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Effects of foreign and domestic central bank government bond purchases in a small open economy DSGE model: Evidence from Sweden before and during the coronavirus pandemic*

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Abstract

This paper evaluates the macroeconomic effects of foreign and domestic central bank government bond purchases on the Swedish economy before and during the Corona pandemic using a small open economy DSGE model with segmented asset markets. In this model, the effects of foreign and domestic quantitative easing on the Swedish economy occur mainly through the exchange rate channel. The calibrated model is able to broadly capture the movements in foreign and domestic bond yields, capital flows and the Krona exchange rate associated with QE since the global financial crisis in 2007-2009. We find that foreign quantitative easing strengthened the Krona exchange rate and had modestly negative effects on Swedish GDP and inflation. Domestic QE, on the other hand, depreciated the Krona and had modestly positive macroeconomic effects. In 2015-2019 the government bond purchases on average depreciated the Krona by 2.5 percent, increased GDP by 0.2 percent, and increased inflation by 0.2 percentage points. The government bond purchases following the pandemic, which were more limited in size, had roughly half of these effects.

JEL Classification: E44, E52, F41.

Keywords: Unconventional Monetary Policy, Quantitative Easing, Effective Lower Bound, International Spillovers, DSGE model.

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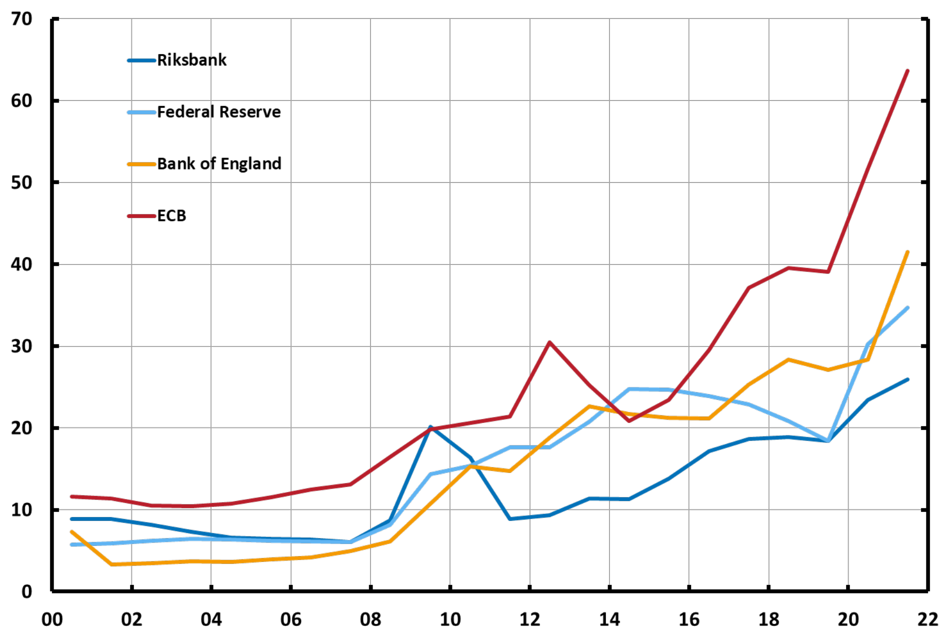
1 Introduction

Since the global financial crisis many central banks have decreased policy rates to their effective lower bounds and in some cases initiated large-scale purchases of financial assets. The Federal Reserve announced its first program of large-scale asset purchases in November 2008, and the Bank of England in March 2009. The European Central Bank (ECB) announced bond purchases for monetary policy purposes in January 2015. In Sweden, the Riksbank lowered the repo rate below zero and started to purchase government bonds in February 2015. The types of assets purchased by central banks have included government bonds, corporate bonds, covered bonds issued by banks and even equities. The increase in the size of the balance sheets of the above-mentioned central banks is shown in figure 1.[1]

Figure 1: Central bank assets as a share of GDP



Note: Percent.

Sources: The Riksbank, the Federal Reserve, the Bank of England and ECB for assets; Statistics Sweden, the U.S. Bureau of Economic Analysis, the U.K. Office for National Statistics and Eurostat for GDP.

The main goal of central bank asset purchases, often referred to as quantitative easing (QE), is to lower interest rates and ease financial conditions in order to support aggregate economic activity and increase inflation. In the mid-to-late 2010s it appeared that these objectives had been broadly attained in many of the countries whose central banks engaged in QE, and the monetary policy discussion concerned the coming reduction of central bank asset holdings, including a stabilisation followed by a reduction of asset holdings.[2] However, in response to the coronavirus pandemic and the sharp fall in economic

[1] Although neither the Riksbank nor the ECB started their QE programs until 2015, their balance sheets increased earlier as they responded with additional lending to liquidity problems and strains in certain credit markets (e.g. the market for mortgage-backed securities) that arose during the financial crisis and in the case of the ECB also during the height of the eurozone debt crisis in 2012.

[2] See for example the Riksbank's strategy for a gradual normalisation of monetary policy, which was presented in the Monetary Policy Report in December 2017, Sveriges Riksbank (2017). Brainard (2017), Constancio (2017) and Flodén (2018) are examples of contributions to the discussion on this topic from individual Federal Reserve, ECB and Riksbank governors.

activity in 2020, central banks lowered short-term interest rates, resumed and substantially increased asset purchases to restore the functioning of financial markets and stimulate the economy.

Research based on data for the US, euro area and UK indicates that central bank asset purchases improve financial conditions, and increase resource utilisation and inflation (see, among others, Borio & Zabai (2016), Haldane et al. (2016), Fabo et al. (2021), Bhattarai & Neely (2022)). There is, however, less evidence on the effects of both foreign and domestic QE on small open economies and the main purpose of our paper is to contribute with such evidence for Sweden. Small open economies are generally strongly influenced by economic developments abroad, including fiscal and monetary policies in large economies, see e.g. Corbo & Strid (2020) and Corbo & Di Casola (2022) for the case of Sweden. The existence of a global financial cycle also deepens the ties of small open economies to the rest of the world (Miranda-Agrippino & Rey 2020). In the case of small open economies, in particular, it is therefore of interest to study the effects of both foreign and domestic QE.

The main objective of this paper is to simulate the effects of foreign and domestic government bond purchase programmes on the Swedish economy in the period 2008-2021, i.e. in the period following the global financial crisis and including the coronavirus pandemic. We use a calibrated small open economy DSGE model with segmented asset markets, building on Kolasa & Wesolowski (2020), who study the effects of pre-pandemic QE conducted in the US, the euro area and the UK on the Polish economy. This model contains two key channels of QE: the portfolio rebalancing channel (through the term premium) and the exchange rate channel.[3,4] Unlike Kolasa & Wesolowski (2020), our paper evaluates the effects of both foreign and domestic QE on the Swedish economy as of the financial crisis in 2007-2009, including the pandemic years 2020-2021.

In a nutshell, the mechanism of QE in the model is as following. Central bank bond purchases lower the domestic term premia on government bonds, induce households to rebalance their asset portfolios and depreciate the domestic currency. In addition, domestic term premia are lowered also when foreign bonds are purchased in the process of foreign central bank QE, with the difference that the domestic currency then appreciates.

