from 2010, therefore we chose to complement this source with Eurostat.

lation outcomes are consistent with empirical evidence on the effects of quantitative easing on asset prices. In particular, the shares of restricted households ω_r and ω_r^*, transaction costs on long-term bonds ξ_H and ξ_F, as well as the degree of smoothing of the public debt composition γ_L^* are all set in accordance with the econometric estimates presented in this source paper, assuming symmetric values for both countries.

The following parameters determine the steady state levels of the interest rates and bond prices, and hence the term premia and bond duration. We set the inflation targets π and π^* to 1.005 (2% annualized) so that they are consistent with those adopted by the three major central banks (the Fed, the Bank of England and the European Central Bank) and the average inflation rate in Poland since 2004. These, together with the discount factors for restricted and unrestricted households β_r and β_u, pin down the steady state long and short-term interest rates. We target them to match the US averages of 5.2% and 4%, respectively, and symmetrically between the two regions. Since long-term bonds are modeled as perpetuities, we need to specify their coupons κ and κ^*. We do it to match the duration of long-term bonds, which is equal to 3 years in Poland according to MoF (2015), and 7.5 years in the US according to Chen et al. (2012). The Calvo probability for domestic sales θ_H and θ_F^* are calibrated at 0.8, which implies higher price duration compared to US micro-data evidence, but results in the slope of the Phillips curve that is within the range reported in the empirical macro literature (Erceg and Linde, 2014).[5] We assume that the price duration for foreign sales is twice lower and set θ_H^* and θ_F to 0.6.

The remaining parameters are either relatively well established in the literature or do not have important effects on our key results. The steady state government spending in both countries is set to 20% of GDP, roughly in line with the long-run averages observed in the data. The elasticity of intertemporal substitution σ, the Frisch elasticity of labor supply φ, price markups μ, interest rate rule coefficients γ_r, γ_π and γ_y, as well as their large economy counterparts, are all set to standard values considered in the DSGE literature. As explained before, we set the portfolio adjustment cost ξ_r^* and the country risk premium parameter ξ to small positive numbers that ensure determinacy and stationarity, and at the same time do not affect significantly the model dynamics.

[5] Moderate slope of the Phillips curve helps avoid extreme reactions of inflation to small extensions in the forward guidance (Carlstrom et al., 2015), which is important for those of our simulations that assume a temporary policy rate peg that aims to mimic a binding zero lower bound constraint.

4 Results

We use the model calibrated as described above to run several simulations. We first generate a quantitative easing scenario in the large economy that resembles the large scale asset purchase programs implemented in the major central banks, and discuss the impact on the small economy. Then, we show that this influence is not much affected if we enrich our baseline model specification with an alternative degree of quantitative easing anticipation or when we allow for the binding zero lower bound on the nominal interest rate in the large economy. We next compare international spillovers of unconventional monetary policy to those associated with conventional policy easing. We argue that our model-based outcomes are consistent with the estimates documented in the empirical literature. Importantly, the differences between spillovers from unconventional and conventional policies are related to the size of capital flows they induce. While monetary accommodation of both forms leads to capital inflow to other countries, it is much stronger in the case of central bank asset purchases, resulting in much sharper appreciation of the recipient countries' exchange rate. Therefore, according to the model simulations, only economic policies that directly address capital inflows can limit substantially the impact of unconventional monetary policy spillovers. We also show that our model can account for the increased international synchronization of the term premia observed since 2009. Finally, we discuss the robustness of our results to alternative model parametrization.

4.1 Unconventional monetary stimulus in the large economy

We design our quantitative easing scenario to mimic the evolution of the share of long-term bonds in the total supply of bonds issued by the BIG3 as in Figure 1 from 2009 through 2016, i.e. the central bank of the large economy buys domestic long-term sovereign bonds in exchange for short-term securities, reducing the share of the former in the private sector portfolio by nearly 10 percentage points. We assume that after 2016 this policy is withdrawn at the same pace as it was implemented so that by 2024 the composition of outstanding bonds is the same as before the crisis. The scenario is implemented by designing an appropriate sequence of shocks to ε_t^{L*} in equation (17). For the moment, we assume that quantitative easing is unanticipated, but once it starts being implemented, the whole path of asset purchases is perfectly known to the agents. We also allow the short-term interest interests to respond endogenously in line with their feedback rules, also in the large economy. These assumptions will be relaxed in the alternative scenarios presented later on.

The outcomes of such defined scenario for selected variables in both economies are presented

in Figure 5. Long and short-term bonds are imperfect substitutes, thus quantitative easing is not neutral for other macrovariables. In particular, it drives down the term premium in the large economy by 30 bps on impact, stays below this level for about 6 years, and then gradually rises, coming back close to its steady state value several years before the asset purchase program is withdrawn. The magnitude of this response is roughly consistent with that obtained by Chen et al. (2012) in a closed economy setup if one takes into account the differences in the size and length of the impulse, and well within the bounds implied by the empirical literature they summarize.[6] Our model also predicts a similar response of inflation, but much weaker expansion in output, suggesting lower efficiency of quantitative easing in stimulating the real activity.[7]

We now turn to the main focus of our paper, which is the response of the small economy. A lower term premium in the large economy induces its investors to search for yield abroad. As a consequence, the share of non-residents in the small economy's long-term bond market increases by 13 pp after around 8 years. Both the scale and timing of this process match the data very well, as can be seen by comparing our simulation outcomes to Figure 2. The inflow of foreign capital into local bond markets is accompanied by a drop in the domestic term premium by 15 bps on impact and 40 bps at its trough around 5 years after the program started. In this way the program is expansionary as lower long-term interest rates stimulate aggregate demand. Furthermore, improved demand in the large economy supports small economy's exports. At the same time, however, the massive inflow of foreign capital, cumulating to about 3% of small economy's GDP, leads to persistent appreciation of its real exchange rate, which deteriorates price competitiveness and leads to a fall in the trade balance.

Overall, the capital inflow induced by quantitative easing abroad affects the small economy via two channels that have opposite effects on its output. According to our simulations, the unfavorable one prevails, at least in the short run.[8] This is in contrast to Alpanda and Kabaca (2017),

[6] Chen et al. (2012) obtain a reduction of the term premium by 30 bps following the LSAP II in the United States. However, the ultimate scale of this program (600 bn USD, i.e. 4% of the US GDP) is about three times smaller than in our case (12% of the combined GDP of the US, the UK and the euro area) and its implementation is less spread over time.

[7] This result contrasts with most of the previous studies, but is driven mainly by an endogenous increase in the short-term interest rate in the large economy. As we show later in this section, once we assume that the central bank in the large economy keeps the policy rate fixed (as under the zero lower bound), the response of output in this area is much larger and in line with the existing estimates. We chose to allow for endogenous fluctuations of the short-term interest rates in our baseline scenario to be consistent with the observed tightening of conventional policy by the European Central Bank in 2011, and because our qualitative findings for the small economy are not significantly affected by this assumption.

[8] Comparing the model response of the small economy's international investment position to the data presented in Figure 24 suggests that, if anything, we underestimate the magnitude of total capital inflows to emerging economies during the period of quantitative easing. Despite that, the negative effects of exchange rate appreciation on GDP prevail over the positive ones.

whose model implies strong output growth outside the US after the Fed starts quantitative easing. The source of this difference is related to the magnitude of net capital flows. In particular, while the model of Alpanda and Kabaca (2017) also predicts an inflow of capital into the markets for long-term bonds issued by other economies, their simulations additionally feature offsetting flows of capital, and in particular a massive increase in short-term US bond holdings by the rest of the world. In contrast, our model generates bigger and arguably more realistic net capital flows following quantitative easing abroad, and their negative effect on the domestic economy's international competitiveness is powerful enough to result in a fall in its output, despite relatively strong compression of local long-term yields. It is important to note that our results seem to fit better the empirical evidence from VARs presented in Bhattarai et al. (2015), who find that long-term asset purchases by the Fed had insignificant, and in some specifications negative, effect on industrial output in emerging economies.

4.2 The role of anticipation and zero lower bound

Our baseline scenario relies on some simplifying assumptions about its implementation. In this section we check how they affect the outcomes of our simulations.

First, we relax the assumption on the fully-anticipated path of asset purchases. This modification aims to bring our simulations more towards how unconventional monetary policy in the BIG3 was conducted in reality. In fact, there were several rounds of asset purchases. Even though they might have been anticipated to some extent by the agents, their implementation was definitely not perfectly foreseen in 2009. In this paper we do not attempt to model in detail how expectations of central bank unconventional actions are formed. Instead, we compare how our results differ between two extreme approaches. In the first one, all rounds of quantitative easing are assumed to be perfectly anticipated by the agents from the moment the large economy's monetary authority starts purchasing long-term bonds. This is our baseline scenario that we presented in section 4.1. As an alternative, we assume that the agents are fully taken by surprise each time the central bank announces a new round of asset purchases. More specifically, we assume that quantitative easing is initially announced for a period of two years, after which it is expected to be gradually withdrawn at the same pace as it was introduced. Then, every period the program is extended by one more quarter, with the last extension announced two years before the program starts being withdrawn.

Figure 6 presents the simulated responses under these alternative assumptions. The scenario is designed such that the actual path of asset purchases is the same as in our baseline, so any differences reflect only the effects of imperfect anticipation. The responses of both financial and

macroeconomic variables are much more gradual than in the baseline and their peaks or troughs are delayed since for most of the time agents expect a smaller scale of total asset purchases. However, the maximum responses are of similar size to those observed in the baseline scenario, suggesting that our main conclusions are only moderately sensitive to the degree to which quantitative easing was anticipated by the agents.

This conclusion is backed by our second robustness check, in which we assume that the central bank in the large economy announces the whole path of quantitative easing one year in advance. The dynamic responses are plotted in Figure 7. Comparing this exercise with the baseline simulation reveals very similar patterns for most of variables. In particular, output in the small economy reacts negatively and the term premia in both countries tightly comove.

Third, we consider the binding zero lower bound (ZLB) for the short term interest rates in the large economy, which was a potentially important feature of the monetary policy conducted by the three major economies that we consider, at least for some period included in our analysis. We combine it with the 'surprises' scenario described in our first robustness check so that when the asset purchase program or its extension is announced, the central bank of the large economy commits to keep the short-term interest rates constant for two years, with the last announcement made at the moment when withdrawal of quantitative easing begins. Figure 8 plots the responses of the key variables to this alternative scenario. As expected, accounting for the ZLB strengthens the positive impact of asset purchases on the large economy since it eliminates endogenous tightening of its conventional monetary policy present in the baseline. In particular, the response of output is now of similar magnitude to that found in the previous studies, which is conducive to higher GDP in the small economy. However, the appreciation of its exchange rate is now stronger as well. These two forces offset each other to a large extent, and the paths of output and absorption in the small economy are very similar to those obtained in our baseline scenario.

4.3 Conventional versus unconventional monetary stimulus in the large economy

Our next step is to compare the effects of quantitative easing to a conventional monetary policy accommodation. Figure 9 plots the dynamic responses to an expansionary monetary policy shock, defined as a negative innovation to the monetary policy feedback rule given by equation (14), but written for the large economy, and compares them to the effects of quantitative easing. The latter is defined as a positive innovation to the rule describing composition of public debt in the large economy and given by equation (17), where the size of this innovation is chosen such that, assuming

that the policy rate is kept constant for two years, the peak response of output in the large economy is the same as following conventional policy easing.

