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On the credit and exchange rate channels of central bank asset purchases in a monetary union

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Abstract

Through the euro area crisis, financial fragmentation across jurisdictions became a prime concern for the single monetary policy. The ECB broadened the scope of its instruments and enacted a series of non-standard measures to engineer an appropriate degree of policy accommodation. The transmission of these measures through the currency union remained highly dependent on the financial structure and conditions prevailing in various regions. This paper explores the country-specific macroeconomic transmission of selected non-standard measures from the ECB using a global DSGE model with a rich financial sector: we extend the six-region multi-country model of Darracq Pariès et al. (2016), introducing credit and exchange rate channels for central bank asset purchases. The portfolio rebalancing frictions are calibrated to match the sovereign yield and exchange rate responses after ECB's Asset Purchase Programme (APP) first announcement. The domestic transmission of the APP through the credit intermediation chain is significant and quite heterogenous across the largest euro area countries. The introduction of global portfolio frictions on euro area government bond holdings by international investors opens up for a larger depreciation of the euro. The interaction between international and domestic channels affect the magnitude and the cross-country distribution of the APP impact.

Keywords: DSGE models, banking, financial regulation, cross-country spillovers, bank lending rates, non-standard measures.

JEL classification: E4, E5, F4.

Non-technical summary

Since mid-2014, the ECB has notably embarked in an expanded asset purchase programme (APP) in order to reinforce its accommodative monetary policy stance. The transmission channels of such measures within the euro area might conceal a large degree of cross-country asymmetries, owing notably to financial heterogeneity across jurisdictions.

The main objective of this paper is to provide a more structural perspective in the effectiveness of such non-standard monetary policy measures and discuss their transmission channels across the euro area. In this respect, we build a large-scale Dynamic Stochastic General Equilibrium (DSGE) framework which accounts for both domestic and international propagation mechanisms and spans the relevant financial heterogeneity across the large euro area member states. While the literature has identified several channels through which non-standard monetary policies are expected to stimulate spending and raise inflation, we mainly focus here on portfolio rebalancing frictions. Some degree of imperfect substitutability between assets implies that changes in the amount of bond supply to private agents will affect asset prices and lead to a change in the desired asset holdings of domestic banks as well as international investors. Such frictions give rise to a credit channel of central bank asset purchases and can directly affect exchange rate determination. The model covers six regions, Germany, France, Italy, Spain, rest of euro area and rest of the world. The largest four euro area countries are well-suited to evaluate the quantitative relevance of financial factors underlying the effectiveness of non-standard monetary policies. In this respect, the model is calibrated to match country-specific financial heterogeneity, thereby providing more realistic transmission mechanism across countries.

Inspecting the transmission mechanism of central bank asset purchases, model simulations shed some light on the relative role of credit versus trade channels at the country level, as well as on the size of cross-country spillovers within the currency union. The interaction between international and domestic channels affects the magnitude and the cross-country distribution of the APP impact. The intra-euro area spillovers might account for more than 20% of output effects on individual countries.

1 Introduction

In the aftermath of the outbreak of the global financial crisis in 2007-2008 and the euro area sovereign debt crisis, many countries have experienced a prolonged period of low inflation with high levels of private and government debt, while short-term policy rates have been close to their effective lower bound (henceforth, ELB). To help reignite economic activity central banks have embarked on various forms of non-standard (unconventional) monetary policies with the main key tools being central bank asset purchase programmes (or quantitative easing), such as the Large-Scale Asset Purchase programmes of the US Federal Reserve (QE), the asset purchase facilities of the Bank of England and more recently the ECB's expanded asset purchase programme (henceforth, APP). Although the starting point for all programs share the same commonalities and objectives, there is a long debate about their macroeconomic effectiveness and the strength of the country-specific transmission mechanism.

Since 2015 in particular, the ECB has embarked in an expanded asset purchase programme, mainly including a public sector purchase programme (PSPP), together with more limited purchases of private securities (i.e. third covered bond purchase programme, CBPP3, the asset-backed securities purchase programme, ABSPP, and the corporate sector purchase programme, CSPP). More general, the APP is part of a package of non-standard measures that also includes targeted longer-term refinancing operations (TLTRO) which aim in providing long-term funding at attractive conditions to banks in order to further ease private sector credit conditions and stimulate bank lending to the real economy. Those measures delivered further monetary policy accommodation, by easing financing conditions and incentivising credit origination to the real economy.

From 2014 to 2017, Figures 2 to 5 show that sovereign bond and credit markets adjustments in the euro area display *i)* a sensible compression of long-term sovereign bond yields, on the back of moderating banks' exposure on domestic government bonds, as well as *ii)* a large decline in bank lending rates to companies, accompanying a turning point in loan dynamics. Those stylised facts conceal a significant degree of cross-country heterogeneity, notably between vulnerable and less-vulnerable countries, with subsequent implications on the effectiveness of the APP. As observed in Figures 2 and 3, the compression in sovereign yields since mid-2014 is stronger for Italy and Spain than for France and Germany while prior to the start of the APP, vulnerable countries (like Italy and Spain) tended to hold a high percentage of domestic government bonds to main assets. From Figures 4 and 5, we see that the broad-based decline in lending rates was relatively more pronounced in Italy and Spain but the growth in loans to non-financial corporations turned out to be stronger in France and Germany. Such an unconditional glance at the data falls short of providing a sound identification strategy for the impact of non-standard measures on sovereign and credit markets. Selected empirical studies nonetheless lent some credence to the strong credit easing impact of asset purchases in the euro area (see for example Altavilla et al. (2016)) while others put the emphasis on exchange rate adjustments and trade channels.

The main objective of this paper is to provide a more structural perspective of the effectiveness of such non-standard monetary policy measures and discuss their transmission channels across the euro area. In this respect, we build a large-scale Dynamic Stochastic General Equilibrium (DSGE) framework which accounts for both domestic and international propagation mechanisms and spans the relevant financial heterogeneity across the large euro area member states. While the literature has identified several channels through which non-standard monetary policies are expected to stimulate spending and raise inflation, we mainly focus on portfolio rebalancing frictions: on the one hand, such frictions give rise to a credit channel of central bank asset purchases and on the other hand, they can directly affect exchange rate determination. Some degree of imperfect substitutability between assets implies that changes in the amount of bond supply to private agents will affect asset prices and lead to a change in the desired asset holdings of domestic banks as well as international investors. Another relevant dimension of our model is related to international linkages, both through trade and financial transactions. Even if the implementation of ECB asset purchase programme has been done relatively symmetric across countries, i.e. with purchases per sovereign issuer conducted according to the respective capital key of the ECB,[1] the heterogeneity in macroeconomic propagation might come from asymmetric domestic transmission mechanism as well as through different trade and financial spillovers.

Against this background, the ***first contribution*** of this paper is to design a multi-country DSGE model for the euro area which can provide a framework for analysing the macroeconomic transmission of non-standard measures, focusing mostly on the bank credit and the exchange rate channels. We start from the model of Darracq Pariès et al. (2016) which features a set of financial frictions in a six-region global DSGE multi-country model and we include long-term government bonds together with portfolio rebalancing frictions in the bankers' decision problem as in Gertler and Karadi (2011a). The granular set of financial frictions also covers oligopolistic retail lending banking segment and risky debt contracts to firms. Such financial features are calibrated to match country-specific heterogeneity and bring along more realistic transmission mechanism across countries. In this respect, the model covers six regions, Germany, France, Italy, Spain, rest of euro area and rest of the world. The largest four euro area countries are well-suited to evaluate the quantitative relevance of financial factors underlying the effectiveness of non-standard monetary policies. Finally, the model introduces quadratic adjustments costs in purchases of government bonds by the households. This adjustment costs for global investors enables to generate significant impact on households who have access to several type of domestic and internationally traded financial assets (i.e. deposits to financial intermediaries, domestic government and private bonds and internationally traded bonds), as shown also in Table 1 for the latter.

The ***second contribution*** of the paper relates to the inspection of the transmission mechanism of central bank asset purchases in a large currency union through scenario analysis. More specifically, we explore three dimension: *i)* cross-country heterogeneity in the transmission of non-standard measures, *ii)* cross-country spillover effects within the currency union and *iii)* the role of credit versus exchange rate channels. In doing so, we select a benchmark scenario corresponding to the initial ECB's Private Sector Purchase Programme (as announced in January 2015). This scenario is simulated in different environments. First, the baseline simulation focuses on the credit channels of asset purchases and allows for the short-term risk-free rate to follow the specified monetary policy rule. In this context, the multi-country nature of the model is exploited in order to evaluate the cross-border spillovers from the asset purchases, through trade and financial linkages. The second simulation deviates from the first one assuming that the short-term risk-free rate has reached its effective lower bound. This simulation also sheds light on the potential for asset purchases to partially alleviate the ELB constraint. Finally, we extend the model in order to incorporate global portfolio

[1] Capital key reflects the respective country's share in the total population and GDP of the EU, with equal weighting. The ECB adjusts the shares every five years and whenever a new country joins the EU.

frictions through which the rest of the world is able to trade euro area bonds. Sales of euro area bonds by the rest of the world, opens up an exchange rate channel of purchases, amplifying the euro depreciation which reshuffles the transmission mechanism towards trade channels.

Looking closer to the literature, the introduction of financial frictions in our model, are mainly based on Darracq Pariès et al. (2016) and on Gertler and Karadi (2011a, 2013). The former follows existing literature on the financial accelerator (Bernanke et al. (1999) (hereafter BGG) Christiano et al. (2010) and Kumhof et al. (2010)), and Gerali et al. (2010) or Darracq Pariès et al. (2011) which introduces a segmented banking sector with a bank capital channel and monopolistic lending rate setting into a DSGE model with financial frictions like Iacoviello (2005). The non-financial side of the model shares a common theoretical framework with the New Open Economy Macroeconomics paradigm and is close to existing multi-country DSGE models like EAGLE (Gomes et al., 2012), NAWM (Coenen et al., 2008), GEM (Laxton and Pesenti (2003) and Pesenti (2008)), GIMF (Kumhof et al., 2010) or QUEST (Ratto et al. (2009) and Kollmann et al. (2014)).

Regarding the credit channel of non-standard measures, Darracq Pariès and Kuehl (2016) augment the work by Gertler and Karadi (2013), featuring segmented banking in an estimated euro area model. Studies which focus on central bank asset purchases through the household portfolio rebalancing channel include Burlon et al. (2015) and Cova et al. (2015), with the latter allowing for holdings of international government bonds across countries.

A number of mainly EA, US and UK-based studies have attempted to quantify the macroeconomic implications of non-standard measures using either VAR-type models or DSGE models, with overall rather wide-ranging model outcomes in terms of the direct effect on the level of long-term interest rates, exchange rates and other asset prices, output and prices but mostly suggesting that the asset purchase programmes have been effective in supporting economic growth. For instance, US-based studies include Chung et al. (2011), Fuhrer and Olivei (2011), Negro et al. (2011), Chen et al. (2012), Gertler and Karadi (2013), UK-based studies include Joyce et al. (2011), Goodhart and Ashworth (2012), Kapetanios et al. (2012), Bridges and Thomas (2012) and Pesaran and Smith (2012) and a few early euro area based studies include Altavilla et al. (2016)), Lenza et al. (2010), Peersman (2011), Altavilla et al. (2014) and Martin and Milas (2012) for a survey. The exchange rate channel of QE has been examined empirically by Haldane et al. (2016) that show that QE can have strong spillover effects cross-border, acting mainly via financial channels. They estimate that the impact of the US QE on the UK economic activity may be as large as the impact on the US economic activity. Furthermore, Borio and Zabai (2016) provides a list of studies which empirically estimate the impact of balance sheet policies on the exchange rate. They claim that these type of policies can have a significant impact on the exchange rate, opening up an exchange rate channel thereafter. Furthermore, they claim that the power of non-standard measures have diminished through domestic channels, as policy may end up relying more on exchange rate depreciation.

The remainder of this paper is organized as follows. Section 2 describes the main parts of the model, that being the financial sector, which is mainly responsible for the cross-country financial heterogeneity in the transmission of non-standard measures. Subsequently, Section 3 discusses the calibration strategy and the parameterizing of those main parts of the model. Section 4 discusses the macroeconomic effect of central bank asset purchases in the economy based on the three scenarios as mentioned above. Subsequently, Section 5 summarizes and concludes.

2 The model

The multi-country DSGE model for the euro area which is developed in this paper, expands on Darracq Pariès et al. (2016) along several dimensions. First of all, we introduce long-term sovereign bonds which are traded domestically by households and bankers. Second, portfolio frictions are introduced in the household sector through adjustment costs and in the banking sector via a moral hazard constraint *à la* Gertler and Karadi (2013), which impacts the asset composition. Altogether, these features open a credit channel of central bank asset purchases. The calibration strategy and the stochastic design for the purchase programmes are inspired from Darracq Pariès and Kuehl (2016). Finally, we relax the full home bias assumption and allow for the foreign sector to trade euro area sovereign bonds subject to some adjustment costs. This enables to amplify the response of the nominal exchange rate to the central bank asset purchases and examine the relative strength of domestic versus international transmission channels.

Figure 1 illustrates in a schematic representation, the different agents that interplay in the model and the respective sectors in the domestic or foreign economy where they operate on. Each country block is populated by various agents that can be clustered into four sectors: the household, the banking, the non-financial corporate and the goods-producing sectors. The banking sector is consisted by the bankers, the retail lending branches and the loan officers. The non-financial corporate sector is consisted by the capital producers and entrepreneurs. Lastly, the production sector is consisted by firms which produce the final and intermediate goods. The model also includes a government and a monetary authority. The model covers six regions, these being Germany, France, Italy, Spain (the four largest euro area countries), rest of euro area and rest of the world. This multi-country nature of the model generate cross-country spillover effects which can arise via trade of intermediate consumption and investment goods and via access to internationally traded financial assets.

On the demand side, households are consisted by infinitely-lived agents where a fraction of them are workers while the remaining are split into entrepreneurs and bankers. In this respect, they have access to financial markets. The financial assets that are domestically traded by euro area households are consisted of deposits and government bonds. In the case of Germany, they also trade private short-term bond. Households can also trade financial assets internationally. As shown in Table 1, euro area government bonds can also be traded by the rest of the world subject to global portfolio frictions. Furthermore, German short-term private bonds are also traded by the rest of euro area countries, while rest of the world short-term private bonds can be traded by euro area countries, both subject to financial transaction premiums. Last, households supply differentiated labour services in monopolistically competitive markets where they act as setters of the nominal wage. It is assumed that wages are determined by staggered nominal contracts *à la* Calvo (Calvo (1983)).

On the supply side, there are two types of firms, the intermediate and the final goods-producing firms. The intermediate goods-producing firms produce the internationally tradable and non-tradable consumption and investment goods. The final-goods producing firms use all intermediate goods (both domestically produced and imported) to produce the final goods which are non-traded and used for consumption and investment. Each firm in the intermediate goods sector sells its differentiated output under monopolistic competition. Therefore, the existence of staggered price contracts as *à la* Calvo result in sluggish price adjustments.

The banking sector is segmented in various parts. First, bankers get financing in the money market and fund to the retail lending branches. Second to finance their asset activities they collect savings from the households which are then placed in the money markets. They also accumulate net worth. Third retail lending branches receive funding from the bankers and allocate it to the loan officers. In the retail segment, banks operate under monopolistic competition and face nominal rigidity in their interest rate setting. The final segment of the banking group is consistent by loan officers which provide loan contracts to entrepreneurs. The underlying banker's balance sheet is shown in Table 2. The presence of nominal stickiness in the retail lending branches generates imperfect pass-through of market rates to bank lending rates. Last, as in Gertler and Karadi (2011b), bankers can divert a fraction of their assets and transfer them without costs to the households. In this case, the depositors force the default on the intermediary and only recover the remaining fraction of the asset.

The credit contracts that are proposed by loan officers to entrepreneurs are characterised by predetermined lending rates. The latter buy capital stock from the capital producers. Due to asymmetric information and costly state verification through monitoring costs, there are external financing premia which depend indirectly on the borrower's leverage. In the end, entrepreneurs default when their income that can be seized by the lender falls short of the agreed repayment of the loan.

In each country the fiscal authority's revenues consist of a set of taxes being imposed to households and firms. Furthermore, the government uses lump-sum taxes collected from households to implement a debt stabilizing fiscal rule and debt accumulates over time according to the fiscal authority's budget constraint.

There are two monetary authorities in the model one for each of the two main regions, those being the euro area, where the policy holds for the aggregated monetary union, and the rest of the world. Both of them can engage in both standard and non-standard monetary policy operations. Standard monetary policy follows an interest rate rule of Taylor-type. On the other hand, non-standard monetary policies can emerge via direct purchases of government bonds from banks and households. In the case where the model allows for global portfolio frictions, euro area bonds are traded also internationally, therefore rest of the world households can sell directly euro area bonds to the ECB.

As illustrated as well in Figure 1, sources of impairments in the standard and non-standard monetary transmission mechanism can arise from three distinct segments of the model, relating both to the demand and the supply of credit. These intermediation wedges constitute specific typologies of financial frictions that emerge via the decomposition of the final lending rate into the chain of financing costs faced by the different agents and the associated financial shocks. In more detail, these segments relate, first to bank-specific vulnerabilities in the form of weak capital positions and funding constraints, second to monopolistic margins in lending rate setting by retail lending branches and last to credit risk compensation in the provision of loans to entrepreneurs.

For the sake of clarity, the model exposition will focus on the new features introduced to Darracq Pariès et al. (2016) to account for the credit and exchange rate channels of non-standard measures. This concerns notably the households and wholesale banks which trade long-term government bonds, as well as other banking segments and entrepreneurs. The full specification of all remaining sectors and agents' problems (in particular capital producers, intermediate and final goods-producing firms and fiscal authority) can be found in Appendix D. For the sake of exposition, the associated decision problems are presented for a single country block and only refer to the open economy dimension whenever necessary. In the description of the model, stock and flow variables are expressed in real terms (except if mentioned otherwise): they are deflated by the consumer price level. Rest of the world variables are denoted with *.

2.1 Households

Households, indexed by $i \in [0, s^H]$, can smooth out consumption by adjusting their holdings of money for transaction purposes and can supply differentiated labor services in monopolistically competitive markets where they act as wage setters. They also have access to financial markets, where in general they hold deposits to financial intermediaries, buy and sell domestic government and private and internationally traded bonds. Table 1 clarifies the asset markets for the global economy. Short-term private bonds in Germany can also be traded by all other euro area countries adjusted for a financial transaction premium, while in the other euro area regions there is no issuance of short-term domestic private bond. Besides, short-term private bonds in the rest of the world can be traded by all euro area countries adjusted again for a financial transaction premium. Long-term government bonds are only traded domestically for all euro area countries subject to some adjustment costs while rest of the world households might be able to trade euro area government bonds. The later case open a global portfolio rebalancing channel of central bank asset purchases.

We cover the decision problem of households for a representative euro area block (EA) and the rest of the world (ROW), as in a two-country formulation of the world economy. In the full model, we distinguish between German (DE), all other euro area and rest of the world households since their trading on financial assets differ slightly.

2.1.1 Euro area households

During period t, the household decides on money holdings $\mathcal{M}_t$ and purchases C_t consumption goods which are subject to a proportional transaction cost defined as follows

$$\Gamma_v(V_t) \equiv \gamma_{v1} V_t + \gamma_{v2} V_t^{-1} - 2\sqrt{\gamma_{v1}\gamma_{v2}} \tag{1}$$

which depends on the consumption-based velocity specified as

$$V_t = \frac{(1+\tau_t^C) P_{C,t} C_t}{\mathcal{M}_t} \tag{2}$$

where $P_{C,t}$ denotes the price of a unit of the private consumption good and τ_t^C is the consumption tax rate .