The model used here is suitable for studying the effects of foreign and domestic QE on the Swedish economy for two reasons. First, it is a small open economy model which features the key channels through which QE may affect both the international and domestic economies. Second, the model is able to broadly replicate the effects of foreign and domestic QE on financial variables in Sweden.

Sweden is a small economy with open goods and capital markets, and there have been large movements in capital flows and the Krona exchange rate in the period of central bank asset purchases following the global financial crisis. The model features cross-country holdings of long-term government debt and the exchange rate is governed by a long-term uncovered interest rate parity (UIP) condition which provides a clear role for asset purchases in the determination of the exchange rate. It is calibrated to replicate the effects of QE on long-term government bond yields found in high-frequency event studies for Sweden and other countries. These model features and our approach to obtaining reasonable effects on bond yields imply that the combined effects of foreign and domestic QE in the model are broadly in line with the developments of a set of key financial variables in Sweden since the financial crisis in 2007-2009. These developments are shown in figures 2 and 3 and may be summarized as follows:

- Foreign QE was followed by an increase in the share of Swedish government bonds owned by foreign

[3]Government bond yields are commonly characterized as the sum of the yield implied by policy rate expectations and a term premium, where the term premium is the compensation investors receive for the risk that a longer time to maturity entails, the term risk.

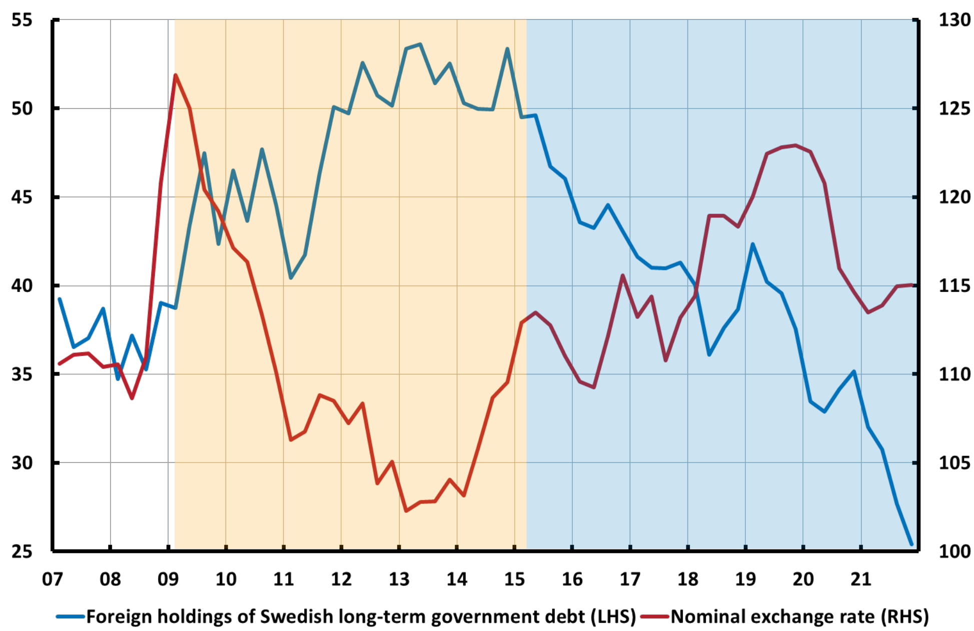
[4]The effects of QE are often described schematically through different channels, see e.g. Haldane et al. (2016) and Melander (2021). When we simulate effects of QE we also allow for the possibility that the central bank keeps the policy rate constant, which may be interpreted as a representation of the signalling channel of asset purchases.

investors but there was a reversal of these capital flows after Riksbank QE was introduced (figure 2).[5]

- The Krona exchange rate depreciated sharply during the financial crisis. Thereafter, in the years of foreign QE, the Krona appreciated until the Riksbank launched its own QE program in 2015 (figure 2).
- The start of QE abroad coincided with an increase in the correlations between foreign and Swedish government bond yields and term premia, but these correlations weakened when Swedish QE was launched (figure 3).

Arguably, other factors than foreign and Swedish QE may also have affected capital flows, the Krona exchange rate and bond yield and term premium correlations. Yet, our simulations indicate that central bank asset purchases likely played an important role for their evolution.

Figure 2: Nominal exchange rate and share of foreign owners of Swedish long-term government debt.



Note: The orange area shows the period of foreign QE and the blue area shows the period of both foreign and Swedish QE. The nominal exchange rate is the competitiveness-weighted krona index (KIX) where an increase reflects a depreciation of the currency. The share of foreign owners of Swedish long-term government debt concerns general government debt and is expressed in percent.

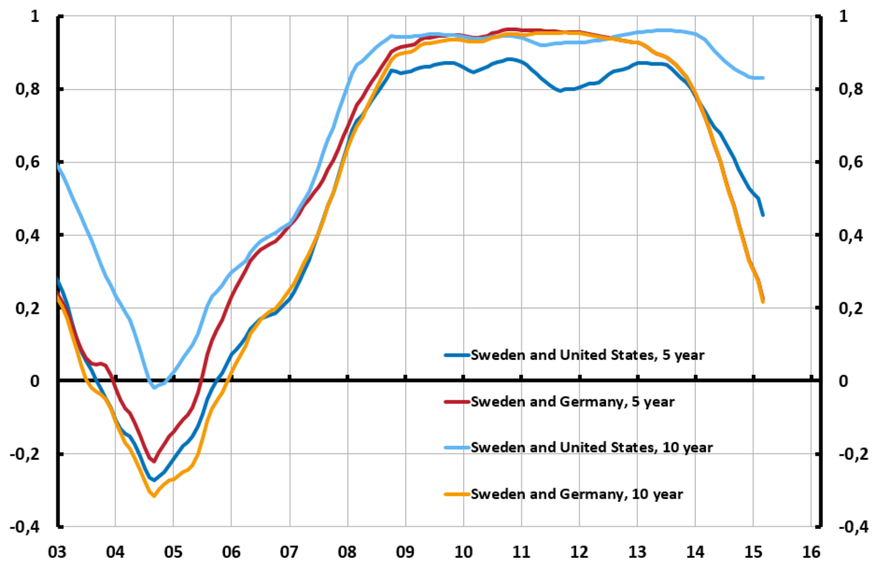
Sources: The Riksbank for the exchange rate and Statistics Sweden for debt.

Our main results are the following. Overall the effects of foreign and domestic QE on Swedish GDP and inflation appear modest in relation to the effects obtained in other studies.[6] We find that

[5] Österholm (2022) studies who has sold bonds to the Riksbank and finds that the foreign sector has accounted for the lion's share of bond sales to the Riksbank, both during the government bond purchase program 2015 to 2017 and during the pandemic. Similar to what we observe for Sweden, Kolasa & Wesolowski (2020) show that the foreign ownership share in sovereign bond markets of a large number of emerging economies increased sharply after the global financial crisis. Unlike in Sweden, however, it did not decrease again.

[6] Our simulated effects of large economy QE on output and inflation in the large economy, as well as the effects of small country QE on its economy, are arguably small when compared to the results in a large set of studies surveyed by Fabo et al. (2021). However, our results are more similar to those in studies which apply a similar

Figure 3: Rolling correlations between Swedish, German and US 5 and 10 year government bond term premia.