As regards standard monetary policy, the results are consistent with what is well documented in the literature, also in the context of spillovers to emerging markets, see references in the introduction. Monetary accommodation in the large economy boosts aggregate demand in this country, which leads to an increase in its output and imports. As regards international spillovers, the mechanism at play is different from that described in the previous section. The reaction of long-term bond yields and the term premia in both regions is small. Furthermore, the value of foreign bond holdings by small country's agents (expressed in local currency) decreases following the exchange rate appreciation so that their balance sheets are negatively affected. As a consequence, conventional monetary easing in the large economy actually depresses aggregate demand in the small economy. At the same time, however, strong expansion in foreign demand stimulates the small economy's exports. As in the case of the quantitative easing scenario, appreciation of the exchange rate deteriorates the price competitiveness of the small economy. This time, however, the net effect on its trade balance and output is clearly positive which, together with a rise in inflation, leads to a slight tightening of monetary policy in the small economy, which additionally curbs its domestic demand. Thus, even though output increases in the large economy are (by construction) of the same scale for conventional and unconventional monetary accommodation, the former leads to GDP increase in the SOE, while the latter to its drop.

The key to understand this difference are capital flows and the associated reaction of the real exchange rate. The latter turns out to be about three times stronger in the case of quantitative easing, and hence results in a more substantial loss in international price competitiveness of the small economy. This difference is driven by the international trade in long-term bonds. The massive inflow of foreign capital into small economy's sovereign bond market is not matched by capital outflows of a comparable size since assets in the large economy yield relatively low returns after central bank purchases. As a consequence, the financial account balance of the small economy is in surplus, which has to be reflected in a large drop in its net exports.

International trade in long-term bonds also implies that the long-term interest rates are crucial for the real exchange rate determination. Indeed, by using the first-order approximation to restricted agents' optimality conditions, one may express the real exchange rate as follows

$$\hat{s}_t \approx D_L^* \hat{R}_{L,t}^* - D_L \hat{R}_{L,t} + \sum_{i=1}^{\infty} \mathbb{E}_t \left\{ (\hat{R}_{L,t+i}^* - \hat{\pi}_{t+i}^*) - (\hat{R}_{L,t+i} - \hat{\pi}_{t+i}) \right\} \tag{31}$$

where hats denote log-deviations from the steady state and the transaction cost term Γ_t^{r*} is ignored as we calibrate it to be very small. Since, as Figure 9 reveals, we observe a much stronger response of long-term rates to quantitative easing, it comes as no surprise that the exchange rate reacts much more compared to the case of conventional policy accommodation.

Naturally, since unrestricted agents trade in home and foreign long-term bonds as well as home short-term bonds, one can also derive a condition similar to (31) that features short-term rather than long-term rates

$$\hat{s}_t \approx \sum_{i=0}^{\infty} \mathbb{E}_t \left\{ (\hat{\zeta}^*_{F,t+i} - \hat{\zeta}_{H,t+i}) + (\hat{R}^*_{t+i} - \hat{\pi}^*_{t+1+i}) - (\hat{R}_{t+i} - \hat{\pi}_{t+1+i}) \right\} \tag{32}$$

where, similarly as before, the transaction cost term Γ_t is ignored. Both equations (31) and (32) must hold in equilibrium. The key difference is the presence of transaction costs in the condition with short-term rates, and that the effect of long-term rates on the exchange rate is amplified by bond duration D_L and D_L^*. This amplification reflects the reaction of long-term bond prices (note that $\hat{P}_{L,t} = -D_L \hat{R}_{L,t}$ and $\hat{P}^*_{L,t} = -D^*_L \hat{R}^*_{L,t}$) and implies that, for a given change in the short-term or long-term rates, the direct effect on the exchange rate of the latter is much stronger.

We conclude this discussion by noting that, in the empirical literature on the effects of asset purchase programs, they are sometimes presented as equivalence of short-term interest rate cuts. For example, Gambacorta et al. (2014) use a back of the envelope calculation to express the impact of doubling of the central bank balance sheets on output as equivalent to a decrease in the policy rate by 300 bps. Our simulations suggest that an analogous way of thinking about international monetary policy spillovers is not valid as the relative importance and direction of channels through which conventional and unconventional measures operate are different, and their effect on output abroad may be even of different sign.

4.4 Policy interventions

Having observed that unconventional monetary policy pursued by major central banks affects adversely other countries by generating massive capital movements and exchange rate adjustments, a natural question emerges to what extent these effects can be counteracted by appropriate policy implemented by the affected economies. In this section we consider the following policy interventions: pegging the exchange rate,[9] imposing capital controls, and engaging in a bond purchase program

[9] The exchange rate peg is implemented by appropriate adjustments in the small economy's short-term rate, i.e. it does not entail direct involvement of the monetary authority in interventions on the foreign exchange market.

targeted at domestic assets.

The outcomes of these three alternative policies, applied to our baseline QE scenario, are presented in Figure 10. While fixing the exchange rate and hence preventing its strong nominal appreciation could be seen as a natural candidate to mitigate the spillovers, the impact of this intervention is very limited and short-lived. Already in the second year after the start of the asset purchases program abroad, the real exchange rate path is virtually indistinguishable from that obtained under free float. Pegging the domestic currency means that the boom in domestic absorption is no longer cooled down by the nominal appreciation and inflation goes markedly up. However, the responses of both the term premium and inflow of foreign capital are hardly modified by this intervention, and the scale of contraction in output is only marginally different. Overall, preventing the nominal exchange rate from appreciating proves inefficient at mitigating spillovers from QE pursued abroad as it does not dampen its key transmission channel, which is the inflow of capital to local bond markets.

The second policy addresses capital flows directly. As argued by Blanchard (2016), capital controls might be a more natural and effective instrument to counteract negative spillovers from quantitative easing in advanced economies to emerging markets. We introduce this type of intervention in the form of a proportional capital tax that is levied on large country residents when they hold small country's long-term bonds. The tax rate is assumed to respond to foreign holdings of local bonds according to

$$\tau_t = \left(\frac{\omega_r^* B_{H,L,t}^{r*} + (1-\omega_r^*) B_{H,L,t}^{u*}}{\omega_r^* B_{H,L}^{r*} + (1-\omega_r^*) B_{H,L}^{u*}} \right)^{\gamma_\tau} - 1 \tag{33}$$

where γ_τ is the elasticity parameter. We set it to 0.1, which ensures that the inflow of non-residents to the small economy's bond markets is effectively halted. As shown in Figure 10, by eliminating capital inflows, the tax essentially isolates the small economy from quantitative easing abroad. Note that the resulting tax rate never exceeds 0.7% in annual terms, which is below the values usually reported in the the macroprudential literature (see e.g. Mendoza and Bianchi, 2010; Bianchi et al., 2016 or Korinek and Sandri, 2016).

Finally, we consider a scenario in which the monetary authority in the small economy embarks itself on an asset purchase program. To generate it, we assume that quantitative easing in the small economy is implemented in exactly symmetric way to that followed by the major central banks, i.e. it implies the same path of the share of long-term bonds issued by the small economy in the private sector portfolio. As Figure 10 reveals, the scale of purchases of local bonds by non-residents is

halved and their price falls by more, the latter outcome being qualitatively different from the effect of imposing capital controls. Importantly, the responses of domestic absorption, real exchange rate and output are now small.

Overall, the policy experiments presented in this section clearly show that negative effects of asset purchases in large economies on international competitiveness of other countries could be mitigated as long as they are addressed with policies that directly counteract the associated capital inflows. Protecting price competitiveness by preventing the nominal exchange rate from appreciating proves ineffective. Our results are thus consistent with arguments made by Blanchard (2016) in favor of capital controls. It also points at the need to coordinate large scale asset purchases as advocated by Rajan (2016).

4.5 Term premia comovement

As we have stressed while discussing Figure 3, one of the striking features of the quantitative easing period is a dramatic increase in the cross-country synchronization of the term premia. Moreover, as shown by Jabłecki et al. (2016), the term premium in Poland has been following almost one-to-one its counterpart in Germany since the outbreak of the crisis. In this section we show that our model is consistent with this observation.

We have already seen from our model simulations that, following the quantitative easing scenario, the term premia in the large and small economy react very similarly and exhibit a similar degree of persistence. We now investigate this comovement more formally, using the model-implied correlations between the term premia in the large and small economy, conditional on the type of shocks included in our model. The calculations are based on the first-order approximation to the model equilibrium conditions. In line with evidence from estimated DSGE models considered in the literature, autoregressive shocks are allowed to exhibit considerable degree of inertia (we set their autoregressive coefficients to 0.9). The smoothing coefficient in the debt composition rule for the large economy (17) is calibrated at 0.99 to reflect high persistence of asset purchase programs. Shocks of same type are assumed to have the same volatility in both countries.

Table 3 reports the outcomes. As expected, shocks to the composition of the large economy's bond supply imply tight comovement between the term premia. None of the other disturbances can generate similarly high correlation, and productivity shocks imply even negative comovement. Moreover, when we allow the volatility of shocks in the small economy to be higher than in the large economy,[10] these correlations become even lower. Hence, we can conclude that our model is

[10] See e.g. Kolasa (2009) for evidence based on a two-country DSGE model estimated for Poland and the euro area.

able to account for the observed increase in the cross-country term premia comovement during the period of quantitative easing compared to the per-crisis times.

4.6 Robustness checks

In this section we show that our assessment of international spillovers of unconventional monetary is robust to a number of modeling choices and assumptions underlying our simulations.

In our benchmark model agents' financial decisions do not affect the economies' productive capacity. We now modify the setup by including physical capital as the second production factor and allowing for its endogenous accumulation.[11] The outcomes are presented in Figure 11. We find that allowing for capital accumulation reduces the impact of quantitative easing on the term premia (and thus on bond prices) in both economies as investment in non-financial assets offers to the agents an additional way of transferring their wealth intertemporally. Since this type of investment is assumed to affect the productive capacity, its expansion affects positively output in both countries. As a result, GDP of the small economy eventually rises above the level observed before quantitative easing abroad started, but only after about four years.[12]

Finally, we check to what extent our results depend on some assumptions regarding the values of calibrated parameters. In a model like ours, two crucial parameters that govern the response of the term premium and its transmission to other macroeconomic variables are ω_r, ξ_H and their large economy counterparts. The first one controls the share of restricted households and is calibrated at a rather small level of 0.1 under our baseline. It might be argued that in emerging economies the degree of bond market segmentation is larger than in developed countries, so as an alternative we consider a higher value of ω_r equal to 0.2. The second parameter determines the slope of the bond transaction cost function. We check how our results change if we decrease its value in both economies by a half so that $\xi_H = \xi_F = 0.0075$. The outcomes of these two robustness checks are plotted in Figure 12. With asymmetric bond market segmentation, quantitative easing in the large economy generates a stronger outflow of its capital to foreign bond markets. The consumption boom in the small economy is bigger, but the exchange rate appreciates more sharply and the fall in output is even deeper than under our baseline parametrization. At the same time, the comovement of the term premia in both economies is still very high. As regards the role of transaction costs, decreasing them does not change the direction of responses of any macrovariable of interest, but

[11] We implement this extension as in Chen et al. (2012). Full details of the extended model are available from the authors upon request.

[12] One can conjecture that the mitigating effect of the presence of non-financial investment on the drop in small economy's output following quantitative easing abroad would be weaker if we allowed some of it to be not directly related to the productive capacity, e.g. residential investment or purchase of other durables.

their magnitude becomes lower.