Furthermore, households decide on the amount of their deposit holdings to the financial intermediaries $P_{C,t}D_t$ which pay interest gross nominal deposit rate $R_{D,t}$ in the following period.

They purchase domestic long-term government bonds, $B_{GH,t}$, at price $Q_{G,t}$. Such transactions are subject to portfolio adjustment costs defined as follows

$$\frac{1}{2}\frac{\gamma_{B_{GH}}}{\overline{B}_{GH}}\left(B_{GH,t} - \widetilde{B}_{GH}\right)^2 \tag{3}$$

where $\overline{B}_{GH}$ is the steady state level of government bonds holdings, $\gamma_{B_{GH}} > 0$ denotes the portfolio adjustment cost parameter and $\widetilde{B}_{GH}$ is adjusted so that in steady state, the first order condition is consistent with the bank-driven excess bond return on sovereign securities. The above specification emerges as important factor for the transmission of non-standard measures: with lower transaction costs, households can more flexibly trade away excess bond return fluctuations which would dampen significantly the bond yield response of central bank asset purchases.

Long-term sovereign debt is introduced by assuming that government securities are perpetuities which pay geometrically-decaying coupons where c_g is the coupon rate and τ_g is the decaying factor.[2] The nominal return on sovereign bond holdings from period t to period $t+1$ is therefore defined as follows

$$R_{G,t+1} = \frac{c_g + (1-\tau_g)Q_{G,t+1}}{Q_{G,t}}. \tag{4}$$

Households invest in domestic short-term private bonds B_t, which pay a gross nominal interest R_t in the next period. They also buy internationally traded short-term private bonds originated by the rest of the world B_t^{ROW}. The gross nominal return on foreign bonds, R_t^*, is adjusted for a financial transaction premium that the household must pay when taking a position in the international bond market and which is defined as follows

$$\Gamma_{B^{ROW}}\left(\frac{S_t^{EA,ROW}P_{C,t}^{*}B_t^{ROW}}{P_{Y,t}Y_t}\right) \equiv \gamma_{B^{ROW}}\left(exp\left(\frac{S_t^{EA,ROW}P_{C,t}^{*}B_t^{ROW}}{P_{Y,t}Y_t} - \overline{B}_Y^{ROW}\right) - 1\right) \tag{5}$$

where $\gamma_{B^{ROW}} > 0$ is a parameter, $\overline{B}_Y^{ROW}$ is the long-run steady state holdings of foreign short-term bonds. $P_{Y,t}$ is the gross domestic product deflator, Y_t is the GDP in real terms and $S_t^{EA,ROW}$ denotes the nominal exchange rate, expressed in terms of units of euro area currency per unit of the rest of the world currency.

Finally, during period t, the household collects after tax income from labour services. In particular, τ_t^N represents the tax rates levied on wage income and $\tau_t^{W_h}$ denotes the additional wage income tax rate that represents the household contribution to social security.

Households also hold state-contingent securities, Φ_t, which are traded amongst themselves and provide insurance against individual income risk. This guarantees that the marginal utility of consumption out of wage income is identical across individual households and consequently all households choose identical allocations in equilibrium.

At the end of period t, households collect after tax dividends $(1-\tau_t^D)DV_t$ paid by intermediate goods-producing firms nominal profits (which are owned by households), where τ_t^D represents the tax rate on dividends from firms ownership. Furthermore, they collect the incurred premium Ξ_t when taking a position in the international bond market which is rebated in a lump-sum manner to domestic households, profits from the financial intermediaries and non-financial corporations $\Pi_{BE,t}$ that are owned by households. At last, TR_t and T_t represent lump-sum transfers and taxes received from or pay to the government, respectively.

[2] In this respect, the bond pays c_g the first period, $(1-\tau_g)c_g$ the second one, $(1-\tau_g)^2c_g$ the third one, etc...

The corresponding budget constraint in nominal terms is given by

$$\begin{aligned} &\mathcal{M}_{t-1} + R_{D,t-1}P_{C,t-1}D_{t-1} + R_{G,t}Q_{G,t-1}P_{C,t-1}B_{GH,t-1} + R_{t-1}P_{C,t-1}B_{t-1} \\ &+ (1-\Gamma_{B^{ROW}})\, R^{*}_{t-1}S_t^{EA,ROW}P^{*}_{C,t-1}B_{t-1}^{ROW} + \left(1-\tau_t^{N}-\tau_t^{W_h}\right)W_tN_t \\ &+(1-\tau_t^{D})DV_t + TR_t + \Phi_t + \Xi_t + \Pi_{BE,t} \\ &= (1+\tau_t^{C}+\Gamma_v(V_t))P_{C,t}C_t + P_{C,t}D_t + P_{C,t}Q_{G,t}\left[B_{GH,t} + \tfrac{1}{2}\tfrac{\gamma_{B_{GH}}}{\overline{B}_{GH}}\left(B_{GH,t}-\widetilde{B}_{GH}\right)^2\right] \\ &+P_{C,t}B_t + S_t^{EA,ROW}P^{*}_{C,t}B_t^{ROW} + T_t + \mathcal{M}_t. \end{aligned} \tag{6}$$

Hence, households have the following intertemporal welfare function

$$E_t\left[\sum_{k=0}^{\infty}\beta^k\zeta_c\frac{(1-\kappa)}{1-\sigma}\left(\frac{C_{t+k}-\kappa\overline{C}_{t+k-1}}{1-\kappa}\right)^{1-\sigma} - \frac{1}{1+\zeta_n}\left(N_{t+k}\right)^{1+\zeta_n}\right] \tag{7}$$

where β $(0<\beta<1)$ is the discount rate, σ $(\sigma>0)$ the inverse of the intertemporal elasticity of substitution, ζ_c and is a parameter that captures consumption preferences. Households value consumption streams C_t following external habits while receiving disutility from providing labour services N_t. In particular, the utility depends positively on the difference between the current level of individual consumption, C_t, and the lagged average consumption level of households, $\overline{C}_{t+k-1}$. We denote κ $(0\le\kappa\le1)$ the degree of habit persistence. ζ_n $(\zeta_n>0)$ is the inverse of the elasticity of work effort with respect to the real wage (Frisch elasticity).

The household, therefore, chooses $\left\{C_t, D_t, \mathcal{M}_t, B_{GH,t}, B_t, B_t^{ROW}\right\}$ for all t to maximize its expected lifetime utility function, subject to the constraints imposed by equation (6) for all t. Λ_t is defined to denote the Lagrange multiplier on the budget constraint (in real terms). The corresponding first-order conditions are

$$\begin{aligned} \zeta_c\left(\frac{C_t-\kappa\overline{C}_{t-1}}{1-\kappa}\right)^{-\sigma} &= \\ \Lambda_t\left(1+\tau_t^C+\Gamma_v(V_t)+\Gamma_v'(V_t)\,V_t\right)& \end{aligned} \tag{8}$$

$$\beta E_t\left[\frac{\Lambda_{I,t+1}}{\Lambda_{I,t}}\Pi_{C,t+1}^{-1}R_{D,t}\right] = 1 \tag{9}$$

$$\beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\Pi_{C,t+1}^{-1}\right] = 1 - V_t^2\left(\gamma_{v1}-\frac{\gamma_{v2}}{V_t^2}\right) \tag{10}$$

$$\beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\Pi_{C,t+1}^{-1}R_{G,t+1}\right] = 1 + \frac{\gamma_{B_{GH}}}{\overline{B}_{GH}}\left(B_{GH,t}-\widetilde{B}_{GH}\right) \tag{11}$$

$$\beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\Pi_{C,t+1}^{-1}R_t\right] = 1 \tag{12}$$

$$\beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\frac{R_t^*}{\Pi_{C,t+1}}\frac{S_{t+1}^{EA,ROW}}{S_t^{EA,ROW}}\right] = \frac{1}{1-\Gamma_{B^{ROW}}\left(\frac{S_t^{EA,ROW}P^*_{C,t}B_t^{ROW}}{P_{Y,t}Y_t}\right)}. \tag{13}$$

2.1.2 Rest of the world households

In this section, we only present the decisions of rest of the world households which are different from the euro area ones.

Global portfolio frictions can emerge in the model by allowing euro area government bonds being traded internationally by rest of the world households. During period t, rest of the world households choose the amount of euro area long-term government bond holdings $B^{*,EA}_{GH,t}$. Similarly to domestic sovereign bonds transactions, rest of the world households face portfolio adjustment costs from their foreign bonds purchases given by

$$\frac{1}{2}\frac{\gamma_{B^{*,EA}_{GH}}}{\overline{B}^{*,EA}_{GH}}\left(B^{*,EA}_{GH,t}-\widetilde{B}^{*,EA}_{GH}\right)^2 \tag{14}$$

where $\gamma_{B^{*,EA}_{GH}} > 0$ denotes the portfolio adjustment cost parameter and $\overline{B}^{*,EA}_{GH}$ denotes the steady state rest of the world representative household holdings of euro area government bonds. As for the euro area households decision problem, $\widetilde{B}^{*,EA}_{GH}$ is adjusted so that in steady state, the first order condition is consistent with the bank-driven excess bond return on sovereign securities.

The first order condition with respect to internationally traded euro area government bond purchases can be written as

$$\beta E_t\left[\frac{\Lambda^*_{t+1}}{\Lambda^*_t}\frac{R_{G,t+1}}{\Pi^*_{C,t+1}}\frac{S^{EA,ROW}_t}{S^{EA,ROW}_{t+1}}\right] = 1+\frac{\gamma_{B^{*,EA}_{GH}}}{\overline{B}^{*,EA}_{GH}}\left(B^{*,EA}_{GH,t}-\widetilde{B}^{*,EA}_{GH}\right) \tag{15}$$

where Λ^*_t denotes the Lagrange multiplier on the budget constraint (in real terms) from the rest of the world households.

2.2 Banks

Every period, a fraction (f) of the representative household's members are workers and have access to financial markets, while the remainder fraction $(1-f)$, the representative household's members, are only workers. A fraction fe of the households are entrepreneurs and the remaining mass $f(1-e)$ are bankers. Bankers face a probability ζ_b of operating as a bank over next period and a probability $(1-\zeta_b)$ of becoming a worker again. When a banker exits, accumulated earnings are transferred to the respective household while newly entering bankers receive initial funds from households. Overall, households transfer a real amount $\Psi_{B,t}$ to the bankers for each period t. In our setting, bankers' decisions are identical so we will expose the decision problem for a representative banker.

2.2.1 Wholesale banks

Bankers operate in competitive markets providing loans to retail lending branches, $L_{BE,t}$. Bankers can also purchase government securities, $B_{GB,t}$, at price $Q_{G,t}$. To finance their lending activity, bankers receive deposits, $D_{B,t}$, from the households and accumulate net worth, $NW_{B,t}$. Their balance identity therefore, in real terms, reads as follows

$$L_{BE,t}+Q_{G,t}B_{GB,t}=D_{B,t}+NW_{B,t}. \tag{16}$$

The one-period return on bank's net worth for the period $t+1$, $R_{B,t+1}$, results from the gross interest received from the loans to the retail lending bank, the return on sovereign bond holding, the lump-sum share of profits (and losses) coming from the retail lending branches and loan officers activities, $\Pi^R_{B,t}$, pro-rated according to each banker's net worth, minus the gross interest paid on deposits and is formulated as follows

$$R_{B,t+1} \equiv \left(R_{BLE,t} - R_{D,t}\right)\kappa^b_{E,t} + \left(R_{G,t+1} - R_{D,t}\right)\kappa^b_{G,t} + R_{D,t} + \frac{\Pi^R_{B,t+1}}{NW_{B,t}} \tag{17}$$

where $R_{BLE,t}$ is the banker's financing rate. Bank leverage ratios to loans and sovereign bond holdings, are respectively denoted as $\kappa^b_{E,t} = \frac{L_{BE,t}}{NW_{B,t}}$ and $\kappa^b_{G,t} = \frac{Q_{G,t}B_{GB,t}}{NW_{B,t}}$.

The accumulation of the bankers' net worth from period t to period $t+1$ is as follows

$$NW_{B,t+1} = \frac{R_{B,t+1}}{\Pi_{C,t+1}} NW_{B,t} \tag{18}$$

where $\Pi_{C,t+1}$ is the one-period ahead CPI inflation rate. $NW_{B,t+1}$ can be iterated backward and be written as follows

$$NW_{B,t+1} = \widetilde{R}_{B,t+1-s,t+1} NW_{B,t+1-s} \tag{19}$$

where $\widetilde{R}_{B,t+1-s,t+1} = \prod_{i=0}^{s} \left\{\frac{R_{B,t+1-i}}{\Pi_{C,t+1-i}}\right\}$ and $\widetilde{R}_{B,t+1-s,t+1-s} = 1$.

The bankers' objective is to maximise their terminal net worth when exiting the industry, which occurs with probability $(1-\zeta_b)$ each period. The value function for each banker is therefore given by

$$\mathcal{V}_{B,t} = (1-\zeta_b)\sum_{k=0}^{\infty} (\zeta_b)^k\, \Xi_{t,t+k+1} NW_{B,t+k+1} \tag{20}$$

where $\Xi_{t,t+k+1} = \beta\frac{\Lambda_{t+k+1}}{\Lambda_t}$ is the period t stochastic discount factor of the households for nominal income streams at period $t+k+1$ and Λ_t is defined to denote the Lagrange multiplier on the budget constraint of the households (in real terms and as shown in Section 2.1). Using equation (19), the value function can be written recursively as follows

$$\mathcal{V}_{B,t} = (1-\zeta_b)\, NW_{B,t}\left(\mathcal{X}_{B,t} - 1\right) \tag{21}$$

with

$$\mathcal{X}_{B,t} = 1 + \zeta_b \mathbb{E}_t\left[\Xi_{t,t+1}\frac{R_{B,t+1}}{\Pi_{C,t+1}}\mathcal{X}_{B,t+1}\right]. \tag{22}$$

As in Gertler and Karadi (2011b), we assume that bankers can divert a fraction of their assets and transfer them without any cost to the households. In this case, the depositors force the default on the intermediary and will only recover the remaining fraction of the asset. The corresponding incentive compatibility constraint reads as follows

$$\mathcal{V}_{B,t} \geqslant \lambda_b\left(L_{BE,t} + \delta_{b,t}Q_{G,t}B_{GB,t}\right) = \lambda_b\left(\kappa^b_{E,t} + \delta_{b,t}\kappa^b_{G,t}\right) NW_{B,t} \tag{23}$$

where λ_b is the diversion rate for private loans while $\lambda_b\delta_{b,t}$ for government securities. Under the parameter values considered thereafter, the constraints are assumed to always bind in the vicinity of the steady state.

Given their initial net worth, the end-of-period t contracting problem for bankers consists in maximising $\mathcal{V}_{B,t}$ for the exposures to private sector loans $\kappa^b_{E,t}$ and government securities $\kappa^b_{G,t}$

$$\mathcal{V}_{B,t} = \max_{\{\kappa^b_{E,t},\kappa^b_{G,t}\}} \left\{\zeta_b \widetilde{\mathcal{X}}_{B,t} NW_{B,t}\right\} \tag{24}$$

subject to the incentive compatibility constraint in equation (23), where $\widetilde{\mathcal{X}}_{B,t}$ is denoted as

$$\widetilde{\mathcal{X}}_{B,t} \equiv (\mathcal{X}_{B,t} - 1)\,\frac{(1-\zeta_b)}{\zeta_b} \tag{25}$$

and follows

$$\widetilde{\mathcal{X}}_{B,t} = \mathbb{E}_t\left[\Xi^I_{t,t+1}\frac{R_{B,t+1}}{\Pi_{C,t+1}}\left(\zeta_b\widetilde{\mathcal{X}}_{B,t+1} + (1-\zeta_b)\right)\right]. \tag{26}$$

The first order conditions for this problem can then be formulated as follows

$$\mathbb{E}_t\left[\Xi_{t,t+1}\frac{\partial R_{B,t+1}}{\partial \kappa^b_{E,t}}\left(\zeta_b\widetilde{\mathcal{X}}_{B,t+1} + (1-\zeta_b)\right)\diagup \Pi_{C,t+1}\right] = \mu_t\lambda_b \tag{27}$$

$$\mathbb{E}_t\left[\Xi_{t,t+1}\frac{\partial R_{B,t+1}}{\partial \kappa^b_{G,t}}\left(\zeta_b\widetilde{\mathcal{X}}_{B,t+1} + (1-\zeta_b)\right)\diagup \Pi_{C,t+1}\right] = \mu_t\lambda_b\delta_{b,t} \tag{28}$$

where μ_t is the lagrange multiplier related to the incentive compatibility constraint.[3]

Finally, aggregating across bankers, a fraction ζ_b continues operating into the next period while the rest exits from the industry. The new bankers are endowed with starting net worth, $\Psi_{B,t}$, proportional to the assets of the old bankers. Accordingly, the aggregate dynamics of bankers' net worth is given by

$$NW_{B,t} = \zeta_b R_{B,t}\frac{NW_{B,t-1}}{\Pi_{C,t}} + \Psi_{B,t}. \tag{29}$$

2.2.2 Retail lending branches and loan officers

A continuum of retail lending branches indexed by j, provide differentiated loans, $L_{E,t}(j)$, to loan officers. The total financing needs of loan officers, $L_{E,t}$, follow a CES aggregation of differentiated loans defined as follows

$$L_{E,t} = \left[\int_0^1 L_{E,t}(j)^{\frac{1}{\mu^R_E}}\,\mathrm{d}j\right]^{\mu^R_E} \tag{30}$$

where $\frac{\mu^R_E}{\mu^R_E - 1} > 1$ is the elasticity of substitution indicating that differentiated loans are imperfect substitutes. Therefore, the corresponding average return on loan is defined as follows

$$R_{LE,t} = \left[\int_0^1 R_{LE,t}(j)^{\frac{1}{1-\mu^R_E}}\,\mathrm{d}j\right]^{1-\mu^R_E}. \tag{31}$$

Retail lending branches are monopolistic competitors which levy funds from the wholesale banks and set the gross nominal interest rates on a staggered basis *à la* Calvo, facing each period a constant probability $1-\xi^R_E$ of being able to re-optimize its interest rate. If a retail lending branch cannot

[3] The stream of transfers $\Pi^R_{B,t+1}$ are considered exogenous by bankers in their decision problem which implies that $\frac{\partial \Pi^R_{*,t+1+s}}{\partial \kappa^b_{*,t}} = 0$.

re-optimize, then the interest rate is left at its previous period level

$$R_{LE,t}(j) = R_{LE,t-1}(j). \tag{32}$$

This staggered lending rate setting acts in the model as maturity transformation in banking activities and leads to imperfect pass-through of market interest rates on bank lending rates.

The monopolistic intermediation of retail branches generates pure profits. Those profits are nonetheless time-varying due to the rigidities in lending rate setting and tend to be positively correlated with the slope of the "risk-free" yield curve.

Turning now to the loan officers, their sole purpose is to provide loan contracts to entrepreneurs by receiving one-period loans from the retail lending branches which pay a gross nominal interest rate $R_{LE,t}$ in a perfectly competitive environment. As they have no other source of funds, the level of loans they provide to the entrepreneurs equals the level of financing they receive, $L_{BE,t}$. Therefore, they seek to maximise their discount intertemporal flow of income and the first order condition of their decision problem reads as follows

$$\mathbb{E}_t \left[\Xi_{t,t+1} \left(\frac{\widetilde{R}_{LE,t+1} - R_{LE,t}}{\Pi_{C,t+1}} \right) \right] = 0 \tag{33}$$

where $\widetilde{R}_{LE,t+1}$ denotes the state-contingent returns on the loan portfolio. This first order condition in equation (33) serves as a participation constraint in the decision problems of entrepreneurs below.