Note: The graph shows correlations between Swedish, German and US 5 and 10 year government bond term premia computed for a rolling sample of 7*12=84 monthly observations. The date on the x axis gives the start date of the sample. The term premia are computed using the model by Adrian et al. (2013). A brief description of the model is provided in the appendix.

Source: Thomson Reuters

foreign quantitative easing strengthened the Krona exchange rate and had modestly negative effects on Swedish GDP and inflation. It is important to note that these effects of foreign QE were obtained under the assumption of the Riksbank not responding to QE abroad with QE of its own. When the Riksbank eventually launched its QE program, it depreciated the Krona and had modestly positive macroeconomic effects. In 2015-2019 the government bond purchases on average depreciated the Krona by 2.5 percent (3.0), increased GDP by 0.2 percent (0.2), and increased inflation by 0.2 percentage points (0.3) with peak effects in parentheses.[7] The government bond purchases associated with the pandemic, which were smaller than the pre-pandemic purchases, had roughly half of these effects.

Our work is primarily related to the literature which uses DSGE models to study the effects of QE. There is a vast literature studying the effects of QE in DSGE models, however usually focused on closed economies. In order to obtain effects of central bank asset purchases on the economy, the models feature various frictions or imperfections in the functioning of financial markets, such as information frictions, imperfect substitutability of assets, or credit constraints for financial intermediaries. Indeed, without such frictions, general equilibrium effects make asset purchases irrelevant in these models, as first argued by Wallace (1981).[8] Chen et al. (2012) rely on asset market segmentation to give rise to an effect of

approach, i.e. DSGE models with asset market segmentation, see Chen et al. (2012), Kolasa & Wesolowski (2020), Burlon et al. (2019) and Harrison (2012).

[7]To put the inflation effects into perspective one may ask how much the policy rate would need to be lowered to obtain the equivalent effect. Using the inflation response to an unanticipated monetary policy shock in the macroeconomic model MAJA for Sweden we find that the policy rate would need to be 0.7 percentage points lower on average in 2015-2019 to increase inflation by 0.2 percentage points on average. For a description of the model see Corbo and Strid (2020). We also note that this policy rate equivalent is similar to the difference between the shadow rate constructed by De Rezende & Ristiniemi (2023) and the repo rate in the pre-pandemic period.

[8]In his famous quote "the problem with quantitative easing is that it works in practice, but it doesn't work in theory", Bernanke referred to this irrelevance result.

QE on the real economy, while Harrison (2012) and Harrison (2017) introduce an explicit preference for a portfolio mix of assets for households.[9] Gertler & Karadi (2013), Carlstrom et al. (2017), Sims & Wu (2020) and Boehl et al. (2022) build on a moral hazard problem between households and financial intermediaries.[10] Only a few papers features the exchange rate channel of QE, such as Coenen et al. (2018). Hohberger et al. (2019) and Alpanda & Kabaca (2020) focus on the QE spillovers among large economies, while Kolasa & Wesolowski (2020) focus on spillovers of foreign QE to small open economies. A key result in the analysis of Kolasa & Wesolowski (2020) is that large economy QE has negative effects on the small open economy's GDP. Two assumptions are particularly important for this result. First, the central bank in the small economy is assumed not to respond by purchasing assets. Second, it is assumed that small economy holdings of large economy short-term debt do not increase in response to foreign QE, i.e. when foreign holdings of long-term debt issued by the small economy increase there is no counteracting outward capital flow.[11]

Our work is also related to research which attempts to estimate the effects of foreign and domestic QE on small economies using alternative methods, mainly different types of structural vector autoregressive (VAR) models. A fundamental question is whether the spillovers are positive or negative, i.e. whether the stimulative effects of lower interest rates are outweighed by the appreciation of the recipient country's exchange rate. A relatively small number of papers study the financial and real spillover effects of major central banks' unconventional monetary policies, see Bluwstein & Canova (2016), Chen et al. (2017), MacDonald & Popiel (2017), Dahlhaus et al. (2018), Moder (2019) and Bhattarai et al. (2021). These papers usually find positive spillovers for the real economy, while the effects on inflation are mixed. There is, however, considerable cross-country heterogeneity and the estimated effects are uncertain.

The evidence of the effects of domestic central bank asset purchases on macroeconomic variables in small economies is relatively limited.[12] An important question is whether the differences in the relative importance of the different channels of QE in large and small countries imply that the quantitative effects are different. The availability of assets treated as close substitutes to government bonds issued by SOE:s could imply that asset purchases by SOE central banks have smaller effects on term premia than purchases by the major central banks, see Diez de los Rios & Shamloo (2017) and Kabaca (2016). However, evidence from event studies on the effects of Riksbank government bond purchases on bond yields suggests that the normalized effects of Riksbank purchases have been similar to those of the major central banks (this is discussed further in section 4).

In the Swedish context, De Rezende & Ristiniemi (2023) construct a shadow policy rate to account for the effects of domestic QE. Combining this with the effects of a conventional policy rate shock from a DSGE model, they find that domestic QE decreased unemployment and increased inflation. Di Casola & Stockhammar (2021) estimate a structural 2-country BVAR model over the period 2015-2018 to study the effects of ECB and Riksbank QE. They find positive spillovers of ECB QE for Sweden, while the effects of domestic QE are positive on the real economy but negligible for inflation.

The paper is organized in the following way. The model is presented in section 2 and the calibration

[9] Burlon et al. (2019) adapt Chen et al. (2012) to the analysis of asset purchases in the euro area.

[10] Mouabbi & Sahuc (2019) rely on a shadow rate to account for the effects of QE in a DSGE, hence there is no explicit modelling of QE channels.

[11] In contrast Alpanda & Kabaca (2020) obtain positive QE spillovers of large economy QE on the rest of the world. The key difference from Kolasa & Wesolowski (2020) is that they do not restrict cross-border holdings of short-term debt. As a consequence large economy QE in their model induces both a capital inflow into the markets for long-term debt issued by other economies and an offsetting capital flow in the form of a large increase of holdings of the large economy short-term debt by other economies. This dampens the exchange rate appreciation and hence the negative effect on the receiving countries' competitiveness.

[12] See Johnson et al. (2020) for an overview of the effects of unconventional monetary policy in small open economies found in the literature.

of the model is discussed in section 3. The effects of quantitative easing in the euro area, the US and the UK (BIG3) and in Sweden in the period from the financial crisis in 2007-2009 until the end of 2021 are described in section 4. A final section concludes.

2 Model description

We use a small open economy DSGE model where agents trade short- and long-term government debt in segmented asset markets. It builds on and extends the small open economy model of Gali & Monacelli (2005) and is presented in more detail by Kolasa & Wesolowski (2020). Here we aim to provide a largely non-technical description. The equations defining the equilibrium of the model are collected in the appendix, see section A.1. The model consists of two countries, a small country (home) and a large country (foreign), and the agents are households, firms and governments. Since the model structure is largely symmetric, we present the model from the perspective of the small (home) country. The key difference between the two economies is that the home economy is smaller, and therefore features a significant role for foreign goods in domestic consumption.