One of our paper's key messages are the negative spillovers of quantitative easing on other economies' output. One might be concerned that this finding crucially depends on the parametrization of the trade block in our model. In particular, one of the key parameter could be the price elasticity of demand for imports ν. Some papers suggest that a lower value of this parameter helps achieve a better fit to the international business cycle, see Bodenstein (2010) for a review. Therefore, we check how our results change if we assume a Cobb-Douglas form of the final goods basket by picking $\nu = \nu^* \approx 1$. We also examine the sensitivity of our main findings to the degree of exchange rate pass-through by considering higher values of Calvo stickiness whenever firms in both countries supply foreign markets, i.e. $\theta_H^* = \theta_F = 0.9$. As can be seen from Figure 13, none of our qualitative results hinge on the parametrization of the trade block. As regards the magnitude of the responses, non-negligible differences relative to our baseline scenario concern only the case of low elasticity of substitution between home goods and imports as it implies a lower inflow of capital and weaker response of the term premium in the small economy, but a stronger appreciation of its exchange rate.

Overall, we can conclude that our main findings, i.e. a negative effect of quantitative easing abroad on international competitiveness and output in the small economy (at least in the short-run) and tightening of the cross-country comovement of the term premia, are robust to the alternative assumptions considered in this section.

5 Conclusions

We have developed a two-country DSGE model with segmented asset markets and used it to quantitatively analyze international spillovers of large scale asset purchase programs pursued in some large economies in the aftermath of the Great Recession. We showed that this framework can replicate key empirical facts observed in small economies pursuing independent monetary policy during the period of quantitative easing abroad. First, it accurately mimics the inflow of foreign capital to small economies' sovereign bond markets. Second, it accounts for the very strong cross-country comovement of the term premia during the period of quantitative easing, but not necessarily during normal times.

Our main finding is that, notwithstanding the positive effects of quantitative easing implemented by the major central banks on asset prices worldwide, such programs tend to undermine international price competitiveness of other economies. As a result, even though domestic demand in small

economy improves, the net impact on their GDP is likely to be negative, at least in the short run. This is in contrast to the effects of conventional monetary easing abroad, which positively affects the small economy's output.

Two caveats to our results should be born in mind, however. Firstly, quantitative easing spillovers do not need to be uniform accross countries since they may be dependent on factors that are hard to include in our framework, such as institutions. As pointed out by Fratzscher et al. (2013), strong domestic institutions in small countries affect risk pricing and may insulate these economies from quantitative easing spillovers. Secondly, we abstract from non-productive investment and macroeconomic imbalances (credit booms, asset bubbles) that might emerge in a small economy experiencing a substantial inflow of capital. Their presence could enhance the response of GDP in the short run at the cost of a downturn in the medium term. We leave this issue for future research.

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Tables and figures

Table 1: Calibrated parameters

Parameter	Value
Size of the small economy; ω	0.014
Share of restricted households; ω_r, ω_r^*	0.1
Inv. elasticity of intertemporal substitution; σ, σ^*	2
Inv. Frisch elasticity of labor supply; φ, φ^*	2
Discount factor, unrestricted households; β^u, β^{u*}	0.992
Discount factor, restricted households; β^r, β^{r*}	0.995
Coupon; κ, κ^*	0.929, 0.979
Transaction cost on long-term bonds (unrestricted households); ξ_H, ξ_F	0.015
Portfolio adjustment cost (large economy's restricted households); ξ_r^*	10^{-5}
Country risk premium; ξ	0.01
Calvo probability for domestic production; θ_H, θ_F^*	0.8
Calvo probability for exports; θ_H^*, θ_F	0.6
Price markup; μ, μ^*	1.15
Elasticity of substitution btw. home and imported goods; ν, ν^*	3
Home-bias; η	0.75
Steady-state inflation; π, π^*	1.005
Interest rate smoothing; γ_r, γ_r^*	0.9
Interest rate response to inflation; γ_π, γ_π^*	2
Interest rate response to output gap; γ_y, γ_y^*	0.125

Table 2: Targeted steady state ratios

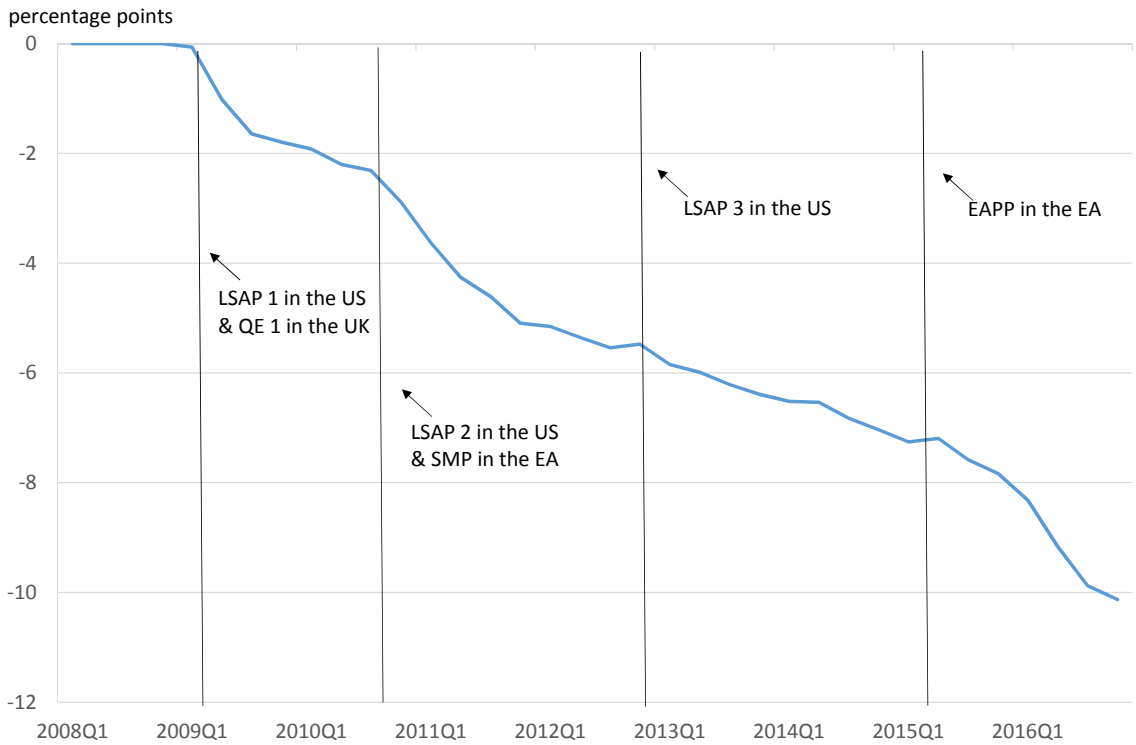
Steady state ratio	Value
Share of government spending in GDP; $\frac{g}{y}$, $\frac{g^*}{y^*}$	0.2
Share of government bonds in GDP; $\frac{b^g+P_L b^g_{H,L}}{y}$, $\frac{b^{g*}+P_L^* b^{g*}_{H,L}}{y^*}$	1.25, 2.65
Share of long-term bonds in total bonds; $\frac{P_L b^g_{H,L}}{b^g+P_L b^g_{H,L}}$, $\frac{P_L^* b^{g*}_{H,L}}{b^{g*}+P_L^* b^{g*}_{H,L}}$	0.71, 0.65
Share of residents in small economy's long-term bonds; $\frac{P_L(\omega_r b^r_{H,L}+(1-\omega_r)b^u_{H,L})}{b^g_{H,L}}$	0.76
Share of foreign bonds in small country's portfolio; $\frac{(1-\omega_r)sP_L^* b^u_{F,L}}{\omega_r P_L b^r_{H,L}+(1-\omega_r)(sP_L^* b^u_{F,L}+P_L b^u_{H,L})}$	0.05

Table 3: Conditional cross-country correlation of the term premia

Shock	correlation
QE in large economy ε_t^{L*}	0.95
Productivity; ε_t^z, ε_t^{z*}	-0.29
Time preference; ε_t^d, ε_t^{d*}	0.20
Government spending; ε_t^g, ε_t^{g*}	0.23
Monetary policy; ε_t^r, ε_t^{r*}	0.66
Country risk premium; ε_t^Γ	0.72

Note: The correlations are calculated using the first-order approximation to the model equilibrium conditions. The inertia of productivity, time preference, government spending and risk premium shocks are all set to 0.9. QE and monetary shocks are assumed to be i.i.d. The smoothing coefficient γ_L^* in equation (17) is calibrated at 0.99.

Figure 1: QE impact on the share of long-term government bonds (excluding central bank holdings) in total public sector liabilities in the US, UK and EA

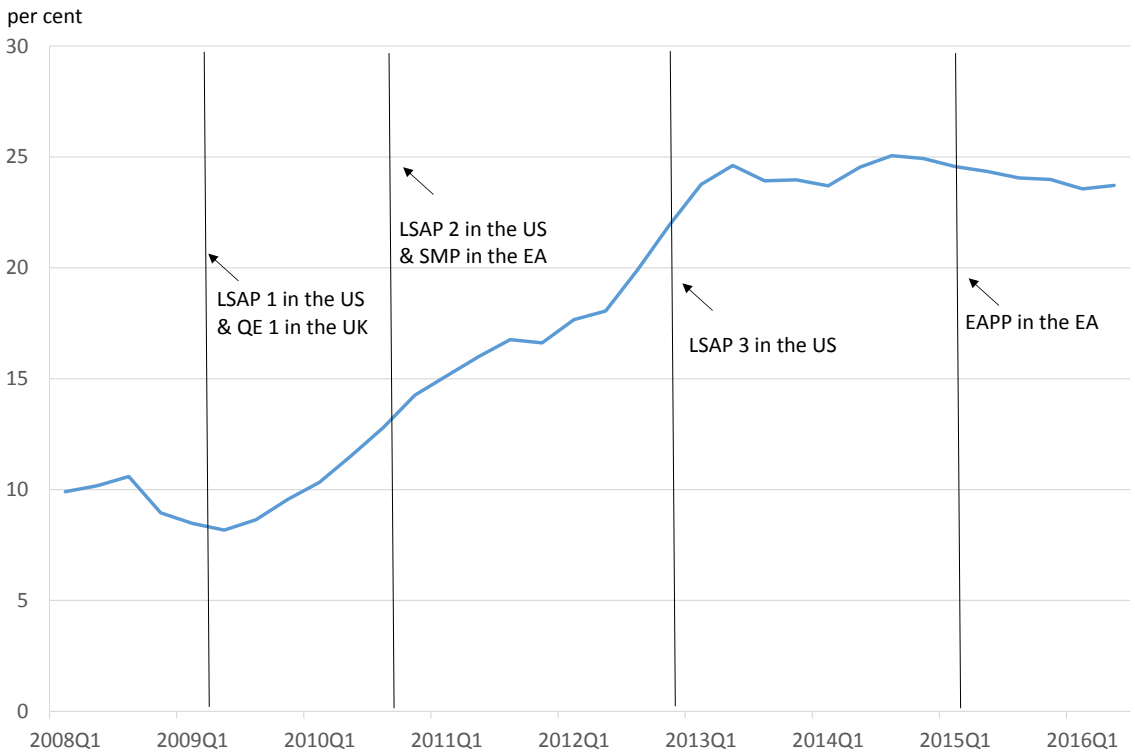


Note: The presented QE impact is calculated as the difference between (i) the share of long-term bonds in total public sector liabilities (that we call bonds in what follows) issued in the BIG3 countries (United States, United Kingdom and euro area), excluding central bank holdings, and (ii) the share of long-term bonds including central bank holdings in total bonds issued by the BIG3 governments. Central bank asset purchases reduce the outstanding amount of long-term bonds, but do not impact the total government debt - when a central bank buys long-term bonds, it creates new central bank reserves, replacing de facto long-term public liabilities with short-term ones. Short-term debt comprises short-term government bonds, as well as central bank short-term interest-bearing liabilities and cash in circulation. Both long and short-term bonds are calculated as a sum of outstanding bonds in the BIG3.

