International Spillovers of Large-Scale Asset Purchases*

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Abstract

This paper evaluates the international spillover effects of large-scale asset purchases (LSAPs) using a two-country dynamic stochastic general equilibrium model with nominal and real rigidities, and portfolio balance effects. Portfolio balance effects arise from imperfect substitution between short and long-term bond portfolios in each country, as well as between domestic and foreign bonds within these portfolios. We show that LSAPs lower both domestic and foreign long-term yields, and stimulate economic activity in both countries. International spillover effects become larger as foreigners hold a larger share of long-term bonds in their portfolios at the steady state, as the elasticity of substitution between short and long-term bonds decreases, or as the elasticity of substitution between domestic and foreign bonds increases. We also find that U.S. asset purchases that generate the same output effect as U.S. conventional monetary policy have larger international spillover effects. This is because portfolio balance effects appear to be stronger under unconventional policy, and foreigners' U.S. bond holdings are heavily weighted towards long-term bonds.

Keywords: Portfolio balance effects, international spillovers, preferred habitat, DSGE.

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1 Introduction

Following the financial turbulence in the fall of 2008, the Federal Reserve cut short-term policy rates to near-zero, and announced unprecedented unconventional policy measures, such as large-scale asset purchases (LSAPs; also known as quantitative easing or QE), at the zero lower bound. Several studies have found significant effects of these asset purchases in terms of lowering U.S. long-term yields and strengthening economic activity (see Baumeister and Benati, 2013; D'amico et al., 2012; Gagnon et al., 2011; and Krishnamurthy and Vissing-Jorgensen, 2011; among others).[1] The domestic effects of these policies may also have increased the attractiveness of foreign assets, and led to portfolio re-balancing by international investors. Figure 1 shows the exchange rate and long-term yield movements during this period in countries where the policy rates were not significantly binding, and QE-type unconventional measures were not expected to be undertaken. The figure suggests that the currencies of these countries tended to appreciate during and after the announcement of LSAPs in the United States. Long-term yields were also in declining trend during this period; on average, long-term rates had fallen by more than 1 percentage point (pp) by mid-2013 when the Fed started talking about "tapering" the quantity of its asset purchases, in preparation for an eventual return to policy normalization.[2] In their analyses, Bauer and Neely (2014) and Neely (2013) find substantial effects of LSAPs on international financial markets through a decline in foreign yields and depreciation of the U.S. dollar. Chen, Q. et al. (2012), Fratzscher et al. (2012), and Lim et al. (2014) also document significant spillover effects of QE on the financial markets of emerging economies.

In this paper, we propose a two-country, open-economy model in which agents in the Rest-of-the-World (ROW) economy hold both short and long-term U.S. government bonds as well as their domestic bonds, but cannot perfectly substitute among these bonds. We show that the model can generate the type of international spillovers mentioned above after a QE announcement in the U.S. through the portfolio balance channel. We capture these portfolio balance effects by introducing a portfolio preference in households' utility function with a CES structure to aggregate individual financial assets. The imperfect substitution between short and long-term bonds, as well as between domestic and foreign bonds, could represent attitutes towards differential risk on these assets, costs of portfolio adjustment, or the institutional use of these bonds for liquidity purposes with varying degrees.[3] When short and long-term bonds are perfectly substitutable, exogenous changes in

[1] Hamilton and Wu (2010) and Doh (2010) find more limited effects of LSAPs on U.S. long-term yields. The estimates in the literature range between 3 to 15 basis points (bps) decline in long-term interest rates per \$100 billion asset purchase conducted by the Federal Reserve (Chen et al., 2012). For LSAP2 in particular, Bernanke (2012) report a range of 2.5 to 7.5 bps decline in long-term yields per \$100 billion asset purchase. Our baseline findings for the decline in the term premium and long-term yields as a result of LSAP2 fall within this range (about 4-5 bps). In section 5, we also conduct sensitivity analysis to analyze under which conditions the effects of LSAPs can be smaller or larger.

[2] Long-term yields increased in the beginning of LSAP2 mainly because central banks in many countries hiked interest rates in expectation of higher inflation. However, this tightening cycle was short (about a year) as these expectations did not materialize. Contagion effects from the Euro crisis could have also put upward pressure on long-term yields during this period.

[3] Financial institutions, for example, use short-term money market instruments as collateral in the interbank market. Thus, they may be less willing to alter their portfolio balances when there is a change in the relative prices of short-term to long-term assets. In addition, regardless of maturity, domestic and foreign assets tend to be less substitutable with each other. Hau and Rey (2004), for instance, finds evidence in support of the portfolio balance channel affecting exchange rates using a

the relative supply of one type of asset would have no effect on the relative price of these bonds (see Curdia and Woodford, 2010). In our set-up, short and long-term bonds are not perfect substitutes; thus, long-term rates fall in response to a drop in their relative supply even when short-term rates remain constant.[4] Lower long-term rates then stimulate the domestic economy, and generate appreciation pressures on the currency of the ROW economy. This in turn leads to current and expected policy rates to fall in the ROW, lowering foreign long-term yields. Long-term rates in the ROW fall not only through the expectations hypothesis, but also due to the fall in the term-premium component, which in turn is caused by a relative increase in the demand for ROW long-term assets. Finally, lower short and long-term interest rates stimulate economic activity in the ROW.

Our results can be summarized as follows: (i) QE is effective to stimulate both U.S. and ROW activity, (ii) QE spillovers are larger than standard monetary policy spillovers when both policies are scaled to have the same output effects in the U.S., (iii) spillovers are larger if the steady-state share of long-term U.S. bond holdings is higher in the ROW portfolio (conversely, QE spillovers are smaller, and get close to those from conventional policy, if the steady-state share of long-term U.S. bond holdings is smaller in the ROW portfolio), (iv) spillovers increase as the elasticity of substitution between short and long-term bonds gets smaller, (v) spillovers increase as the elasticity of substitution between long-term US and ROW bonds gets larger. An advantage of introducing maturity structure in a two-country open economy model is that it allows us to analyze the effects of maturity composition of U.S. government bonds in foreigners' portfolios. Figure 2 shows U.S. residents' and ROW holdings of U.S. government bonds as a ratio of their GDP. The picture highlights a clear difference in the maturity composition in the U.S. and ROW portfolios. In particular, U.S. residents hold twice as many short-term U.S. government bonds as long-term ones. On the other hand, the ratio switches in favor of long-term U.S. government bonds in the ROW. This difference in the maturity composition is crucial to generate a stronger spillover from LSAPs relative to conventional policy in our model.

Our paper is related to the literature on the portfolio balance channel that dates back at least to Tobin (1969). Andres et al. (2004) incorporate Tobin's ideas into a DSGE model generating imperfect substitution between assets through transaction costs on long-term bonds. Chen et al. (2012) use this kind of a set up to study the effects of QE in a closed economy context. Dorich et al. (2012) also consider a similar set-up and analyze the effects of QE within a small open economy featuring the exchange rate channel. We extend these analyses to a two-country context to be able to study the cross-country spillover effects of QE policies. Note that the models in the literature typically feature "restricted agents" that can only hold long-term bonds to

VAR framework. Benes et al. (2010), Blanchard et al. (2005) and Kumhof (2010) investigate the portfolio balance channel in theoretical frameworks. These papers focus on current account determination and the effects of sterilized interventions, and do not explore the spillover effects of QE.

[4] This is consistent with empirical evidence presented by Gagnon et al. (2011) and Greenwood and Vayanos (2010; 2014) on the relationship between relative bond supplies and the relative returns on government bonds of different maturities.

smooth consumption; hence, long-term interest rates have an effect on aggregate demand separate from the effects coming from changes in short-term rates. In our set-up, though, we do not need to introduce restricted agents separately to generate real effects from changes in long-term rates. This is because our representative households get utility from holding financial assets; thus, their marginal decision with respect to holding a short-term bond or spending depends not only on the short-term rate but also on their relative bond holdings. Large increases in the U.S. short-term bond holdings following QE lowers the marginal benefit of holding these bonds, thus making short-term U.S. bonds less attractive relative to consumption even when the domestic short-term rate remains constant.[5]

The remainder of the paper proceeds as follows. The next section introduces the model. Section 3 discusses the calibration of model parameters. Section 4 presents the results of the baseline QE experiment. Section 5 conducts sensitivity analysis, and section 6 concludes.

2 Model

The model is a two-country large-open-economy DSGE model with real and nominal rigidities, and portfolio balance effects.[6] The latter is achieved through modeling households' preferences on the composition of their financial portfolio with imperfect substitution between short and long-term assets for both domestic and foreign sovereign debt. Each country in the model is populated by households, capital producers, final goods aggregators, domestic producers, and importers, as well as fiscal and monetary policy rules. In what follows, we focus on the agents in the domestic economy, but the foreign economy is analogous in our set-up. When variables from the foreign economy are necessary, we denote them with a (*) superscript.

2.1 Households

The economy is populated by a unit measure of infinitely-lived patient households indexed by i, whose intertemporal preferences over consumption, c_t, financial asset portfolio, a_t, and labor supply, n_t, are described by the following expected utility function:

$$E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[\log \left[c_\tau (i) - \zeta c_{\tau-1} \right] + \xi_a \log a_\tau (i) - \xi_n \frac{n_\tau (i)^{1+\vartheta}}{1+\vartheta} \right], \tag{1}$$

[5] Harrison (2012) also analyzes the effects of asset-purchases by using a preferred short-to-long-term bond ratio in households' preferences, similar to our paper, but in a closed-economy environment. We use a more general CES structure for financial assets, which allows for a more compact way to introduce imperfect substitution among four different bonds (short-term and long-term bonds in domestic-asset and foreign-asset portfolios), and also lets us evaluate the economic consequences of different elasticities of substitution between these bonds. Note also that it is common in the finance literature to consider financial wealth in the utility function for determining optimal portfolios. For example, Vayanos and Vila (2009) model the term structure of interest rates using a preference specification for specific maturities. In footnote 7 in the next section, we discuss several alternative modeling choices that would yield similar results with our asset preference specification.

[6] We assume that both regions have the same economic size, which is motivated by the fact that the output of countries that faced the zero lower bound at the end of 2010 - i.e. U.S., U.K. and Japan - constitute more than 46 percent of world GDP over the sample period 1960-2010. The ratio is slightly lower if we consider a more recent sample period 2000-2010.

where t indexes time, $\beta < 1$ is the time-discount parameter, ζ is the external habit parameter for consumption, ϑ is the inverse of the Frisch-elasticity of labor supply, and ξ_a and ξ_n are level parameters that determine the relative importance of financial assets and labor in the utility function.

2.1.1 Preferences on portfolio composition

We capture imperfect substitution across assets of different currencies and maturities using a nested CES structure for financial assets.[7] In particular, the asset portfolio in the utility function, a_t, is a CES aggregate of sub-portfolios consisting of short-term bonds, $a_{S,t}$, and long-term bonds, $a_{L,t}$:

$$a_t(i) = \left[\gamma_a^{\frac{1}{\lambda_a}} a_{S,t}(i)^{\frac{\lambda_a - 1}{\lambda_a}} + (1 - \gamma_a)^{\frac{1}{\lambda_a}} a_{L,t}(i)^{\frac{\lambda_a - 1}{\lambda_a}} \right]^{\frac{\lambda_a}{\lambda_a - 1}}, \tag{2}$$

where γ_a determines the share of short-term assets in the aggregate portfolio, and λ_a is the elasticity of substitution between short and long-term assets.

The short-term bond sub-portfolio is a CES aggregate of short-term domestic government bonds, $B_{HS,t}$, and short-term foreign government bonds, $B_{FS,t}$:

$$a_{S,t}(i) = \left[\gamma_S^{\frac{1}{\lambda_S}} \left(\frac{B_{HS,t}(i)}{P_t} \right)^{\frac{\lambda_S - 1}{\lambda_S}} + (1 - \gamma_S)^{\frac{1}{\lambda_S}} \left(\frac{e_t B_{FS,t}(i)}{P_t} \right)^{\frac{\lambda_S - 1}{\lambda_S}} \right]^{\frac{\lambda_S}{\lambda_S - 1}}, \tag{3}$$

where P_t is the aggregate price level, e_t is the nominal exchange rate (in units of domestic currency per unit of foreign currency), γ_S is the share of domestic bonds in the short-term bond sub-portfolio, and λ_S is the elasticity of substitution between domestic and foreign short-term bonds.