2.1 Households

Households obtain utility from consumption of domestically produced and imported goods and services, as well as from leisure time. They are paid a wage for working, receive dividends from firms and pay taxes to the government. Being determined in a competitive labour market, wages are flexible. Household income can be used for consumption or it can be saved. There are four assets available for saving: domestic and foreign short- and long-term government debt instruments. Hereafter, the long-term government debt instruments will simply be referred to as government bonds, or bonds for short.[13] Households are assumed not to have access to short-term debt issued abroad, an assumption that is motivated further below.[14,15]

A key feature of the model is asset market segmentation - across maturities along the lines of Vayanos & Vila (2021), as well as across borders. This asset market segmentation is introduced by means of the assumption that some households in each country are restricted to saving in government bonds and that restricted households in the home economy only have access to domestic bonds while restricted households in the foreign economy may save both through domestic and foreign bonds.[16] The lack of access to short-term debt instruments means that the consumption-savings decision of restricted households, described by their Euler equation, is determined by the domestic long-term interest rate. Unrestricted households have access to a wider set of saving instruments: short-term debt issued by their own country's government as well as foreign and domestic government bonds. When they trade in bonds, however, they incur transaction costs. These transaction costs are assumed to be increasing in holdings

[13] Kolasa & Wesolowski (2020) use the term "bonds" for both short-term and long-term government debt instruments whereas in the empirical application the short-term government debt instruments considered include money and other non-bond instruments and are in all cases more short-term in character (maturity of less than one year) than the debt instruments that in common practice are referred to as bonds. As a result, in order to avoid confusion when transitioning from the description of the model to its empirical application, we have chosen not to use the term "short-term bonds" and instead write "short-term government debt instruments" or "short-term government debt". Furthermore, since the only long-term government debt instruments under consideration are government bonds, we will on many occasions simply write "government bonds" instead of "long-term government debt".

[14] In section 3.3.6 we show that the share of short-term debt in the Swedish portfolio of foreign government debt instruments has averaged around a mere 2 percent in the period 2002-2020.

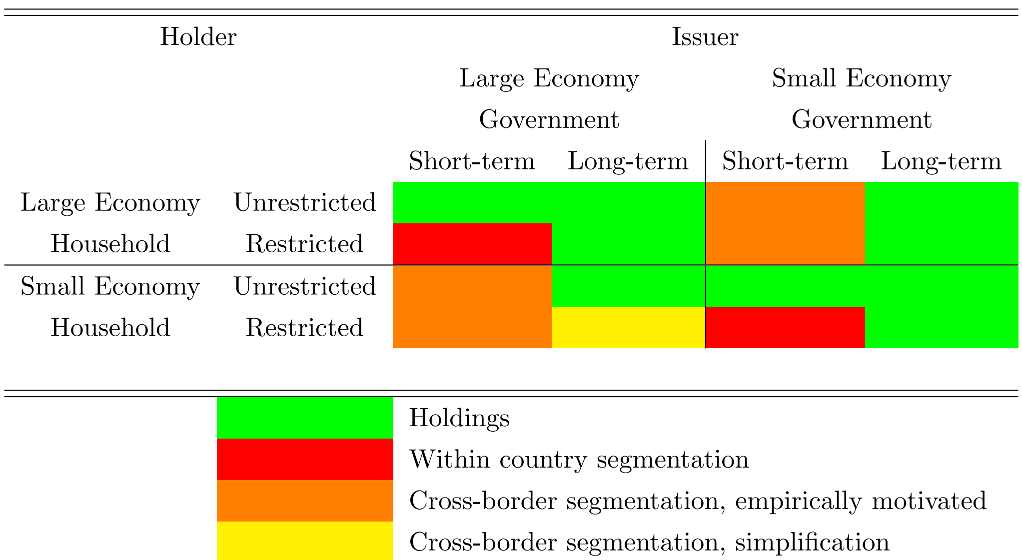
[15] The price of domestic short-term government debt is used as the numeraire in the model. The long-term government debt, i.e. the government bonds, are modelled as perpetuities, following Woodford (2001).

[16] The latter is a simplifying assumption which is shown not to have a significant impact on results in Kolasa & Wesolowski (2020).

of long-term debt, implying that they can be interpreted as “liquidity costs”, see e.g. Andrés et al. (2004) or Chen et al. (2012). This means that the long-term interest rate will not obey the expectations hypothesis - instead there is a non-zero term premium reflecting the transaction costs. The asset market segmentation assumptions are summarised in Table 1 which shows the different types of households and the assets which are available to them.[17]

The optimality conditions for households, coupled with the asset market segmentation and transaction costs, give rise to an uncovered interest rate parity (UIP) condition that differs from the one in standard DSGE models. The exchange rate is related not only to the expected difference in short-term rates, but also to the difference in term premia. In this way, domestic and foreign QE policies that affect domestic and foreign term premia propagate through the economies via the exchange rate channel.

Table 1: Household Types and Asset Allocation



2.2 Firms

There are many firms in the home economy which produce goods and services using labor as input (while there is no capital in the model).[18] Production occurs in three stages. Competitive final goods producers combine home-produced and imported goods into final goods using a constant elasticity of substitution (CES) technology. At the previous stage homogeneous goods are produced by perfectly competitive aggregators using intermediate goods as inputs. Intermediate inputs are produced by monopolistically competitive firms using labor as input. We focus mainly on the firms producing intermediate goods. They are domestically owned and ownership shares are assumed to be equally distributed across households. They have some degree of monopoly power and determine their production and prices in order to maximise profits. They set prices in their buyers’ local currencies. Price stickiness is introduced by assuming that firms do not re-optimise their prices continuously, and instead set prices in a staggered fashion (Calvo 1983). When firms do not re-optimise they are assumed to increase their prices in line with steady state consumer price inflation.

[17] Chen et al. (2012) show that the term premium on domestic government bonds can be approximated to first order as the discounted sum of anticipated future transaction costs associated with trade in those bonds. Hence in the absence of transaction costs the term premium is zero.

[18] Kolasa & Wesolowski (2020) provide robustness results for a version of the model with capital accumulation. The simulated effects of QE with this model version are quite similar to the model without capital which we use.

2.3 Government

The government controls the short-term interest rate, exogenous spending and the supply of short- and long-term government debt instruments, which are issued in local currency. The central bank has a reaction function where the policy rate depends on resource utilisation and inflation. The fiscal authority sets exogenous spending on goods and finances it with taxes levied on households and net debt issuance. Both types of households are assumed to pay the same per capita taxes.

2.4 Quantitative easing in the model

Quantitative easing refers to central bank purchases of long-term government debt financed by the creation of new central bank reserves. The purchases shift the portfolio mix of assets held by the private sector, which comes to hold a larger quantity of reserves and a smaller quantity of bonds. Total government debt, that is the sum of short-term government debt including central bank reserves and long-term government debt not held by the central bank, is assumed to be kept constant.[19] Quantitative easing thus amounts to changing the share of long-term government debt in total government debt.

Simulating the effects of QE using the model thus involves constructing a path for the central bank long-term government debt holdings as a share of total government debt.[20] In the following we will refer to this as QE, or the QE path. A more detailed discussion on the definition of the QE path in the model and its computation using data is provided in the appendix, section A.2.