Source: World Bank, central bank web pages, authors' calculations.

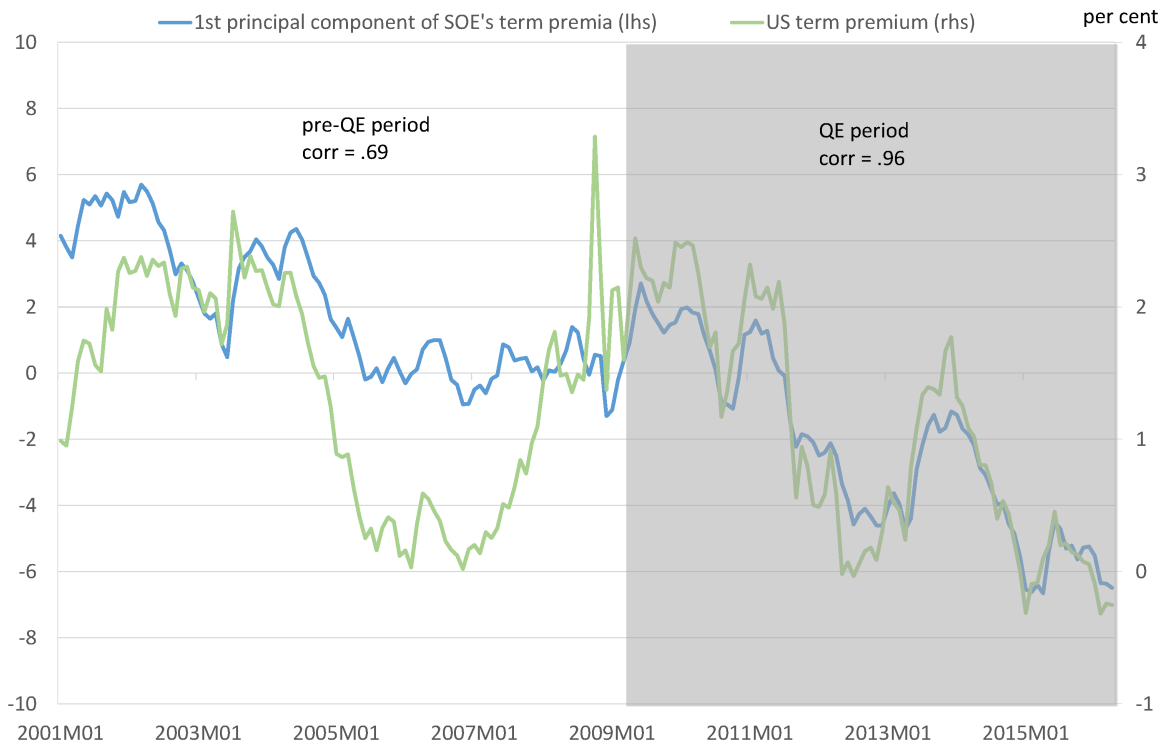
Memo: LSAP - Large-Scale Asset Purchases; SMP - Securities Markets Programme; EAPP - Expanded Asset Purchase Programme.

Figure 2: Share of foreign investors in sovereign bond markets of emerging economies



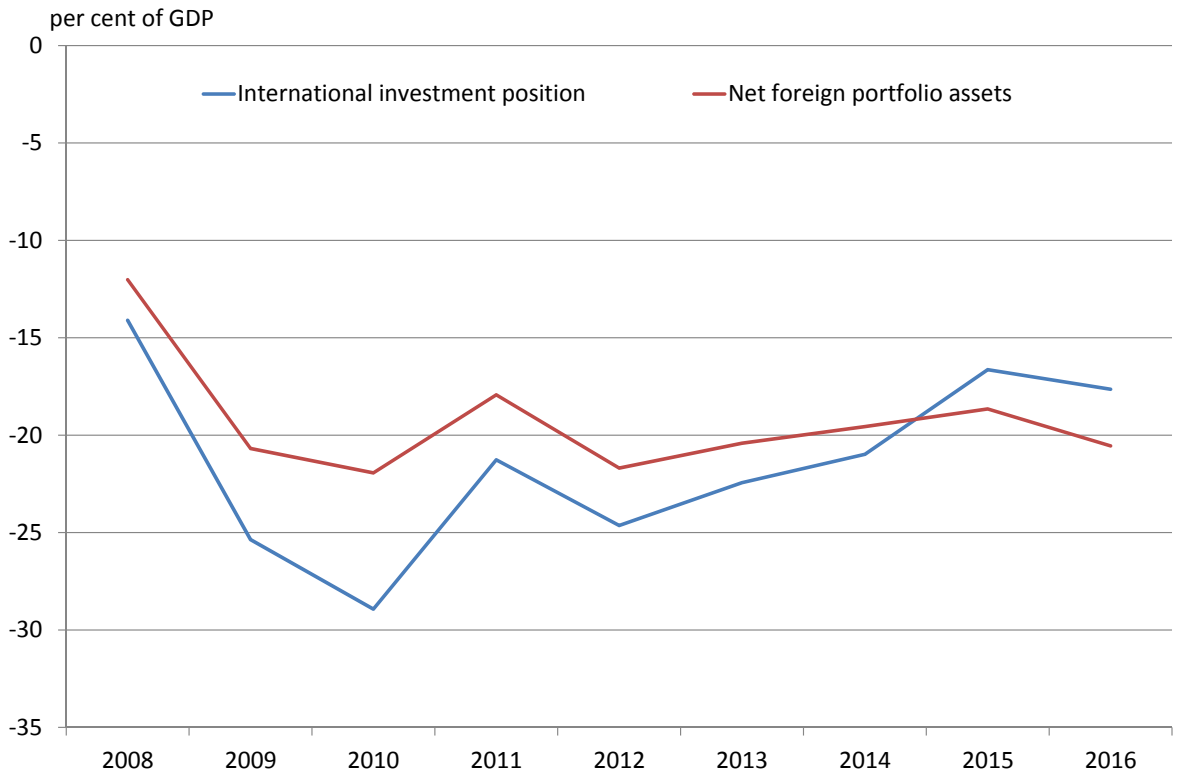
Note: This plot presents the share of bonds issued by the emerging economies' governments held by non-residents. The emerging economies included are: Brazil, Colombia, Czech R., Hungary, Indonesia, Israel, Malaysia, Mexico, Peru, Poland, Russia, South Africa, South Korea, Thailand, Turkey. Source: Credit Suisse. For exact definitions, calculation and data sources, see Credit Suisse monthly note "Emerging Markets: Non-residents' holdings in local currency government bonds".

Figure 3: Term premium on 10-year bonds in the US and small open economies



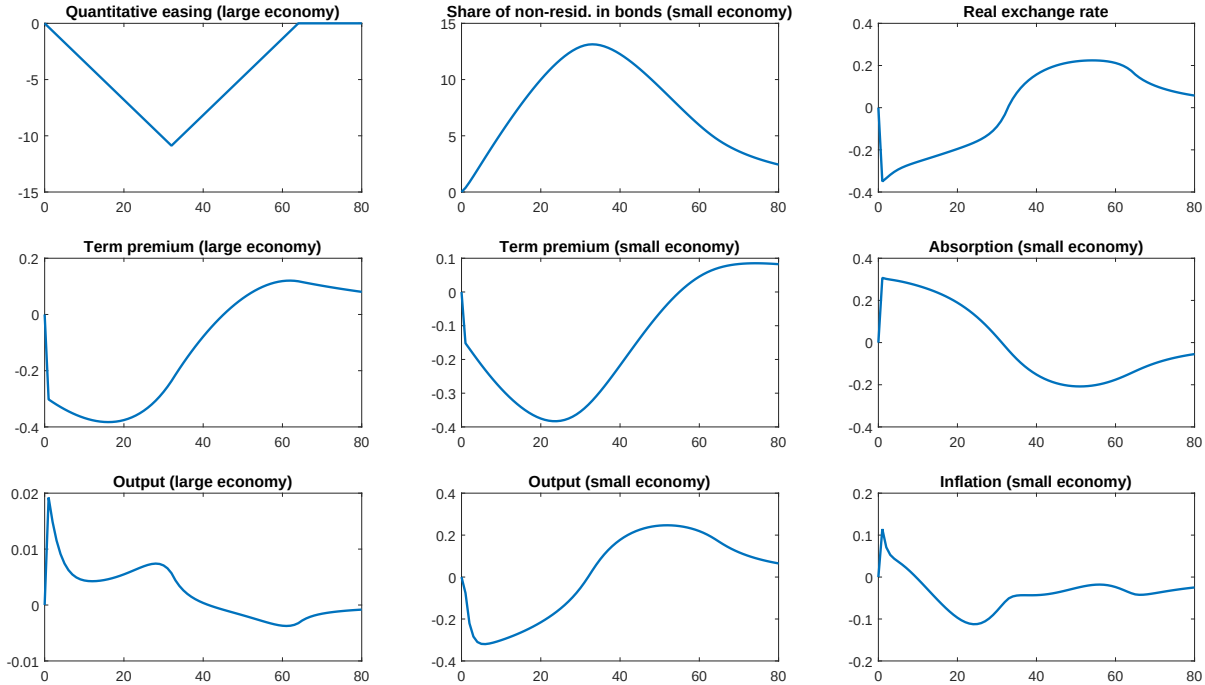
Note: This plot presents the 10-year term premium in the United States and the first principal component of 10-year term premia in small open economies (SOEs). SOEs comprise: Australia, Canada, Chile, Czech Republic, Hong Kong, Hungary, Indonesia, Israel, Japan, South Korea, Malaysia, New Zealand, Norway, Philippines, Poland, Singapore, South Africa, Sweden, Turkey. The term premia in SOEs were calculated based on the Adrian et al. (2013) model. Source: Bloomberg, New York Fed, authors' calculations.