Similarly, the long-term bond sub-portfolio is a CES aggregate of long-term domestic government bonds, $B_{HL,t}$, and long-term foreign government bonds, $B_{FL,t}$:

$$a_{L,t}(i) = \left[\gamma_L^{\frac{1}{\lambda_L}} \left(\frac{q_{L,t} B_{HL,t}(i)}{P_t} \right)^{\frac{\lambda_L - 1}{\lambda_L}} + (1 - \gamma_L)^{\frac{1}{\lambda_L}} \left(\frac{e_t q_{L,t}^* B_{FL,t}(i)}{P_t} \right)^{\frac{\lambda_L - 1}{\lambda_L}} \right]^{\frac{\lambda_L}{\lambda_L - 1}}, \tag{4}$$

where $q_{L,t}$ and $q_{L,t}^*$ denote the relative prices of domestic and foreign long-term bonds, respectively, γ_L is the share of domestic bonds in the long-term bond sub-portfolio, and λ_L is the elasticity of substitution between domestic and foreign long-term bonds.

[7] Alternatively, we could capture imperfect substitution across the four types of assets by considering portfolio adjustment costs in the budget constraint of households (Chen et al., 2013). One could also capture this imperfect substitutability in the objective function, or in the flow constraint, of portfolio managers who own the different financial assets, and sell mutual fund shares backed by these assets to households, similar to Harrison (2011). These approaches would yield similar results with our approach in terms of portfolio dynamics and relative asset demand.

2.1.2 Wage rigidity

Labor services are heterogenous across the patient households, and are aggregated into a homogenous labor service by perfectly-competitive labor intermediaries, who in turn rent these labor services to goods producers. The labor intermediaries use a standard Dixit-Stiglitz aggregator; therefore, the labor demand curve facing each patient household is given by

$$n_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\eta_n} n_t, \tag{5}$$

where W_t and n_t are the aggregate nominal wage rate and labor services for patient households, respectively, and η_n is the elasticity of substitution between the differentiated labor services, implying a steady-state mark-up of real wage over the marginal rate of substitution, $\theta_w = \eta_n/(\eta_n - 1)$.

Wage-stickiness is introduced via a quadratic cost of wage adjustment in the budget constraint similar to Rotemberg (1982),

$$\frac{\kappa_w}{2}\left(\frac{W_t(i)/W_{t-1}(i)}{\pi_{t-1}^{\varsigma_w}\pi^{1-\varsigma_w}} - 1\right)^2 \frac{W_t}{P_t} n_t, \tag{6}$$

where κ_w is a scale parameter, $\pi_t = P_t/P_{t-1}$ is the aggregate inflation factor, and ς_w determines indexation of wage adjustments to past inflation.

2.1.3 Budget constraint

The households' period budget constraint is given by

$$\begin{aligned} c_t(i) + q_t\left[k_t(i) - (1-\delta)k_{t-1}(i)\right] + \frac{B_{HS,t}(i)}{P_t} + \frac{e_t B_{FS,t}(i)}{P_t} + \frac{q_{L,t}B_{HL,t}(i)}{P_t} + \frac{e_t q_{L,t}^* B_{FL,t}(i)}{P_t} \\ \leq \frac{W_t(i)}{P_t} n_t(i) + r_{k,t}k_{t-1}(i) + \frac{R_{t-1}B_{HS,t-1}(i)}{P_t} + \frac{e_t R_{t-1}^* B_{FS,t-1}(i)}{P_t} + \frac{(1+\kappa q_{L,t})B_{HL,t-1}(i)}{P_t} \\ + \frac{e_t\left(1+\kappa q_{L,t}^*\right)B_{FL,t-1}(i)}{P_t} + \frac{\Pi_{H,t}}{P_t} + \frac{\Pi_{F,t}}{P_t} - \frac{TAX_t}{P_t} - \text{wage adj. cost} \end{aligned} \tag{7}$$

where k_t is the capital stock, q_t is the relative price of capital, and $r_{k,t}$ is the rental rate of capital. $\Pi_{H,t}$ and $\Pi_{F,t}$ denote the profits of monopolistically-competitive domestic producers and importers, while TAX_t is lump-sum taxes paid by households to the government. Short-term domestic and foreign bonds pay pre-determined interest rates of R_{t-1} and R_{t-1}^*, respectively, while long-term bonds are perpetuities that pay a coupon payment of 1 unit in the first period after issuance, and have coupon payments decaying at a rate of κ for each period after that, as in Woodford (2001). Since these long-term bonds are tradable, we can write them in recursive form in the budget constraint above. The yields on domestic and foreign long-term bonds are defined respectively as

$$R_{L,t} = \frac{1+\kappa q_{L,t}}{q_{L,t}} \text{ and } R_{L,t}^* = \frac{1+\kappa q_{L,t}^*}{q_{L,t}^*}. \tag{8}$$

2.1.4 Short-term and long-term IS curves

The households' objective is to maximize utility subject to the budget constraint, the labor demand curve of labor intermediaries, and appropriate No-Ponzi conditions. The first-order conditions for consumption and capital are standard, and are given by

$$\frac{1}{c_t - \zeta c_{t-1}} = \lambda_t, \tag{9}$$

$$q_t = E_t \left[\left(\beta \frac{\lambda_{t+1}}{\lambda_t} \right) \left[(1-\delta) q_{t+1} + r_{k,t+1} \right] \right], \tag{10}$$

where λ_t is the Lagrange multiplier on the budget constraint. Similarly, the optimality conditions with respect to labor and wages can be combined to derive a New-Keynesian wage Phillips curve, which after log-linearization can be written as:

$$\widehat{\pi}_{w,t} - \varsigma_w \widehat{\pi}_{t-1} = \beta E_t \left[\widehat{\pi}_{w,t+1} - \varsigma_w \widehat{\pi}_t \right] - \frac{\eta_n - 1}{\kappa_w} \left(\widehat{w}_t - \vartheta \widehat{n}_t - \frac{1}{1-\zeta} \left(\widehat{c}_t - \zeta \widehat{c}_{t-1} \right) \right), \tag{11}$$

where the nominal wage inflation, $\widehat{\pi}_{w,t}$, and the real wage rate, $\widehat{w}_t$, are related as

$$\widehat{\pi}_{w,t} - \widehat{\pi}_t = \widehat{w}_t - \widehat{w}_{t-1}. \tag{12}$$

The optimality conditions with respect to domestic short and long-term bonds are given by

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{R_t}{\pi_{t+1}} \right] + \frac{\xi_a}{a_t} \frac{\partial a_t}{\partial a_{S,t}} \frac{\partial a_{S,t}}{\partial b_{HS,t}}, \tag{13}$$

$$q_{L,t} \lambda_t = \beta E_t \left[\lambda_{t+1} \frac{1 + \kappa q_{L,t+1}}{\pi_{t+1}} \right] + \frac{\xi_a}{a_t} \frac{\partial a_t}{\partial a_{L,t}} \frac{\partial a_{L,t}}{\partial b_{HL,t}}, \tag{14}$$

where $b_{HS,t} = B_{HS,t}/P_t$, and $b_{HL,t} = B_{HL,t}/P_t$. The two expressions above can be log-linearized and combined to generate an expression for the yield on long-term bonds as

$$\widehat{R}_{L,t} = \left(1 - \frac{\kappa}{R_L} \right) \Omega E_t \sum_{s=0}^{\infty} \left(\beta \frac{R}{\pi} \frac{\kappa}{R_L} \Omega \right)^s \left[\beta \frac{R}{\pi} \widehat{R}_{t+s} + \left(1 - \beta \frac{R}{\pi} \right) \widehat{T}_{t+s} \right], \tag{15}$$

where

$$\widehat{T}_t = \frac{1}{\lambda_a} \left(\widehat{a}_{L,t} - \widehat{a}_{S,t} \right) - \frac{1}{\lambda_L} \left(\widehat{a}_{L,t} - \widehat{b}_{HL,t} \right) + \frac{1}{\lambda_S} \left(\widehat{a}_{S,t} - \widehat{b}_{HS,t} \right), \tag{16}$$

and

$$\Omega = \frac{1}{1 - \left(1 - \beta \frac{R}{\pi} \right) \left(1 - \frac{1}{\lambda_L} \right)}. \tag{17}$$

The above expression implies that the yield on long-term bonds, $R_{L,t}$, is a function of expected short-term rates as well as a term-premium, which in turn depends on the relative holdings of bonds in agents' portfolios. Note that when the elasticity of substitution across the different assets are set equal to each other (i.e.,

$\lambda_a = \lambda_S = \lambda_L$), the above expression reduces to

$$\widehat{R}_{L,t} = \left(1 - \frac{\kappa}{R_L}\right) \Omega E_t \sum_{s=0}^{\infty} \left(\beta \frac{R}{\pi} \frac{\kappa}{R_L} \Omega\right)^s \left[\beta \frac{R}{\pi} \widehat{R}_t + \left(1 - \beta \frac{R}{\pi}\right) \frac{1}{\lambda_a} \left(\widehat{b}_{HL,t} - \widehat{b}_{HS,t}\right)\right], \tag{18}$$

where the relative quantities of only the domestic short and long-term bonds affect the domestic term-premium, and λ_a determines the pass-through from changes in relative bond holdings to the long-term yields. When we calibrate the model in the next section, we assume that U.S. households do not hold any ROW bonds; thus, this reduced expression for long-term yields above would apply to the U.S. economy exactly, since $a_{L,t} = b_{HL,t}$ and $a_{S,t} = b_{HS,t}$ in this case.

The equation above implies that, even when short rates are kept constant (e.g., at the zero-lower-bound), the long-rate can be altered with asset purchase policies. Particularly, LSAPs in the domestic economy lower the supply of long-term bonds, and, in return, increase the supply of short-term bonds through the consolidated government budget constraint.[8] When quantities involved are large, this can lower the yields on long-term bonds, and affect aggregate demand even when short rates are constant. The portfolio preference specification in our representative agent framework is crucial for this result, since, now, the representative agent's marginal utility depends not only on the short-term interest rate, but also on bond quantities. To see this, observe that the first-order-condition for short-term domestic bonds (equation 13), yields the following expression after log-linearization

$$\widehat{\lambda}_t = \beta \frac{R}{\pi} \left(E_t \widehat{\lambda}_{t+1} + \widehat{R}_t - E_t \widehat{\pi}_{t+1}\right) + \left(1 - \beta \frac{R}{\pi}\right) \left[\left(\frac{1}{\lambda_S} - \frac{1}{\lambda_a}\right) \widehat{a}_{S,t} + \left(\frac{1}{\lambda_a} - 1\right) \widehat{a}_t - \frac{1}{\lambda_S} \widehat{b}_{HS,t}\right], \tag{19}$$

which reduces to the following when all portfolio elasticities are set to 1:

$$\widehat{\lambda}_t = \beta \frac{R}{\pi} \left(E_t \widehat{\lambda}_{t+1} + \widehat{R}_t - E_t \widehat{\pi}_{t+1}\right) - \left(1 - \beta \frac{R}{\pi}\right) \widehat{b}_{HS,t}. \tag{20}$$

In the absence of the portfolio choice term in preferences, $\beta R/\pi$ would be equal to 1 at the steady-state, and the equation above would become the standard IS curve; thus, aggregate demand would depend only on the current and expected future real short-term interest rates. With our portfolio specification in preferences, the marginal benefit of holding short-term bonds diminishes as short-term bond holdings increase; this in turn stimulates aggregate demand even when short rates are constant. In particular, our portfolio specification allows for changes in the outstanding quantity of bonds to affect demand even in a representative agent framework, unlike papers in the literature which rely on transaction costs in trading long-term bonds and segmented markets (see for example Andres et al., 2004, and Chen et al., 2012). In these papers, the presence of transaction costs leads to a term premium between long-term and short-term bonds; however, a representative agent can by-pass these costs completely by relying only on short-term bonds to smooth

[8] This is akin to balance sheet policies of a central bank, which buys long-term bonds by increasing its short-term liabilities; namely, the monetary base.

consumption. Therefore, these models need to introduce a separate type of agent that can only save through long-term bonds to ensure that the long-term rate has real implications for the aggregate economy. In the absence of these restricted agents in these set-ups, the IS curve determining aggregate demand would depend only on short-term rates, and not on the quantities of bonds outstanding.

Given our calibration in Section 3, the coefficient in front of the bond quantity term in equation (20), $1 - \beta R/\pi$, is rather small (less than 1%). Thus, for the channel emphasized in our paper to be quantitatively important, the supply of short-term bonds needs to change by a significant amount. During an LSAP, a large increase in the outstanding quantity of short-term bonds lowers the willingness of agents to hold these bonds, and stimulates aggregate demand through the "short IS" relationship in equation (20). Note that the "long IS" relationship in equation (14) is also satisfied, where lower long-term interest rates stimulate aggregate demand through this relationship.