2.5 Responses to foreign and domestic quantitative easing shocks

In this section we describe how foreign and domestic QE shocks propagate in the model economy, with a focus on the mechanisms and the qualitative, i.e. sign, effects on macroeconomic variables.[21] We assume here that the central bank policy rate reacts endogenously to QE, i.e. that it is raised in response to increased resource utilisation and inflation.[22] In section 4 we simulate the macroeconomic effects of the actual BIG3 (euro area, US and UK) and Swedish central bank asset purchase programs and there the focus is instead on the quantitative effects. There we also consider different assumptions for the policy rate response.

2.5.1 Effects of large economy QE on the large economy

The effects of QE on the economy stem from the assumption of asset market segmentation. As noted in section 2.1 there is segmentation (1) across the term structure and (2) across borders. In this subsection we focus on the first dimension since it is the important dimension in the context of the large economy.

[19] The assumption of constant government debt may be put into question, not least as QE arguably facilitates further government borrowing. Kolasa & Wesolowski (2020) investigate the effect of instead using a tax rule where QE leads to a decrease in taxes and thus an increase in total public debt. However, with the parameter controlling the response of taxes to QE being set to the value estimated by Chen et al. (2012) the effects of QE are only marginally affected by switching from the constant debt assumption to such a tax rule.

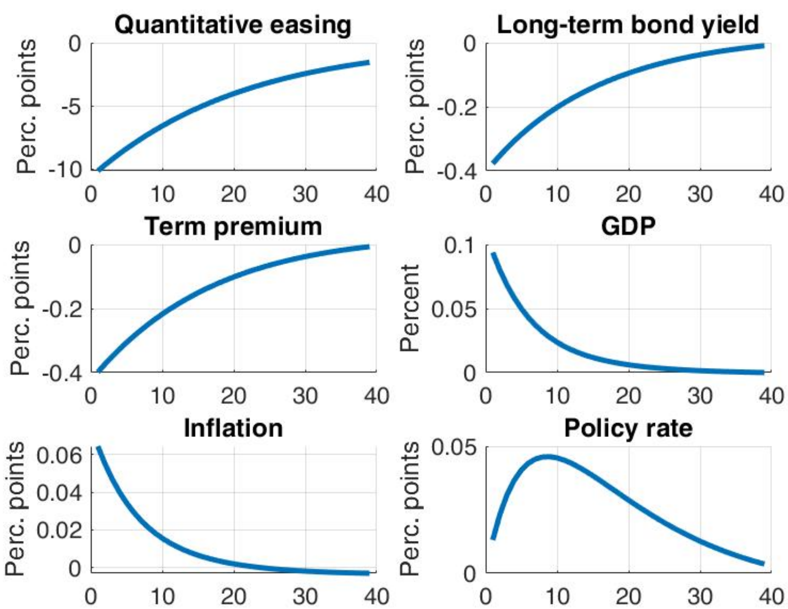
[20] In the figures, we follow the practice of Kolasa & Wesolowski (2020) in expressing this measure of QE with a negative sign as it reflects a reduction in the supply of government bonds available to investors.

[21] The impulse responses to foreign and domestic quantitative easing shocks shown in this section are computed based on the calibration of the model presented in section 3. The only difference here is that we use a persistence parameter for the QE shock equal to 0.9 instead of 0.99 such that the effects of QE on most variables wear off within 10 years. The responses have been scaled to reflect QE amounting to 10 percent of total government debt (on impact).

[22] It is not important for the discussion in this section whether QE is combined with an assumption of a constant policy rate, or if the policy rate is allowed to respond endogenously. If the policy rate is kept low while conducting QE, the effects on aggregate demand and inflation are amplified.

The effects of large economy quantitative easing on large economy variables are shown in figure 4. When the central bank purchases government bonds financed by issuance of money, the government bond holdings of (restricted and unrestricted) households decrease, while unrestricted households' holdings of short-term government debt instruments increase, in order to equalize the expected returns. As the relative supply of long-term debt falls, its relative price increases i.e. the term premium falls. How much the term premium falls depends on the extent to which the transaction (or liquidity) cost falls as the share of long-term debt in household portfolios decreases.[23,24]

Figure 4: Effects of a large economy quantitative easing shock on the large economy.



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The QE shock is normalised such that this share decreases by 10 percentage points on impact. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

The increase in the price of bonds implies that saving becomes a less attractive option for the restricted households, inducing an increase in their consumption demand.[25] The effects on unrestricted

[23] In other words, the effect of QE on bond yields is governed by the elasticity of transaction costs to the size of unrestricted households' bond holdings, ξ_F^*. It is instructive to consider the case when $\xi_F^* = 0$. In this case QE does not affect transaction costs, the term premium or bond yields. The bond holdings of restricted households are not affected while the unrestricted households' portfolios are adjusted in line with the change in the effective supply of bonds. In this case short- and long-term debt instruments are perfect substitutes and QE does not have any effects on bond prices or real economic variables.

[24] The case of no asset market segmentation across the yield curve, i.e. within a country, is obtained by assuming that the fraction of restricted households, ω_r^*, is close to zero. In this case the effects of QE on bond yields and bond holdings are similar to the effects in the baseline case. But there are no effects on real aggregate variables. This also illustrates that the effects of QE on unrestricted households' allocations are 'indirect', i.e. they follow from general equilibrium effects triggered by the effects on restricted households. The effects of large economy QE are quite sensitive to the fraction of restricted households. Interestingly, however, the effects of large economy QE on the small economy do not depend importantly on ω_r^*. This illustrates that the exchange rate is the key channel for QE spillovers from the large to the small economy.

[25] The increase in their wealth also induces a fall in their supply of labour but as long as they constitute a relatively small share of households the negative effects on production are limited.

households' consumption and hours worked are qualitatively opposite to those of the restricted households but quantitatively smaller since their decisions are affected by the returns on both long- and short-term debt which are affected in opposite directions by QE. The reason is that the upward pressure on output and prices makes the central bank raise its policy rate thus increasing the returns on short-term debt.

Since QE is usually undertaken as an alternative when it is considered difficult or ineffective to lower policy rates further, it is in practice likely that the policy rate is instead anticipated to be kept constant at its effective lower bound.[26] Such a policy, where QE is reinforced by forward guidance (FG), would yield a larger increase in aggregate demand and inflation. This is illustrated further in section 4 below where we estimate the effects of foreign and Swedish QE. In practice, the policies of quantitative easing and forward guidance have often been coincident and their effects are therefore difficult to disentangle empirically.

In summary, QE reduces bond yields and increases aggregate demand and inflation. For the large economy, those effects of QE which depend on interactions with the small economy, i.e. through the exchange rate and trade, are negligible and the positive effects of QE in the large economy derive from the positive effects on domestic demand.

2.5.2 Effects of large economy QE on the small economy

The effects of large (here foreign) economy QE on the small (here home) economy are displayed in figure 5. They occur mainly through two channels, the trade channel and the exchange rate channel, with opposite effects on output and inflation. The net effect of QE spillovers on GDP is generally ambiguous but with our calibration of the model the exchange rate channel dominates - the effect of increased demand for goods in the large economy is dominated by the negative effect of the small economy exchange rate appreciation.