Figure 4: Net financial position of emerging economies



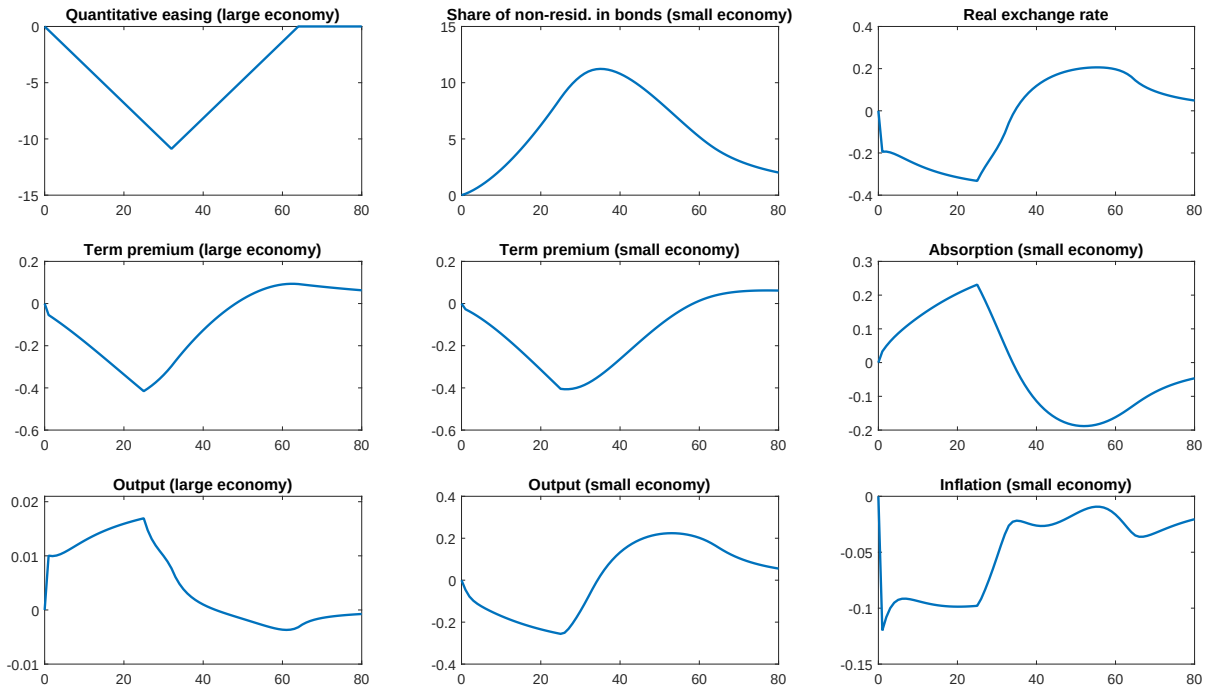
Note: This figure presents the international investment position and net foreign portfolio assets, both expressed relative to GDP, of the same group of emerging economies as in Figure 2. Source: International Monetary Fund statistics.

Figure 5: Effects of quantitative easing in the large economy



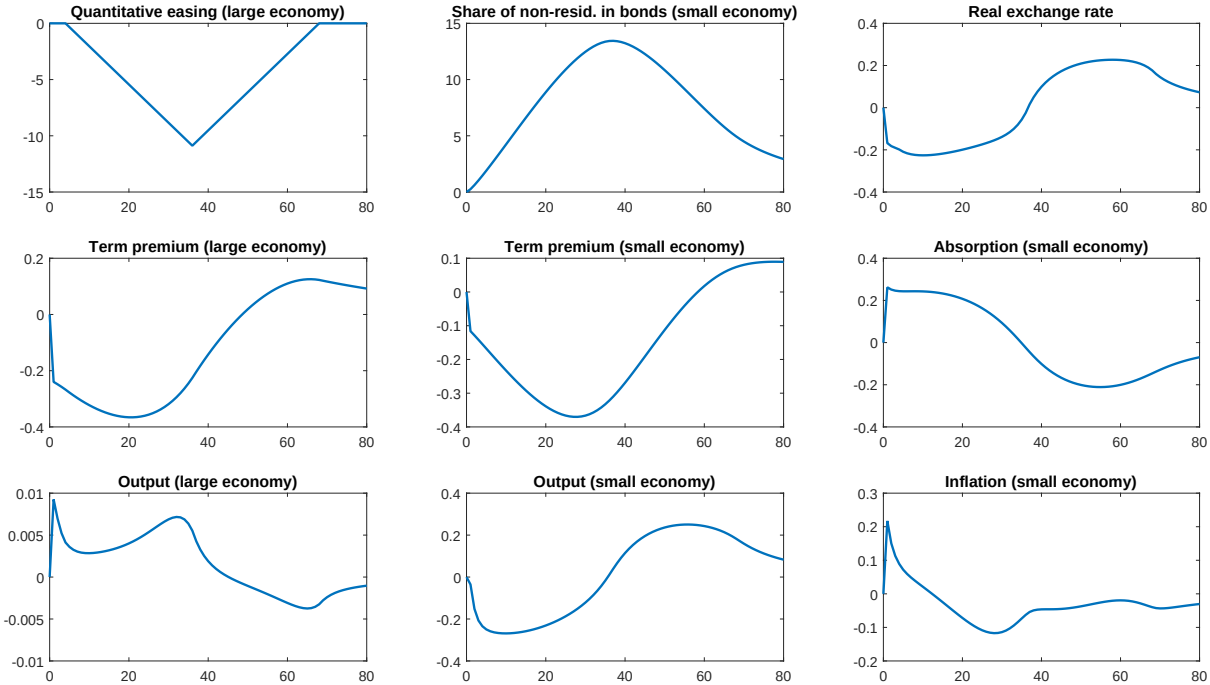
Note: This figure presents the effects of quantitative easing in the large economy, calibrated to mimic the evolution of the share of long-term bonds in total large economy's government debt as in Figure 1, and assuming that it will be withdrawn at the same pace as it was implemented. All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 6: Effects of quantitative easing in the large economy with asset purchases extended every quarter



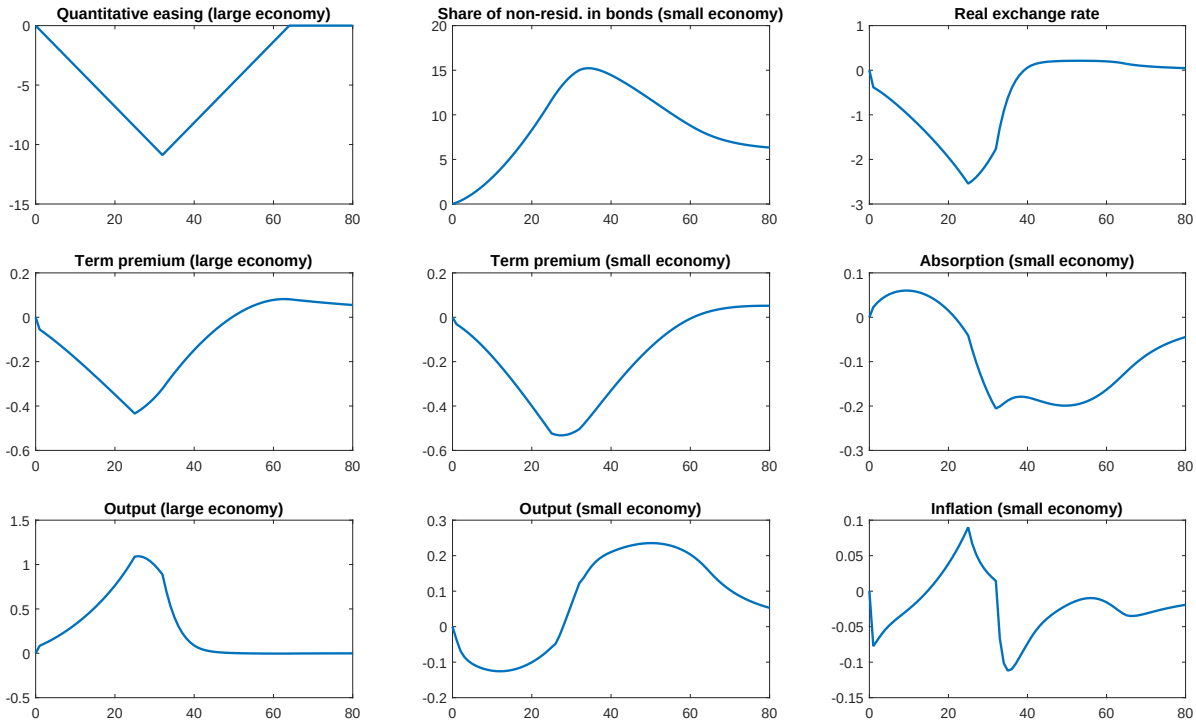
Note: This figure presents the effects of quantitative easing in the large economy under the assumption that its central bank announces a subsequent round of asset purchases every quarter. All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 7: Effects of quantitative easing in the large economy announced one year in advance



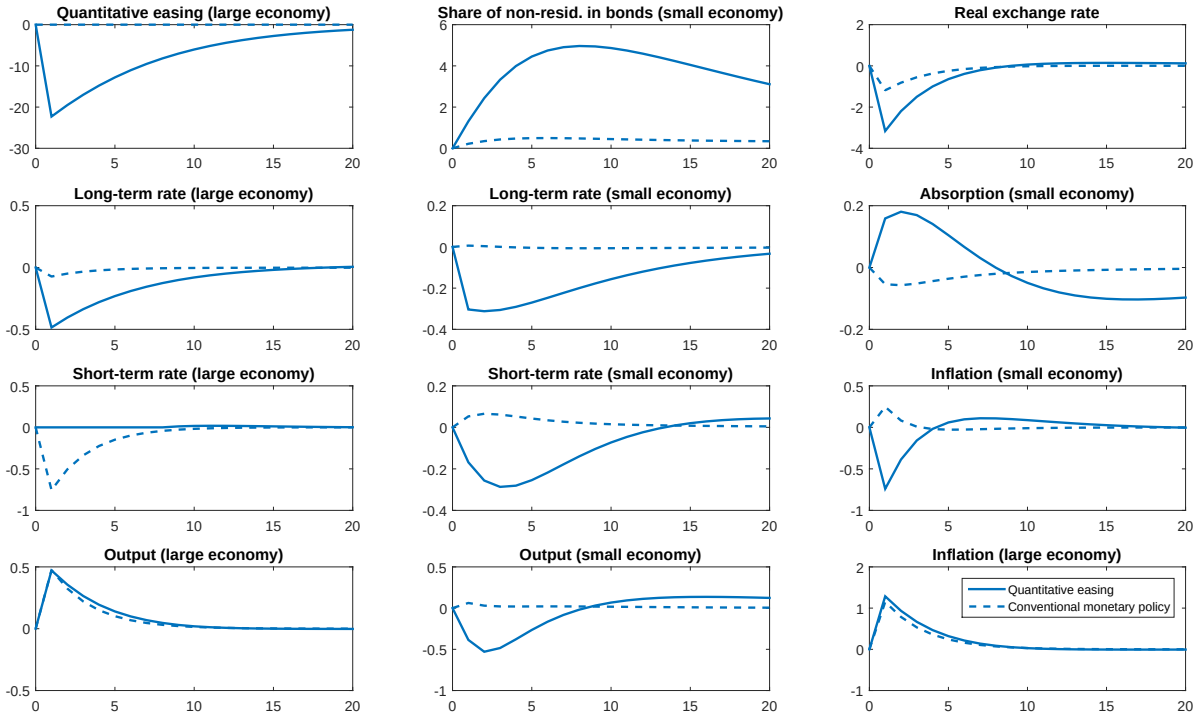
Note: This figure presents the effects of quantitative easing in the large economy under the assumption that its central bank announces the path of asset purchases one year before they start. All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 8: Effects of quantitative easing in the large economy with asset purchases announcements every quarter at the zero lower bound