In the ROW economy, the term-premium on long-term yields is determined by relative holdings of both U.S. and ROW bonds (see equation (15)). Assuming $\lambda_S = \lambda_L$ as in our baseline calibration, we can rewrite $\widehat{T}_t$ as follows:

$$\widehat{T}_t = \left(\frac{1}{\lambda_a} - \frac{1}{\lambda_L}\right)(\widehat{a}_{L,t} - \widehat{a}_{S,t}) + \frac{1}{\lambda_L}\left(\widehat{b}_{HL,t} - \widehat{b}_{HS,t}\right), \tag{21}$$

The first expression in the above equation represents the effects from portfolio balancing between short and long-term bond sub-portfolios, while the second represents the additional effects coming from relative holdings of domestic short and long-term bonds. Following QE in the U.S., ROW residents lower their holdings of long-term U.S. bonds and increase their holdings of short-term U.S. bonds, thereby decreasing the share of their long-term bonds in the aggregate ROW portfolio. Assuming that the ROW government does not change its supply of domestic bonds, the decrease in the long-term bond holdings relative to the short-term bond sub-portfolio would lower the term premium in the ROW when $\lambda_a < \lambda_L = \lambda_S$. Intuitively, as long as the elasticity of substitution between domestic and foreign bonds is larger than the elasticity of substitution between short and long-term bonds, the decline in the holdings of long-term U.S. bonds is associated with an increase in the demand for long-term ROW bonds, and the increase in higher holdings of short-term U.S. bonds is associated with a decrease in the demand for short-term ROW bonds. The increased demand for ROW long-term bonds relative to ROW short-term bonds drives up long-term bond prices and lowers the term premium and long-term bond yields in the ROW.

Figure 3 summarizes the equilibria in the U.S. and the ROW bond markets using relative bond demand and supply schedules. The x-axes denote the quantity of short-term bonds relative to the quantity of long-terms in the respective bond market while the y-axes denote the term premium. The relative demand for short-term bonds is downward sloping due to imperfect substitution between short and long-term bonds. The relative demand schedule for the ROW can be seen as an illustration of the aforementioned expression, $\widehat{T}_t$, with changes in foreign bond quantities shifting this schedule upwards or downwards. In addition, relative bond supplies are assumed to be controlled by the government in each region. The left panel in Figure 3 presents the movements in the U.S. term premium following QE in the United States. QE increases the relative supply of short-term bonds and lowers the term premium on the U.S. long-term bonds. Both U.S. and ROW residents start holding relatively more short-term U.S. bonds than long-term U.S. bonds. The right panel shows the effects of the increased relative short-term U.S. bonds on the ROW term premium. On the one hand, the relative demand for ROW short-term bonds shifts downwards as ROW agents compensate for the decline in the share of long-term bonds in their overall portfolio, whose magnitude depends on the extent of imperfect substitution between short and long-term bonds, λ_a. On the other hand, the increased holdings of short-term U.S. bonds and the decreased holdings of long-term U.S. bonds shifts the relative demand for ROW short-term bonds upwards due to the imperfect substitution between domestic and foreign assets. A sufficiently low λ_L (i.e, if agents do not prefer to deviate much from the steady-state ratio of domestic–to-foreign assets in their long-term bond sub-portfolio) would cancel out the incentives to substitute away from long-term U.S. bonds, and would in fact increase the term premium in the ROW. This off-setting effect is smaller as domestic and foreign assets become more substitutable, thereby increasing the net demand for long-term ROW bonds and lowering the term premium. Thus, the term premium in the ROW may decrease or increase depending on the portfolio elasticities; with our baseline calibration, we have $\lambda_a < \lambda_L = \lambda_S$, and therefore, the term premium and long-term yields in the ROW decline following QE in the U.S..

2.1.5 Short-term and long-term UIP conditions

The effects of LSAPs on exchange rates can be illustrated by considering the optimality conditions of ROW households with respect to foreign short and long-term bonds:

$$rer_t \lambda_t = \beta E_t \left[\lambda_{t+1} rer_{t+1} \frac{R_t^*}{\pi_{t+1}^*} \right] + \frac{\xi_a}{a_t} \frac{\partial a_t}{\partial a_{S,t}} \frac{\partial a_{S,t}}{\partial b_{FS,t}}, \tag{22}$$

$$rer_t q_{L,t}^* \lambda_t = \beta E_t \left[\lambda_{t+1} rer_{t+1} \frac{1 + \kappa q_{L,t+1}^*}{\pi_{t+1}^*} \right] + \frac{\xi_a}{a_t} \frac{\partial a_t}{\partial a_{L,t}} \frac{\partial a_{L,t}}{\partial b_{FL,t}}, \tag{23}$$

where $b_{FS,t} = B_{FS,t}/P_t^*$, $b_{FL,t} = B_{FL,t}/P_t^*$, and $rer_t = e_t P_t^*/P_t$ denotes the real exchange rate. The first-order conditions for short-term domestic and foreign bonds can be combined to yield a short-term uncovered interest parity (UIP) condition. After log-linearization, this short-term UIP condition can be written as

$$\widehat{R}_t - \widehat{R}_t^* = E_t \widehat{d}_{t+1} + \left(\frac{1 - \beta \frac{R}{\pi}}{\beta \frac{R}{\pi}} \right) \frac{1}{\lambda_S} \left[\widehat{b}_{HS,t} - \left(\widehat{rer}_t + \widehat{b}_{FS,t} \right) \right], \tag{24}$$

where $\widehat{d}_t = \widehat{e}_t - \widehat{e}_{t-1}$ denotes the nominal depreciation rate of the ROW currency. The above condition implies that the country risk-premium is determined by the relative holdings of short-term domestic and foreign bonds. Thus, even when the short-term rate differentials cannot change due to the zero lower bound, LSAPs can still affect the exchange rate through the country risk-premium. More generally, equation (24) can be interpreted as the relative demand schedule between short-term U.S. and ROW bonds. Following QE in the U.S., ROW holdings of short-term U.S. bonds would increase relative to the their holdings of short-term ROW bonds, thereby increasing the share of U.S. bonds in the ROW residents' short-term sub-portfolio. Higher relative holdings of short-term U.S. bonds in the ROW economy would thus put downward pressure on the ROW short-term interest rates and appreciate on the ROW currency.[9] As these bonds become more substitutable (i.e., as λ_S increases), the appreciation effects on the ROW currency becomes more muted; conversely, as λ_S converges to zero, LSAPs would lead to a larger appreciation of the ROW currency.

The long-term UIP condition can be obtained by combining the first-order conditions of ROW households with respect to long-term domestic and foreign bonds as

$$\begin{aligned}\frac{R_L}{R_L-\kappa}\left(\widehat{R}_{L,t}-\widehat{R}^*_{L,t}\right)-\frac{\kappa}{R_L-\kappa}\left(E_t\widehat{R}_{L,t+1}-E_t\widehat{R}^*_{L,t+1}\right)\\ =E_t\widehat{d}_{t+1}+\left(\frac{1-\beta\frac{R}{\pi}}{\beta\frac{R}{\pi}}\right)\frac{1}{\lambda_L}\left[\widehat{q}_{L,t}+\widehat{b}_{HL,t}-(\widehat{rer}_t+\widehat{q}^*_{L,t}+\widehat{b}_{FL,t})\right],\end{aligned} \tag{25}$$

which implies that the appreciation of the ROW currency also depends on the long-rate differential and the relative holdings of domestic and foreign long-term bonds. Note that, now, the right-hand-side of (25) will tend to move in the opposite direction relative to that of the short-term UIP. In particular, following QE in the U.S., ROW households would like to increase their domestic long-term bond holdings (which, nevertheless, would stay the same in equilibrium due to their constant supply in the absence of QE in the ROW) relative to their long-term U.S. bond holdings. Thus, the long-term interest rate differential, $R_{L,t}-R^*_{L,t}$, would increase. Most of this adjustment is due to the larger decline in U.S. long-term rates however; thus, the long-term UIP condition still validates a small decline in ROW long-term rates, as well as an appreciation in the ROW currency. As we further discuss in section 5, the spillover effects of LSAPs on ROW long-term yields and the exchange rate depend importantly on the substitutability between domestic and foreign long-term bonds in the ROW portfolio. As λ_L increases, domestic and foreign long-term bonds become more substitutable, and the ROW long-term rates decline more closely mirroring the fall in the U.S. long-term rates. Conversely, as λ_L approaches 0, the ROW long-term rates decline less, or can even increase; the latter can happen with a low enough λ_L, since the right-hand-side of the long-term UIP condition becomes very responsive to changes in the relative long-term bond holdings, and increases sharply, as a result of QE.

The maturity composition of steady-state U.S. bond holdings in the ROW also plays an important role in determining the magnitude of QE spillovers. Consider a case where the ROW's U.S. bond portfolio is more skewed towards long-term U.S. bonds, with their total U.S. portfolio the same as before. Since the

[9] In our baseline simulations, we assume that the short-term interest rate in the ROW economy is not bounded by the zero lower bound following the QE shock in the U.S. economy. The resulting decline in ROW policy rates thus partly cushion the appreciation effects on the ROW currency. This appreciation effect would be larger if the ROW economy was also constrained by the zero lower bound during this period.

steady-state share of U.S. bonds in their short-term bond sub-portfolio is now smaller, the same amount of QE in percentage terms would increase their relative holdings of short-term U.S. bonds further, which would result in a larger appreciation of the ROW currency through the short-term UIP (see equation (24)). Note that the long-term UIP condition would also validate the higher appreciation of the ROW currency in equilibrium. Since the steady-state share of long-term U.S. bonds is now larger in the long-term bond sub-portfolio, the percentage change in the relative U.S. long-term bonds would be smaller; therefore, the dampening effect mentioned above in the long-term UIP condition coming from the relative bond holdings would also be smaller. As a result, ROW long-term rates fall more along with a larger appreciation of the ROW currency. Furthermore, as we discuss in the quantitative section, higher appreciation would increase disinflationary pressures, and lead to lower policy rates in the ROW. Therefore, international spillovers would increase when ROW residents' holdings of U.S. bonds are more weighted towards long-term bonds.

2.2 Final goods aggregators

There are two types of final goods aggregators; for consumption goods, c_t, and for investment goods, i_t. In what follows, we mainly describe the consumption goods aggregators, but investment goods aggregators are modeled in an analogous fashion.

Consumption aggregators are perfectly competitive, and they produce the final goods as a CES aggregate of home and foreign goods, $c_{h,t}$ and $c_{f,t}$:

$$c_t = \left[\gamma_c^{\frac{1}{\lambda_c}} c_{h,t}^{\frac{\lambda_c - 1}{\lambda_c}} + (1 - \gamma_c)^{\frac{1}{\lambda_c}} c_{f,t}^{\frac{\lambda_c - 1}{\lambda_c}} \right]^{\frac{\lambda_c}{\lambda_c - 1}}, \tag{26}$$

where γ_c denotes the share of domestic goods, and λ_c is the elasticity of substitution between home and foreign goods, in the consumption aggregate. For any level of aggregate consumption, their optimal demand for the domestic and imported consumption goods are given by

$$c_{h,t} = \left(\frac{P_{h,t}}{P_t} \right)^{-\lambda_c} \gamma_c c_t, \text{ and } c_{f,t} = \left(\frac{P_{f,t}}{P_t} \right)^{-\lambda_c} (1 - \gamma_c)\, c_t, \tag{27}$$

where $P_{h,t}$ and $P_{f,t}$ are the prices of the home and foreign goods, respectively. The aggregate price index for consumption goods is given by

$$P_t = \left[\gamma_c P_{h,t}^{1-\lambda_c} + (1 - \gamma_c)\, P_{f,t}^{1-\lambda_c} \right]^{\frac{1}{1-\lambda_c}}. \tag{28}$$

The analogous expressions for investment goods aggregators are given by:

$$i_t = \left[\gamma_i^{\frac{1}{\lambda_i}} i_{h,t}^{\frac{\lambda_i - 1}{\lambda_i}} + (1-\gamma_i)^{\frac{1}{\lambda_i}} i_{f,t}^{\frac{\lambda_i - 1}{\lambda_i}} \right]^{\frac{\lambda_i}{\lambda_i - 1}}, \tag{29}$$

$$i_{h,t} = \left(\frac{P_{h,t}}{P_{i,t}} \right)^{-\lambda_i} \gamma_i i_t \text{ and } i_{f,t} = \left(\frac{P_{f,t}}{P_{i,t}} \right)^{-\lambda_i} (1-\gamma_i)\, i_t, \tag{30}$$

$$P_{i,t} = \left[\gamma_i P_{h,t}^{1-\lambda_i} + (1-\gamma_i)\, P_{f,t}^{1-\lambda_i} \right]^{\frac{1}{1-\lambda_i}}, \tag{31}$$

where $P_{i,t}$ denotes the price of the aggregate investment good.

2.3 Domestic firms

There is a unit measure of monopolistically competitive domestic firms indexed by j. Their technology is described by the following production function:

$$y_t(j) = \left[u_t(j)\, k_{t-1}(j) \right]^{\alpha} \left[n_t(j) \right]^{1-\alpha} - f, \tag{32}$$

where α is the share of capital, u_t is the capital utilization rate, and f is a fixed cost of production.[10]

Domestic goods produced are heterogeneous across firms, and are aggregated into a homogenous domestic good by perfectly-competitive final goods producers using a standard Dixit-Stiglitz aggregator. The demand curve facing each firm is given by

$$y_t(j) = \left(\frac{P_{h,t}(j)}{P_{h,t}} \right)^{-\Theta_h} y_t, \tag{33}$$

where y_t is aggregate domestic output, and Θ_h is the elasticity of substitution between differentiated goods, implying a steady-state gross mark up of price over marginal cost of $\theta_h = \Theta_h / (\Theta_h - 1)$.