Therefore, in period t, the loan officers break even on their next period intermediation activity but only in expected terms. In period $t+1$, once aggregate uncertainty is resolved, the loan officers may incur an *ex post* loss or a profit. Like for retail branches, such profits and losses are transferred back to the wholesale banks.

In equilibrium the state-contingent transfers from the retail branches and loan officers to the wholesale banks, $\Pi^R_{B,t+1}$ (see equation (17)), are given by

$$\Pi^R_{B,t+1} = \left(\widetilde{R}_{LE,t+1} - R_{BLE,t} \right) L_{BE,t}. \tag{34}$$

2.3 Entrepreneurs

Every period, a fraction fe of workers are entrepreneurs, facing a probability ζ_e of staying entrepreneurs over next period and a probability $(1 - \zeta_e)$ of becoming a worker again. To keep the share of entrepreneurs constant, we assume that similar number of workers randomly becomes entrepreneurs. When an entrepreneur exits, their accumulated earnings are transferred to the respective household. At the same time, newly entering entrepreneurs receive initial funds from households. Overall, households transfer a real amount $\Psi_{E,t}$ to entrepreneurs each period t. Finally, as it will become clear later, entrepreneurs decisions for leverage and lending rate are independent from their net worth and therefore identical. Accordingly, we will expose the decision problem for a representative entrepreneur.

A segment of perfectly competitive capital producer firms, owned by the households, produce the stock of fixed capital in the economy using tradable investment goods. At the end of the period t entrepreneurs buy the capital stock, K_t, from the capital producers at real price Q_t (expressed in terms of consumption goods). They transform it into an effective capital stock $u_{t+1}K_t$ by choosing the utilisation rate u_{t+1}. The adjustment of the capacity utilization rate entails some costs per unit of capital stock $\Gamma_u(u_{t+1})$.

The effective capital stock can then be rented out to intermediate goods producers at a nominal rental rate of $r_{K,t+1}$. Finally, by the end of period t, entrepreneurs sell back the depreciated capital stock $(1-\delta)K_t$ to capital producer at price Q_{t+1}. The gross nominal rate of return on capital, $R_{KK,t+1}$, across from period t to $t+1$ is therefore given by

$$R_{KK,t+1} \equiv \frac{((1-\tau_{t+1}^K)(r_{K,t+1}u_{t+1} - \Gamma_u(u_{t+1}))P_{I,t+1} + \tau_t^K \delta P_{I,t+1} + (1-\delta)Q_{t+1})}{Q_t \Pi_{C,t+1}} \tag{35}$$

where τ_t^K is the tax rate to capital, $P_{I,t+1}$ is the relative price of investment goods in terms of consumption goods and $\Gamma_u(u_{t+1})$ is defined as follows

$$\Gamma_u(u_{t+1}) = \frac{\left(\frac{\overline{R}_{KK}}{\overline{R}\beta} - 1 + \delta\right)\overline{Q} - \delta\tau^K\overline{P}_I}{(1-\tau^K)\overline{P}_I}(u_t - 1) + \frac{\gamma_{u2}}{2}(u_t-1)^2 \tag{36}$$

where γ_{u2} is the capital utilization rate and $\overline{R}_{KK}$, $\overline{Q}$ and $\overline{P}_I$ denote the steady state values of the respective variables.

Each entrepreneurs' return on capital is subject to a multiplicative idiosyncratic shock $\omega_{e,t}$. These shocks are independent and identically distributed across time and across entrepreneurs and follow a lognormal CDF $F_e(\omega_{e,t})$, with mean 1 and variance $\sigma_{e,t}$. By the law of large number, the average across entrepreneurs (denoted with the operator $\widetilde{E}$) for expected return on capital is given by

$$\widetilde{E}\left[\mathbb{E}_t\left(\omega_{e,t+1}R_{KK,t+1}\right)\right] = \mathbb{E}_t\left(\int_0^\infty \omega_{e,t+1}\mathrm{d}F_{e,t}(\omega)R_{KK,t+1}\right) = \mathbb{E}_t\left(R_{KK,t+1}\right). \tag{37}$$

Entrepreneur's choice over capacity utilization is independent from the idiosyncratic shock and implies that

$$r_{K,t} = \Gamma_u'(u_t). \tag{38}$$

Entrepreneurs finance their purchase of capital stock with their net worth $NW_{E,t}$ and one-period loan $L_{E,t}$ from the loan officers, where

$$Q_t K_t = NW_{E,t} + L_{E,t}. \tag{39}$$

In the tradition of costly state verification frameworks, loan officers cannot observe the realisation of the idiosyncratic shock unless they pay a monitoring cost μ_e per unit of assets that can be transferred to the bank in case of default.

The set of lending contracts available to entrepreneurs are constrained to those that the lending rate $R_{LLE,t}$ is predetermined at the previous time period, the ***first*** assumption which is different from the one of Bernanke et al. (1999). In BGG, it is the return to the lender that is predetermined[4] while the contractual lending rate is state contingent. This implies that from period t to $t+1$, the realisation of aggregate shocks has no impact of lender's balance sheet. The assumption

[4] If the lending rates offered by banks are not contingent on the *ex post* realization of aggregate uncertainty (i.e. predetermined lending rates) shocks hitting the economy tend to have a more muted effect relative to the benchmark scenario. In this case, this reflects the less pronounced interactive effects between macroeconomic developments (e.g. the accelerator effects on borrower net worth) and the credit market. This mitigates somewhat the macroeconomic amplification implied by the existence of credit frictions observed in the benchmark case.

of predetermined contractual lending rate relaxes this property and allows for innovations on the lender's return. Besides, the restrictions imposed on the contracting problem imply that it is not optimal in the sense of Carlstrom et al. (2013a,b).

Default occurs when the entrepreneurial income that can be seized by the lender falls short of the agreed repayment of the loan. At period $t+1$, once aggregate shocks are realised, this will happen for draws of the idiosyncratic shock below a certain threshold $\overline{\omega}_{e,t}$, given by

$$\overline{\omega}_{e,t+1}\chi_e R_{KK,t+1}\kappa_{e,t} = \left(R_{LLE,t}+1\right)\left(\kappa_{e,t}-1\right) \tag{40}$$

where $R_{LLE,t}$ is the nominal lending rate determined at period t and $\kappa_{e,t}$ is the corporate leverage defined as

$$\kappa_{e,t} = \frac{Q_t K_t}{NW_{E,t}} \tag{41}$$

and χ_e captures the assumtion on limited seizability of entrepreneurs assets in case of default, which is the ***second*** assumption that is different from the one of Bernanke et al. (1999). It implies that only a share χ_e from entrepreneurs assets (gross of capital return) banks can recover in case of default. When banks take over entrepreneur's assets, they have to pay the monitoring costs.

The *ex post* return to loan officers, denoted as $\widetilde{R}_{LE,t}$, can then be expressed as

$$\widetilde{R}_{LE,t} = G(\overline{\omega}_{e,t})\chi_e R_{KK,t}\frac{\kappa_{e,t-1}}{\kappa_{e,t-1}-1} \tag{42}$$

where

$$G_e(\overline{\omega}) = (1-F_e(\overline{\omega}))\overline{\omega} + (1-\mu_e)\int_0^{\overline{\omega}} \omega \mathrm{d}F_e(\omega)\,. \tag{43}$$

We assume that entrepreneurs are myopic, therefore their end-of-period t contracting problem consists in maximising next period return on net worth for lending rate, $R_{LLE,t}$ and leverage $\kappa_{e,t}$, defined as follows

$$\max_{\{R_{LLE,t},\kappa_{e,t}\}} \mathbb{E}_t\left[\left(1-\chi_e\Gamma_e(\overline{\omega}_{e,t+1})\right)R_{KK,t+1}\kappa_{e,t}\right] \tag{44}$$

subject to the participation constraint of the lender (33) and the equation (40) for the default threshold $\overline{\omega}_{e,t+1}$ and where

$$\Gamma_e(\overline{\omega}) = (1-F_e(\overline{\omega}))\overline{\omega} + \int_0^{\overline{\omega}} \omega \mathrm{d}F_e(\omega)\,. \tag{45}$$

After some manipulations, the first order conditions for the lending rate and the leverage lead to the following condition

$$\mathbb{E}_t\left[\left(1-\chi_e\Gamma_e(\overline{\omega}_{e,t+1})\right)R_{KK,t+1}\kappa_{e,t}\right] = \frac{\mathbb{E}_t\left[\chi_e\Gamma'_e(\overline{\omega}_{e,t+1})\right]}{\mathbb{E}_t\left[\Xi_{t,t+1}G'_e(\overline{\omega}_{e,t+1})\right]}\mathbb{E}_t\left[\Xi_{t,t+1}\right]R_{LE,t} \tag{46}$$

where

$$\Gamma'_e(\overline{\omega}) = (1-F_e(\overline{\omega})) \tag{47}$$

$$G'_e(\overline{\omega}) = (1-F_e(\overline{\omega})) - \mu_e\overline{\omega}\mathrm{d}F_e(\overline{\omega})\,. \tag{48}$$

As anticipated at the beginning of the section, the solution of the problem shows that all entrepreneurs choose the same leverage and lending rate. Moreover, the features of the contracting problem imply that the *ex post* return to the lender $\widetilde{R}_{LE,t}$ will defer from the *ex ante* return $R_{LE,t-1}$.[5]

Finally, the dynamic of net worth is given by

$$NW_{E,t} = \zeta_e \left(1 - \chi_e \Gamma_e(\overline{\omega}_{e,t})\right) R_{KK,t} \kappa_{e,t-1} \frac{NW_{E,t-1}}{\Pi_{C,t}} + \Psi_{E,t}. \tag{49}$$

2.4 Standard and non-standard monetary policies

The monetary authority in our model can engage in both types of policies, standard (conventional) and non-standard (unconventional).[6]

In the case of standard monetary policy, we assume that the central bank aims at steering the interest on short-term domestic bonds held by households, R_t. It is assumed that standard monetary policy follows an interest rate rule, of Taylor-type, defined as follows

$$R_t = max\left(\underline{R}, R_t^{shadow}\right) \tag{50}$$

$$R_t^{shadow} = \left(R_{t-1}^{shadow}\right)^{\phi_R} \left[\left(\overline{R}\right) \left(\frac{\Pi_{C,t}}{\overline{\Pi}_C} \right)^{\phi_\Pi} \right]^{(1-\phi_R)} \left(\frac{\Pi_{C,t}}{\Pi_{C,t-1}} \right)^{\phi_{\Delta\Pi}} \left(\frac{Y_t}{Y_{t-1}} \right)^{\phi_{\Delta Y}} \tag{51}$$

specified in terms of the deviation of the region-wide CPI inflation rate $\Pi_{C,t}$ from the target $\overline{\Pi}_C$ and of changes in inflation and output growth. The intercept of the rule corresponds to the equilibrium interest rate $\overline{R}$, while ϕ_R is the interest rate inertia (smoothing) and ϕ_Π, $\phi_{\Delta\Pi}$ and $\phi_{\Delta Y}$ are the interest rate sensitivities to inflation gap, changes to inflation and output growth, respectively. In the case that the short-term domestic bonds interest rate is constraint at its effective lower bound, then the outcome of the interest rate rule is $\underline{R}$.

Non-standard monetary policy can be operationalised via direct purchases of government bonds from banks and households by the monetary authority. In order to account for the design and announcement strategy of the purchase programmes, we adopt the approach of Darracq Pariès and Kuehl (2016) and assume that the purchases evolve according to the following stochastic process

$$B_{CB,t} = \rho_{CB} B_{CB,t-1} + \gamma_0 \varepsilon_{CB,t} + \gamma_1 \varepsilon_{CB,t-1} + \gamma_2 \varepsilon_{CB,t-2} + ... + \gamma_n \varepsilon_{CB,t-n} \tag{52}$$

where $B_{CB,t}$ denote the government bond purchases by the central bank. $\varepsilon_{CB,t-i}$ from $i = 0, ..., n$ represent the evolution of purchases (news shocks) which are carried out in the build-up phase and are assumed to be known in period $t - n$. Once all purchases are carried out and $B_{CB,t}$ reaches its peak, they start decaying following an AR(1) process with parameter ρ_{CB}.

2.5 Market clearing conditions in asset markets

On the credit market, due to nominal rigidity in the setting of interest rate by retail lending branches, the following conditions holds

$$L_{BE,t} = \Delta_{E,t}^R L_{E,t} \tag{53}$$

[5] Log-linearising equation (46) and the participation constraint (33), one can show that innovations in the *ex post* return are notably driven by innovations in $R_{KK,t}$.

[6] For the sake of simplicity the analysis of the central bank balance sheet is beyond the scope of this paper and we leave it for future research.

where

$$\Delta_{E,t}^{R} = \int_0^1 \left(\frac{R_{E,t}(j)}{R_{E,t}} \right)^{-\frac{\mu_E^R}{\mu_E^R - 1}} \mathrm{d}j \tag{54}$$

is the dispersion index among retail bank interest rates.

The deposits issued by the euro area wholesale banks and held by the euro area households are given by

$$D_{B,t} = D_t. \tag{55}$$

The euro area short-term private bonds is only traded domestically and is in zero net supply. The rest of the world short-term private bond is traded by both ROW households (with net holdings B_t^*) and EA households (with net holdings B_t^{ROW}), and is also in zero net supply. This implies

$$B_t^{ROW} = -B_t^*. \tag{56}$$

In the euro area sovereign bond market, issuance by the government is held by euro area households, euro area wholesale banks, euro area central bank and rest of the world households, therefore being

$$B_{G,t} = B_{GB,t} + B_{GH,t} + B_{CB,t} + B_{GH,t}^{*,EA}. \tag{57}$$

Finally, the accumulation of euro area net foreign asset position relates the euro area households holdings of rest of the world private bonds and the rest of the world households holdings of euro area government bonds to the euro area current account.

$$\begin{aligned} CA_t = {} & S_t^{EA,ROW} P_{C,t}^* B_t^{ROW} - (1 - \Gamma_{B^{ROW}}) R_{t-1}^* S_t^{EA,ROW} P_{C,t-1}^* B_{t-1}^{ROW} \\ & - P_{C,t} Q_{G,t} B_{GH,t}^{*,EA} + R_{G,t} Q_{G,t-1} P_{C,t-1} B_{GH,t-1}^{*,EA} \end{aligned} \tag{58}$$

where CA_t is the current account of the euro area.

3 Calibration

As in Darracq Pariès et al. (2016) the model is a global DSGE where the euro area is decomposed into five regions, whereas the sixth region corresponds to the rest of the world and is consisted by the major countries. The countries consisting the euro area are Germany, France, Italy and Spain, namely the four largest countries and the fifth region corresponds jointly to all other euro area countries. The calibration of the model's steady state is based on country-specific structural conditions, empirical evidence, historical data and on existing literature on DSGE models (e.g. EAGLE, GEM and NAWM) and is very closely related to Darracq Pariès et al. (2016). Therefore, cross-country heterogeneity may manifest itself in several dimensions, for instance through country specific calibration of the macroeconomic environment (e.g. great ratios, fiscal stance, debt levels, trade), as well as asymmetries in the corporate and banking sector balance sheets and intermediation spreads. We also allow for international financial and trade linkages via detailed calibration of bilateral trade of consumption and investment intermediate goods and of internationally traded private and government bonds.

We follow three different calibration strategies for assigning parameter values. The ***first*** one involves the direct setting of parameters based on information from existing literature or historical data. If that is not possible, then the ***second*** strategy uses information on endogenous variables which can shed light on the target parameters.[7] ***Lastly***, when dealing with the dynamic model, we try to specify sensitivities and degrees of adjustments through the usage of information on elasticities or pass-through parameters or multipliers available from econometric studies. The fact that the calibration of the model is fine-tuned to capture selected country-specific structural conditions, it allows us to derive macroeconomic simulations at the country level. In that respect, the country-specific calibration allows for cross-country heterogeneity which helps in quantifying the role of country-specific financial frictions in the domestic propagation of central bank asset purchases and international spillover effects.

Table 3 reports the calibration for households. The discount factor, β, is set symmetrically across countries and equal to 0.995. This implies that the equilibrium gross annual real interest rate, $(1/\beta)^4$, is approximately equal to 1.02. The parameters for the intertemporal elasticity of substitution, σ, and the inverse of the Frisch elasticity of labour, ζ_n, are also calibrated symmetrically and equal to 1 and 2. The habit persistence parameter, κ, is calibrated symmetrically to 0.9. The first consumption transaction cost parameter γ_{v1} is calibrated as such so that the consumption-based velocity is symmetric across countries and equal to 2.38. The second consumption transaction cost parameter, γ_{v2} is calibrated as such so that the interest (semi-)elasticity of money demand is set symmetrically across cross countries at -0.75. The adjustment cost parameter on the holding of domestic sovereign securities, $\gamma_{B_{GH}}$, is calibrated symmetrically to 0.04. A positive value impacts the transmission of asset purchase programmes as it affects the distribution of sales of sovereign securities between households and banks in the context of central bank asset purchases. The higher the value, the less the households' selling of government bonds to the central bank. The aforementioned calibrated value is chosen in order to ensure that at the peak of the central bank portfolio, in the case there is no international trading of these bonds outside the euro area, households for all euro area regions, bear approximately 40% of adjustments in sovereign bond holdings, while banks account for the rest. These ballpark figures are not fully at odds with observed changes in sectoral holdings in the euro area since 2015. The portfolio adjustment cost of the rest of the world from trading euro area government bond securities, $\gamma_{B^{*,EA}_{GH}}$, is also calibrated symmetrically to 0.01. The internationally traded private bonds transaction cost, $\gamma_{B^{ROW}}$ is calibrated symmetrically, being equal to 0.01 for euro area countries.

With respect to the financial sector, we use data on loans and lending rates from the BSI and MIR statistics from the ECB. In this respect, Table 4 reports the ***wholesale bankers*** calibration. The parameters λ_b and δ_b of the Gertler and Karadi (2011b) specification, that capture the diversion rate for private loans and the relative diversion rate for government bonds, respectively, are calibrated non-symmetrically. These parameters are instrumental in controlling the strength of the portfolio rebalancing channel of central bank asset purchases since they capture the relative diversion rate for government bond. More explicitly, a value of δ_b very close to 0 would weaken the bank portfolio constraints on holdings of sovereign bonds and vanish the macroeconomic impact of asset purchases. In this respect, the relative diversion rate for government bonds is chosen as such in order to match the decrease in sovereign yields following the asset purchase programme with those estimated in event studies like Altavilla et al. (2016). The calibration of δ_b is done in combination to the calibration

[7] We map an endogenous variable at the steady state with a parameter and adjust the later to match the target value for the former.

$\gamma_{B_{GH}}$, as the selling pattern of government bonds from households and banks influence the decrease in sovereign yields following the asset purchase programme. The diversion rate for private loans, λ_b, is determined endogenously. The ratio of government bonds held by banks to loans is calibrated based on empirical evidence amounting to approximately 15%, 15%, 30%, 20% and 20% in Germany, France, Italy, Spain and rest of euro area, respectively. Due to the fact that the modeldoes not allow for any cross border lending, bank NFC loans are equal to total indebtedness in the economy, with the latter being calibrated based on empirical evidence, amounting to 34%, 35%, 44%, 61% and 43% in Germany, France, Italy, Spain and rest of euro area, respectively. Last, the continuation probability of bankers, ζ_b, is calibrated as such in order to ensure that the bank capital wedge over the funding cost is equal to 0.6% which results in the household transfer to bankers to clear the net worth accumulation equation for given spreads.