The large economy households' holdings of bonds issued by the small economy is a small fraction of their portfolio yet accounts for a substantial share of outstanding small economy bonds. Therefore the re-balancing of domestic and foreign holdings in the large economy portfolio have small real effects on the large economy but may have larger effects on the small economy via capital inflows and the associated effects on the exchange rate.

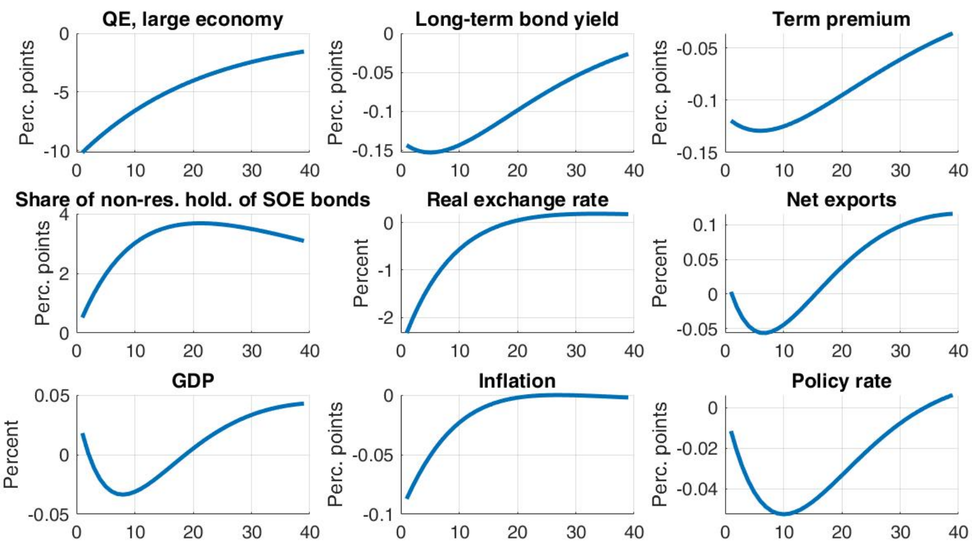
The lowering of the yield on foreign bonds induced by foreign QE induces foreign restricted households to increase their holdings of small economy bonds, while small economy households reduce their holdings of these bonds. The higher yield on small economy bonds implies that the small economy currency needs to depreciate, in order to fulfill uncovered interest rate parity. This in turn requires an (initial) appreciation of the small economy currency.

The reduction in domestic (i.e. small economy) bond holdings implies that unrestricted households' bond transaction costs and thus the term premium decreases also in the small economy. The small economy bond yield therefore decreases which partially dampens the strengthening of the small economy exchange rate.

The strengthening of the small economy exchange rate implies that its exports decrease while its imports and consumption increase slightly. The effect on import prices implies that inflation decreases and that the policy rate is lowered in response.

[26] The central bank's purchases may contribute to re-inforcing the signal that the policy rate will be low, which would lower expectations of future short-term interest rates.

Figure 5: Effects of a large economy quantitative easing shock on the small economy.



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The QE shock is normalised such that this share decreases by 10 percentage points on impact. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

2.5.3 Effects of small economy QE on the small economy

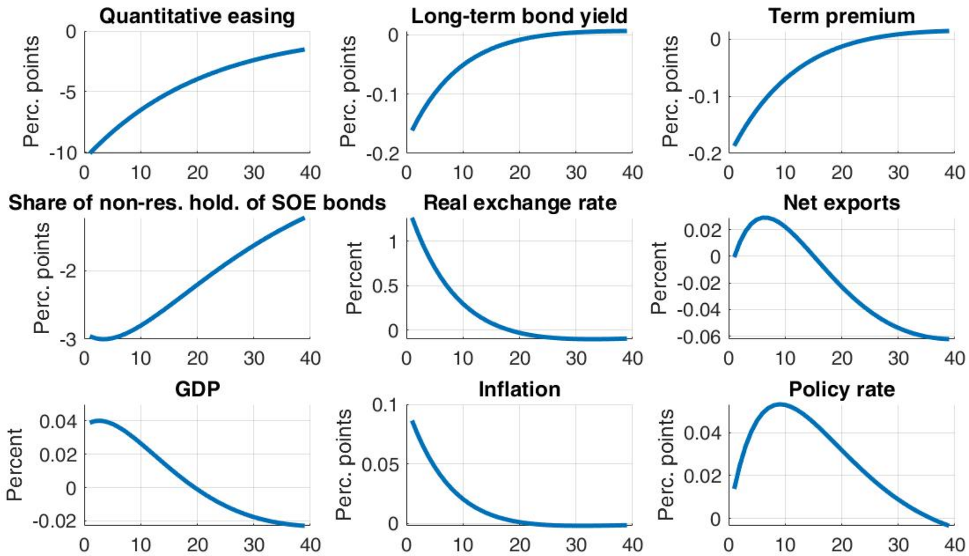
The effects of small economy QE are shown in figure 6. Small economy QE affects the composition of government debt, transaction costs, bond yields and the term premium in the same way as in the large economy, which was discussed above. The main difference between large and small economy QE is the relative importance of domestic and cross-border re-balancing of portfolios. In the large economy, re-balancing of domestically issued debt accounts for the effects of QE while re-balancing between domestic and foreign bonds only plays a marginal role. In the small economy, the effects of portfolio re-balancing between domestic and foreign bonds are larger, i.e. the exchange rate channel of QE is more important. This reflects the larger degree of openness of the small economy in comparison with the large economy - the share of imports in consumption, the share of exports in GDP and the share of bonds owned by foreigners are all larger in the small economy.

Bond purchases by the small economy central bank implies that domestic (restricted and unrestricted) households and foreign restricted households sell bonds, while domestic unrestricted households increase their holdings of domestic short-term debt and foreign bonds. The lower yield on small economy bonds implies that the small economy exchange rate needs to appreciate for uncovered interest rate parity to hold, which in turns implies that it first needs to depreciate.[27]

Just as in the case of large economy QE, the increased price of bonds raises the wealth of restricted households but makes saving less attractive to them, while the opposite happens to unrestricted house-

[27]The effects of QE on transaction costs and bond yields are governed by the parameter ξ_H. If $\xi_H = 0$ there are no effects on financial variables and hence no effects on the real economy. A difference from the large economy, however, is that the degree of asset market segmentation matters less for the effects of QE. If we let the share of restricted households, ω_r, approach zero the effects of QE are quite similar to the baseline calibration case where $\omega_r = 0.10$.

Figure 6: Effects of a small economy quantitative easing shock



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The QE shock is normalised such that this share decreases by 10 percentage points on impact. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

holds. A key difference between the effects of large and small economy QE is the strength of the effects on domestic consumption and trade via the exchange rate channel. The large economy is essentially a closed economy and QE stimulates the economy by increasing domestic demand while the change in net exports has a negligible impact on GDP. In the small economy the share of traded goods in GDP is larger and therefore fluctuations in the exchange rate become more important. While large economy QE yields an increase in consumption (see the discussion above), QE in the small economy makes consumption decrease as the exchange rate depreciation lowers the demand for imported consumption goods. However, the increase in exports dominates the negative effect on consumption such that the net effect on GDP is positive. Furthermore, the positive contribution from the increase in import prices exceeds the negative contribution from the decrease in the prices of domestically produced goods so that CPI inflation increases. Finally, as in the case of large economy QE discussed above, if the central bank keeps the policy rate unchanged instead of increasing it, the positive effects on aggregate demand and inflation are amplified.