Firm j's profits at period t is given by

$$\begin{aligned} \frac{\Pi_{h,t}(j)}{P_t} &= \frac{P_{h,t}(j)}{P_t} y_t(j) - \frac{W_t}{P_t} n_t(j) - r_{k,t} k_{t-1}(j) \\ &\quad - \frac{\kappa_u}{1+\varpi} \left[u_t(j)^{1+\varpi} - 1 \right] k_{t-1}(j) - \frac{\kappa_{ph}}{2} \left(\frac{P_{h,t}(j) / P_{h,t-1}(j)}{\pi_{h,t-1}^{\varsigma_h} \pi^{1-\varsigma_h}} - 1 \right)^2 \frac{P_{h,t}}{P_t} y_t, \end{aligned} \tag{34}$$

where κ_u and ϖ are the level and elasticity parameters for the utilization cost. Similar to wage-stickiness, price-stickiness is introduced via quadratic adjustment costs with level parameter κ_{ph}, and ς_h captures the extent to which price adjustments are indexed to past inflation.

A domestic firm's objective is to choose the quantity of inputs and output, and the price of its output each period to maximize the present value of profits (using the households' stochastic discount factor) subject to the demand function they are facing with respect to their individual output from the aggregators. The

[10] The fixed cost parameter f is set equal to $\theta_h - 1$ times the steady-state level of detrended output to ensure that pure economic profits are zero at the steady-state; hence, there is no incentive for firm entry and exit in the long-run.

first-order conditions of the firm with respect to labor and capital can be combined to relate the capital-labor ratio to the relative price of inputs as

$$\widehat{w}_t - \widehat{r}_{k,t} = \widehat{u}_t + \widehat{k}_{t-1} - \widehat{n}_t. \tag{35}$$

The first-order conditions for capital and utilization can be combined to yield

$$\widehat{u}_t = \frac{1}{\varpi}\widehat{r}_{k,t}. \tag{36}$$

Finally, the first-order-condition with respect to price yields the New Keynesian Phillips curve in domestic prices as:

$$\widehat{\pi}_{h,t} = \frac{\varsigma_h}{1+\varsigma_h\beta}\widehat{\pi}_{h,t-1} + \frac{\beta}{1+\varsigma_h\beta}E_t\widehat{\pi}_{h,t+1} - \frac{\Theta_h - 1}{(1+\varsigma_h\beta)\,\kappa_{ph}}\left[\widehat{p}_{h,t} + z_t + \alpha\left(\widehat{u}_t + \widehat{k}_{t-1} - \widehat{n}_t\right) - \widehat{w}_t\right], \tag{37}$$

where $p_{h,t} = P_{h,t}/P_t$ is the relative price of home goods.

2.4 Importers

There is a unit measure of monopolistically competitive importers indexed by j. They import foreign goods from abroad, differentiate them and mark-up their price, and then sell these heterogenous goods to perfectly competitive import aggregators, who aggregate these into a homogenous import good using a standard Dixit-Stiglitz aggregator. The demand curve facing each importer is given by

$$y_{f,t}(j) = \left(\frac{P_{f,t}(j)}{P_{f,t}}\right)^{-\Theta_f} y_{f,t}, \tag{38}$$

where $y_{f,t}$ is aggregate imports, and Θ_f is a time-varying elasticity of substitution between the differentiated goods, implying a steady-state gross mark-up of the domestic price of imported goods over its import price of $\theta_f = \Theta_f/(\Theta_f - 1)$.

Importers maximize the present value of profits (using the households' stochastic discount factor) subject to the demand function they are facing from the aggregators with respect to their own output. The importer's profits at period t are given by:

$$\frac{\Pi_{f,t}(j)}{P_t} = \frac{P_{f,t}(j)}{P_t}y_{f,t}(j) - \frac{e_t P^*_{h,t}}{P_t}y_{f,t}(j) - \frac{\kappa_{pf}}{2}\left(\frac{P_{f,t}(j)/P_{f,t-1}(j)}{\pi^{\varsigma_f}_{f,t-1}\pi^{1-\varsigma_f}} - 1\right)^2 \frac{P_{f,t}}{P_t}y_{f,t}, \tag{39}$$

where κ_{pf} and ς_f are the price adjustment cost and indexation parameters, respectively. These import price-stickiness features ensure that exchange rate movements do not immediately pass-through to the domestic price of imported goods.

The first-order condition of importers with respect to price yields the import-price New Keynesian Phillips curve (after log-linearization)

$$\widehat{\pi}_{f,t}=\frac{\varsigma_f}{1+\varsigma_f\beta}\widehat{\pi}_{f,t-1}+\frac{\beta}{1+\varsigma_f\beta}E_t\widehat{\pi}_{f,t+1}-\frac{\Theta_f-1}{(1+\varsigma_f\beta)\,\kappa_{pf}}\left(\widehat{p}_{f,t}-\widehat{rer}_t-\widehat{p}^*_{h,t}\right),\tag{40}$$

where $\pi_{f,t}=P_{f,t}/P_{f,t-1}$ is the import-price inflation factor, and $p_{f,t}=P_{f,t}/P_t$ is the relative price of imported goods.

The balance of payments identity in the model is given by

$$\begin{aligned}&\left(\frac{e_tB_{FS,t}}{P_t}-\frac{e_tR^*_{t-1}B_{FS,t-1}}{P_t}\right)+\left(\frac{e_tq^*_{L,t}B_{FL,t}}{P_t}-\frac{e_tR^*_{L,t}q^*_{L,t}B_{FL,t-1}}{P_t}\right)\\&\quad-\left(\frac{B^*_{FS,t}}{e_tP_t}-\frac{R_{t-1}B^*_{FS,t-1}}{e_tP_t}\right)-\left(\frac{q_{L,t}B^*_{FL,t}}{e_tP_t}-\frac{R_{L,t}q_{L,t}B^*_{FL,t-1}}{e_tP_t}\right)=\frac{P_{h,t}}{P_t}y^*_{f,t}-\frac{e_tP^*_{h,t}}{P_t}y_{f,t}.\end{aligned}\tag{41}$$

2.5 Capital producers

Capital producers are perfectly competitive. After goods production takes place, these firms purchase the undepreciated part of the installed capital from entrepreneurs at a relative price of q_t, and the new capital investment goods from final goods firms at a price of $P_{i,t}$, and produce the capital stock to be carried over to the next period. This production is subject to adjustment costs in the change in investment, and is described by the following law-of-motion for capital:

$$k_t=(1-\delta)\,k_{t-1}+\left[1-\frac{\varphi}{2}\left(\frac{i_t}{i_{t-1}}-1\right)^2\right]i_t,\tag{42}$$

where φ is the adjustment cost parameter.

After capital production, the end-of-period installed capital stock is sold back to entrepreneurs at the installed capital price of q_t. The capital producers' objective is thus to maximize

$$E_0\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\left[q_ti_t-q_t\frac{\varphi}{2}\left(\frac{i_t}{i_{t-1}}-1\right)^2i_t-\frac{P_{i,t}}{P_t}i_t\right],\tag{43}$$

subject to the law-of-motion of capital, where future profits are discounted using the patient households' stochastic discount factor. The first-order-condition of capital producers with respect to investment yields the following investment demand equation (after log-linearization):

$$\widehat{i}_t-\widehat{i}_{t-1}=\beta E_t\left[\widehat{i}_{t+1}-\widehat{i}_t\right]+\frac{1}{\varphi}\left(\widehat{q}_t-\widehat{p}_{i,t}\right),\tag{44}$$

where $p_{i,t}=P_{i,t}/P_t$ is the relative price of investment goods.

2.6 Monetary and fiscal policy

The central bank targets the nominal interest rate using a Taylor rule

$$\log R_t = \rho \log R_{t-1} + (1-\rho)\left(\log R + r_\pi \log \frac{\pi_t}{\pi} + r_y \log \frac{y_t}{y} + r_{\Delta y} \log \frac{y_t}{y_{t-1}}\right) + \varepsilon_{r,t}, \tag{45}$$

where R is the steady-state value of the (gross) nominal policy rate, ρ determines the extent of interest rate smoothing, and the parameters r_π, r_y, and $r_{\Delta y}$ determine the importance of inflation, output gap and output growth in the Taylor rule, respectively. y is the detrended steady-state level of output, and $\varepsilon_{r,t}$ is a monetary policy shock which follows an AR(1) process.

The consolidated government budget constraint is given by

$$p_{h,t} g_t + \frac{R_{t-1}}{\pi_t} b_{S,t-1} + \frac{R_{L,t}}{\pi_t} q_{L,t} b_{L,t-1} = \frac{TAX_t}{P_t} + b_{S,t} + q_{L,t} b_{L,t}, \tag{46}$$

where $b_{S,t}$ and $b_{L,t}$ represent real short and long-term goverment debt, respectively. Lump-sum taxes adjust with the level of government debt to rule out a Ponzi scheme for the government:

$$\frac{TAX_t}{P_t} = \Xi y \left(\frac{y_t}{y}\right)^{\tau_y} \left(\frac{b_{S,t-1} + q_{L,t-1} b_{L,t-1}}{b_S + q_L b_L}\right)^{\tau_b}, \tag{47}$$

where Ξ is a level parameter, τ_y and τ_b determine the response of taxes to output and government debt.

Finally, government controls the supply of long-term bonds in real terms following an AR(1) process:

$$\log(q_{L,t} b_{L,t}) = (1-\rho_b)\log(q_L b_L) + \rho_b \log(q_{L,t} b_{L,t-1}) + \varepsilon_{b,t}, \tag{48}$$

where ρ_b governs the persistence of long-term bonds, and $\varepsilon_{b,t}$ represents the unconventional monetary policy shock (i.e., QE shock) in the model.

2.7 Market clearing conditions

The domestic goods are used in the final goods production for consumption, investment, government expenditure, and exports:[11]

$$c_{h,t} + i_{h,t} + g_t + y^*_{f,t} = y_t. \tag{49}$$

Similarly, the imported goods are used only for consumption and investment; hence:

$$c_{f,t} + i_{f,t} = y_{f,t}. \tag{50}$$

The model's equilibrium is defined as prices and allocations such that households maximize discounted

[11] Note that utilization costs are assumed to accrue to households in lump-sum fashion, and therefore do not enter the feasibility condition.

present value of utility, and all firms maximize discounted present value of profits, subject to their constraints, and all markets clear.

3 Calibration

In our benchmark calibration, we set the structural parameters of both countries to equal values, except for the portfolio and labor level parameters in preferences, as well as the level parameter in the tax policy function.[12] We calibrate the parameters using steady-state relationships in the model and U.S. data from the National Income and Product Accounts (NIPA; Bureau of Economic Analysis) and the Flow of Funds Accounts (FOF; Federal Reserve Board) averaged over the post-war period.[13] We first discuss the choice of parameters governing portfolios and preferences, followed by parameters related to technology and government policy. A list of parameter values is given in Table 1.

Portfolios. We assume that only U.S. bonds are traded internationally; therefore, the share of domestic assets in the U.S. short and long-term portfolios, γ_S^* and γ_L^*, are both set to 1. We calibrate the share of short-term bonds in the U.S. portfolio, γ_a^*, to 0.66 based on U.S. residents' relative holdings of short-term government liabilities (see Figure 2). Here, short-term government liabilities include privately held marketable U.S. treasury securities with a remaining maturity of less than one year and the monetary base (i.e., financial institutions' reserves at the Federal Reserve System, vault cash and currency outside banks) as in Chen et al. (2012).[14] Monetary base is included since it is a perfect substitute for short term T-bills at the zero lower bound.

To obtain the share parameters in the ROW portfolio, we first consider their domestic-to-foreign bond ratio to be 0.75, based on the facts documented in Coeurdacier and Rey (2013). We also assume that ROW agents hold domestic bonds in short-term maturities by the same fraction U.S. residents hold short-term bonds in their portfolio; thus, 66% of ROW domestic bonds are assumed to be held in short-term maturities. We use these figures to calculate the domestic shares in the ROW short and long-term sub-portfolios and the share of short-term bonds in the ROW overall portfolio. Thus, γ_S and γ_L are set to 0.85 and 0.62, respectively. Note that γ_L is smaller than γ_S, reflecting a larger share of ROW holdings of U.S. long-term bonds relative to short-term ones in the data. Finally, the implied share of short-term bonds in the ROW overall portfolio, γ_a, is set to 0.59.

We calibrate the elasticity of substitution between short and long-term bonds based on the portfolio

[12] A non-zero net foreign asset position requires these parameters to be different across regions (see Table 1).