Table 5 shows the calibration of the ***retail lending branches***. The elasticity of substitution μ_E^R of the CES aggregation of differentiated loans is calibrated so that the monopolistic wedge is symmetric across countries and equal to 0.8%. Regarding staggered lending rate setting, the probability of not being able to re-optimise lending rates each quarter, ξ_E^R, is calibrated as such so that in Germany and France there is lower maturity transformation than in Spain and Italy. Therefore, the probability of not re-optimising lending rates in Germany and France, is up to 60%, and lower in Spain and Italy, down to 20%. This value allows to reproduce the euro area wide average pass-through of short-term rates to composite bank lending rates (see notably the evidence provided by Darracq Pariès et al. (2014)).

As shown in Table 6, we calibrate the standard deviation of the idiosyncratic shock in the ***entrepreneurs*** problem, σ_e, as such so that to account for lower default probabilities for Germany and France but higher for Spain and Italy, in line with corresponding evidence from Moody's Expected Default Frequency.[8] In this respect, the corporate default probability equals approximately 2.8%, 2.8%, 4%, 3.6% and 2.8% in Germany, France, Italy, Spain and rest of euro area, respectively. The monitoring cost μ_e of the costly state verification set-up is set to 0.07. The recovery ratio in case of default, χ_e, is calibrated as such so that the private sector indebtedness in the steady state is broadly consistent with an interpretation of bank intermediation which would cover only firms borrowing and its ratio to GDP is consistent with empirical evidence. In this respect, total indebtedness amounts to 34%, 35%, 44%, 61% and 43% in Germany, France, Italy, Spain and rest of euro area, respectively, and is equal to bank NFC loans as it is assumed that there is no cross border lending. The external finance premium and the entrepreneurs leverage are determined endogenously. Last, the continuation probability of bankers, ζ_e, clears the net worth accumulation equation for given spreads.

Table 7 reports the calibration of the standard and non-standard monetary policy tools. The interest rate reacts to its lagged value as well as to the inflation gap from the target, to quarterly inflation changes and to the quarterly output growth. It is calibrated non-symmetrically across countries as we allow for higher interest rate inertia and interest rate sensitivity to inflation gap in the rest of the world rather than in the euro area, while the sensitivity of output growth in the rest of the world is lower than in the euro area. The inflation target is set to 2% per year on all regions. The announced monthly flow of the central bank asset purchases scenario is introduced

[8]The probabilities of default are calculated based on the Moodys Expected Default Frequency (EDF). The EDFs corresponds to the expected probability of default 1-year ahead.

through news shocks in the rule in equation (52). The calibration of the parameters γ_i are such that government bond purchases that are carried out per period for approximately a bit less than two years ($i = 0, ..., 6$) and at a pace where the peak of the build-up phase, correspond to purchases of approximately 9.6% of annual GDP per country/region in the euro area. This scenario corresponds to the initial ECB's Private Sector Purchase Programme (as announced in January 2015). Consistent with the assumption that bonds are 10-year equivalent and are held to maturity, it is further assumed that subsequently the portfolio holdings start decaying following an AR(1) process, with ρ_{CB} being calibrated to 0.972.

Table 8 reports the calibration of **long-term sovereign bonds**. The calibration of the geometric-decay of the perpetual coupons government bonds, τ_g, ensures that the duration of the securities is 10 years. The initial coupon level, c_g, is adjusted to ensure that the steady state sovereign bond price, Q_G, is normalised to 1.

The calibration of the country specific tax rates corresponding to are reported in Table 12 in Appendix D.5 together with the rest of the calibration of the fiscal authority.

4 The transmission mechanism of central bank asset purchases through the monetary union

In this section, we evaluate the transmission through the monetary union of ECB's asset purchase programme. The benchmark scenario corresponds to the initial Private Sector Purchase Programme as part of the expanded asset purchase programme, designed in line with the central bank's announcements of January 2015. More specifically, it involves monthly purchases of €60 billion, from March 2015 until September 2016, amounting to 1.14 trillion. This is equivalent to approximately 9.6% of euro area annual GDP. The share of purchases in the home market is proportional to the nominal GDP of the corresponding euro area country. This assumption is broadly consistent with the Governing Council decision for the share of purchases conducted by each national central bank's (NCB) to be determined by the ECB's capital key, with NCBs focusing exclusively on their home market.

In what follows, this scenario is simulated in three different environments. ***First***, the baseline simulation abstracts from global portfolio frictions, focuses accordingly on the credit channels of asset purchases and allows for the short-term risk-free rate to be unconstrained to the effective lower bound and in this respect follow the specified monetary policy rule. In this context, we exploit the multi-country nature of the model in order to evaluate the cross-border spillovers from the asset purchases, through trade and financial linkages. The ***second*** simulation deviates from the first one assuming that the short-term risk-free interest rates reached their effective lower bound, according to the interest rate rule in equation (50). This simulation also sheds light on the timing of the ELB exit. The ***third*** case, extends the model in order to incorporate global portfolio frictions through which the rest of world is able to trade euro area bonds. In this case, any sellings of euro area bonds from the rest of the world, as part of the public purchase programme, opens up the exchange rate channel of central bank purchases, amplifying the euro depreciation vis-à-vis the rest of the world, thereby rebalancing the transmission mechanism towards trade channels. For each simulation, Impulse Response Functions (IRFs) are reported for selected variables which illustrate best the macroeconomic propagation mechanism. Figures report in greater details outcomes for the euro area economy while spillovers to the rest of the world are mainly shown through output, inflation responses, monetary policy rate and selling pattern on the euro area government bond market.

4.1 The credit channels of central bank asset purchases

As explained previously, the baseline case assumes that central bank asset purchases mimic the first government bond purchase programme of the ECB.

Starting from the initiation of the APP program, as observed in Figure 6, we assume that purchases are symmetric across euro area countries/regions and are carried out every period for approximately a bit less than two years, with the sovereign bond portfolios peaking at approximately 9.6% of annual GDP per country. Our calibration of households portfolio adjustment costs are homogenous across regions and imply that at the peak of the central bank portfolio, households for all euro area regions, bear approximately 40% of adjustments in sovereign bond holdings, while banks account for the rest. Given that we do not account of the rest of the world sales of bonds in this simulation (which is explored thereafter once we allow for global portfolio frictions), those ballpark figures are not fully at odds with observed changes in sectoral holdings in the euro area since 2015.

While the selling patterns are symmetric across euro area regions, we induce heterogeneity in the drop of sovereign yields through the calibration of portfolio frictions for bankers. As mentioned before, the specification of the agency problem between bankers and its creditors distorts bank asset composition and opens up a role for central bank purchases to affect long-term bond yields. In quantitative terms, our calibration aimed at being consistent with the findings of event studies like Altavilla et al. (2016). Accordingly, the sovereign yields decline more in Spain and Italy than in France and Germany.

Due to the bankers portfolio frictions, the risk-adjusted excess return on loan origination is proportional to the risk-adjusted return on sovereign bond holding. This creates a pass-through of sovereign yield decline into lending rate spreads. Across regions, the asymmetric calibration for these frictions, implies that the larger the yield impact, the lower the relative pass-through to lending rates. Overall the credit easing effect of the asset purchase programme is sizeable and persistent.

The more favourable financing conditions are then transmitted to entrepreneurs and spur capital expenditures. In the model, the credit channel of asset purchases primarily impact on private investment. As observed in Figure 7, the peak response of investment is relatively similar across regions at around 1%, with France being on the low side, whereas the expansionary effects turns out more persistent in Italy and Spain. The heterogeneity in the increase of corporate loans appears more significant. In Italy and Spain, where firms are more risky and indebtedness is higher, the response of loans is milder and more protracted. Turning to consumption, the tightening of standard monetary policy depresses consumption in the short run while higher income generation ultimately supports household expenditures over the medium term. The impact on output ranges from 0.2 to 0.27 across countries: it is stronger and more persistent for Italy and Spain but somewhat lower at the peak for Germany and less persistent for France. The relative weakness of Germany on output effect despite its high investment response is partially due to less favourable trade spillover both intra-euro area (see thereafter) and extra-euro area (through higher exposure to the slight appreciation of the exchange rate). Finally, inflationary effects materialise by 0.06 p.p. of annual CPI inflation on average at the peak. The inflation response is relatively less pronounced but also less volatile in Germany.

In the rest of the world economy, the international spillovers of euro area central bank asset purchases are mainly operating through trade channels. Indeed, we assume that cross-border financial flows only take place in the rest of the world private short-term bond market and this market is not directly affected by the non-standard measures in the absence of global portfolio frictions. Consequently, the rest of the world economy is mainly facing higher import demand from the euro area economy, given the marginal changes in the exchange rate. In line with the limited trade openness of the euro area economy, the output spillover to the rest of the world reaches around 12% at the peak.

The multi-country dimension of the model is also well-suited to investigate the cross-country spillover of asset purchases within the monetary union, stemming from either international trade or financial linkages. We measure the cross-country spillovers on a given region as the difference between two scenarios: one in which the sovereign bonds from all euro area jurisdictions are purchased and one in which only the region-specific ones are purchased. Therefore, the spillovers on Germany for example, could be interpreted as the effects of central bank asset purchases on the other sovereign markets. Figures 8 and 9 presents such spillovers for the same variables and countries as in Figures 6 and 7, which facilitates the comparison. Starting with economic activity, the peak spillover effects range from 0.04% for Germany to 0.08% for the rest of the euro area. This represents 20% and 40% of the overall impact shown in Figure 7 for those two regions, respectively. For France, Italy and Spain, output spillovers are between 25% to 30% of the total effect. On inflation, the spillovers reach a maximum at around 0.03 p.p. for Germany and 0.05 p.p. for the other countries. Again, the large country size and net export position of Germany partly explain the lower spillovers, which in comparison from the overall effect remain very high. Inspecting the limited spillovers on sovereign markets and the banking spreads, it appears that most of the macro spillovers might be explained by trade channels. All in all, the international transmission of asset purchases from one jurisdiction to the other is significant within the monetary union and even so for a large country like Germany.

4.2 Asset purchases at the effective lower bound on interest rates

Asset purchase programmes were usually introduced as an additional policy tool when the short-term interest rate reached its effective lower bound and thus the room for further easing of the monetary stance through standard measures has been exhausted. Therefore, they were implemented in an environment where the short-term interest rates are constrained by their effective lower bound. To analyse such a policy configuration, we simulate an endogenous lower bound scenario. Specifying the central bank interest rate policy as in equation (50) implies that the length of the lower bound period becomes endogenous. Such an occasionally binding constraint brings some non-linearity into the model and makes the macroeconomic multipliers of central bank asset purchases quite sensitive to the underlying crisis scenario.

Indeed, one needs to provide a meaningful selection of shocks which can severely depress economic conditions so that the policy rate reaches its lower bound. In most of the literature, the lower bound scenario is generated by a single shock, for example a discount factor shock. Since our model has satisfactory data consistency, it allows for well-founded shocks located in the financial sphere which are combined on the basis of selected stylised facts. An analysis of the shocks that have directed the economy into that position is beyond the scope of this paper. Nevertheless, a detailed exposition of the three layers of shocks, these being corporate risk shocks, sovereign tensions and adverse bank deleveraging process, that hit the economy during the recent financial crisis and led the interest rates to the effective lower bound can be found in Darracq Pariès et al. (2016). Consequently, we simulate the effect of the benchmark asset purchase programme on the back of the crisis scenario. In this scenario, the ELB would still be binding until 2018.

The simulations at the ELB are presented in Figures 10 and 11. The constraint on the policy rate leads to a strong amplification of the asset purchases impact on output and inflation. The expansionary effect on investment almost doubles for all regions, reaching around 2% at the peak, whereas the response of consumption now turns positive all through the simulation horizon, increasing to 0.2%. The increase in economic activity now culminates between 0.6% and 0.7% across regions, which is actually more than twice the effect reported under endogenous standard monetary policy. Indeed, the international trade channels become more supportive as the real effective exchange rate of the euro depreciates by 0.6% (against a marginal appreciation in the endogenous policy case). Across regions, the asymmetric transmission to real and credit variables is broadly preserved at the ELB. The amplification on inflation turns out to be even more pronounced, with CPI inflation increasing by around 0.3% across all regions. On the financial side however, the presence of the ELB does not significantly affect the responses of sovereign markets and banking spread variables. Regarding the course of standard monetary policy instrument, the economic stimulus from the purchase programme enables to start removing some policy accommodation earlier, with the lift-off date for the short-term interest rate being brought forward by three quarters.

On the rest of the world economy, the international transmission through import demand is stronger than in the absence of ELB but the larger exchange rate depreciation generates partial compensation. The overall spillover to rest of the world output is now around 8% (of the euro area output increase) at the peak. Rest of the world CPI inflation reacts marginally as the inflationary pressures from higher demand are broadly compensated by the pass-through of the euro depreciation.

4.3 Global portfolio frictions and the exchange rate channel of asset purchases

The previous scenario at the ELB, displayed some depreciation of the real exchange rate but showed the quantitative prevalence of the credit channel of central bank asset purchases over international transmission mechanism. In this section, we consider additional portfolio frictions which could meaningfully change this typology.

In this case, the euro area monetary authority can purchase sovereign securities from banks, domestic and rest of the world households. Depending on the relative portfolio frictions, the sectoral distribution of bond sell-off would be affected and the domestic credit or the exchange rate channels would be more or less active. Regarding the later, the adjustment cost on the international trading of euro area sovereign bonds introduces an imperfect substitution between short-term (private) and long-term (sovereign) foreign assets that the rest of the world region can hold. Indeed, in the absence of global trading on euro area sovereign bonds, the model only allow the rest of the world to buy and sell a short-term private bond which includes a region-specific risk premia (as a function of the net holding position on the market). The first order conditions related to the holdings of such an asset lead to a traditional uncovered interest rate parity whereby the expected exchange rate depreciation depends on the short-term interest rate differential and net foreign asset position. With the additional global portfolio frictions on euro area sovereign bonds, one can show that the modified uncovered interest rate parity would also depend on long-term interest rate differentials as well as on the relative external position on the two asset classes.

Inspecting the exchange rate determination mechanism with global portfolio frictions requires combining the first order conditions for private and government bond holdings across the rest of the world and euro area regions. In this respect, in order to get a better intuition, we linearise the corresponding first order conditions. Small cap letters denote (log-)linear deviations from steady state.[9]

From the euro area households we derive a first relationship between expected nominal exchange rate changes, short-term interest rate differentials and the position of the euro area households in the rest of the world short-term bond market, as follows

$$r_t^* - r_t + E_t s_{t+1}^{EA,ROW} - s_t^{EA,ROW} = \widetilde{\gamma}_{B^{ROW}} \tilde{b}_t^{ROW} \tag{59}$$

Besides, from the rest of the world households decision problem, a second relationship ties the excess return on euro area government bonds, adjusted for expected exchange rate changes, to the position of the rest of the world households in his market, defined as follows

$$E_t r_{G,t+1} - r_t^* - E_t s_{t+1}^{EA,ROW} + s_t^{EA,ROW} = \widetilde{\gamma}_{B_{GH}^{*,EA}} \tilde{b}_{GH,t}^{*,EA} \tag{60}$$

Combining both equations in order to retrieve the euro area net foreign assets gives

$$\left(\frac{1}{\widetilde{\gamma}_{B_{GH}^{*,EA}}} + \frac{1}{\widetilde{\gamma}_{B^{ROW}}}\right)\left(r_t^* + E_t s_{t+1}^{EA,ROW} - s_t^{EA,ROW}\right) - \frac{1}{\widetilde{\gamma}_{B_{GH}^{*,EA}}} E_t r_{G,t+1} - \frac{1}{\widetilde{\gamma}_{B^{ROW}}} r_t = nfa_t \tag{61}$$

where $nfa_t = \tilde{b}_{GH,t}^{*,EA} - \tilde{b}_t^{ROW}$ corresponds to the euro area net foreign asset deviation from the baseline (in real terms and as a share of steady state output).

Some straight forward rearrangements lead to a modified uncovered interest rate parity where the expected nominal exchange rate depreciation is a function of interest rate differentials, weighted by degrees of transaction costs and a time-varying premium related to net foreign assets.

$$\begin{gathered} E_t s_{t+1}^{EA,ROW} - s_t^{EA,ROW} = \\ \frac{\widetilde{\gamma}_{B^{ROW}}}{\widetilde{\gamma}_{B_{GH}^{*,EA}} + \widetilde{\gamma}_{B^{ROW}}} E_t r_{G,t+1} + \frac{\widetilde{\gamma}_{B_{GH}^{*,EA}}}{\widetilde{\gamma}_{B_{GH}^{*,EA}} + \widetilde{\gamma}_{B^{ROW}}} r_t - r_t^* + \frac{\widetilde{\gamma}_{B^{ROW}} \widetilde{\gamma}_{B_{GH}^{*,EA}}}{\widetilde{\gamma}_{B_{GH}^{*,EA}} + \widetilde{\gamma}_{B^{ROW}}} nfa_t. \end{gathered} \tag{62}$$

Let us assume that the euro area central bank asset purchases of domestic government bonds lead to a persistent compression of $E_t r_{G,t+1}$ through the credit channels exposed in the previous section. Everything else being equal, equation (62) shows that it would lead to a depreciation of the euro on announcement (i.e. higher $s_t^{EA,ROW}$), followed by gradual appreciation (similar to the overshooting dynamics of the uncovered interest rate parity). This would hold in partial equilibrium, assuming unchanged monetary policy rates and stable net foreign assets, the later being a state variable which adjusts mainly through changes in the current account. Pushing the mechanics further, rest of the world households would have some incentive to sell euro area government bonds as the expected

[9] $\widetilde{\gamma}_{B^{ROW}}$ and $\widetilde{\gamma}_{B_{GH}^{*,EA}}$ are scaled parameters of the corresponding $\gamma_{B^{ROW}}$ and $\gamma_{B_{GH}^{*,EA}}$, respectively.

return is lower. This can be seen from the combination of the associated first order condition in equation (60) and the modified uncovered interest rate parity in equation (62)

$$\tilde{b}^{*,EA}_{GH,t} = \frac{1}{\widetilde{\gamma}_{B^{*,EA}_{GH}} + \widetilde{\gamma}_{B^{ROW}}} \left(E_t r_{G,t+1} - r_t\right) - \frac{\widetilde{\gamma}_{B^{ROW}}}{\widetilde{\gamma}_{B^{*,EA}_{GH}} + \widetilde{\gamma}_{B^{ROW}}} nfa_t. \quad (63)$$

In general equilibrium, the exchange rate depreciation and the sales of euro area government bond holdings would also feedback on interest rates and net foreign assets. The trade channel of exchange rate depreciation tends to improve net foreign assets over the short-to-medium term. The sales of euro area government bonds limit the scope for portfolio rebalancing by euro area banks, thereby limiting the compression of euro area bond return. Short-term interest rates react along with the respective interest rate rules. These feedbacks are self-equilibrating but compared with the simulations of the previous sections, the presence of global portfolio frictions can be expected to trigger a stronger exchange rate depreciation and smaller or less persistent bond yield decline. Regarding the impact on output and inflation, the additional stimulus stemming from the trade channels of the exchange rate depreciation might be partly compensated by a weaker credit channel.