3 Calibration

3.1 Overview

Following Kolasa & Wesolowski (2020) we calibrate the large economy to a block of three economies which engaged in quantitative easing: the United States, the euro area and the United Kingdom (BIG3). Since we use the same measure of the large economy, our calibration of the large economy parameters are to a large extent based on their calibrations. The small economy is here represented by Sweden and the relative size of this country is captured by the parameter $\omega = 0.015$ which is calibrated based on how Sweden's nominal GDP relates to that of the BIG3 during the period 1995-2019.

The model parameters can be divided broadly into two groups for expositional purposes. First, a subset of the parameters are common to many New Keynesian DSGE models, e.g. the Calvo parameters which govern the degree of price stickiness. The second group consists of parameters related to the steady state composition of the bond portfolios held by agents in the large and small economies as well as other parameters which can be considered more specific to the model we use here. To simplify the exposition we refer to these two groups of parameters as 'standard' and 'debt' parameters, respectively.

Values for the large economy debt parameters are taken from Kolasa & Wesolowski (2020), and the calibration of these parameters is therefore not discussed further here. The small economy debt parameters are calibrated based on Swedish data for the period 2002-2019, and are discussed extensively below. The values for the large economy standard parameters are broadly in line with Kolasa & Wesolowski (2020) and when we deviate from their calibration the reasons for doing so are discussed below. The values for the small economy standard parameters are largely based on the estimated parameter values in MAJA, a two-country DSGE model for Sweden; see Corbo & Strid (2020). The calibrated parameter values are collected in tables 2 (standard parameters and some debt parameters) and 3 (steady state ratios).

Table 2: Calibrated parameters

Parameter	BIG3	Sweden
Discount factor, unrestricted households; β^u	0.997	0.997
Discount factor, restricted households; β^r	0.999	0.999
Duration, long-term debt; Dur_{ss}	30	24
Home bias; η		0.7
Debt composition, persistence parameter; γ_L	0.99	0.99
Monetary policy rule, response to inflation; γ_π	1.75	1.75
Monetary policy rule, response to output; γ_y	0.125	0.125
Monetary policy rule, interest rate smoothing; γ_r	0.92	0.92
Elasticity of substitution between home and foreign goods; μ_p	1.1	1.1
Price markup, domestic goods and exported goods; μ	1.2	1.2
Size of small economy, share of nominal GDP; ω		0.015
Share of restricted households; ω^r	0.1	0.1
Steady state gross quarterly inflation; π	1.005	1.005
Inverse elasticity of intertemporal substitution; σ	2	2
Calvo probability, domestic production; θ_H, θ_F^*	0.94	0.93
Calvo probability, exports; θ_H^*, θ_F	0.93	0.93
Inverse Frisch elasticity of labor supply; φ	4	4
Transaction cost of bonds; ξ_H	0.015	0.015
Portfolio adjustment cost (large economy restricted households); ξ_r^*	0.00001	

3.2 The measure of government debt

In the model, the transmission channel of QE relies on holdings of government bonds and how those holdings are adjusted. An important part of the calibration thus relates to the steady state composition of agents' bond portfolios and the steady state ratio of government debt to GDP. We need to start by defining an appropriate measure of government debt and how we divide it into short-term and long-term

Table 3: Steady state ratios

Parameter	BIG3	Sweden
Government spending, share of GDP; $\frac{g}{y}$	0.21	0.28
Share of long-term debt in government debt; ω_L	0.65	0.8
Share of resident holdings of small country government bonds		0.65
Government debt to quarterly GDP	2.665	1
Share of foreign government bonds in small country's portfolio		0.5

since that is the basis both for the calibrations of the just mentioned steady state ratios and the measure of quantitative easing (see section 2.4 and the appendix, section A.2).

Our measure of total government debt consists of (the nominal value of) government debt securities reported by the Swedish National Debt Office (SNDO) and a subset of Riksbank (i.e. central bank) liabilities. These are divided into short-term debt (maturing in one year or less) and long-term debt. In the following we discuss which classes of debt securities are included in these two categories. The components included in our debt measure is summarised in table A.1 in the appendix and contrasted with the standard measure of government debt. The quantitative importance of each component is summarised by its average share of government debt in the period 2002-2021.

3.2.1 Long-term government debt

The components of long-term debt are nominal, inflation-linked (i.e. inflation protected or 'real') and so-called green bonds issued by the SNDO.[28] We have chosen to exclude foreign currency bonds and private placements in foreign currency from our measure of long-term debt.

We exclude foreign currency bonds despite them constituting a fairly large share of long-term government debt, on average 15 percent during the years 2002-2021. The main reasons for this are threefold. First, in the model it is assumed that governments issue bonds in local currency. Second, most of the foreign currency bonds have been issued by the SNDO on behalf of the Riksbank to strengthen the foreign currency reserve (Sveriges Riksbank 2021).[29,30] Third, the Riksbank has not purchased foreign currency bonds as part of its asset purchase programs. Purchasing these bonds would amount to a currency intervention.

Our exclusion of private placements in foreign currency is motivated not only by the same reasons as those for excluding foreign currency bonds, but also by them having had the value zero since March 2017 and historically never accounted for more than about 4 percent of bonds issued by the SNDO. Finally, bonds intended for the retail market, i.e. lottery bonds and national debt savings, are also excluded from the measure of debt used here. They have been of declining importance during a number of years and

[28] The first green bond was issued in September 2020 which means that while it is included in our measure of long-term debt it is not important for the analysis.

[29] In the Debt Office's balance sheet for 2020 the on-lending to the Riksbank is reported in the entry "Other lending" and "Lending in foreign currency" (see note 24). In the Riksbank balance sheet for 2020 the Debt Office's deposits of foreign currency is reported in the entry "Liabilities to residents in Sweden denominated in foreign currency", see also note 20 where the distribution of deposits in Euro and US dollars, respectively, are reported. Foreign currency from the SNDO has been reported under this item in the Riksbank balance sheet since June 2009.

[30] In the period 2016-2020 the on-lending from the SNDO to the Riksbank accounted for between 60 and 70 percent of the outstanding foreign currency bonds. In the years prior to the coronavirus pandemic, government budget surpluses have implied that there has been no need to issue foreign currency bonds for other purposes. The part of the currency reserve which is financed via the SNDO will be gradually wound up and replaced by self-financing (Swedish National Debt Office 2021). The primary remaining reason for issuance in foreign currency is to maintain an ease of access to a broad set of investors and large borrowing should the need arise.

are no longer offered as savings vehicles.