[13] For portfolio parameters, we use data averaged over 2000-2010 as in Figure 2, reflecting more recent government bond supply and international developments in financial markets.

[14] FOF data reports holdings of US treasury securities with the *original* maturity. We adjust these so that short-term holdings include long-term securities with a remaining maturity of less than one year, using Treasury data on the maturity of privately-held Treasury securities. When distributing long-term securities with a remaining maturity of less than one year to ROW and US residents, we use the weights in holdings of Treasury bills (i.e., original maturity of less than one year) from FOF tables.

balance estimates in Gagnon et al. (2011). In particular, our calibrated value $\lambda_a = 2$ implies about a 4 bps reduction in the ten-year yields in the U.S. economy following a $100 billion asset purchase in the U.S., consistent with the average value of their estimates.[15] For the elasticity of substitution between domestic and foreign assets, we combine the short and long-term UIP conditions (see equations (24) and (25)) assuming λ_S and λ_L are equal to each other, and regress the deviations from UIP (i.e., the difference between the nominal depreciation rate and the lagged interest rate differential) on the share of foreign bonds in the ROW portfolio. The data on domestic and foreign debt securities come from the Bank of International Settlements (BIS), the sample period is 1989Q4-2013Q4, and the ROW data captures all countries except the United States. The policy rate in the ROW and the exchange rate are constructed using the weighted average of data from G-20 countries excluding the U.S.. The regression implies that a 1 pp increase in foreign bond holdings in the ROW portfolio generates about a 1 bp drop in UIP deviations.[16] The corresponding value for the portfolio elasticity parameters is $\lambda_S = \lambda_L = 3.4$.

We use the aforementioned values for the portfolio share and elasticity parameters in our baseline calibration, but we also conduct sensitivity analysis on these parameters in section 5. Finally, the coupon rate on long-term bonds, κ, is calibrated to imply a duration of 30 quarters, similar to the average duration of long-term U.S. Treasury securities outstanding in the secondary market.

Preferences. We calibrate the time discount factor, β, to match a target capital-output ratio, k/y, of 10, using the the optimality condition for household's capital decision at the steady-state. Traditionally, the discount factor is calibrated to match the steady-state interest rate using the first-order condition on short-term bonds. We instead use this condition to calibrate the portfolio level coefficient, ξ_a, in preferences using the ratio of government bond holdings to GDP, a/y; thus, we set ξ_a to 0.04 and 0.05 in the U.S. and the ROW economies, respectively. Since the ROW holds a higher level of government assets as a proportion of its output, its portfolio level coefficient is calculated to be slightly larger than in the U.S.. We set the habit parameter, ζ, to 0.70, close to values found in Smets and Wouters (2007) and Adolfson et el. (2008). The inverse of the Frisch-elasticity of labor supply, ϑ, is set to 1. This value is in line with the estimates presented in Blundell and Macurdy (1999), and represents a compromise between the estimates in the Real Business Cycle and New Keynesian literatures (Smets and Wouters, 2007). The labor level parameter, ξ_n, is calibrated to match the working hours of the economically active population as a ratio of total non-sleeping hours of 32%.[17]

Technology. We calibrate the capital share in home-goods production, α, to 0.34 in order to match a labor

[15] This also falls within the range of estimates reported in Bernanke (2012) regarding the fall in long-term yields due to LSAP2.

[16] The small estimate from this regression is consistent with empirical studies finding high elasticity of substitution between home and foreign assets (see for example Lewis, 1995).

[17] A non-zero trade balance requires the consumption-output ratio or the investment-output ratio to be different in the two regions, when the same home-bias parameters are assumed in both regions' aggregator functions. We choose, c/y, to be different across regions, which also implies a different labor level coefficient in preferences.

income share of 66%. Depreciation rate of capital, δ, is calibrated to match an investment-output ratio, i/y, of 19%. Home-bias parameters in the consumption and investment aggregators, γ_c and γ_i, are both set to 0.9. Elasticity of substitution parameters in these aggregators are similar to those used in the New-Keynesian DSGE literature (see Gertler et al., 2007). Similarly, the mark up and indexation parameters in the labor and goods markets (both for domestic producers and importers) are set using corresponding values in the literature.[18]

Adjustment cost parameters on prices and wages, κ_{ph}, κ_{pf}, κ_w, are calibrated so that the resulting New Keynesian Phillips curves have slopes equivalent to assuming Calvo probabilities of 0.9 and 0.85 for wages and prices, respectively. The investment adjustment cost parameter, φ, is calibrated so that investment is 2.5 times more volatile than output with a standard monetary policy shock. The capacity utilization elasticity, ϖ, is set to 0.12, while the utilization cost level parameter, κ_u, is calibrated to imply a unit utilization rate at the steady-state without loss of generality.

Government Policy. Taylor Rule parameters are set to values close to those found in the literature (see Smets and Wouters, 2007, and Adolfson et al., 2008). The interest rate smoothing parameter, ρ, is set to 0.75, and the inflation response coefficient, r_π, is set to 1.75. The literature typically finds small response coefficients for output gap and output growth. Thus, we set these to 0.05 in our benchmark calibration. We set the elasticity parameters in the tax function, τ_y and τ_b, large enough to ensure a sustainable debt path (see Chen et al., 2012), while making sure that debt converges within 10 years. The tax level parameters in the two countries, Ξ and Ξ^*, are set to ensure that each government's budget constraint is satisfied given the bond ratios and interest rates at the steady-state.[19]

4 Results

In this section, we first use our model to evaluate the impact of QE on both the U.S. and the ROW economies. We then compare the spillover effects of conventional monetary policy in the U.S. to the ROW with those from a QE shock originating in the U.S..[20]

4.1 The impact of a QE shock

The QE shock is calibrated to match a $600 billion drop in the privately-held long-term U.S. government bonds, similar to the purchase amount announced for LSAP2 in the last quarter of 2010. Following Chen et al. (2012), we assume no change in the U.S. policy rate for four quarters following the asset purchase

[18] Note that we have conducted sensitivity analysis using different values for these parameters. Their effect on key results is only modest compared to the portfolio parameters.

[19] Note that these tax parameters have to be different across the two regions to match a non-zero trade balance since we have different consumption-output ratios. The resulting government-output ratios are 17% and 18% for the ROW and the U.S., and the tax level parameters are 0.17 and 0.19 for the ROW and the U.S., respectively.

[20] We use a first-order approximation of the model to obtain our results, and use IRIS routines for all simulations.

announcement, after which the central bank keeps its balance sheet size constant for eight quarters, and then gradually sells these bonds over the next eight quarters. The assumption of no change in the short-term rate in the first four quarters following the LSAP announcement is consistent with interest rate expectations in the Blue Chip survey conducted in 2011 (Chen et al., 2012). Note that the whole path of the aformentioned QE policy is known by all agents at the impact period.[21]

Figure 4 shows the impulse responses of U.S. variables after a QE shock in the U.S.. Due to imperfect substitution between short and long-term bonds, the term premium on long-term rates in the U.S. falls by 30 bps, driving long-term yields down by about 22 bps.[22] Long-term yields fall less than the term premium, since expected future short-term rates (after four quarters) increase as a result of the QE shock, dampening the portfolio balance effect. If agents expect the policy rate to stay constant for more than four quarters, long-term yields would fall even more at impact.

As a result of QE, short-term bond holdings of U.S. residents increase. Higher short-term bond holdings and lower long-term rates stimulate aggregate demand through the short and long-term IS curves, respectively. Higher aggregate demand leads to an increase in inflation. GDP increases by 0.6% due to the increase in consumption, investment and net exports, and inflation increases by 0.4%. The trade balance improves mainly due to the increase in exports as a result of the 1.6% depreciation in the U.S. dollar, while the immediate impact on imports is smaller as the income and price effects move in opposite directions.

The impulse responses of ROW variables to the QE shock in the U.S. are shown in Figure 5. The international effects of the QE spill over to the other country partly through the short and long-term UIP conditions. QE generates a cross-country differential in long-term rates at impact, which puts downward pressure on ROW long-term rates (which decreases by slightly more than 4 bps at impact), and appreciation pressures on its currency (which increases by about 1.6%) through the long-term UIP condition. Note that the resulting appreciation has to satisfy the short-term UIP condition as well. Although short-term rates do not change in the U.S., bond quantities matter for the exchange rate and the ROW short-term rate. The relative increase in ROW holdings of short-term U.S. bonds pushes the value of the ROW currency upwards, consistent with the direction implied by the long-term UIP condition. As a result, the ROW currency appreciates, which leads to lower inflation in the ROW, which in turn leads to a decline in current and expected short-term (policy) rates in the ROW economy. This effect is quantitatively small however

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[21]In reality, policy rates in the U.S. stayed at the zero lower bond for much longer than four quarters following the LSAP2 announcement, although this was not expected by most market participants at the time. In our simulations, the policy rate starts to rise after four quarters following QE due to the QE shock's stimulative effects on inflation and output. The effects of QE would be larger, if the policy rate is assumed to stay at the zero lower bound for longer. Given initial expectations on the policy rate path with 4 quarters at the zero lower bound, one can think of the additional duration at the zero lower bound as negative conventional monetary policy shocks, which get realized in periods following the announcement of QE. We do not measure the effects of these additional surprises in our estimations, and keep the QE experiment as close to Chen et al. (2012) as possible.

[22]The impact on long-term yields are consistent with findings for LSAP2 from event studies in the literature, which range from -15 bps to -45 bps. See Gagnon et al. (2011), Hamilton and Wu (2012), Krishnamurthy and Vissing-Jorgensen (2011), Meaning and Zhu (2011), D'Amico et al. (2012), and Wright (2012), among others.

(compare the magnitudes for the long-term rate and the term premium in the ROW in Figure 5).

The main effect on ROW long-term rates comes through the term premium component. In particular, QE lowers the yields on long-term U.S. bonds, which prompts ROW residents to increase their relative demand for long-term ROW bonds, which in turn leads to a fall in the ROW term premium by about 4 bps. ROW long-term rates fall by slightly more than 4 bps due to the fall in current and expected future short-term rates. Note that, since the impact on the ROW long-rate through the expectations hypothesis is very small, the results on long-term yields would not change much if we had assumed the same zero lower bound environment in the ROW as in the U.S. (i.e., for four quarters). Thus, ROW countries which are at the zero lower bound would also not be immune from the international spillover effects of QE performed in other large economies.

The decline in short and long-term rates in the ROW generates an increase in aggregate consumption and investment through the short and long-term IS equations. Increased demand for consumption and investment goods, along with appreciation of the ROW currency, leads to a larger rise in imports than exports in the ROW. This lowers their net exports, putting negative pressure on the ROW GDP. However, stimulus coming from the domestic channel in the ROW dominates the fall in net exports, and generates an overall increase in output. These quantitative results highlight that QE spillovers from the U.S. to the ROW is mainly through financial channels, and not through the trade channel (i.e., not through higher demand for ROW goods in the U.S.).[23] The strength of the financial channel depends critically on the elasticity of substitution parameters in the portfolio preference specification, as we show in the next section on sensitivity analysis.

Following QE, ROW starts to hold more short-term U.S. bonds and less long-term U.S. bonds, similar to U.S. residents. The result of increased US short-term bond holdings in the ROW merits some discussion. Note that even though the ROW has a flexible exchange rate regime (i.e., does not conduct any foreign exchange intervention to offset the currency appreciation pressures during the U.S. QE), the imperfect substitution between assets leads the ROW agents to increase short-term U.S. bond holdings. If the ROW had fixed or managed exchange rate regimes, their short-term U.S. bond holdings would need to increase even more following QE. Their long-term rates would thus fall more as well, as a result of a larger decrease in current and expected short-term rates.[24]

4.2 QE shock versus interest rate shock

In this subsection, we compare the spillover effects of a QE shock and a conventional interest rate shock in the U.S.. Both policies result in qualitatively similar spillover effects on the ROW economy (see Figure 6). For our quantitative comparison, we scale the interest rate shock (about 150 bps cut in the policy rate) to

[23] Dahlhaus et al. (2014) empirically show that the financial channel was the predominant factor in the transmission of U.S. QE spillovers to the Canadian economy.

[24] IMF data indicate that central banks of emerging market economies (EMEs) tended to increase their U.S. dollar-denominated reserves during QE episodes, partly to offset the appreciation pressures on their currencies. The quantitative effects of these foreign exchange interventions, and the foreign reserve accumulation that accompanied this type of policy, is beyond the scope of this paper and is left for future research.

have the same peak output response in the U.S. with the QE shock described previously (i.e., around 0.6% of steady-state GDP).[25]

In our baseline model, the QE shock leads to a much larger (more than twice) spillover effect on ROW economic activity relative to the interest rate shock. The difference comes mainly from the fact that portfolio balance effects on the ROW long-term yields are stronger in the case of QE, compared to conventional monetary policy. In particular, QE in the U.S. generates a drop in the ROW term premium as a result of portfolio balancing, whereas this effect is not present in the case of conventional monetary policy. Long-rates in the ROW also fall with the interest rate shock in the U.S., but far less relative to the QE shock. Also note that this decline in the ROW long-term yields is mainly due to the expectations hypothesis (i.e., based on the expected path of the policy rate), and not due to any significant change in the term premium.[26] The decline in short and long-term interest rates in the ROW stimulates economic activity, more so in the case of QE compared to an interest rate cut in the U.S..