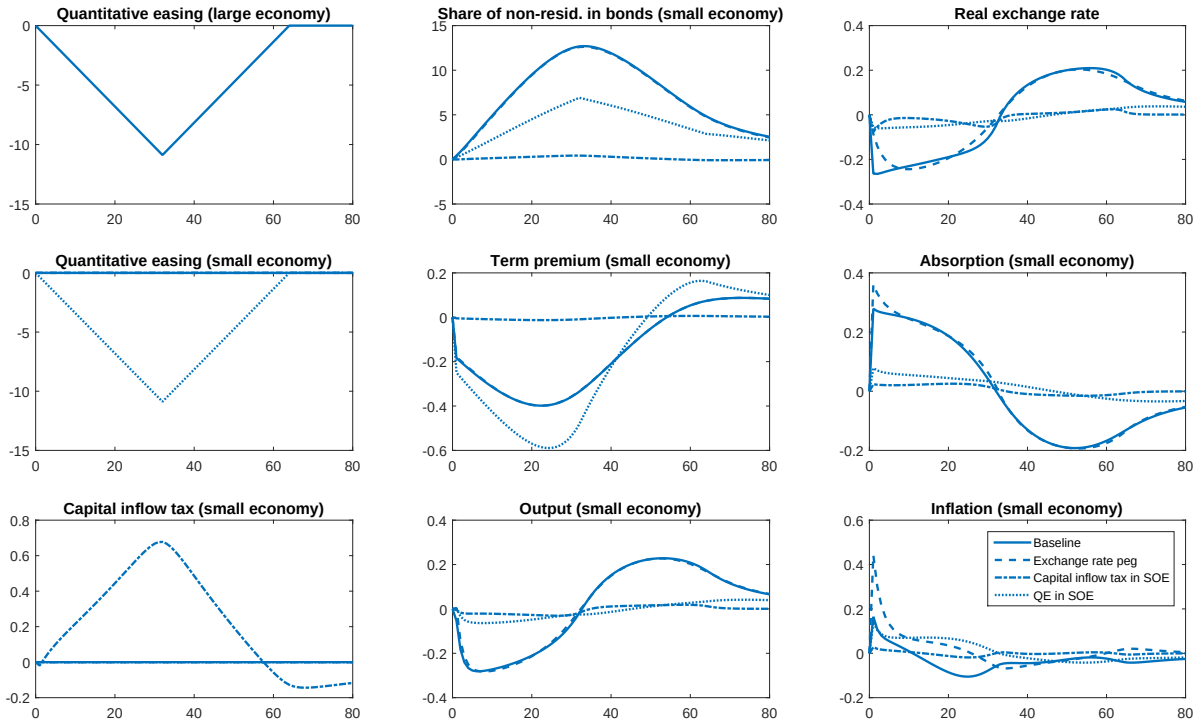
Note: This figure presents the effects of quantitative easing in the large economy under the assumption that its central bank announces a subsequent round of asset purchases every quarter and the short-term interest rates are expected to stay at the zero lower bound for two years after every announcement. All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 9: Conventional and unconventional monetary policy easing in the large economy



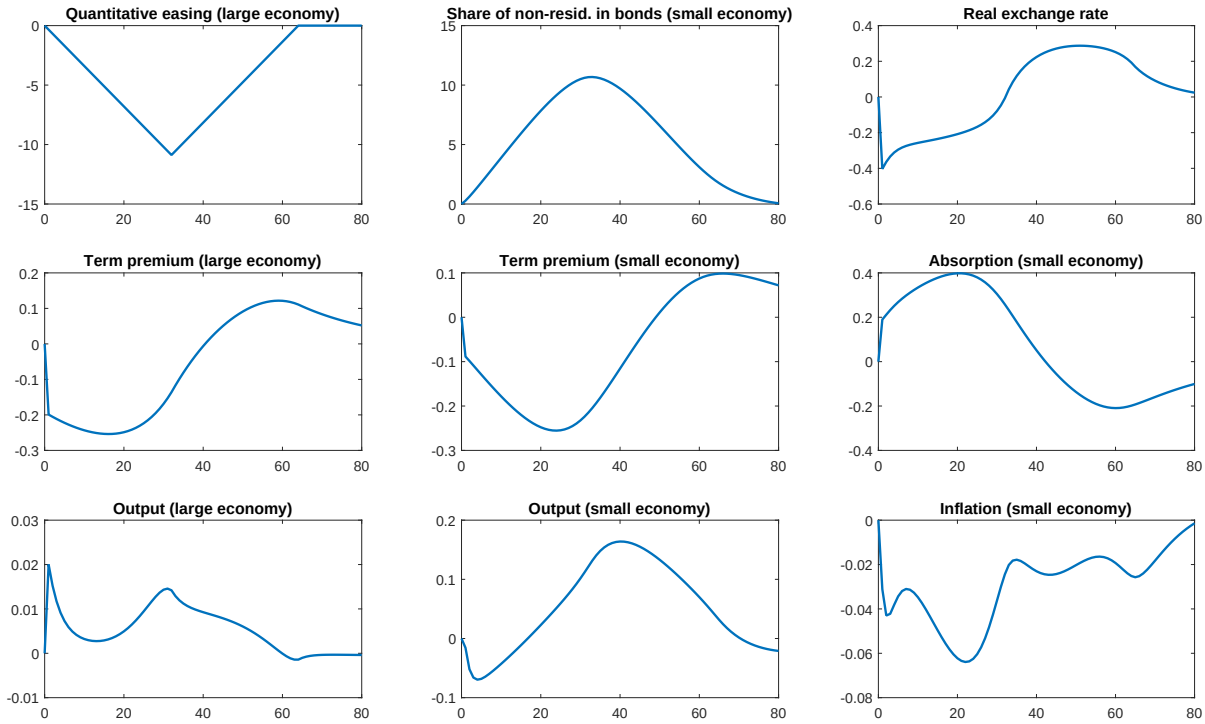
Note: This figure presents the effects of conventional and unconventional monetary policy in the large economy. The former is defined as a shock of 1 percentage point (annualized) to the monetary feedback rule. The latter is a shock to the composition of public debt, the magnitude of which is calibrated such that it generates the same peak reaction of output in the large economy, assuming that the short-term interest rate in this country is fixed for two years. All responses are in percent deviations from the steady state. The responses of the term premium, interest rates and inflation are annualized.

Figure 10: Impact of policy responses in the small economy to quantitative easing in the large economy



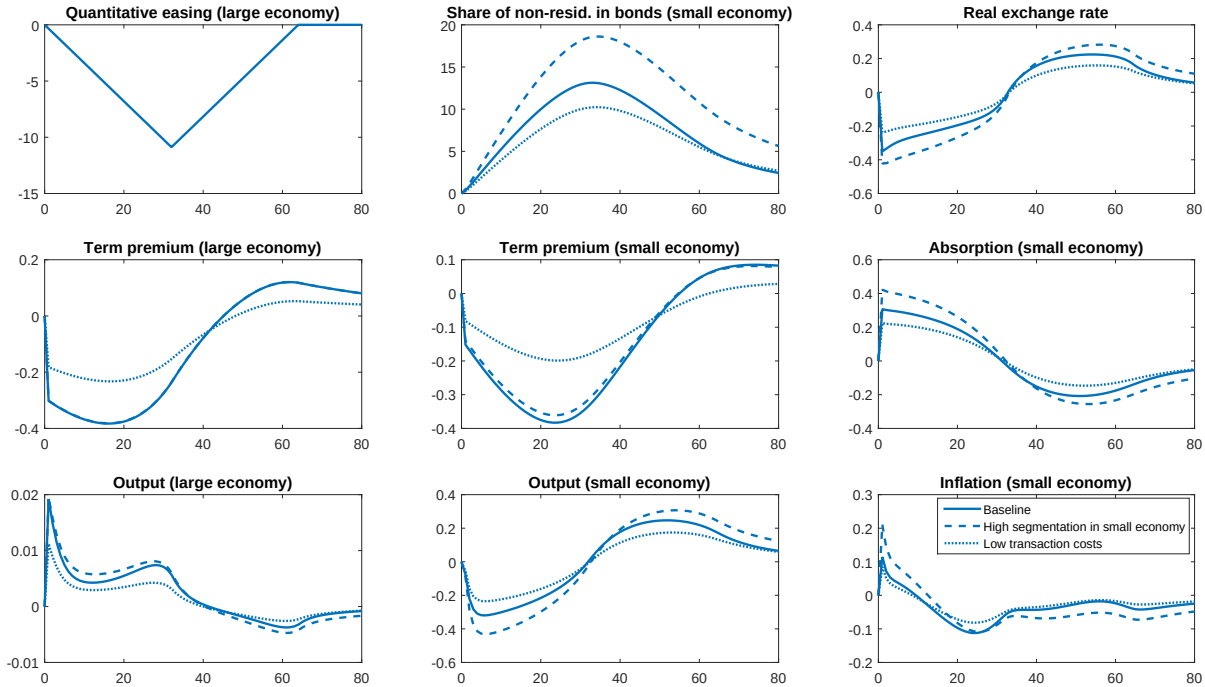
Note: This figure presents the effects of quantitative easing in the large economy with three alternative economic policy interventions in the small economy: (i) exchange rate peg, (ii) capital tax paid by foreign agents for holding bonds issued by the small economy's government, and (iii) bond purchases by the monetary authority in the small economy that mimics actions undertaken by the central bank of the large economy. All responses are in percent deviations from the steady state. The responses of the term premium, inflation and capital inflow tax are annualized.

Figure 11: Effects of quantitative easing in the large economy in the model with endogenous formation of productive capital



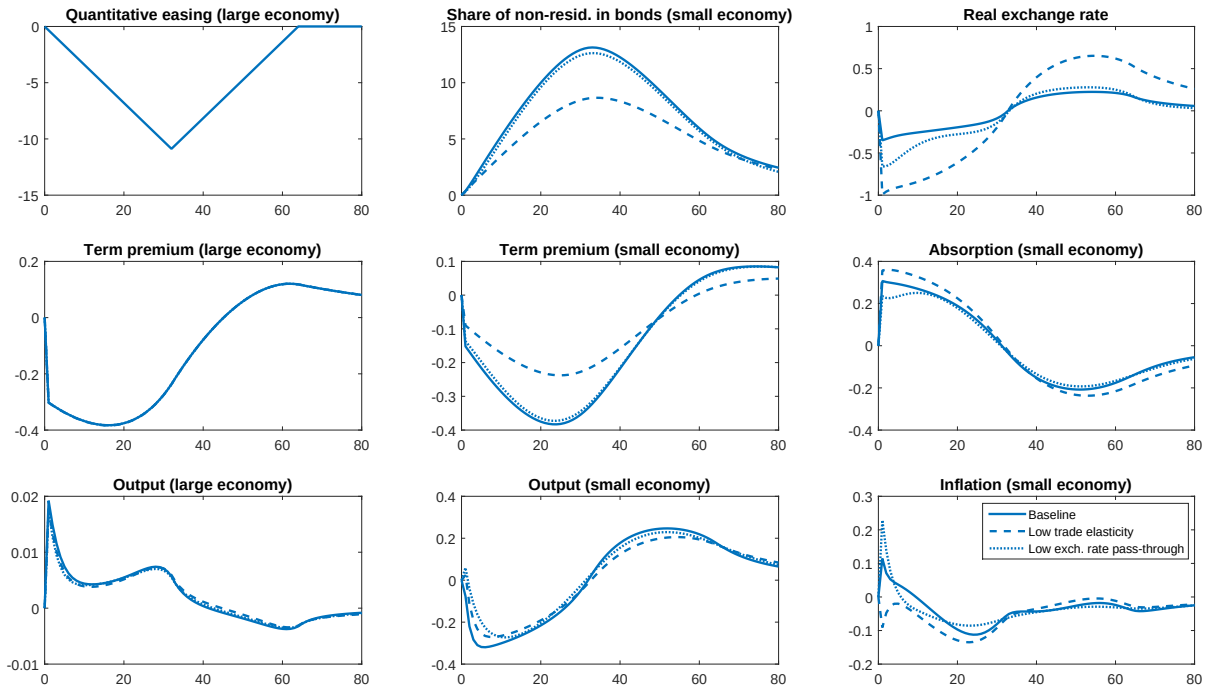
Note: This figure presents the effects of quantitative easing in the large economy according to the model with a two-factor production function and endogenous capital formation. All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 12: Effects of quantitative easing in the large economy - role of market segmentation and transaction costs



Note: This figure presents the effects of quantitative easing in the large economy for the baseline and two alternative parametrizations: high bond market segmentation in the small economy ($\omega_r = 0.2$) and low transaction costs ($\xi_H = \xi_F = 0.0075$). All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Figure 13: Effects of quantitative easing in the large economy - role of trade elasticity and exchange rate pass-through



Note: This figure presents the effects of quantitative easing in the large economy for the baseline and two alternative parametrizations: low trade elasticity ($\nu = \nu^* \approx 1$) and low exchange rate pass-through ($\theta_H^* = \theta_F = 0.9$). All responses are in percent deviations from the steady state. The responses of the term premium and inflation are annualized.