We now turn to a quantitative assessment of those propagation mechanisms in the full model. Figures 12 and 13 show the impact on the benchmark asset purchase programme from the presence of the global portfolio frictions and subject to the constraint of the effective lower bound. We calibrated the adjustment cost parameters in the trading on international assets such that the effective exchange rate depreciation of the euro reaches 3%. This magnitude is on the low side but qualitatively in line with available event studies (like Altavilla et al. (2016)). In comparison to the results of Figures 10 and 11, the global portfolio frictions have a significant influence on the magnitude of the macroeconomic multipliers as well as on the typology of the transmission mechanism. Focusing first on the sovereign bond market, it turns out that the rest of the world now accommodates one fourth of the central bank purchases at the peak of the portfolio build-up while domestic banks bear less than 40% of the adjustment in holdings. Consequently, the strength of the bank-centric term spread channel weakens so that the compression of sovereign yields becomes smaller and much less persistent. Further down in the intermediation chain, the peak easing effect on bank lending rate spreads is reduced and the investment boom becomes less credit intensive. Therefore, the global portfolio frictions are overall dampening the credit channel of asset purchases.

However, on the real side, the expansionary impact of the purchase programme is reinforced. Investment increases by almost 3% at the peak for all regions, compared with 2% in the absence of global portfolio frictions. Due to stronger external impulse (which particularly benefits Germany) the output increase becomes twice larger, reaching 1.3% at the peak and is relatively homogenous across regions. On consumption, heterogenous import content across regions generates more asymmetric profiles due to varying imported inflation effects. The inflationary impact of the programme is also dramatically amplified by the exchange rate depreciation, bringing the maximum CPI inflation increase to almost 1%. Such macroeconomic conditions imply a significant shortening of the period where the ELB binds. In this scenario, the lift-off date is brought forward by more than 6 quarters. This feature is of course very much dependent of the inflation rate that enters the monetary policy rule. Should one specify the rule in terms of domestic inflation instead of CPI inflation, the course of interest rate policy might be less affected.

Finally, on the rest of the world economy, the transmission of the APP on activity is now ambiguous *a priori*: the expansionary impact on the euro area economy should have positive demand spillovers through trade while the stronger exchange rate adjustments would significantly erode the competitiveness of rest of the world producers. On balance, rest of the world CPI inflation declines by less than 0.1 p.p and rest of the world output increases marginally above baseline.

5 Conclusion

We have developed and calibrated a large-scale multi-country DSGE model for the euro area which features relevant transmission channels of non-standard monetary policies. In particular, the model can account for a significant degree of cross-country heterogeneity, notably on the financial side. It also enables to examine the propagation mechanism of central bank asset purchases through domestic credit conditions as well as through the exchange rate.

Inspecting the transmission mechanism of central bank asset purchases, model simulations shed some light on the relative role of credit versus trade channels at the country level, as well as on the size of cross-country spillovers within the currency union. The interaction between international and domestic channels affects the magnitude and the cross-country distribution of the APP impact. Besides the intra-euro area spillovers might account for more than 20% of output effects on individual countries.

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Appendices

A Model description

Figure 1: Schematic representation of the model with global portfolio frictions

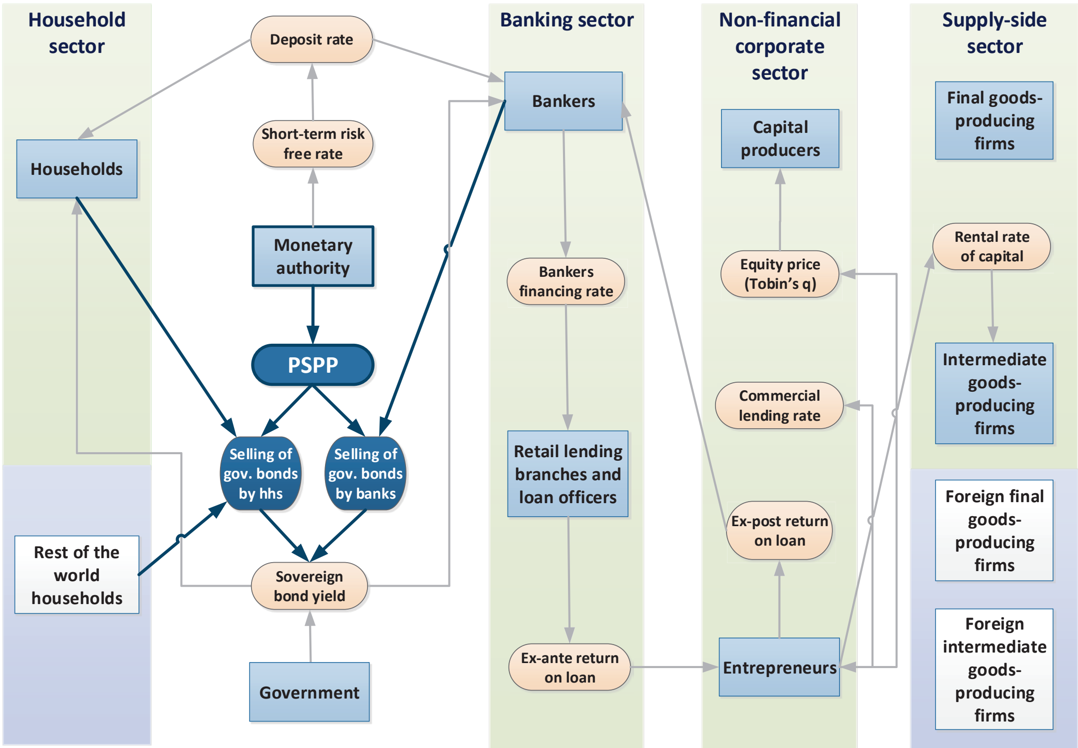


Table 1: Financial assets internationally traded by households

	Trading region					
	DE	FR	SP	IT	REA	ROW
DE government bonds	•					•
FR government bonds		•				•
SP government bonds			•			•
IT government bonds				•		•
REA government bonds					•	•
ROW government bonds						•
DE private bonds	•	•	•	•	•	
ROW private bonds	•	•	•	•	•	•

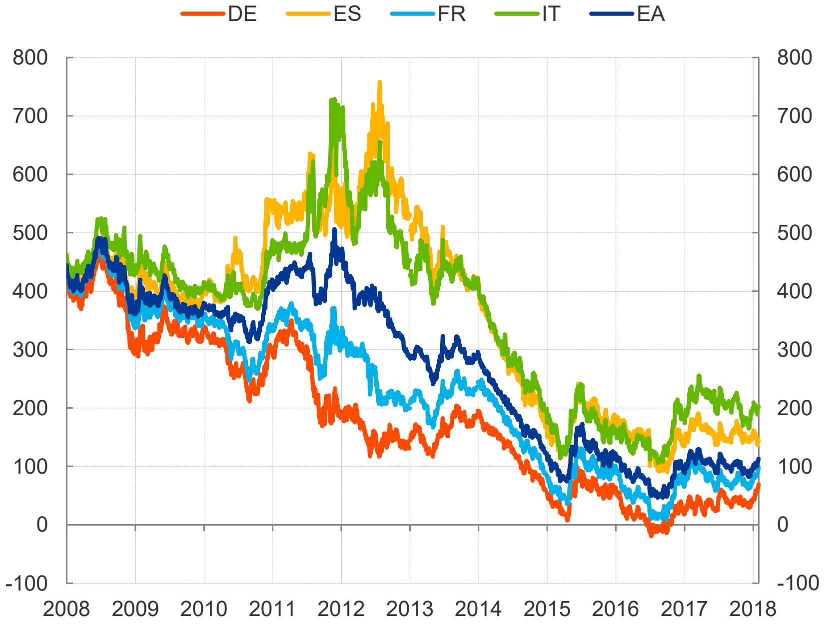
Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 2: Bankers' balance sheet

Assets	Liabilities
Loans	Deposits
Government securities	Net worth

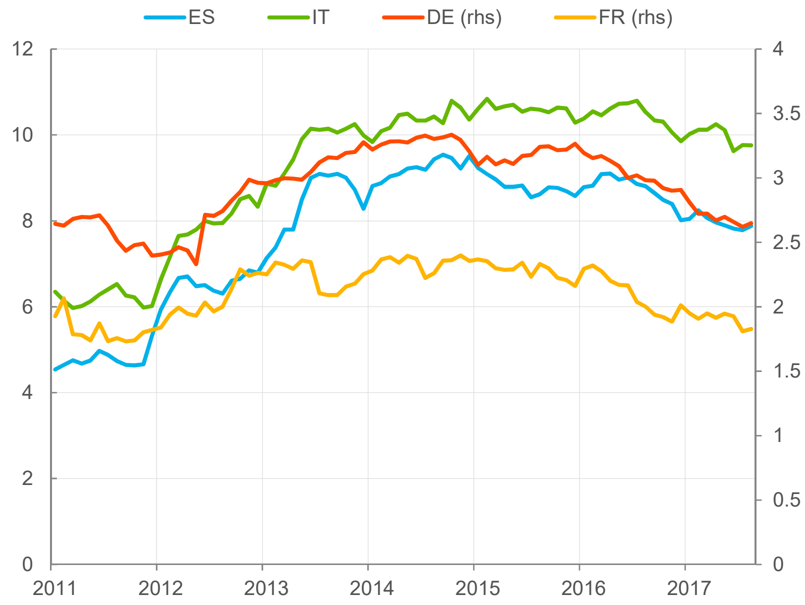
B Stylised facts

Figure 2: 10-year government bond yields



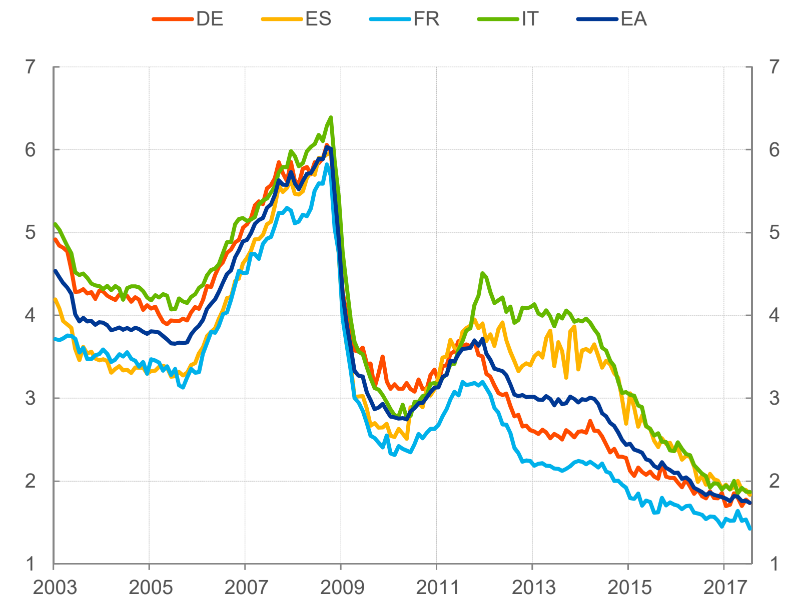
Notes: ECB calculations. Yields. EA is GDP weighted. DE = Germany; FR = France; IT = Italy; ES = Spain; EA = Euro area.

Figure 3: Holdings of domestic government bonds by MFIs other than the Eurosytem



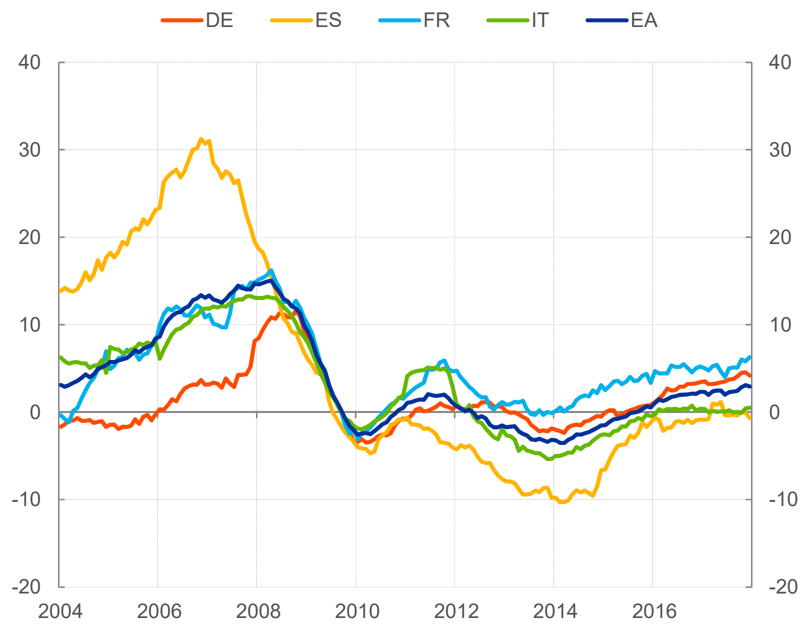
Notes: ECB calculations. Percentage of total assets. DE = Germany; FR = France; IT = Italy; ES = Spain.

Figure 4: Composite indicator of the cost of borrowing for non-financial corporations



Notes: ECB calculations. Percentages per annum. DE = Germany; FR = France; IT = Italy; ES = Spain; EA = Euro area.

Figure 5: MFI loans to non-financial corporations



Notes: ECB calculations. Annual growth rate; adjusted for sales, securitisation and cash pooling activities; adjusted for calendar or working day effects. DE = Germany; FR = France; IT = Italy; ES = Spain; EA = Euro area.

C Model calibration

Table 3: Households

Parameter		DE	FR	SP	IT	REA	ROW
Preferences							
Discount factor	β	0.995	0.995	0.995	0.995	0.995	0.995
Intertemporal elasticity of substitution	σ	1.000	1.000	1.000	1.000	1.000	1.000
Inverse of the Frisch elasticity of labour	ζ_n	2.000	2.000	2.000	2.000	2.000	2.000
Habit persistence	κ	0.900	0.900	0.900	0.900	0.900	0.900
Consumption goods transaction costs							
First transaction cost function parameter	γ_{v1}	0.029	0.029	0.029	0.029	0.029	0.029
Second transaction cost function parameter	γ_{v2}	0.153	0.153	0.153	0.153	0.153	0.153
Portfolio adjustment costs							
Domestic trade of gov. bonds	$\gamma_{B_{GH}}$	0.040	0.040	0.040	0.040	0.040	0.040
ROW trade of EA gov. bonds	$\gamma_{B_{GH}^{*,EA}}$	–	–	–	–	–	0.010
EA trade of ROW private bonds	$\gamma_{B^{ROW}}$	0.010	0.010	0.010	0.010	0.010	–

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 4: Wholesale banks

Parameter		DE	FR	SP	IT	REA	ROW
Diversion rate for loans	λ_b	0.240	0.236	0.168	0.151	0.209	0.216
Relative diversion rate for gov. bonds	δ_b	1.200	1.300	3.700	3.600	2.000	2.000
Household transfer to bankers	Ψ_B/L_{BE}	0.003	0.003	0.004	0.005	0.004	0.003
Continuation probability of bankers	ζ_b	0.955	0.948	0.944	0.935	0.945	0.948
Variable							
Gov. bonds held by banks to loans (percent)	$Q_G B_{GB}/L_{BE}$	15.00	15.00	20.00	30.00	20.00	15.00
Bank NFC loans to GDP (percent)	$L_{BE}/(4Y)$	34.00	35.00	61.00	44.00	43.00	40.00
Bank leverage to loans	κ_E^b	5.602	5.639	4.979	4.944	5.605	5.029
Bank leverage to gov. bonds	κ_G^b	2.773	3.102	2.397	2.916	2.511	3.018
Bank capital wedge (percent)	$4(R_{BLE}/R-1)$	0.600	0.600	0.600	0.600	0.600	0.600

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 5: Retail lending branches

Parameter		DE	FR	SP	IT	REA	ROW
Elasticity of substitution of dif. loans	μ_E^R	1.002	1.002	1.002	1.002	1.002	1.002
Prob. of not re-opt. lending rates (percent)	ξ_E^R	60.00	60.00	20.00	20.00	40.00	40.00
Variable							
Monopolistic wedge (percent)	$4(R_{LE}/R_{BLE}-1)$	0.800	0.800	0.800	0.800	0.800	0.800

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 6: Entrepreneurs

Parameter		DE	FR	SP	IT	REA	ROW
St.dev. of idiosyncratic shock	σ_e	0.235	0.236	0.269	0.308	0.224	0.230
Monitoring cost	μ_e	0.070	0.070	0.070	0.070	0.070	0.070
Recovery ratio in case of default (percent)	χ_e	29.54	29.08	47.61	44.82	36.26	32.72
Continuation probability of entrepreneurs	ζ_e	0.99	0.98	0.98	0.98	0.98	0.98
Variable							
Prob. of default (percent)	$1-(1-F(\overline{\omega}_e))^4$	2.771	2.771	3.552	3.940	2.771	2.771
Leverage	κ_e	1.193	1.189	1.323	1.265	1.257	1.222
Indebtedness to annual GDP (percent)	$L_E/(4Y)$	34.00	35.00	61.00	44.00	43.00	40.00
External financing premium (percent)	$4(1+R_{KK})/R_{LE}-1)$	2.000	2.000	2.000	2.000	2.000	2.000
Credit risk compensation (percent)	$4(1+R_{LLE})/R_{LE}-1)$	0.383	0.384	0.531	0.635	0.375	0.379
Total commercial lending spread (percent)	$4(1+R_{LLE})/R-1)$	2.075	2.341	2.875	3.148	2.500	2.505

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 7: Monetary policy

Parameter		EA	ROW
Standard (interest rate rule)			
Annual inflation target (percent)	$\overline{\Pi}_C^4 - 1$	2.000	2.000
Interest rate inertia	ϕ_R	0.750	0.820
Interest rate sensitivity to inflation gap	ϕ_Π	1.500	1.830
Interest rate sensitivity to inflation changes	$\phi_{\Delta\Pi}$	0.050	0.050
Interest rate sensitivity to output growth	$\phi_{\Delta Y}$	0.150	0.060
Non-standard (PSPP rule)			
AR(1) parameter	ρ_{CB}	0.972	–

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 8: Long-term sovereign bonds

Parameter		DE	FR	SP	IT	REA	ROW
Coupon payment	c_g	0.028	0.030	0.033	0.035	0.031	0.031
Decaying rate for coupon payments	τ_g	0.020	0.020	0.020	0.020	0.020	0.020

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

D Global economic environment

In this Appendix we provide details on the sectors not covered in the main part, these being euro area households other than Germany, capital producers, goods-producing firms and government. The model exposition in the main part of the paper simplified the euro area block into a single region. In the full model, the region corresponding to Germany is specified similarly but the other euro area regions (France, Italy, Spain and rest of euro area) display some differences in specifications regarding the asset structure of the households.

D.1 Households for euro area regions other than Germany

In the following, the exposition refers to a generic euro area country other than Germany.

Regarding the asset structure, as mentioned previously, there are no short-term domestic private bonds issued in those regions. Instead, households can trade the German short-term private bond.

More specifically, the representative household of euro area countries other than Germany enter period t with holdings of German short-term private bonds B_t^{DE}, with corresponding gross nominal interest rate R_t. The return is also adjusted for a financial intermediation premium that the household must pay when taking a position in the corresponding market, defined as follows

$$\Gamma_{B^{DE}}\left(\frac{S_{r,t}^{H,DE}B_t^{DE}}{P_{Y,t}Y_t}\right) \equiv \gamma_{B^{DE}}\left(exp\left(\frac{S_{r,t}^{H,DE}B_t^{DE}}{\Pi_{C,t}^{DE}P_{Y,t}Y_t} - \overline{B}_Y^{DE}\right) - 1\right) \quad \text{(D.1)}$$

where $S_{r,t}^{H,DE}$ is the real exchange rate.