Figure 6 also shows that U.S. conventional monetary policy leads to a smaller drop in U.S. long-term yields compared to QE. This is because bond quantity implications of the interest rate shock are not as severe as in the QE policy. Similar to the ROW, the long-term yields in the U.S. fall mainly due to the expected path of the short-term rate, and not due to any significant change in the term premium. In fact, the term premium increases very slightly due to the decline in short-term bond holdings of U.S. agents. This occurs because the government needs to supply less short-term bonds given the decline in its overall interest burden (note that long-term bonds are kept in fixed supply in the absence of QE).[27]

In the next section, we show that a lower share of long-term U.S. bonds in the ROW portfolio would reduce the international spillover effects of QE on the ROW term premium and aggregate demand, while not altering its domestic effects in the U.S. significantly.

5 Sensitivity Analysis

5.1 The share of long-term bonds in the foreign-asset portfolio

Figure 7 shows the domestic and the international spillover effects of QE with different values for the share of U.S. long-term bonds in the ROW portfolio. If the ROW holds only long-term bonds in their foreign portfolios, the effects of QE on both the U.S. and ROW output levels increase relative to the baseline case.

[25] We thus implicitly assume that policymakers in the U.S. face a given output gap, and have both conventional and unconventional monetary policy tools at their disposal in order to close this gap.

[26] In fact, the term premium increases very slightly due to the decline in the short-term domestic bond holdings of ROW agents. This occurs as the government supplies less short-term bonds given the decline in its overall interest burden, while keeping long-term bonds in fixed supply in the absence of QE.

[27] The result on the U.S. term premium would be similar even if we introduce money into our model and implement conventional policy changes using open market operations, as long as short-term bonds and money are treated as perfect substitutes by agents (which would be the case at the zero lower bound). In particular, open market purchases would change the relative amounts of currency and short-term bonds held by agents, but would not alter the relative composition of long-term assets to short-term assets (which in this case would include currency as well).

In particular, the same QE shock in percentage terms now results in a higher relative supply change in U.S. long-term bonds outstanding, therefore lowering the U.S. term premium and long-term rates further. More importantly, there is less overall substitution towards short-term U.S. bonds following QE, when ROW agents do not hold any US short-term bonds. Since ROW agents do not absorb any of the increase in short-term U.S. bonds, a change in the relative supply of short-term bonds now has a larger impact on the U.S. term premium; in particular, the fall in the U.S. long-term yields is now twice more than it is in the baseline scenario.

In terms of international spillovers, when ROW holds only long-term U.S. bonds in their foreign-asset portfolios, the ROW currency appreciates by 4.5%, ROW GDP increases by 0.35% and ROW long-term rates fall by 6.5 bps, compared to 1.6%, 0.2% and 4 bps, respectively, under the baseline case. Note that, unlike the baseline case, the fall in long-term yields is now driven by lower current and future expected short-term rates in the ROW. The long-term interest rate differential is now larger, and therefore, leads to a bigger appreciation of the ROW currency, which in turn generates lower inflation and policy rates in the ROW. Thus, the larger share of U.S. long-term bonds in the ROW portfolio amplifies the effects from the long-term UIP condition. On the other hand, the ROW term premium increases in this scenario rather than fall. This is because, unlike in the baseline scenario, U.S. QE does not increase ROW residents' relative holdings of their domestic long-term bonds. QE in the U.S. makes ROW agents switch their demand towards bonds other than U.S. long-term bonds. However, ROW government bond supply does not increase (since there is no QE in the ROW), and ROW does not hold any short-term U.S. bonds in this case, meaning that ROW holdings of U.S. long-term bonds does not change significantly in equilibrium. The share of long-term assets in the overall portfolio slightly increases in this scenario since lower interest payments decreases the issuance of ROW short-term government bonds through the government budget constraint. As a result, relative holdings of domestic long-term bonds decreases, increasing the ROW term premium slightly. This, however, does not offset the effect of lower policy rates on long-term yields.

Conversely, when ROW does not hold any long-term U.S. government bonds, QE does not significantly transmit cross-border, but still affects U.S. economic activity, albeit slightly less than it does under the baseline case. Although very small, international spillovers are not zero in this case, since the rise in U.S. GDP increases imports from ROW, generating inflationary pressures without a large appreciation. In this case, QE spillovers mainly work through the trade channel rather than the financial channel.[28] The fact that the trade channel by itself cannot significantly increase ROW GDP confirms the notion that the financial channel is crucial to generate large international spillovers from QE.

[28]Note that the ROW trade balance now improves, compared to the deterioration in the baseline case. Also, ROW consumption and investment do not change on impact.

5.2 Elasticity of substitution parameters in the portfolio specification

We now analyze the sensitivity of results to elasticity parameters in our portfolio specification. We start with the elasticity of substitution between short and long-term assets, λ_a. Figure 8 shows the impulse responses from a QE shock in the U.S. for different values of λ_a; namely when $\lambda_a = 0.5$, 2, and 50.[29] The figure suggests that spillovers increase when short and long-term bonds are less substitutable with each other. A lower degree of substitution amplifies the effects of a change in the relative supply of bonds, resulting in a greater fall in long-term rates, which in turn stimulates the U.S. economy further. ROW economic activity increases more as well through the financial channel, with the ROW term premium and long-term yields declining more than it does in the baseline case. Conversely, a value as large as 50 for this elasticity parameter leads to insignificantly small spillovers, since short and long-term bonds are almost perfectly substitutable.

International spillovers increase with a higher elasticity of substitution between domestic and foreign assets in the ROW's long-term sub-portfolio, λ_L (see Figure 9). If ROW residents more easily substitute U.S. bonds with ROW bonds, their relative demand for long-term ROW bonds increases more after a negative shock to the supply of U.S. bonds, thereby lowering long-term yields further, and stimulating aggregate demand more, in the ROW. Higher substitution between these bonds also increase the appreciation rate of the ROW currency. On the contrary, when domestic and foreign bonds are less substitutable, ROW agents do not increase their relative demand for domestic long-term bonds as much as they do in the baseline scenario. This results in a smaller decline (or even an increase) in the ROW term premium relative to the baseline scenario.

In the case of a sufficiently low substitution between domestic and foreign long-term bonds (green dotted line), ROW term premium increases, rather than falls, after a QE shock in the United States. This is as a result of two offsetting effects on the relative demand for ROW long-term bonds (see equation (16) and Figure 3). Following a QE shock in the U.S., on the one hand, ROW households increase their relative demand for long-term domestic bonds as the yields on long-term U.S. bonds decline (a downward shift in the right panel of Figure 3). On the other hand, lower substitutability, or equivalently higher complementarity, between domestic and foreign bonds in the long-term sub-portfolio pushes ROW to decrease its relative demand for long-term domestic bonds, while U.S. long-term bond holdings fall to keep the ratio of ROW-to-U.S. assets in the ROW long-term sub-portfolio closer to its steady-state value (an upward shift in the right panel of Figure 3). Under sufficiently high complementarity between domestic and foreign assets, the latter effect dominates the former, and leads to a net decrease in the relative demand for long-term domestic bonds, and therefore, to an increase in the ROW term premium. Increases in the term premium and long-term yields dampen the stimulative effect on aggregate demand. However, note that the ROW output still increases in this scenario despite the increase in domestic long-term rates. Lower U.S. long-term bond holdings leads to an increase in the share of domestic bonds in the ROW's long-term sub-portfolio. This lowers the marginal benefit of

[29] Note that we change this parameter for both regions in this exercise.

holding an additional long-term domestic bond, especially under low degrees of substitution between domestic and foreign long-term bonds. The domestic effects of QE in the U.S. increases in this case, albeit only slightly, when ROW substitutes U.S. long-term bonds less with their domestic bonds. This is because a low elasticity of substitution between ROW and U.S. long-term bonds also lowers the overall substitutability of short and long-term U.S. bonds in the world, making a supply shock in the U.S. long-term bond market more effective in altering the U.S. term premium.

Spillover results are somewhat similar when we change the elasticity of substitution between home and foreign bonds in the ROW's short-term sub-portfolio, λ_S (see Figure 10). A higher elasticity of substitution between ROW and U.S. bonds in the short-term sub-portfolio increases spillovers on the ROW GDP. However, now, GDP in the ROW is more sensitive to changes in this elasticity parameter than the one in the long-term sub-portfolio. This is mainly because the ROW currency appreciates less when ROW and U.S. short-term bonds are more substitutable, unlike the case with substitution between the long-term bonds. Because short-term interest rates cannot change in the U.S., ROW currency does not appreciate significantly when short-term ROW and U.S. bonds are almost perfectly substitutes (i.e., $\lambda_S = 50$). As a result, the ROW trade balance improves, and contributes more to the increase in real GDP, relative to an increase in the elasticity parameter in the long-term sub-portfolio. Furthermore, lower appreciation lifts the disinflationary pressures of appreciation present in the baseline case, and leads to lower short-term real rates, stimulating domestic demand as well.

6 Conclusion

In this paper, we study the international spillovers of QE policies in a two-country, open-economy model with portfolio balance effects. Portfolio balance effects arise from imperfect substitution between short and long-term bonds in portfolio preferences that we introduce into an otherwise stylized two-country DSGE model with nominal and real rigidities. This imperfect substitution leads to lower long-term yields in the U.S. economy as a response to QE, generating appreciation pressures on the ROW currency as well as lower bond yields. Lower yields, in turn, stimulate the economy in the ROW. We show that appreciation occurs even when the short-term rates are constant in the U.S. economy because the decision between holding a short-term domestic and foreign bond depends not only on the short-term rate differential, but also on the quantity of short-term bonds. The latter falls with QE, making domestic short-term bonds less attractive.

When calibrated to the U.S. and ROW economies, our model suggests that international spillover effects of QE in the U.S. on ROW economic activity and asset prices are larger than those from conventional policy. This is because portfolio balance effects on the ROW's term premium appear more strongly in the case of unconventional monetary policy, causing a larger drop in ROW long-term yields, relative to a U.S. interest-rate cut. Furthermore, the fact that ROW's foreign portfolio is heavily weighted towards long-term U.S.

bonds amplifies the spillover effects of unconventional monetary policy relative to a conventional one. Our results indicate that the spillover effects of QE would increase if ROW agents hold more U.S. long-term bonds in their portfolios at the steady state, if they substitute short-term bonds for long-term ones in lower degrees, or if they substitute long-term home bonds for long-term foreign bonds in higher degrees.

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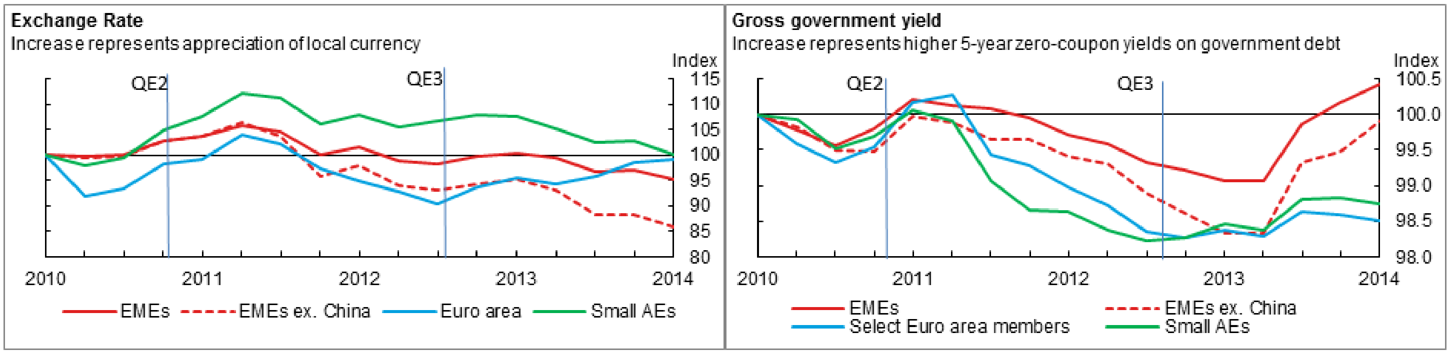
Table 1: Parameter Values