Appendix

A List of model equations

The following equations describe the equilibrium in our two-country model. Small letters for variables defined in the main text indicate their real counterparts.

A.1 Households

Marginal utility

$$\lambda_t^r = \exp\{\varepsilon_t^d\}(c_t^r)^{-\sigma} \tag{A.1}$$

$$\lambda_t^{r*} = \exp\{\varepsilon_t^{d*}\}(c_t^{r*})^{-\sigma^*} \tag{A.2}$$

$$\lambda_t^u = \exp\{\varepsilon_t^d\}(c_t^u)^{-\sigma} \tag{A.3}$$

$$\lambda_t^{u*} = \exp\{\varepsilon_t^{d*}\}(c_t^{u*})^{-\sigma^*} \tag{A.4}$$

$$\lambda_t = \omega_r \lambda_t^r + (1-\omega_r)\lambda_t^u \tag{A.5}$$

$$\lambda_t^* = \omega_r^* \lambda_t^{r*} + (1-\omega_r^*)\lambda_t^{u*} \tag{A.6}$$

Bond prices

$$P_{L,t} = \frac{1}{R_{L,t} - \kappa} \tag{A.7}$$

$$P_{L,t}^* = \frac{1}{R_{L,t}^* - \kappa^*} \tag{A.8}$$

Restricted households' budget constraint

$$c_t^r + P_{L,t} b_{H,L,t}^r + t_t^r = P_{L,t}\frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^r + w_t n_t^r + d_t^r \tag{A.9}$$

$$\begin{aligned} c_t^{r*} + P_{L,t}^* b_{F,L,t}^{r*} + s_t^{-1} P_{L,t} b_{H,L,t}^{r*} + t_t^{r*} = \\ P_{L,t}^* \frac{R_{L,t}^*}{\pi_t^*} b_{F,L,t-1}^{r*} + s_t^{-1} P_{L,t}^* \frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^{r*} + w_t^* n_t^{r*} + d_t^{r*} \end{aligned} \tag{A.10}$$

Unrestricted households' budget constraint

$$\begin{aligned} c_t^u + b_{H,t}^u + P_{L,t} b_{H,L,t}^u + s_t P_{L,t}^* b_{F,L,t}^u + t_t^u = \\ \frac{R_{t-1}}{\pi_t} b_{H,t-1}^u + P_{L,t}\frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^u + s_t P_{L,t}^* \frac{R_{L,t}^*}{\pi_t^*} b_{F,L,t-1}^u + w_t n_t^u + d_t^u \end{aligned} \tag{A.11}$$

$$c_t^{u*} + b_{F,t}^{u*} + s_t^{-1} P_{L,t}^* b_{H,L,t}^{u*} + P_{L,t}^* b_{F,L,t}^{u*} + t_t^{u*} =$$
$$\frac{R_{t-1}^*}{\pi_t^*} b_{F,t-1}^{u*} + s_t^{-1} P_{L,t} \frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^{u*} + P_{L,t}^* \frac{R_{L,t}^*}{\pi_t^*} b_{F,L,t-1}^{u*} + w_t^* n_t^{u*} + d_t^{u*} \tag{A.12}$$

Consumption-leisure choice

$$(n_t^r)^\varphi = \lambda_t^r w_t \tag{A.13}$$

$$(n_t^{r*})^{\varphi*} = \lambda_t^{r*} w_t^* \tag{A.14}$$

$$(n_t^u)^\varphi = \lambda_t^u w_t \tag{A.15}$$

$$(n_t^{u*})^{\varphi*} = \lambda_t^{u*} w_t^* \tag{A.16}$$

Restricted households' optimal bond holdings

$$\lambda_t^r P_{L,t} = \beta^r \mathbb{E}_t \left\{ \lambda_{t+1}^r P_{L,t+1} \frac{R_{L,t+1}}{\pi_{t+1}} \right\} \tag{A.17}$$

$$\lambda_t^{r*} P_{L,t}^* = \beta^{r*} \mathbb{E}_t \left\{ \lambda_{t+1}^{r*} P_{L,t+1}^* \frac{R_{L,t+1}^*}{\pi_{t+1}^*} \right\} \tag{A.18}$$

$$\lambda_t^{r*}(1+\Gamma_t^{r*}) s_t^{-1} P_{L,t} = \beta^{r*} \mathbb{E}_t \left\{ \lambda_{t+1}^{r*} s_{t+1}^{-1} P_{L,t+1} \frac{R_{L,t+1}}{\pi_{t+1}} \right\} \tag{A.19}$$

Unrestricted households' optimal bond holdings

$$\lambda_t^u = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^u \frac{R_t}{\pi_{t+1}} \right\} \tag{A.20}$$

$$\lambda_t^u (1+\zeta_{H,t}) P_{L,t} = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^u P_{L,t+1} \frac{R_{L,t+1}}{\pi_{t+1}} \right\} \tag{A.21}$$

$$\lambda_t^u s_t (1+\zeta_{F,t}) P_{L,t}^* = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^u s_{t+1} (1+\Gamma_t) P_{L,t+1}^* \frac{R_{L,t+1}^*}{\pi_{t+1}^*} \right\} \tag{A.22}$$

$$\lambda_t^{u*} = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^{u*} \frac{R_t^*}{\pi_{t+1}^*} \right\} \tag{A.23}$$

$$\lambda_t^{u*} s_t^{-1} (1+\zeta_{H,t}^*) P_{L,t} = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^{u*} s_{t+1}^{-1} P_{L,t+1} \frac{R_{L,t+1}}{\pi_{t+1}} \right\} \tag{A.24}$$

$$\lambda_t^{u*} (1+\zeta_{F,t}^*) P_{L,t}^* = \beta \mathbb{E}_t \left\{ \lambda_{t+1}^{u*} P_{L,t+1}^* \frac{R_{L,t+1}^*}{\pi_{t+1}^*} \right\} \tag{A.25}$$

Transaction costs

$$\frac{1+\zeta_{H,t}}{1+\zeta_H} = \left(\frac{P_{L,t} b_{H,L,t}^u}{P_L b_{H,L}^u} \right)^{\xi_H} \tag{A.26}$$

$$\frac{1+\zeta_{H,t}^*}{1+\zeta_H^*} = \left(\frac{P_{L,t} b_{H,L,t}^{u*}}{P_L b_{H,L}^{u*}} \frac{s}{s_t} \right)^{\xi_H} \tag{A.27}$$

$$\frac{1+\zeta_{F,t}}{1+\zeta_F} = \left(\frac{P^*_{L,t} b^u_{F,L,t}}{P^*_L b^u_{F,L}} \frac{s_t}{s}\right)^{\xi_F} \tag{A.28}$$

$$\frac{1+\zeta^*_{F,t}}{1+\zeta^*_F} = \left(\frac{P^*_{L,t} b^{u*}_{F,L,t}}{P^*_L b^{u*}_{F,L}}\right)^{\xi_F} \tag{A.29}$$

$$1+\Gamma_t = \exp\left\{-\xi(a_t - a) + \varepsilon^\Gamma_t\right\} \tag{A.30}$$

$$1+\Gamma^{r*}_t = \exp\left\{\xi^*_r \left(\frac{P_{L,t} B^{r*}_{H,L,t}}{S_t P^*_{L,t} B^{r*}_{F,L,t}} - \kappa^{r*}\right)\right\} \tag{A.31}$$

A.2 Firms

Final goods basket

$$\tilde{y}_t = \left[\eta^{\frac{1}{\nu}} \left(y_{H,t}\right)^{\frac{\nu-1}{\nu}} + (1-\eta)^{\frac{1}{\nu}} \left(y_{F,t}\right)^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} \tag{A.32}$$

$$\tilde{y}^*_t = \left[\eta^{*\frac{1}{\nu^*}} \left(y^*_{H,t}\right)^{\frac{\nu^*-1}{\nu^*}} + (1-\eta^*)^{\frac{1}{\nu^*}} \left(y^*_{F,t}\right)^{\frac{\nu^*-1}{\nu^*}}\right]^{\frac{\nu^*}{\nu^*-1}} \tag{A.33}$$

Optimal composition of final goods basket

$$y_{H,t} = \eta \left(p_{H,t}\right)^{-\nu} \tilde{y}_t \tag{A.34}$$

$$y_{F,t} = (1-\eta) \left(p_{F,t}\right)^{-\nu} \tilde{y}_t \tag{A.35}$$

$$y^*_{H,t} = \eta^* \left(p^*_{H,t}\right)^{-\nu^*} \tilde{y}^*_t \tag{A.36}$$

$$y^*_{F,t} = (1-\eta^*) \left(p^*_{F,t}\right)^{-\nu^*} \tilde{y}^*_t \tag{A.37}$$

Real price indices

$$p_{H,t}^{\frac{1}{1-\mu}} = \theta_H \left(p_{H,t-1} \frac{\pi}{\pi_t}\right)^{\frac{1}{1-\mu}} + (1-\theta_H) \left(\tilde{p}_{H,t}\right)^{\frac{1}{1-\mu}} \tag{A.38}$$

$$p_{F,t}^{\frac{1}{1-\mu^*}} = \theta_F \left(p_{F,t-1} \frac{\pi}{\pi_t}\right)^{\frac{1}{1-\mu^*}} + (1-\theta_F) \left(\tilde{p}_{F,t}\right)^{\frac{1}{1-\mu^*}} \tag{A.39}$$

$$p^{*\frac{1}{1-\mu}}_{H,t} = \theta^*_H \left(p^*_{H,t-1} \frac{\pi^*}{\pi^*_t}\right)^{\frac{1}{1-\mu}} + (1-\theta^*_H) \left(\tilde{p}^*_{H,t}\right)^{\frac{1}{1-\mu}} \tag{A.40}$$

$$p^{*\frac{1}{1-\mu^*}}_{F,t} = \theta^*_F \left(p^*_{F,t-1} \frac{\pi^*}{\pi^*_t}\right)^{\frac{1}{1-\mu^*}} + (1-\theta^*_F) \left(\tilde{p}^*_{F,t}\right)^{\frac{1}{1-\mu^*}} \tag{A.41}$$