The household then faces the following budget constraint in nominal terms

$$\begin{aligned} &\mathcal{M}_{t-1} + R_{D,t-1}P_{C,t-1}D_{t-1} + R_{G,t}Q_{G,t-1}P_{C,t-1}B_{GH,t-1} \\ &+ (1-\Gamma_{B^{DE}})\,R_{t-1}P_{C,t-1}^{DE}B_{t-1}^{DE} + (1-\Gamma_{B^{ROW}})\,R_{t-1}^{*}S_t^{EA,ROW}P_{C,t-1}^{*}B_{t-1}^{ROW} \\ &+ \left(1-\tau_t^N-\tau_t^{W_h}\right)W_tN_t + (1-\tau_t^D)DV_t + TR_t + \Phi_t + \Xi_t + \Pi_{BE,t} \\ = &(1+\tau_t^C+\Gamma_v\left(V_t\right))P_{C,t}C_t + P_{C,t}D_t + P_{C,t}Q_{G,t}\left[B_{GH,t} + \frac{1}{2}\frac{\gamma_{B_{GH}}}{\overline{B}_{GH}}\left(B_{GH,t}-\widetilde{B}_{GH}\right)^2\right] \\ &+P_{C,t}^{DE}B_t^{DE} + S_t^{EA,ROW}P_{C,t}^{*}B_t^{ROW} + T_t + \mathcal{M}_t. \end{aligned} \quad \text{(D.2)}$$

The first order condition on holdings of the euro area private bonds issued in Germany reads as

$$\beta E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t} \frac{R_t}{\Pi_{C,t+1}} \right] = \frac{1}{1 - \Gamma_{B^{DE}} \left(\frac{B_t^{DE}}{P_{Y,t} Y_t} \right)}. \tag{D.3}$$

The rest of the euler equations are identical to the ones of the German case.

D.2 Capital producers

At the beginning of period t, those firms buy back the depreciated capital stocks $(1-\delta)K_{t-1}$ at real prices (in terms of consumption goods) Q_t. Then using distributed goods they augment the various stocks through the following capital law of motion

$$K_t = (1-\delta)K_{t-1} + \left[1 - \Gamma_I \left(\frac{I_t}{I_{t-1}} \right) \right] I_t \tag{D.4}$$

where Γ_I represents a non-negative quadratic adjustment cost function formulated in terms of the gross rate of change in investment and it is defined as follows

$$\Gamma_I \left(\frac{I_t}{I_{t-1}} \right) \equiv \frac{\gamma_I}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2. \tag{D.5}$$

The augmented stocks are sold back to entrepreneurs at the end of the period t at the same prices. Hence, capital producer choose $\{K_t, I_t\}$ to maximise intertemporal profits for all t. Λ_t is defined to denote the Lagrange multiplier on the budget constraint (in real terms). Therefore, the decision problem of capital stock producers is given by

$$\max_{\{K_t, I_t\}} \mathbb{E}_t \sum_{k=0}^{\infty} \beta^k \frac{\Lambda_{t+k}}{\Lambda_t} \left\{ Q_{t+k}(K_{t+k} - (1-\delta)K_{t+k-1}) - P_{I,t+k} I_{t+k} \right\} \tag{D.6}$$

subject to the capital law of motion. When substituting equation (D.4) into equation (D.6), the resulting first order condition is the following

$$P_{I,t} = Q_t \left[1 - \Gamma_I \left(\frac{I_t}{I_{t-1}} \right) - \Gamma_I' \left(\frac{I_t}{I_{t-1}} \right) I_t \right] + \beta \mathbb{E}_t \left[Q_{t+1} \frac{\Lambda_{t+1}}{\Lambda_t} \left(\frac{I_{t+1}}{I_t} \right)^2 \Gamma_I' \left(\frac{I_t}{I_{t-1}} \right) \right] \tag{D.7}$$

where

$$\Gamma_I' \left(\frac{I_t}{I_{t-1}} \right) \equiv \gamma_I \left(\frac{I_t}{I_{t-1}} - 1 \right) \frac{1}{I_{t-1}}. \tag{D.8}$$

D.3 Firms

There are two types of firms in the model, the intermediate and the final goods producing firms. The intermediate goods consist of internationally tradable and non-tradable goods for consumption and investments. The final-goods producing firms use all intermediate goods to produce the final goods which are nontraded and used for consumption and investment.

D.3.1 Final goods-production firms

Firms producing final non-tradable goods are symmetric, act under perfect competition and use non-tradable, domestic and imported tradable intermediate goods as inputs. The intermediate goods are assembled according to a constant elasticity of substitution (CES) technology. Final goods can be used for private consumption and investment. For simplicity, as the decision problem between consumption and investment goods is symmetric, for simplicity in what follows the model exposition is given only for a generic good. Therefore, it should be noted that all variables and parameters in the full model are indexed with either C or I.

Each firm indexed by x ($x \in [0, s^H]$) produces a final good $\mathcal{Y}_t(x)$ using a CES technology

$$\mathcal{Y}_t(x) = \left[v^{\frac{1}{\mu}} \left(\left[v_T^{\frac{1}{\mu_T}} T_t(x)^{\frac{\mu_T - 1}{\mu_T}} + (1 - v_T)^{\frac{1}{\mu_T}} IM_t(x)^{\frac{\mu_T - 1}{\mu_T}} \right]^{\frac{\mu_T}{\mu_T - 1}} \right) + (1 - v)^{\frac{1}{\mu}} NT_t(x)^{\frac{\mu - 1}{\mu}} \right]^{\frac{\mu}{\mu - 1}}. \tag{D.9}$$

Three intermediate inputs are used in the production of this good. A basket NT_t of non-tradable goods, a basket T_t of domestic goods and a basket IM_t of imported goods. The parameter $\mu > 0$ denotes the intratemporal elasticity of substitution between tradable and non-tradable goods, v $(0 \leq v \leq 1)$ measures the weight of the tradable bundle in the production of the consumption good, the parameter $\mu_T > 0$ denotes the intratemporal elasticity of substitution between the bundles of domestic and foreign tradable intermediate goods and v_T $(0 \leq v_T \leq 1$ $)$ measures the weight of domestic tradable intermediate goods. Imports $IM_t(x)$ are a CES function of basket of goods imported from other countries, denoted as

$$IM_t(x) = \left[\sum_{J \neq I} \left(v_M^{I,J} \right)^{\frac{1}{\mu_M}} \left(IM_t^J(x) \left(1 - \Gamma_M^{I,J}(x) \right) \right)^{\frac{\mu_M - 1}{\mu_M}} \right]^{\frac{\mu_M}{\mu_M - 1}} \tag{D.10}$$

where $\mu_M > 0$ and the coefficients $v_M^{H,CO}$ are such that $0 \leq v_{M^C}^{I,J} \leq 1$, $\sum_{J \neq H} v_M^{I,J} = 1$. The term $\Gamma_M^{I,J}(x)$ represents adjustment costs on bilateral consumption imports of country I from country J (IM_t^J) defined as follows

$$\Gamma_M^{I,J}(x) \equiv \frac{\gamma_M}{2} \left(\frac{IM_t^J(x) / Q_t(x)}{IM_{t-1}^J / Q_{t-1}} - 1 \right)^2 \tag{D.11}$$

where $\gamma_M \geq 0$. By assumption, each firm x takes the previous period (sector-wide) import share, IM_{t-1}^J / Q_{t-1}, and the current demand for its output, $Q_t(x)$, as given. The adjustment costs lower the short-run price elasticity of imports.

Firm x chooses the combination of the tradable and non-tradable bundles T_t, IM_t and NT_t that minimizes the expenditure

$$P_{T,t} T_t + P_{M,t} IM_t + P_{NT,t} NT_t \tag{D.12}$$

subject to the technology constraint in equation (D.9) and given the input price indexes $P_{T,t}$, $P_{M,t}$ and $P_{NT,t}$.

In the case of the basket NT_t, the following CES technology is exploited by final firms x

$$NT_t(x) = \left[\left(\frac{1}{s^H} \right)^{\frac{1}{\theta_N}} \int_0^{s^H} NT_t(x,n)^{\frac{\theta_N - 1}{\theta_N}} dn \right]^{\frac{\theta_N}{\theta_N - 1}} \tag{D.13}$$

where $NT_t(x,n)$ defines the use of the non-tradable intermediate goods n by the firm x and $\theta_N > 1$ is the intratemporal elasticity of substitution between the differentiated goods.

The firm x takes the prices of the non-tradable goods $P_t(n)$ as given and chooses the optimal use of each differentiated intermediate good n by minimizing the expenditure

$$\int_0^{s^H} P_t(n) \, NT_t(x,n) dn \tag{D.14}$$

subject to the production function. This yields the following demand for each non-tradable intermediate good n

$$NT_t(x,n) = \frac{1}{s^H} \left(\frac{P_t(n)}{P_{NT,t}} \right)^{-\theta_N} NT_t(x) \tag{D.15}$$

where $P_{NT,t}$ is the cost-minimizing price of one unit of the non-tradable basket defined as follows

$$P_{NT,t} = \left[\frac{1}{s^H} \int_0^{s^H} P_t(n)^{1-\theta_N} dn \right]^{\frac{1}{1-\theta_N}}. \tag{D.16}$$

D.3.2 Intermediate goods-production firms

There are firms producing tradable and non-tradable intermediate goods (brands) under monopolistic competition regime. Each tradable brand is produced by a firm h belonging to the continuum of mass s^H ($h \in [0, s^H]$). Similarly, each non-tradable brand is produced by a firm n, also defined over the continuum of mass s^H ($n \in [0, s^H]$). We will focus this section on the non-tradable sector. Similar considerations though hold for the generic firm in the tradable sector as well.

Non-tradable intermediate goods (n) are produced using a Cobb-Douglas technology

$$Y^S_{N,t}(n) = \max\{z_{N,t} K^D_t(n)^{\alpha_N} N^D_t(n)^{1-\alpha_N} - \psi_N, 0\}. \tag{D.17}$$

The inputs are homogenous capital services, $K^D_t(n)$ and an index of differentiated labor services, $N^D_t(n)$. Capital and labor services are supplied by domestic households under perfect competition and monopolistic competition, respectively. $z_{N,t}$ is a sector-specific productivity shocks.

The labor varieties supplied by domestic households and are input into the production of intermediate goods of firm n, $N^D_t(n)$, is as follows

$$N^D_t(n) = \left[\left(\frac{1}{s^H} \right)^{\frac{1}{\eta}} \int_0^{s^H} N^D_t(n,i)^{\frac{\eta-1}{\eta}} di \right]^{\frac{\eta}{\eta-1}} \tag{D.18}$$

where η is the elasticity of substitution between the differentiated services of labor varieties. Similar equation hold for the firms producing tradables, h.

Given rental cost of capital R^K_t and the aggregate wage index W_t, firms minimize the cost $R^K_t K^D_t(n) + \left(1 + \tau^{W_f}_t\right) W_t N^D_t(n)$ subject to the production function in equation (D.17) where $\tau^{W_f}_t$ is the payroll tax rate.

Nominal wage contracts for differentiated labor services are set in monopolistic competitive markets by households. Each firm takes wages as given and chooses the optimal input of each variety by minimizing the cost of forming household-specific labor bundles subject to the aggregation constraint in equation (D.18). This setup yields the following demand functions for varieties i by the generic firm n

$$N^D_t(n,i) = \frac{1}{s^H} \left(\frac{W_t(i)}{W_t} \right)^{-\eta} N^D_t(n) \tag{D.19}$$

where

$$W_t = \left[\frac{1}{s^H} \int_0^{s^H} W_t(i)^{1-\eta} di \right]^{\frac{1}{1-\eta}} \tag{D.20}$$

where η denotes the wage implied elasticity of substitution. It is further assumed that there is sluggish wage adjustment *à la* Calvo (Calvo (1983)) with ξ denoting the wage calvo parameter and χ the wage degree of indexation.[10]

It is assumed that there is sluggish price adjustment due to staggered price contracts *à la* Calvo (Calvo (1983)) in both tradable and non-tradable sectors. With respect to the tradable sector each firm charges different prices in local currency at home and in each foreign region, therefore the pricing problem distinguishes between the domestic and export markets. The probability of optimally resetting prices in a given period t equals ξ_H, ξ_N and ξ_X while the degree of indexation is χ_H, χ_N and χ_X, for the domestic tradable, non-tradable and export markets, respectively.

[10] This specification is similar to the EAGLE model as described in Gomes et al. (2012), therefore for space considerations is not shown explicitly here.

D.4 Government

In each country, the fiscal authority levies taxes on the household's gross income and spending. In particular, τ_t^C denotes the consumption tax rate levied on consumption purchases, τ_t^N represents the tax rates levied on wage income and τ_t^D represents the tax rate on dividends from firms ownership. Total revenues of the government increase further via social security contributions, first by households $\tau_t^{W_h}$ and secondly by firms $\tau_t^{W_f}$. Last, τ_t^K is the capital tax rate. In addition, the fiscal authority earns seignorage on outstanding money holdings, which consist only by cash holdings by households and not deposits to financial intermediaries.

Furthermore, the government receive lump-sum taxes from households as a fraction of steady state nominal output $T_t \equiv t_t \overline{P}_Y \overline{Y}$, where they are adjusted according to the following rule in order to make public debt stable across time

$$t_t \equiv \phi_{B_{GY}} \left(\frac{B_{G,t}}{\overline{P}_Y \overline{Y}} - \overline{B}_{GY} \right) \tag{D.21}$$

where $\frac{B_{G,t}}{\overline{P}_Y \overline{Y}}$ is the fiscal authority's target for the ratio of government debt to output and $\phi_{B_{GY}} > 0$ is a parameter.

Distortionary tax rates $\tau_t^C, \tau_t^D, \tau_t^K, \tau_t^N, \tau_t^{W_h}, \tau_t^{W_f}$ are assumed to follow an AR(1) process. The government uses its revenues to finance government purchases G_t, a final good which is a composite of non-tradable intermediate good only, and transfer payments to households TR_t, which are both defined as a fraction of steady state nominal output $P_{NT,t} G_t \equiv g_t \overline{P}_Y \overline{Y}$ and $TR_t \equiv tr_t \overline{P}_Y \overline{Y}$, respectively, that follow the following AR(1) process.

In the end, fiscal authority every period issues government bonds $B_{G,t+1}$ on a discount to refinance its debt and neutralise its budget. Therefore, the fiscal authority's budget constraint in nominal terms is as follows

$$\begin{aligned} P_{NT,t} \left(G_t + \Omega_{b,t} \right) + TR_t + \mathcal{M}_{t-1} + R_{G,t} Q_{G,t-1} P_{C,t-1} B_{G,t-1} \\ = \tau_t^C P_{C,t} C_t + \left(\tau_t^N + \tau_t^{W_h} + \tau_t^{W_f} \right) \left(W_t N_t \right) \\ \tau_t^K \left(R_{k,t} u_t - \left(\Gamma_u \left(u_t \right) + \delta \right) P_{I,t} \right) K_t + \tau_t^D DV_t + T_t + P_{C,t} Q_{G,t} B_{G,t} + \mathcal{M}_t \end{aligned} \tag{D.22}$$

where $R_{G,t}$ being the gross government bond interest rate.

D.5 Calibration

In what follows, we provide the calibration of the parts of the model that appear only in the Appendix.

Table 9 reports the additional calibration for **euro area households other than Germany**. The portfolio adjustment cost from trading Germany short-term private bond, γ_B^{DE}, is also calibrated symmetrically to 0.01.

Table 9: Households for euro area regions other than Germany

Parameter		DE	FR	SP	IT	REA	ROW
Portfolio adjustment costs							
EA trade of DE private bonds	γ_{BDE}	–	0.01	0.01	0.01	0.01	–

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 10 reports the calibration of the **capital producers and firms** behaviour. With respect to the capital producers, the annual depreciation rate, δ, the investment adjustment cost parameter, γ_I, and the capital utilisation rate, γ_{u2}, are calibrated symmetrically across countries being equal to 10%, 6 and 7, respectively. In the intermediate goods sector, the bias towards capital is almost the same for tradable goods (α_T) and non-tradable goods (α_N). As for the final goods baskets, the degree of substitutability between domestic and imported tradables, μ_{TC}, is higher than that between tradables and non-tradables, μ_C, consistent with existing literature (e.g. GEM or EAGLE). In particular, we set the elasticity of substitution between tradables and non-tradables to 0.5 while the elasticity between domestic and imported tradable goods to 1.5. In most countries, the bias towards the tradable bundle is higher in the investment basket than in the consumption baskets. The weight of domestic tradable goods in the consumption and investment tradable baskets is different across countries, to be coherent with multilateral import-to-GDP ratios. Price markups in the two sectors are higher in the euro area than in the rest of the world. Specifically, the net price markup in the tradables sector ($\theta_T/(\theta_T-1)$) is around 20% in the euro area and around 15% in the rest of the world. The markup in the non-tradable good's sector ($\theta_N/(\theta_N-1)$) is equal to 40% in the euro area and below 30% in the rest of the world.[11] Calvo price parameters in the domestic tradables, ξ_H, and non-tradables, ξ_N, sectors are set to 0.85 ($1/(1-\xi_H)=10$ quarters) in the euro area, consistently with estimates by Christoffel et al. (2008) and Smets and Wouters (2003). Corresponding nominal rigidities outside the euro area are also equal to 0.85. Calvo price parameters in the export sector, χ_X, are equal to 0.3 in all the regions. The indexation parameters on prices, χ_H and χ_N, are both equal to 0.3.

Table 10: Capital producers and firms

Parameter		DE	FR	SP	IT	REA	ROW
Capital producers							
Depreciation rate (percent)	δ	10.00	10.00	10.00	10.00	10.00	10.00
Investment adjustment cost parameter	γ_I	6.000	6.000	6.000	6.000	6.000	6.000
Capital utilization rate	γ_{u2}	7.000	7.000	7.000	7.000	7.000	7.000
Intermediate-good firms							
Bias towards capital, tradable goods	α_T	0.400	0.400	0.450	0.400	0.400	0.400
Bias towards capital, nontradable goods	α_N	0.404	0.445	0.525	0.424	0.379	0.470
Share of nontradables		0.411	0.524	0.516	0.540	0.404	0.649
Final consumption-good firms							
Subst. btw. domestic and imported trad. cons. goods	μ_{TC}	1.500	1.500	1.500	1.500	1.500	1.500
Bias towards domestic trad. cons. goods	υ_{TC}	0.468	0.454	0.263	0.426	0.204	0.847
Substitution btw. trad. and nontrad. cons. goods	μ_C	0.500	0.500	0.500	0.500	0.500	0.500
Bias towards trad. cons. goods	υ_C	0.737	0.617	0.536	0.577	0.783	0.379
Final investment-good firms							
Subst. btw. domestic and imported trad. inv. goods	μ_{TI}	1.500	1.500	1.500	1.500	1.500	1.500
Bias towards domestic trad. inv. goods	υ_{TI}	0.235	0.445	0.386	0.494	0.116	0.806
Substitution btw. trad. and nontrad. inv. goods	μ_I	0.500	0.500	0.500	0.500	0.500	0.500
Bias towards trad. inv. goods	υ_I	0.746	0.614	0.544	0.623	0.784	0.475
Price markups							
Tradables	$\theta_T/(\theta_T-1)$	1.213	1.213	1.213	1.213	1.213	1.150
Nontradables	$\theta_N/(\theta_N-1)$	1.400	1.400	1.400	1.400	1.400	1.279
Implied elasticities of substitution							
Tradables	θ_T	5.700	5.700	5.700	5.700	5.700	7.670
Nontradables	θ_N	3.500	3.500	3.500	3.500	3.500	4.580
Calvo parameters							
Prices - domestic tradables	ξ_H	0.850	0.850	0.850	0.850	0.850	0.850
Prices - domestic nontradables	ξ_N	0.850	0.850	0.850	0.850	0.850	0.850
Prices - exports	ξ_X	0.850	0.850	0.850	0.850	0.850	0.850
Degree of indexation							
Prices - domestic tradables	χ_H	0.300	0.300	0.300	0.300	0.300	0.300
Prices - domestic nontradables	χ_N	0.300	0.300	0.300	0.300	0.300	0.300
Prices - exports	χ_X	0.300	0.300	0.300	0.300	0.300	0.300
Degree of indexation							
Substitution btw. consumption good imports	μ_{MC}	1.500	1.500	1.500	1.500	1.500	1.500
Substitution btw. investment good imports	μ_{MI}	1.500	1.500	1.500	1.500	1.500	1.500

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 11 reports the calibration of the **labour market**. Wage implied elasticity of substitution, η is calibrated to be country specific across regions. They imply higher wage markup in the euro

[11] The chosen values are consistent with estimates from Martins et al. (1996), suggesting that the degree of competition in the non-tradable sector is lower than in the tradable sector. Also, these values are in line with other similar studies, such as Bayoumi et al. (2004), Faruquee et al. (2007) and Everaert and Schule (2008).

area around 30% compared to the rest of the world which is around 16%. Calvo wage parameter, ξ is calibrated as well symmetrically to be 0.85. The indexation parameter, χ is also calibrated symmetric across regions and equal to 0.30.