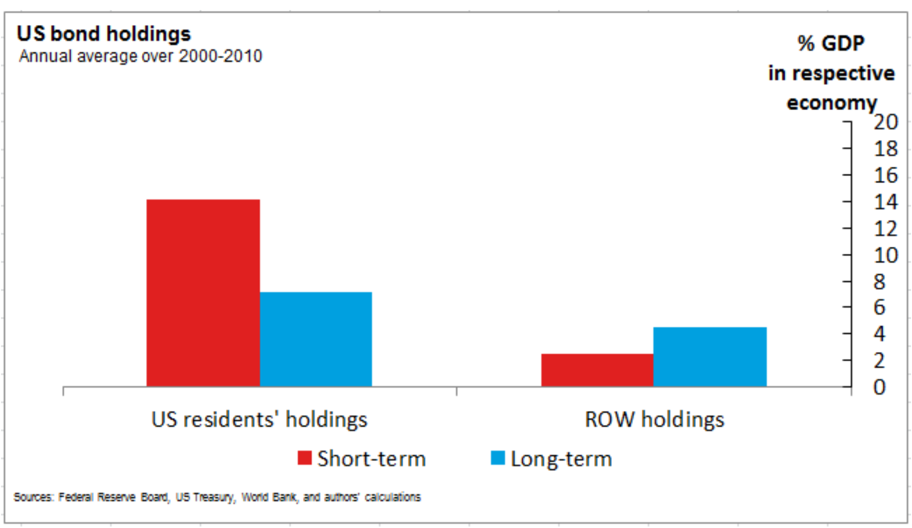
Parameter	Value	Source	Parameter	Value	Source
Portfolio			*Preferences*		
Home share (short), γ_S, γ_S^*	0.85, 1	calibrated	Discount factor, β	0.98	calibrated
Home share (long), γ_L, γ_L^*	0.62, 1	calibrated	Cons. Habit, ζ	0.7	literature
Short share, γ_a, γ_a^*	0.59, 0.66	calibrated	Labor Elasticity, ϑ	1	literature
Elasticity, λ_a	2	calibrated	Portfolio Coeff., ξ_a, ξ_a^*	0.05, 0.04	literature
Elasticity, λ_S, λ_L	3.4	calibrated	Labor Coefficient, ξ_n, ξ_n^*	22.46, 23.10	calibrated
Coupon, κ	0.98	calibrated			
Technology			*Taylor Rule and Gov't*		
Home biasness, γ_c, γ_i	0.90	calibrated	R persistence, ρ	0.80	literature
Elas. H and F cons., λ_c	1	literature	Inflation sensitivity, r_π	1.75	literature
Elas. H and F inv., λ_i	0.25	literature	Output gap sensitivity, r_y	0.05	literature
Mark-up, θ_w, θ_h, θ_f	1.5	literature	Output growth sensitivity, $r_{\Delta y}$	0.05	literature
Indexation, ς_w, ς_h, ς_f	0.50	literature	Tax coefficient, Ξ, Ξ^*	0.17, 0.19	calibrated
Price adj. cost, κ_{ph}, κ_{pf}	35	calibrated	Elasticities in tax policy, τ_y,τ_b	0.5	set
Wage adj. cost, κ_w	80	calibrated	QE shock persistency, ρ_b	0.95	set
Capital exponent, α	0.34	calibrated			
Depreciation rate, δ	0.02	calibrated			
Inv. adj. cost, φ	2	calibrated			
Utilization elasticity, ϖ	0.12	literature			
Utilization adj. cost, κ_u	0.03	calibrated			

Figure 1: Nominal Exchange Rates and Government Bond Yields over 2010-2014



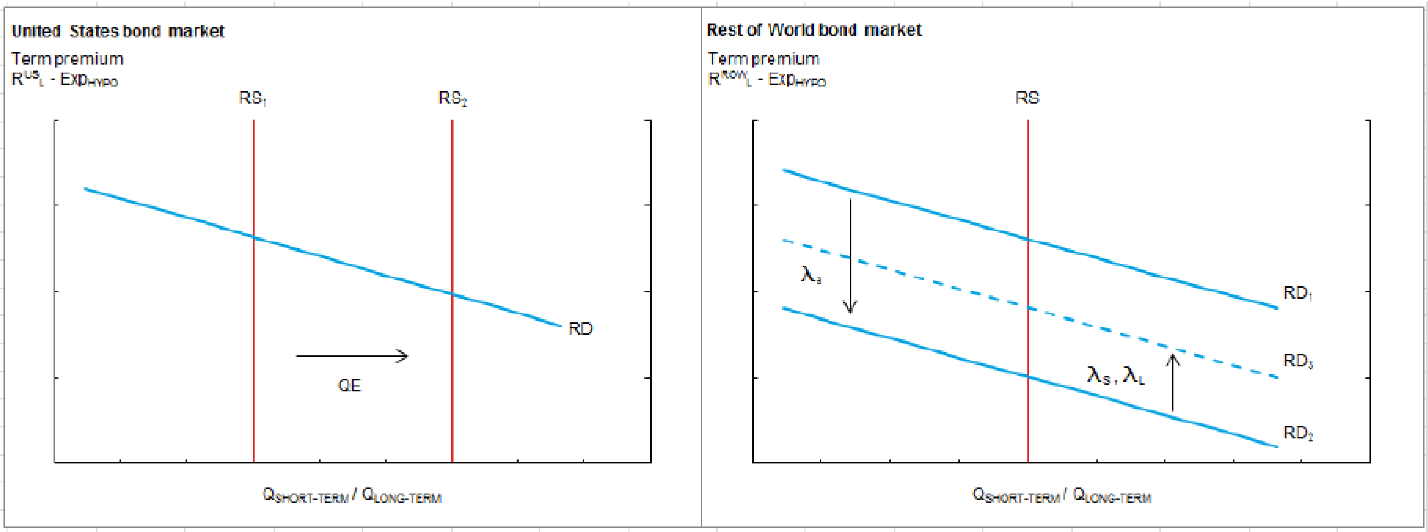
Note: EMEs include Brazil, Chile, China, Colombia, Hungary, India, Indonesia, Israel, Korea, Malaysia, Mexico, Peru, Philippines, Poland, Russia, South Africa, Taiwan, Thailand, Turkey. Small advanced economies include Australia, Canada, Denmark, Norway, Sweden, Switzerland. Select Euro members are Austria, Finland, France, Germany, Netherlands.

Figure 2: U.S. Residents' and ROW Holdings of U.S. Short-term and Long-term Government Bonds



Note: Short term bonds include U.S. treasury securities with a maturity of less than one year, financial institutions' reserves at the Federal Reserve System, vault cash and currency outside banks. Long-term bonds consist of US Treasury bills with a maturity of more than one year

Figure 3: Term Premium in the United States and the Rest of the World



Note: The vertical and horizontal axes represent the term premium and the quantity of short-term bonds relative to long-term bonds in the bond markets of each region. "RD" and "RS" denote relative demand and relative supply, respectively. λ's denote the elasticity of substitution parameters in the portfolio specification as defined in the text.

Figure 4: U.S. Responses to a QE shock in the U.S.

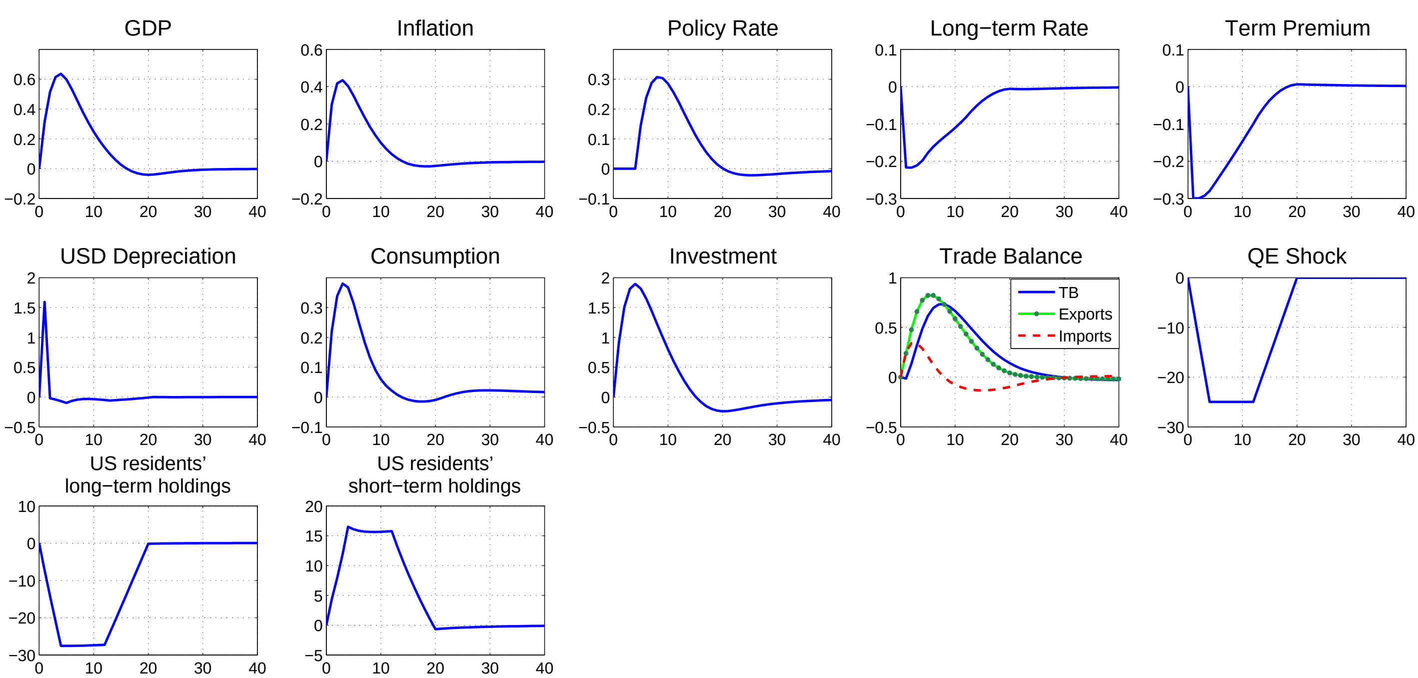


Figure 5: ROW Responses to a QE Shock in the U.S.