Optimal reset prices

$$\tilde{p}_{H,t} = \mu \frac{\Omega_{H,t}}{\Upsilon_{H,t}} \tag{A.42}$$

$$\Omega_{H,t} = \lambda_t \frac{w_t}{\exp\{\varepsilon^z_t\}} p_{H,t}^{\frac{\mu}{\mu-1}} y_{H,t} + \beta\theta_H \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu}{1-\mu}} \Omega_{H,t+1} \tag{A.43}$$

$$\Upsilon_{H,t} = \lambda_t p_{H,t}^{\frac{\mu}{\mu-1}} y_{H,t} + \beta\theta_H \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{1}{1-\mu}} \Upsilon_{H,t+1} \tag{A.44}$$

$$\tilde{p}_{F,t} = \mu^* \frac{\Omega_{F,t}}{\Upsilon_{F,t}} \tag{A.45}$$

$$\Omega_{F,t} = \lambda_t^* \frac{w_t^*}{\exp\{\varepsilon_t^{z*}\}} p_{F,t}^{\frac{\mu^*}{\mu^*-1}} y_{F,t} + \beta\theta_F \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu^*}{1-\mu^*}} \Omega_{F,t+1} \tag{A.46}$$

$$\Upsilon_{F,t} = \lambda_t^* s_t^{-1} p_{F,t}^{\frac{\mu^*}{\mu^*-1}} y_{F,t} + \beta\theta_F \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{1}{1-\mu^*}} \Upsilon_{F,t+1} \tag{A.47}$$

$$\tilde{p}_{H,t}^* = \mu \frac{\Omega_{H,t}^*}{\Upsilon_{H,t}^*} \tag{A.48}$$

$$\Omega_{H,t}^* = \lambda_t \frac{w_t}{\exp\{\varepsilon_t^z\}} p_{H,t}^{*\frac{\mu}{\mu-1}} y_{H,t}^* + \beta^*\theta_H^* \mathbb{E}_t \left(\frac{\pi^*}{\pi_{t+1}^*}\right)^{\frac{\mu}{1-\mu}} \Omega_{H,t+1}^* \tag{A.49}$$

$$\Upsilon_{H,t}^* = \lambda_t s_t p_{H,t}^{*\frac{\mu}{\mu-1}} y_{H,t}^* + \beta^*\theta_H^* \mathbb{E}_t \left(\frac{\pi^*}{\pi_{t+1}^*}\right)^{\frac{1}{1-\mu}} \Upsilon_{H,t+1}^* \tag{A.50}$$

$$\tilde{p}_{F,t}^* = \mu^* \frac{\Omega_{F,t}^*}{\Upsilon_{F,t}^*} \tag{A.51}$$

$$\Omega_{F,t}^* = \lambda_t^* \frac{w_t^*}{\exp\{\varepsilon_t^{z*}\}} p_{F,t}^{*\frac{\mu^*}{\mu^*-1}} y_{F,t}^* + \beta^*\theta_F^* \mathbb{E}_t \left(\frac{\pi^*}{\pi_{t+1}^*}\right)^{\frac{\mu^*}{1-\mu^*}} \Omega_{F,t+1}^* \tag{A.52}$$

$$\Upsilon_{F,t}^* = \lambda_t^* p_{F,t}^{*\frac{\mu^*}{\mu^*-1}} y_{F,t}^* + \beta^*\theta_F^* \mathbb{E}_t \left(\frac{\pi^*}{\pi_{t+1}^*}\right)^{\frac{1}{1-\mu^*}} \Upsilon_{F,t+1}^* \tag{A.53}$$

Dividends

$$d_t = p_{H,t} y_{H,t} + \frac{1-\omega}{\omega} s_t p_{H,t}^* y_{H,t}^* - w_t n_t \tag{A.54}$$

$$d_t^* = \frac{\omega}{1-\omega} p_{F,t} y_{F,t} \frac{1}{s_t} + p_{F,t}^* y_{F,t}^* - w_t^* n_t^* \tag{A.55}$$

$$d_t^r = \omega_r d_t \tag{A.56}$$

$$d_t^u = (1-\omega_r) d_t \tag{A.57}$$

$$d_t^{r*} = \omega_r^* d_t^* \tag{A.58}$$

$$d_t^{u*} = (1-\omega_r^*) d_t^* \tag{A.59}$$

A.3 Government

Monetary policy rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\gamma_r} \left[\left(\frac{\pi_t}{\pi}\right)^{\gamma_\pi} \left(\frac{y_t}{y}\right)^{\gamma_y}\right]^{1-\gamma_r} \exp\{\varepsilon_t^r\} \tag{A.60}$$

$$\frac{R_t^*}{R^*} = \left(\frac{R_{t-1}^*}{R^*}\right)^{\gamma_r^*} \left[\left(\frac{\pi_t^*}{\pi^*}\right)^{\gamma_\pi^*} \left(\frac{y_t^*}{y^*}\right)^{\gamma_y^*}\right]^{1-\gamma_r^*} \exp\{\varepsilon_t^{r*}\} \tag{A.61}$$

Government budget constraint

$$b_{H,t}^g + P_{L,t} b_{H,L,t}^g + t_t = \frac{R_{t-1}}{\pi_t} b_{H,t-1}^g + P_{L,t} \frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^g + g \exp\{\varepsilon_t^g\} \tag{A.62}$$

$$b_{F,t}^{g*} + P_{L,t}^* b_{F,L,t}^{g*} + t_t^* = \frac{R_{t-1}^*}{\pi_t^*} b_{F,t-1}^{g*} + P_{L,t}^* \frac{R_{L,t}^*}{\pi_t^*} b_{F,L,t-1}^{g*} + g^* \exp\{\varepsilon_t^{g*}\} \tag{A.63}$$

Total government debt

$$b_{H,t}^g + P_{L,t} b_{H,L,t}^g = b_H^g + P_L b_{H,L}^g \tag{A.64}$$

$$b_{F,t}^{g*} + P_{L,t}^* b_{F,L,t}^{g*} = b_F^{g*} + P_L^* b_{F,L}^{g*} \tag{A.65}$$

Composition of government debt

$$P_{L,t} b_{H,L,t}^g = P_L b_{H,L}^g \tag{A.66}$$

$$\frac{P_{L,t}^* b_{F,L,t}^{g*}}{P_L^* b_{F,L}^{g*}} = \left(\frac{P_{L,t-1}^* b_{F,L,t-1}^{g*}}{P_L^* b_{F,L}^{g*}}\right)^{\gamma_L^*} \exp\{\varepsilon_t^{L*}\} \tag{A.67}$$

A.4 Aggregation and market clearing

Aggregate labor

$$n_t = \omega_r n_t^r + (1-\omega_r) n_t^u \tag{A.68}$$

$$n_t^* = \omega_r^* n_t^{r*} + (1-\omega_r^*) n_t^{u*} \tag{A.69}$$

Goods market clearing

$$\tilde{y}_t = \omega_r c_t^r + (1-\omega_r) c_t^u + g_t \tag{A.70}$$

$$\tilde{y}_t^* = \omega_r^* c_t^{r*} + (1-\omega_r^*) c_t^{u*} + g_t^* \tag{A.71}$$

Aggregate production function

$$y_t = \exp\{\varepsilon_t^z\} n_t - \phi_t \tag{A.72}$$

$$y_t^* = \exp\{\varepsilon_t^{z*}\} n_t^* - \phi_t^* \tag{A.73}$$

Aggregate output

$$y_t = y_{H,t} \Delta_{H,t} + \frac{1-\omega}{\omega} y_{H,t}^* \Delta_{H,t}^* \tag{A.74}$$

$$y_t^* = \frac{\omega}{1-\omega} y_{F,t} \Delta_{F,t} + y_{F,t}^* \Delta_{F,t}^* \tag{A.75}$$

Price dispersion

$$\Delta_{H,t} = \left(\frac{p_{H,t}}{p_{H,t-1}}\right)^{\frac{\mu}{\mu-1}} \theta_H \Delta_{H,t-1} \left(\frac{\pi}{\pi_t}\right)^{\frac{\mu}{1-\mu}} + (1-\theta_H) \left(\frac{\tilde{p}_{H,t}}{p_{H,t}}\right)^{\frac{\mu}{1-\mu}} \tag{A.76}$$

$$\Delta^*_{H,t} = \left(\frac{p^*_{H,t}}{p^*_{H,t-1}}\right)^{\frac{\mu}{\mu-1}} \theta^*_H \Delta^*_{H,t-1} \left(\frac{\pi^*}{\pi^*_t}\right)^{\frac{\mu}{1-\mu}} + (1-\theta^*_H)\left(\frac{\tilde{p}^*_{H,t}}{p^*_{H,t}}\right)^{\frac{\mu}{1-\mu}} \tag{A.77}$$

$$\Delta_{F,t} = \left(\frac{p_{F,t}}{p_{F,t-1}}\right)^{\frac{\mu^*}{\mu^*-1}} \theta_F \Delta_{F,t-1} \left(\frac{\pi}{\pi_t}\right)^{\frac{\mu^*}{1-\mu^*}} + (1-\theta_F)\left(\frac{\tilde{p}_{F,t}}{p_{F,t}}\right)^{\frac{\mu^*}{1-\mu^*}} \tag{A.78}$$

$$\Delta^*_{F,t} = \left(\frac{p^*_{F,t}}{p^*_{F,t-1}}\right)^{\frac{\mu^*}{\mu^*-1}} \theta^*_F \Delta^*_{F,t-1} \left(\frac{\pi^*}{\pi^*_t}\right)^{\frac{\mu^*}{1-\mu^*}} + (1-\theta^*_F)\left(\frac{\tilde{p}^*_{F,t}}{p^*_{F,t}}\right)^{\frac{\mu^*}{1-\mu^*}} \tag{A.79}$$

Aggregate taxes

$$t_t = \omega_r t^r_t + (1-\omega_r) t^u_t \tag{A.80}$$

$$t^*_t = \omega^*_r t^{r*}_t + (1-\omega^*_r) t^{u*}_t \tag{A.81}$$

Short-term bond market clearing

$$(1-\omega_r) b^u_{H,t} = b^g_{H,t} \tag{A.82}$$

$$(1-\omega^*_r) b^{u*}_{F,t} = b^{g*}_{F,t} \tag{A.83}$$

Long-term bond market clearing

$$\omega(1-\omega_r) b^u_{H,L,t} + (1-\omega)(1-\omega^*_r) b^{u*}_{H,L,t} + \omega\omega_r b^r_{H,L,t} + (1-\omega)\omega^*_r b^{r*}_{H,L,t} = \omega b^g_{H,L,t} \tag{A.84}$$

$$\omega(1-\omega_r) b^u_{F,L,t} + (1-\omega)(1-\omega^*_r) b^{u*}_{F,L,t} + (1-\omega)\omega^*_r b^{r*}_{F,L,t} = (1-\omega) b^{g*}_{F,L,t} \tag{A.85}$$

Net foreign assets to output ratio

$$a_t = \frac{(1-\omega_r)(b^u_{H,t} + s_t b^u_{F,t} + P_{L,t} b^u_{H,L,t} + s_t P^*_{L,t} b^u_{F,L,t}) + \omega_r P_{L,t} b^r_{H,L,t} - b^g_{H,t} - P_{L,t} b^g_{H,L,t}}{y_t} \tag{A.86}$$

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