Table 11: Labour market

Parameter		DE	FR	SP	IT	REA	ROW
Wage mark-up	$\eta/(\eta-1)$	1.303	1.303	1.303	1.303	1.303	1.159
Wage implied elasticity of substitution	η	4.300	4.300	4.300	4.300	4.300	7.300
Wage calvo parameter	ξ	0.850	0.850	0.850	0.850	0.850	0.850
Wage degree of indexation	χ	0.300	0.300	0.300	0.300	0.300	0.300

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 12 reports the calibration of the **fiscal authority**. Taxes are calibrated to be non-symmetric across regions and are based on the 2000-2012 period. All tax rates are implicit using Eurostat with the exception of the tax on capital which is based on OECD data (see Table II.4 in OECD (2014)). Steady-state tax rates on consumption τ_t^C, income τ_t^N, capital τ_t^K, dividend income τ_t^D, social security contributions by households $\tau_t^{W_h}$ and by firms $\tau_t^{W_f}$ differ across countries in order to capture country differences in the allocation of taxes imposed by the government. Finally, the lump-sum taxes sensitivity to debt-to-GDP ratio is calibrated symmetrically across all regions.

Table 12: Fiscal authority

Parameter		DE	FR	SP	IT	REA	ROW
Taxes							
Consumption tax rate	τ^C	0.178	0.196	0.169	0.203	0.201	0.101
Divident tax rate	τ^D	0.066	0.128	0.079	0.128	0.115	0.102
Capital income tax rate	τ^K	0.372	0.352	0.331	0.321	0.286	0.398
Labor income tax rate	τ^N	0.174	0.102	0.109	0.150	0.127	0.127
Rate of social security contr. by firms	τ^{W_f}	0.168	0.303	0.233	0.246	0.174	0.094
Rate of social security contr. by hhs	τ^{W_h}	0.174	0.095	0.059	0.070	0.120	0.073
Fiscal rule							
Lump-sum taxes sens. to debt-to-GDP ratio	$\phi_{B_{GY}}$	0.650	0.650	0.650	0.650	0.650	0.650

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

Table 13 shows the steady state values of **main macro variables** in the model. Great ratios and import shares are computed using National Accounts over the 1999-2012 sample. Variables which are part of national accounts and represent the domestic demand and trade in the economies are reported as ratios to GDP. The endogenous variable investment to GDP ratio is calibrated in the steady state to much the respective ratio of each country. This is achieved through parameterizing accordingly share of capital in the production of non-tradables intermediate goods. Government expenditure are set equal to their steady state values. With respect to trade, the bilateral quasi shares of imports of consumption and investment goods are calibrated as such so that the corresponding shares are equal to the steady state values. Consumption to GDP is calculated endogenously by the solution of the steady state. Lastly, the same table reports the share of each region to the world GDP. Sizes of the regions are set to match their respective shares in terms of world GDP and net foreign asset position of each economy are set to zero at the steady state.

Table 13: Main macro variables

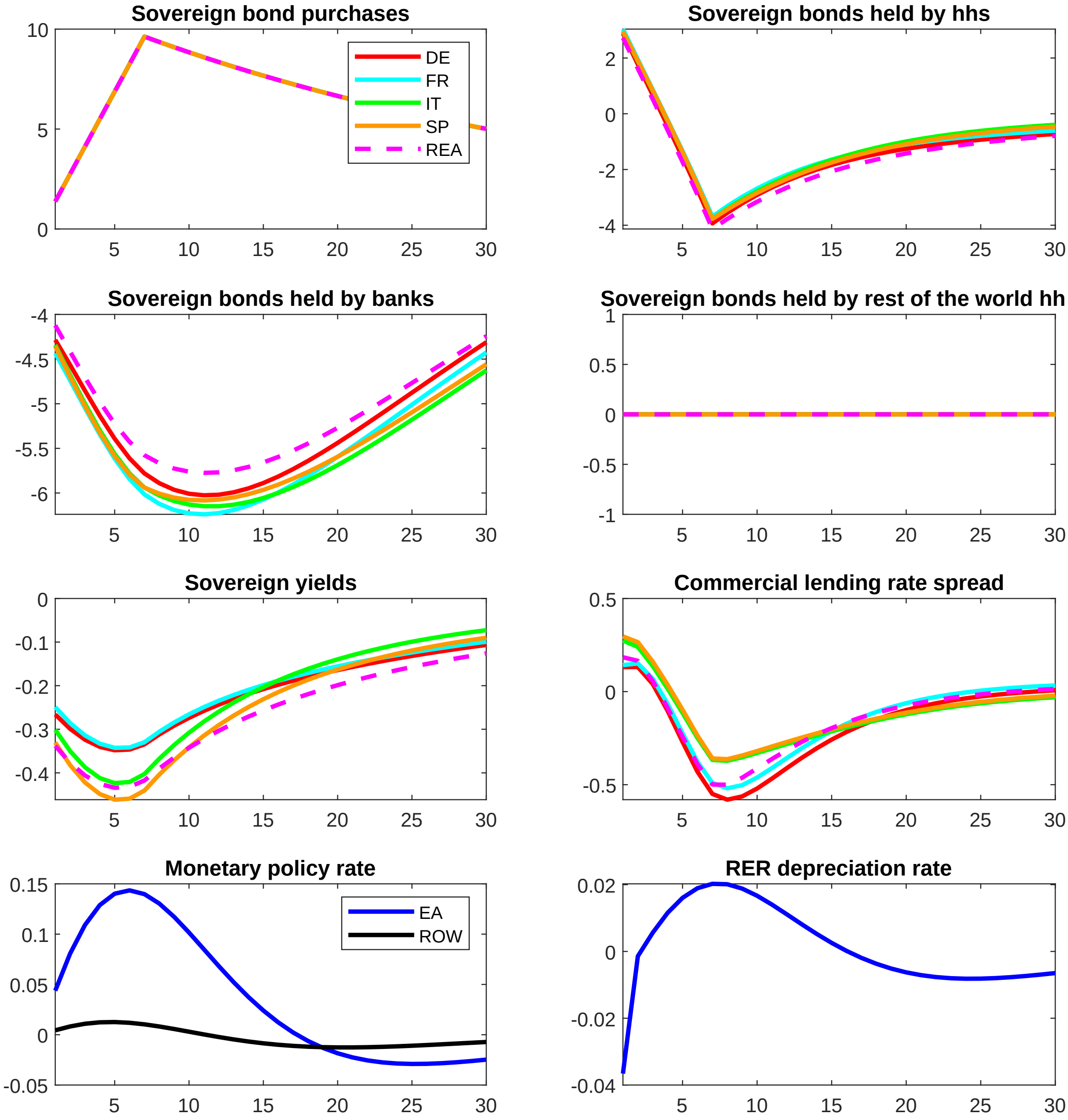
Variable		DE	FR	SP	IT	REA	ROW
Domestic demand (ratio to GDP)							
Private consuption	C/Y	0.623	0.565	0.551	0.597	0.577	0.603
Private investment	I/Y	0.210	0.220	0.250	0.210	0.210	0.220
Public consumption	G/Y	0.164	0.212	0.196	0.190	0.210	0.178
Trade (ratio to GDP)							
Total imports	IM/Y	0.371	0.272	0.306	0.265	0.492	0.050
Imports of consumption goods	IM_C/Y	0.253	0.196	0.225	0.198	0.351	0.032
Imported from DE		–	0.015	0.010	0.015	0.061	0.152
FR		0.026	–	0.015	0.016	0.037	0.102
SP		0.027	0.030	–	0.014	0.032	0.122
IT		0.025	0.020	0.010	–	0.034	0.110
REA		0.065	0.031	0.016	0.017	–	0.222
ROW		0.010	0.005	0.002	0.004	0.011	–
Imports of investment goods	IM_I/Y	0.118	0.077	0.081	0.067	0.141	0.018
Imported from DE		–	0.013	0.002	0.005	0.020	0.078
FR		0.016	–	0.003	0.006	0.011	0.040
SP		0.013	0.010	–	0.009	0.010	0.039
IT		0.013	0.006	0.002	–	0.011	0.036
REA		0.029	0.008	0.004	0.006	–	0.094
ROW		0.008	0.003	0.001	0.002	0.005	–
Share of world GDP		0.060	0.039	0.015	0.032	0.043	0.811

Note: DE = Germany; FR = France; SP = Spain; IT = Italy; REA = Rest of euro area; ROW = Rest of the world.

E Simulations

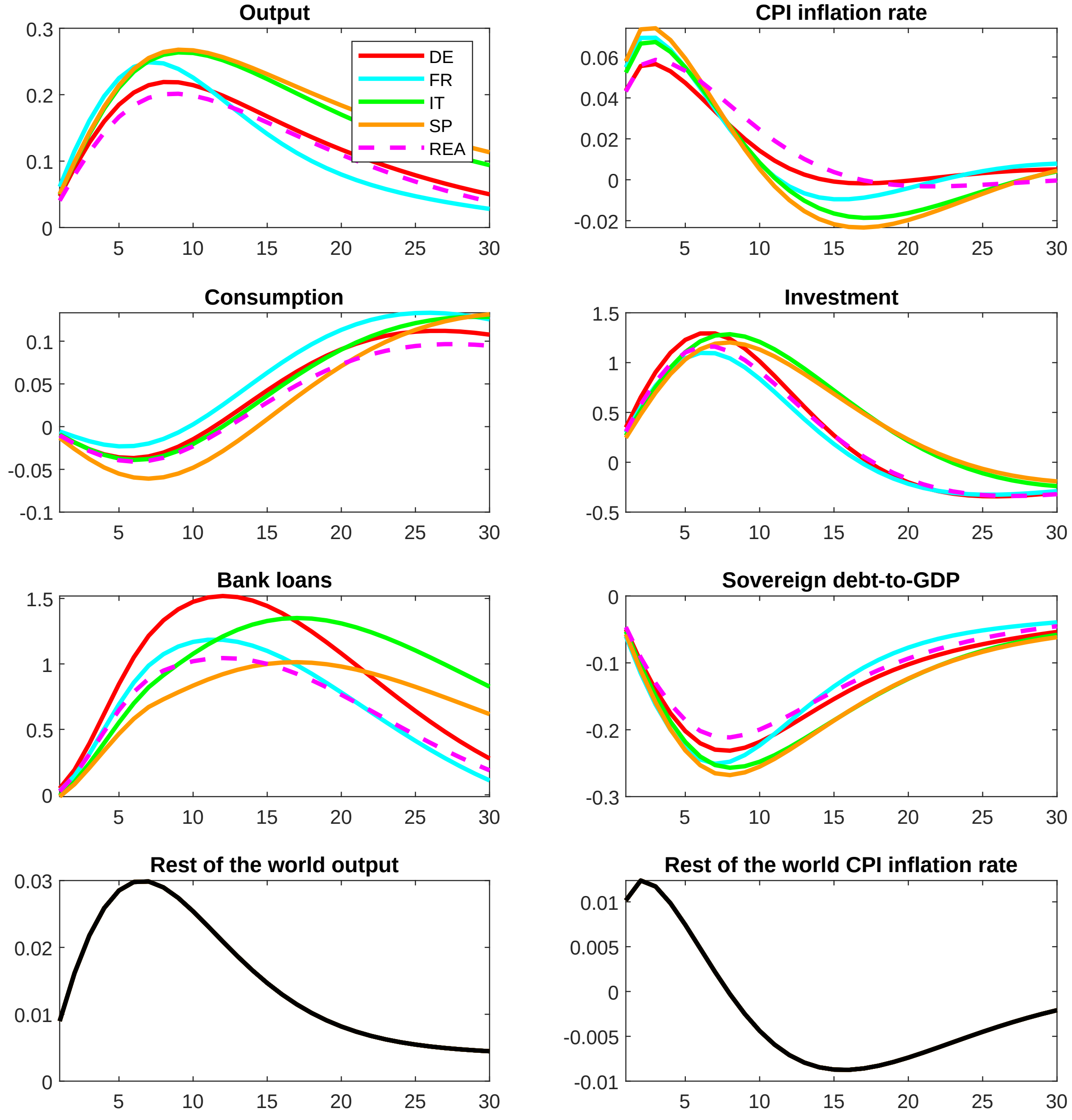
E.1 Baseline transmission of asset purchases

Figure 6: Central bank asset purchases baseline transmission- Simulations 1



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP). Horizontal axis: quarters. Vertical axis: annual percentage-point deviations, except for sovereign bond purchases, sovereign bonds held by hhs and sovereign bonds held by banks which are expressed as a percent of annual real GDP. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

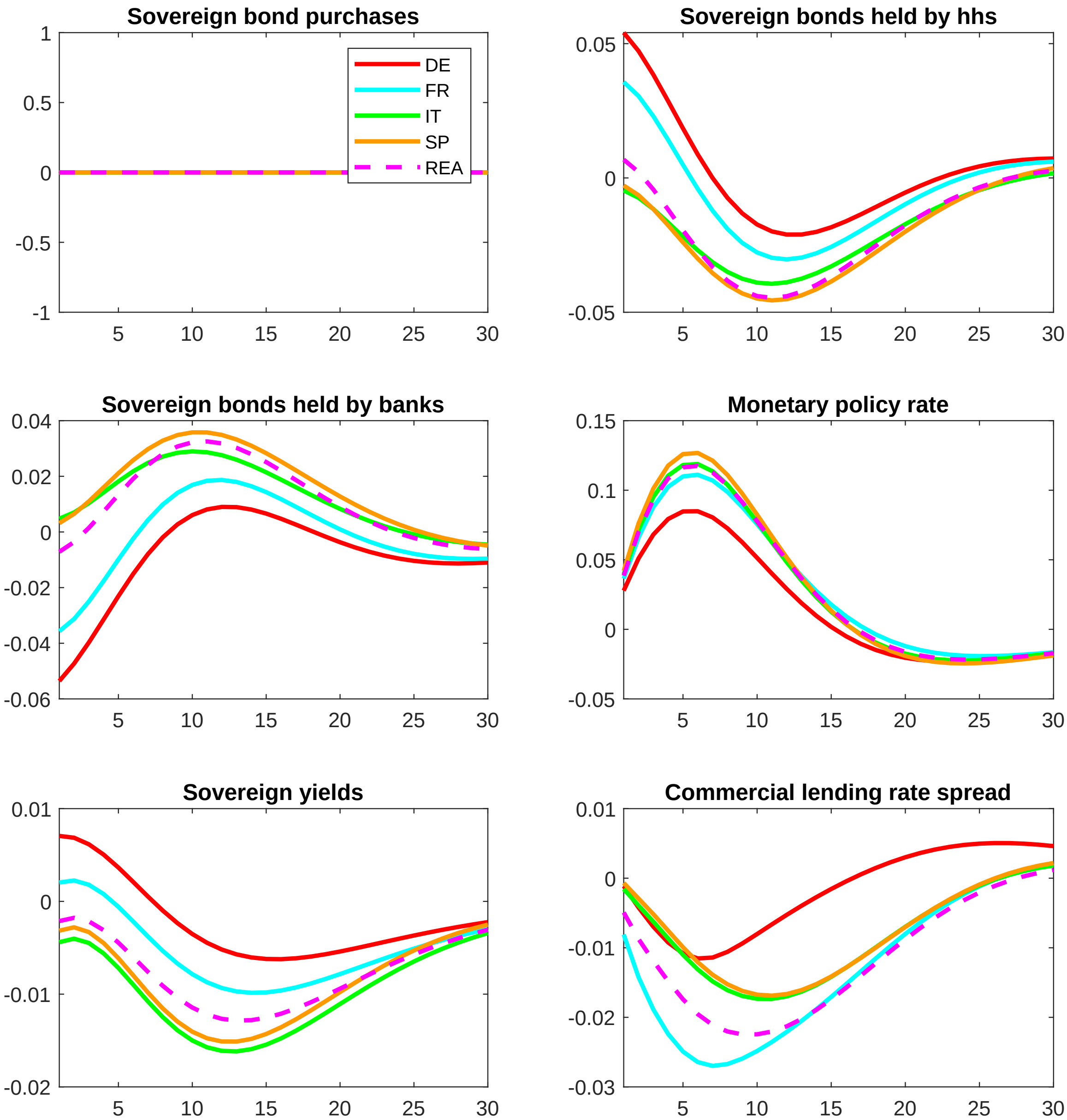
Figure 7: Central bank asset purchases baseline transmission- Simulations 2



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP). Horizontal axis: quarters. Vertical axis: percentage deviations from baseline, except for inflation, monetary policy rate and real exchange rate depreciation as annual percentage-point deviations. GDP, its components and banks loans are reported in real terms. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

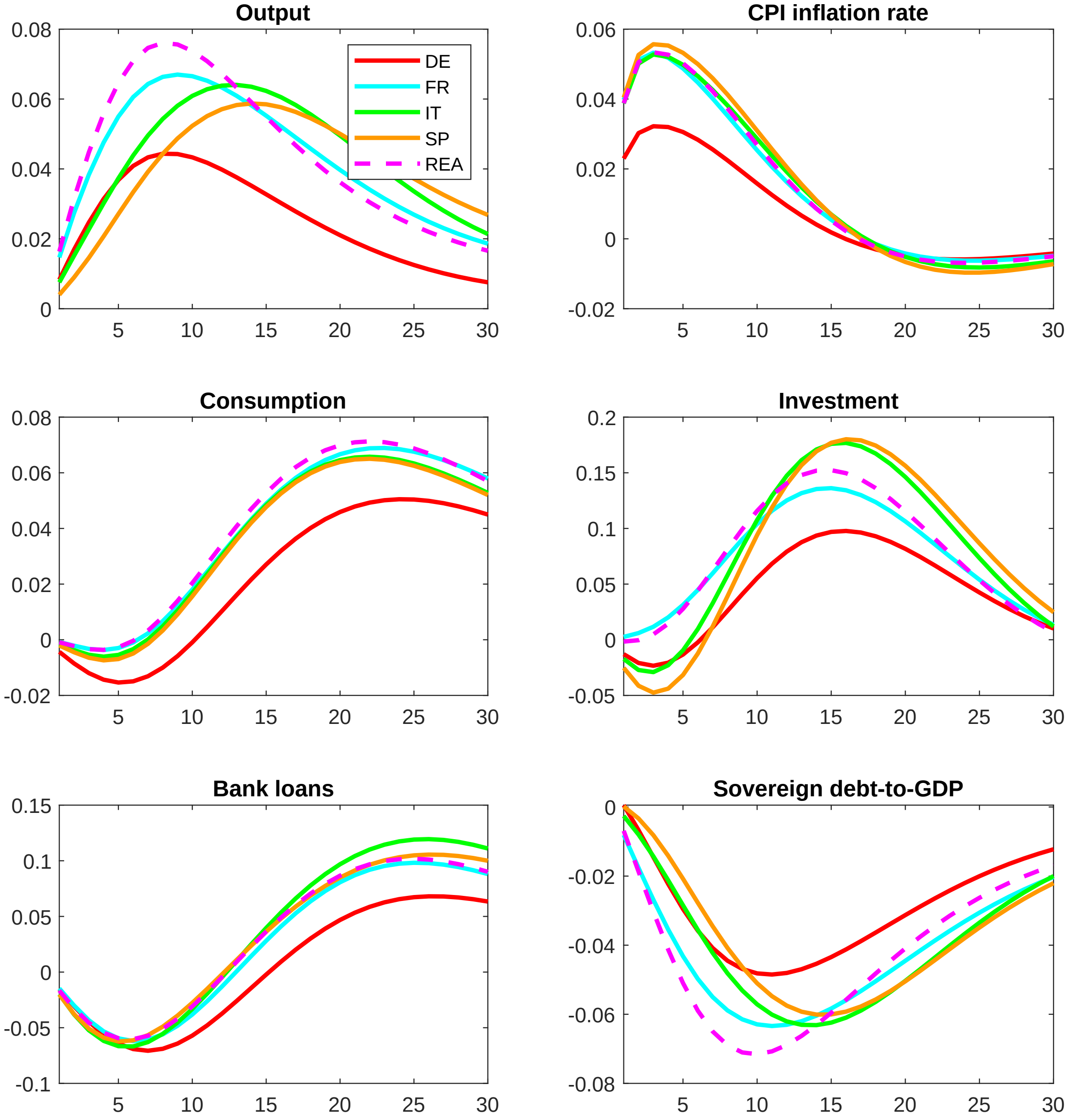
E.2 Cross-country spillover effects

Figure 8: Cross-country spillover effects from central bank asset purchases - Simulations 1



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP). Horizontal axis: quarters. Vertical axis: annual percentage-point deviations, except for sovereign bond purchases, sovereign bonds held by hhs and sovereign bonds held by banks which are expressed as a percent of annual real GDP. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area.