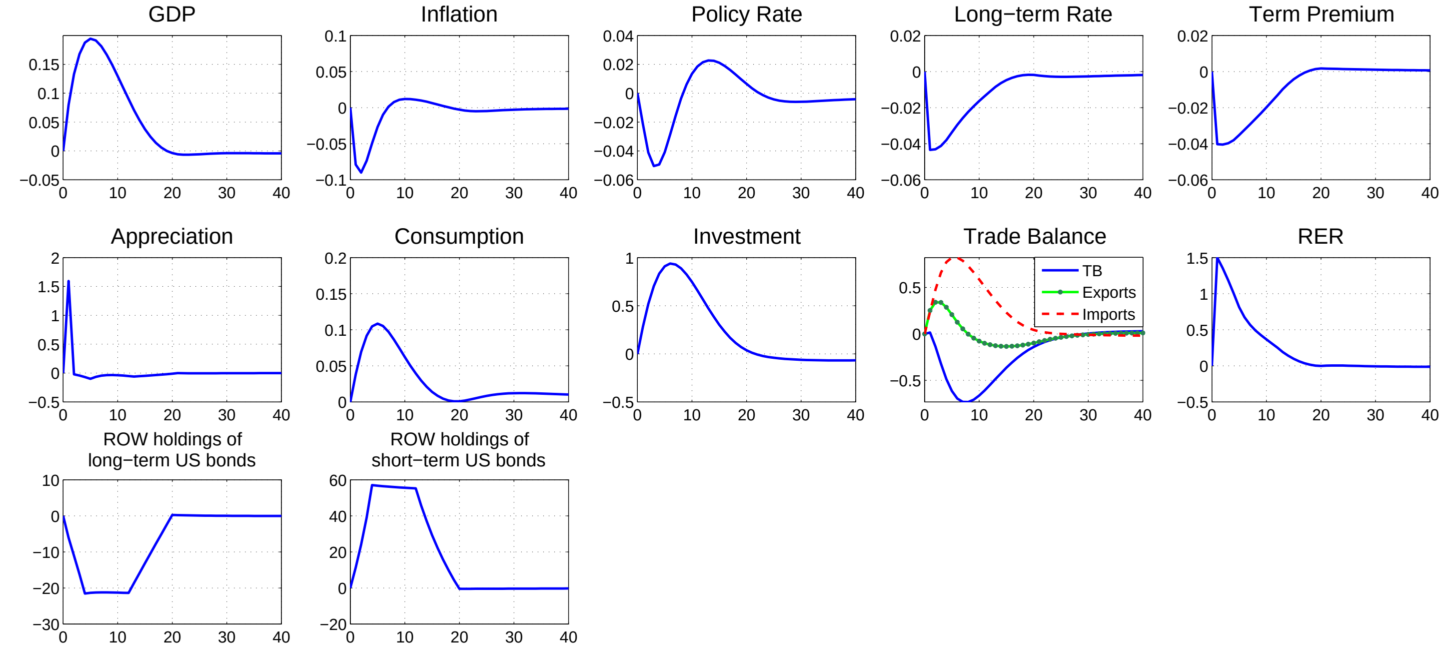


Figure 6: Effects of Conventional versus Unconventional Monetary Policy

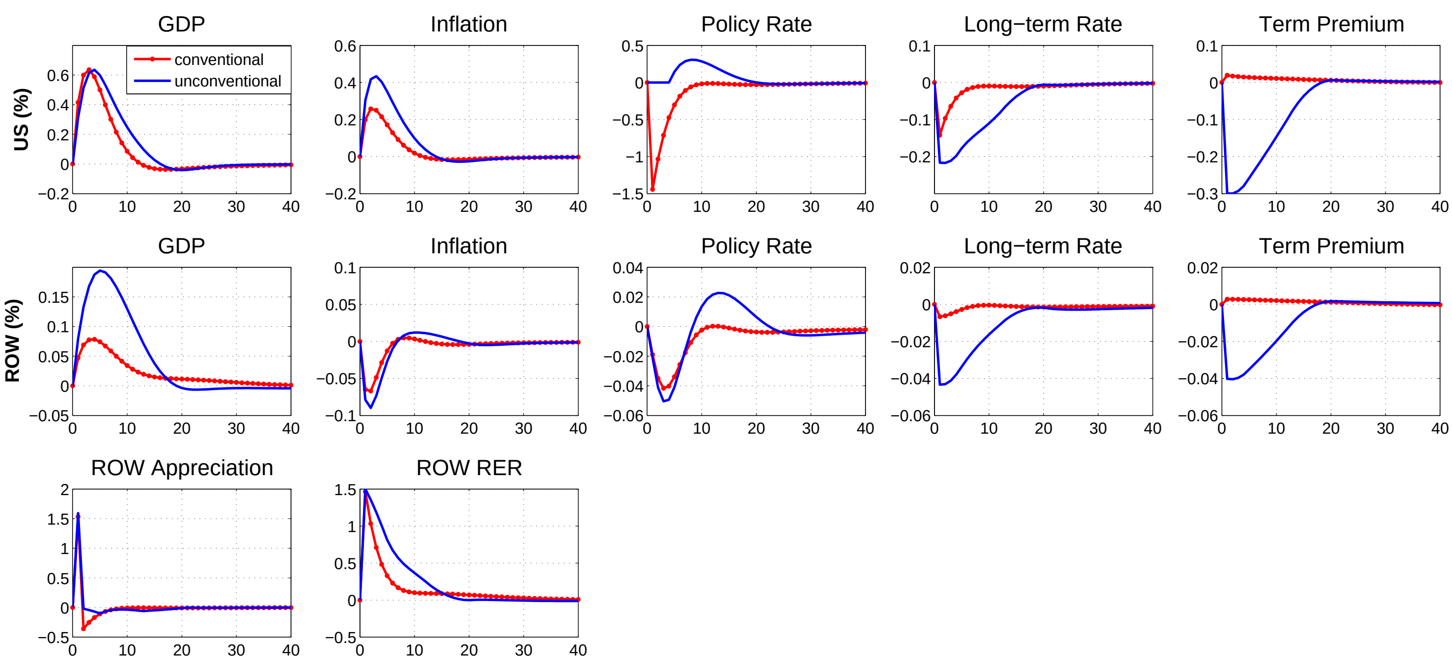


Figure 7: Sensitivity Analysis with Different Maturity Compositions of US Bonds in the ROW Portfolio

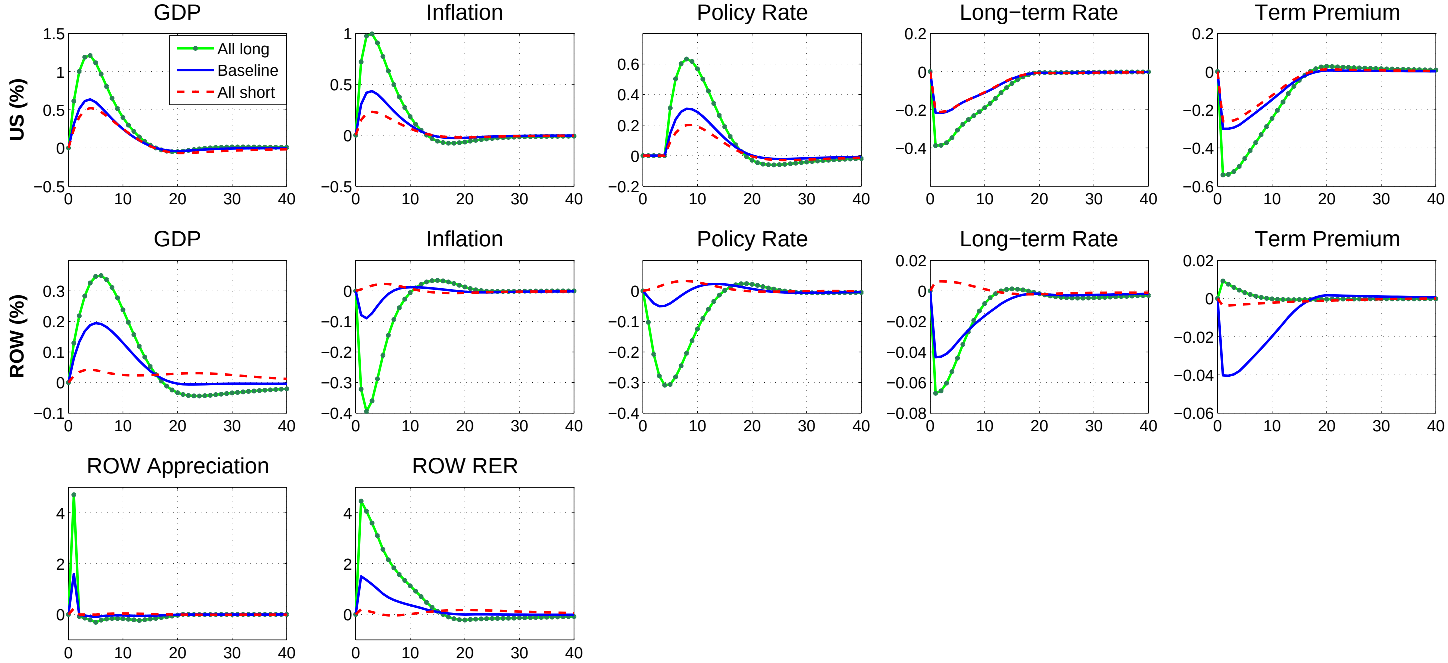


Figure 8: Sensitivity Analysis with Different Elasticity of Substitution between Short-term and Long-term Portfolios

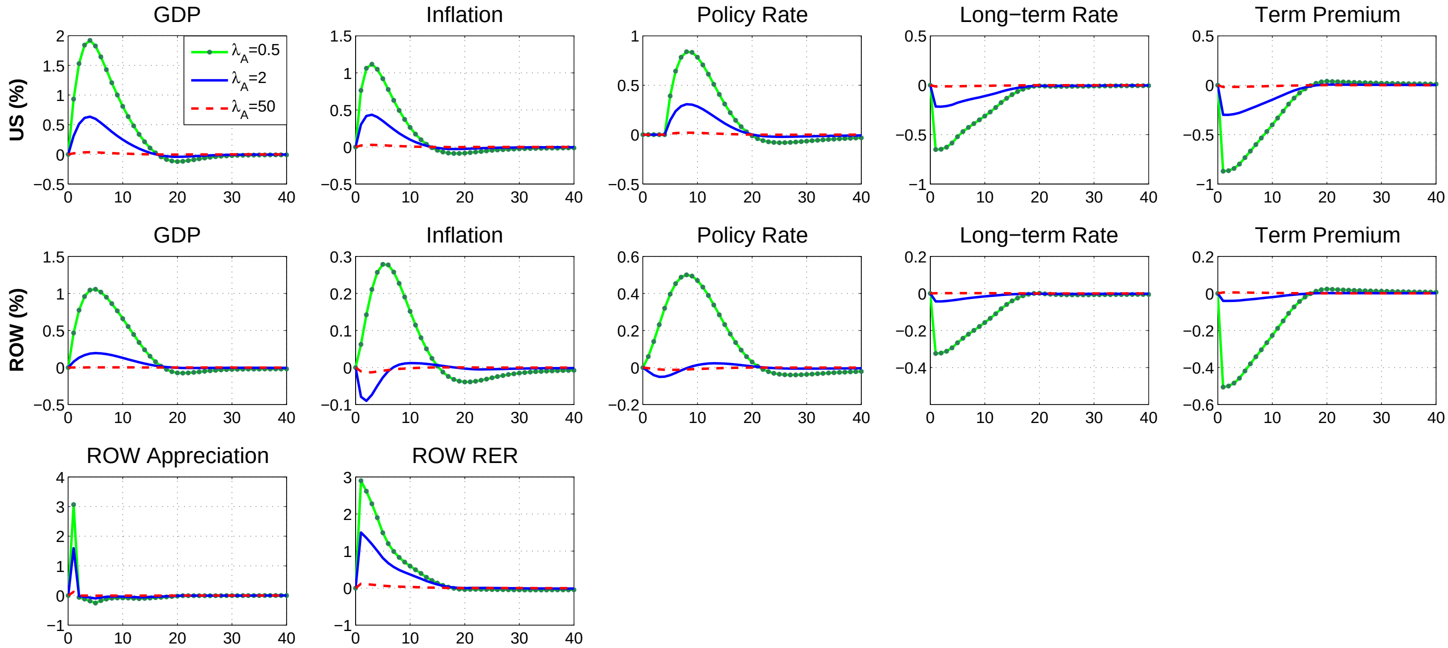


Figure 9: Sensitivity Analysis with Different Elasticity of Substitution between Home and Foreign Bonds in ROW's Long-term Portfolio

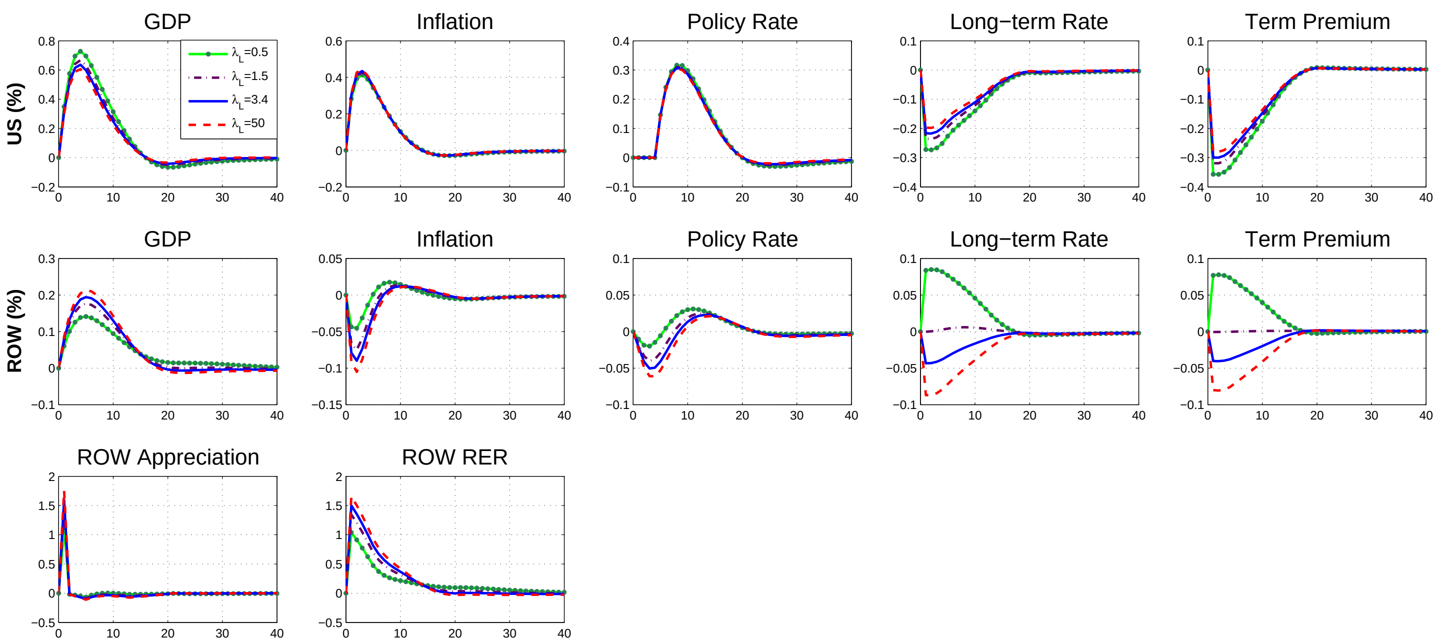


Figure 10: Sensitivity Analysis with Different Elasticity of Substitution between Home and Foreign Bonds in ROW's Short-term Portfolio