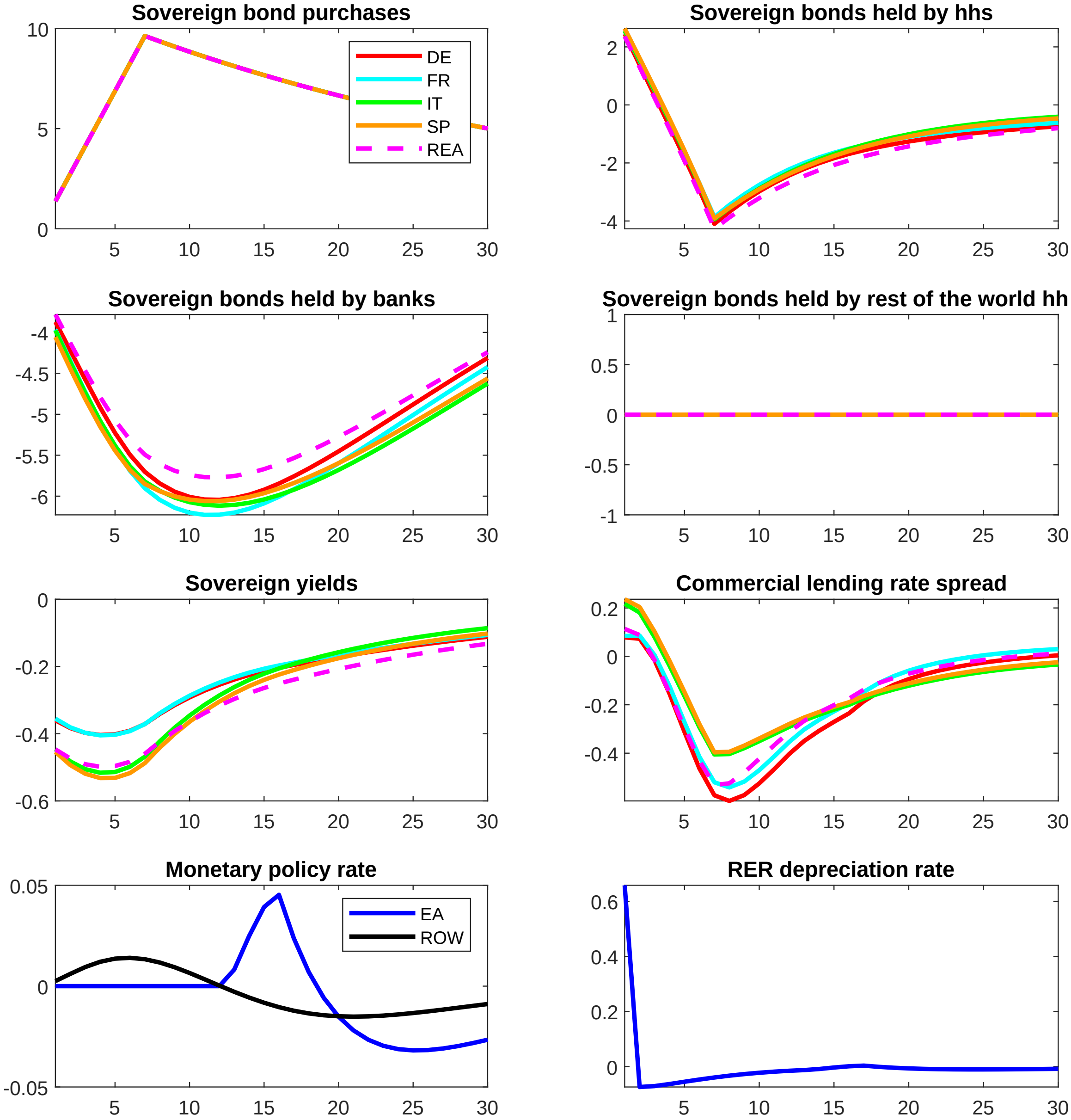
Figure 9: Cross-country spillover effects from central bank asset purchases - Simulations 2



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP). Horizontal axis: quarters. Vertical axis: percentage deviations from baseline, except for inflation and monetary policy rate as annual percentage-point deviations. GDP, its components and banks loans are reported in real terms. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area.

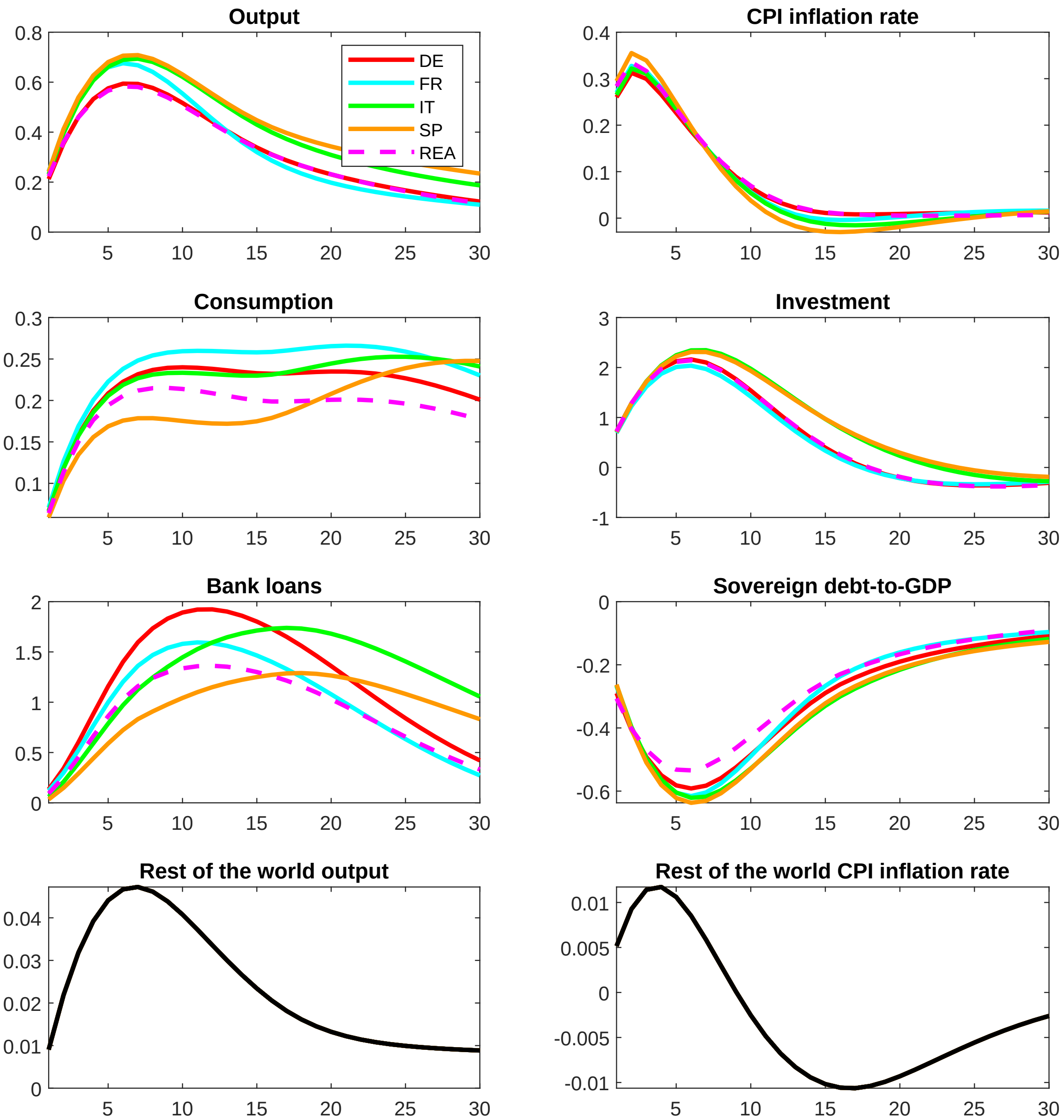
E.3 Impact of the effective lower bound on interest rates

Figure 10: Central bank asset purchases transmission subject to the effective lower bound - Simulations 1



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP) subject to the effective lower bound. Horizontal axis: quarters. Vertical axis: annual percentage-point deviations, except for sovereign bond purchases, sovereign bonds held by hhs and sovereign bonds held by banks which are expressed as a percent of annual real GDP. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

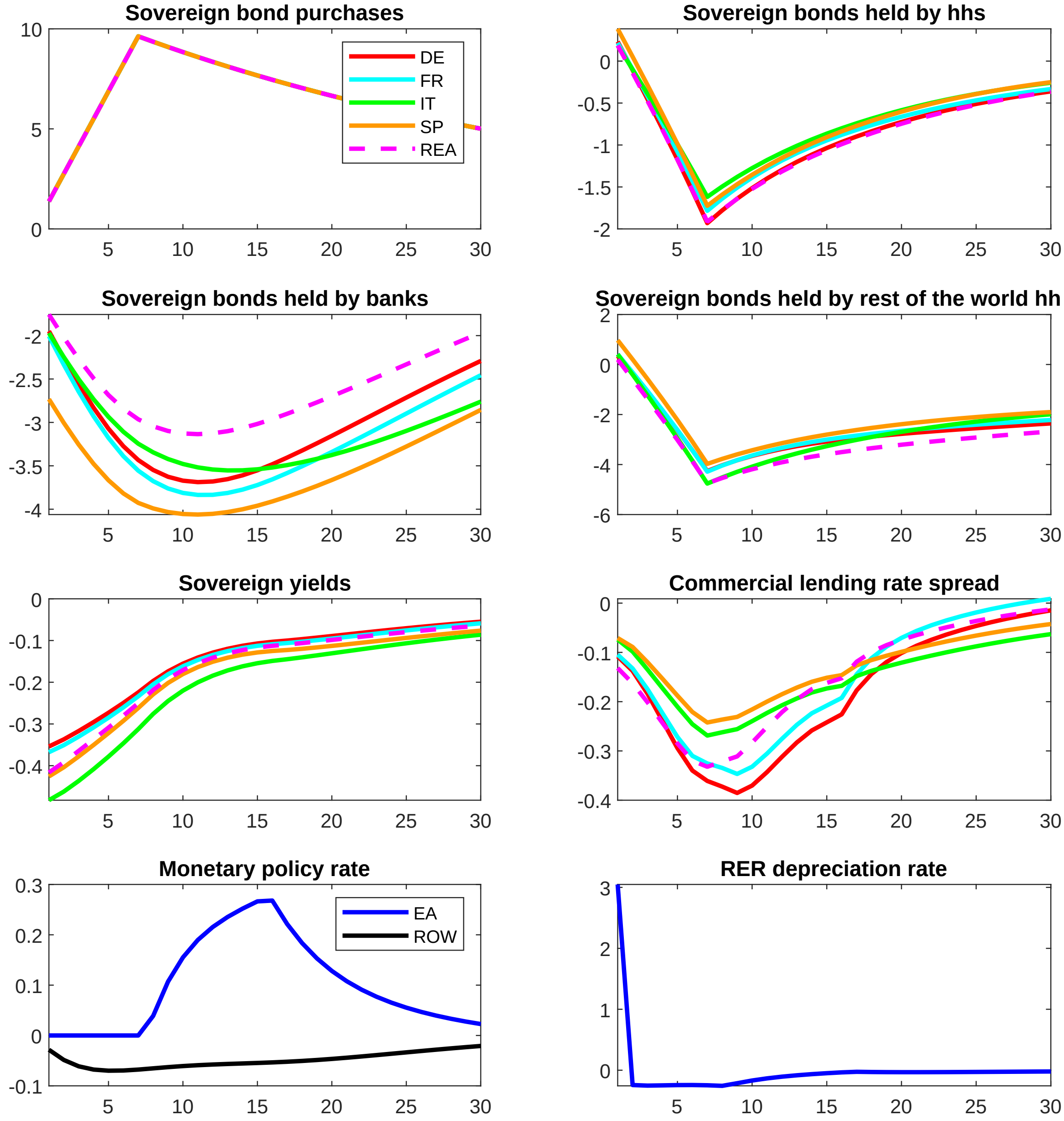
Figure 11: Central bank asset purchases transmission subject to the effective lower bound - Simulations 2



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP) subject to the effective lower bound. Horizontal axis: quarters. Vertical axis: percentage deviations from baseline, except for inflation, monetary policy rate and real exchange rate depreciation as annual percentage-point deviations. GDP, its components and banks loans are reported in real terms. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

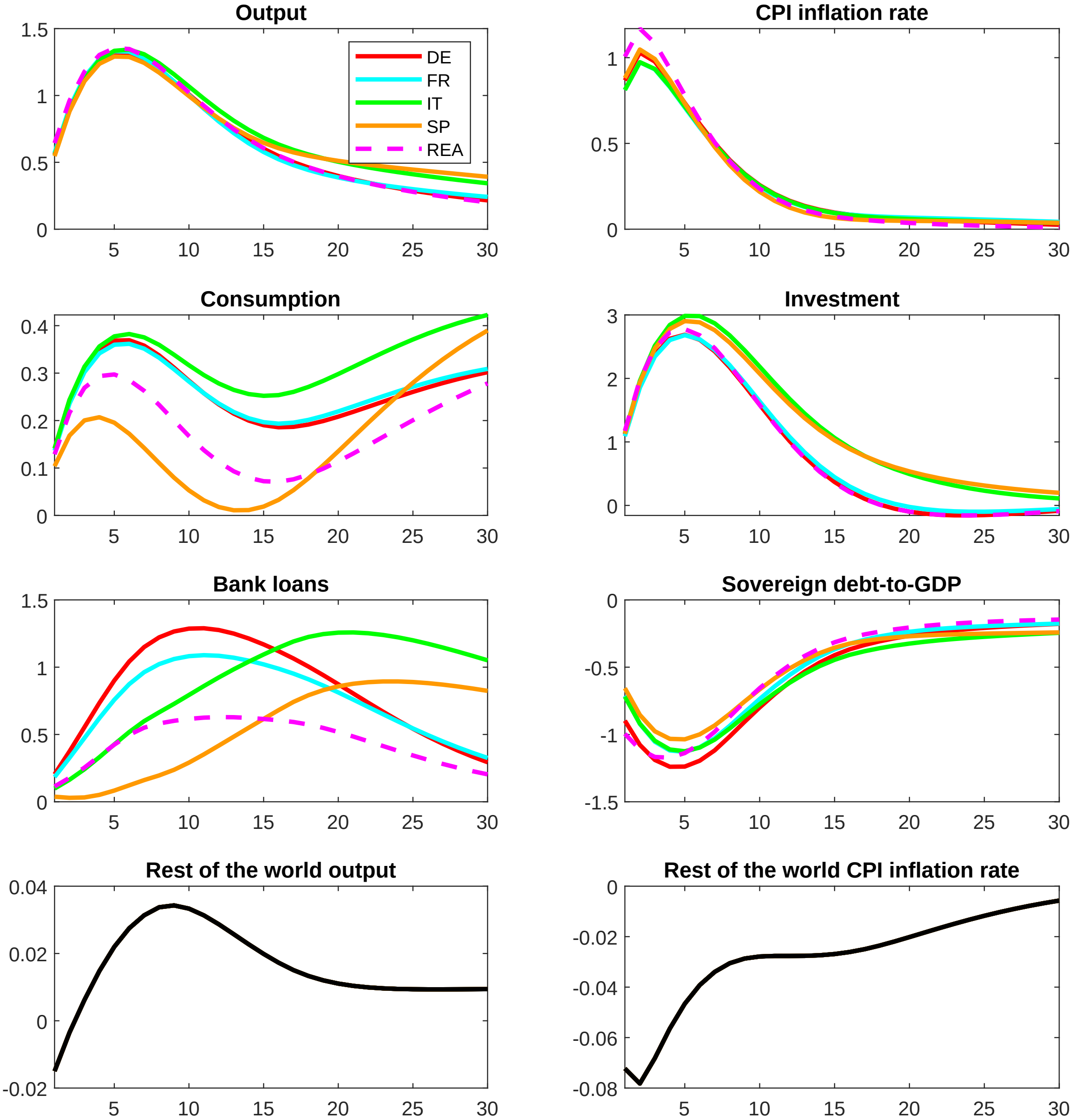
E.4 Impact of global portfolio frictions

Figure 12: Central bank asset purchases and global portfolio frictions transmission subject to the effective lower bound - Simulations 1



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP) subject to the effective lower bound and with global portfolio frictions. Horizontal axis: quarters. Vertical axis: annual percentage-point deviations, except for sovereign bond purchases, sovereign bonds held by hhs and sovereign bonds held by banks which are expressed as a percent of annual real GDP. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

Figure 13: Central bank asset purchases and global portfolio frictions transmission subject to the effective lower bound - Simulations 2



Notes: Central bank asset purchases approximately amounting to 9.6 percent of annual real GDP in eight quarters (equivalent to the January 2015 PSPP) subject to the effective lower bound and with global portfolio frictions. Horizontal axis: quarters. Vertical axis: percentage deviations from baseline, except for inflation, monetary policy rate and real exchange rate depreciation as annual percentage-point deviations. GDP, its components and banks loans are reported in real terms. DE = Germany; FR = France; IT = Italy; SP = Spain; REA = Rest of euro area; ROW = Rest of the world.

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