3.2.2 Short-term government debt

Short-term government debt includes treasury bills issued by the SNDO and other short-term debt (liquidity management instruments and collateral included in the money market category) as well as money issued by the Riksbank. Money holdings are close substitutes to risk-free short-term debt when the policy rate is close to zero. Here "money" includes debt certificates issued, as well as liabilities to credit institutions in Sweden related to monetary policy operations, which consist of the deposit facility and fine-tuning operations. This measure of money equals the monetary base excluding banknotes and coins in circulation.[31]

3.3 Calibration of Swedish debt parameters

We now discuss our calibration of the Swedish debt parameters. The values of the debt-related steady state ratios for the BIG3, which are taken from Kolasa & Wesolowski (2020), and Sweden are collected in table 3.

3.3.1 Government debt to GDP

Swedish government debt peaked above 70 percent of GDP after the economic crisis in the 1990s and since then it has declined to a level which is low in an international comparison. In figure 7 we contrast our debt measure to the standard measure of government debt reported by the SNDO. The main difference between the two measures is that our measure excludes foreign currency borrowing, which implies that it is somewhat lower than the standard measure. In the years after the financial crisis in 2008 and prior to the start of Riksbank asset purchases in 2015 the debt-to-GDP ratio has been stable below but close to 25 percent. We calibrate the steady state ratio of government debt to quarterly GDP to $b^g_{ss} = 4 * 0.25 = 1.0$.

3.3.2 Share of long-term debt in government debt

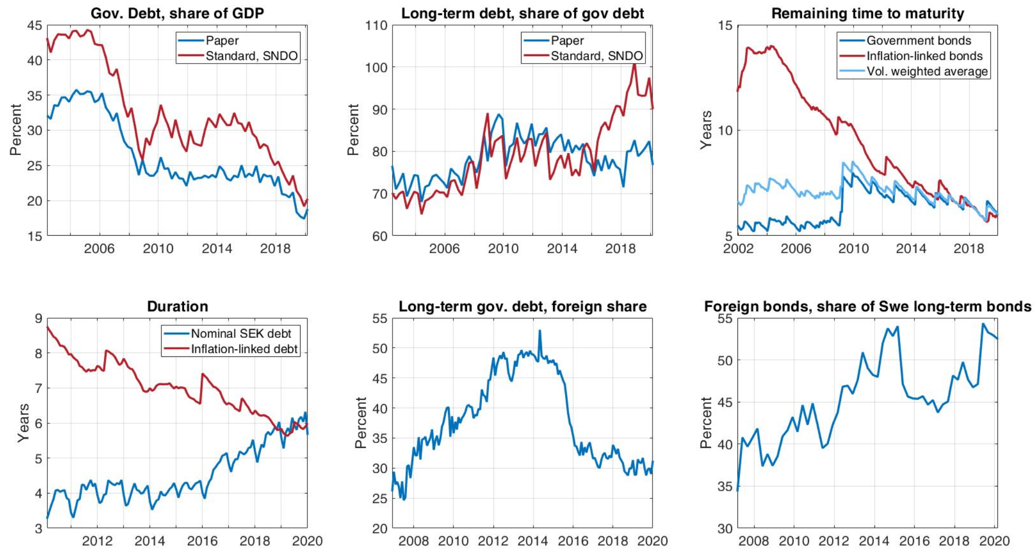
The share of long-term debt in government debt is displayed in figure 7. Again we contrast our measure with the corresponding share computed based on the SNDO:s standard measure of government debt. The share increased from around 70 percent in 2002 to around 80 percent after the global financial crisis. In the period after the global financial crisis and before Swedish QE began in 2015 the share has been stable above but close to 80 percent. We calibrate the share of long-term debt to $\omega_L = 0.8$.

3.3.3 Duration of long-term government debt

In calibrating the average duration of Swedish long-term government debt we consider data on the duration of government bonds available from 2010 and complement this with data on the time to maturity of government bonds which is available from 2002. In figure 7 the time to maturity of nominal government bonds and inflation-linked bonds, and a volume-weighted average of these two bond categories, are displayed. In figure 7 the duration of nominal government (short- and long-term) government debt and inflation-linked government bonds are shown. The time to maturity of long-term government debt (excluding foreign currency bonds) was around 7 years before the financial crisis, increased to around 8 years during the crisis and has since declined to around 6 years in 2020. We note that the time to maturity

[31] Banknotes and coins have been excluded for Sweden on account of their limited and declining importance there during the QE period.

Figure 7: Data series used to inform the calibration of Swedish steady state debt ratios



Note: Data on government debt and its components, the remaining time to maturity, the duration and the share of foreign owners of Swedish government bonds are obtained from the Swedish National Debt Office (SNDO). Data on Swedish portfolio holdings of foreign government bonds are obtained from Statistics Sweden. The difference between our measure of government debt and the standard measure provided by the SNDO is described in the text and it is summarised in table A.1 in the appendix.

and duration of index-linked bonds display a similar downward trend since 2008, while the duration is (by definition) somewhat lower than the time to maturity. Based on these data our assessment is that the duration of government bonds has been fairly stable close to 6 years since 2010. We therefore calibrate the duration as $D_{ss} = 24$ quarters.

3.3.4 Foreign ownership of Swedish government bonds

The share of Swedish government bonds (including inflation-linked bonds) held by foreigners is reported by the SNDO and is displayed in figure 7.[32] It increased from around 25 percent in 2007 to around 50 percent in 2014 and since then it has decreased again. As further discussed in section 4 these capital inflows followed by outflows presumably reflect the timing of foreign and Swedish quantitative easing. We calibrate the steady state share of foreign ownership of Swedish government bonds to 35 percent, which is close to the average since the financial crisis. Consequently the steady state share of resident ownership of Swedish government bonds is assumed to be $r_{HF} = 65\%$.

3.3.5 Share of foreign bonds in the Swedish portfolio of government bonds

Swedish holdings of foreign government bonds have roughly doubled in value between 2005 and 2019, from around 300 billion to 600 billion SEK, while the holdings of domestic debt have increased from around 450 billion SEK in 2006 to 550 billion SEK in 2020.[33] The share of foreign bonds in the Swedish portfolio of government bonds is displayed in figure 7. Based on this time series we calibrate the share

[32] Österholm (2022) discuss some issues concerning the classification of foreign investors.

[33] The Swedish statistical office (SCB) provides annual data on Swedish portfolio holdings of long-term debt securities issued by foreign governments from 2002 and bi-annual data from 2015.

of foreign bonds in the Swedish portfolio of government bonds to 50 percent.

3.3.6 Cross-border holdings of short-term government debt

As noted above, a key assumption in the model is that households cannot trade short-term debt issued abroad. The data indicate that the portfolio shares of short-term debt issued abroad are indeed small in both countries. The share of short-term debt in the Swedish portfolio of foreign government debt has averaged roughly 2 percent in the period 2002-2020, i.e. a very small proportion of the portfolio. The corresponding share for the portfolio including both domestic and foreign government bonds is then around 1 percent. These shares for Sweden are in line with those for other small open economies, see Kolasa & Wesolowski (2020). The share of Treasury bills in the foreign portfolio of Swedish government debt securities has averaged 10 percent in the period 2006-2020 and the average amount of Swedish Treasury bills held by foreigners has equalled roughly SEK 30 billion. Arguably this implies that Swedish T-bills constitute a very small share of the overall BIG3 portfolio of government debt securities since government debt issued by Sweden is a small share of the overall asset pool.[34]

3.3.7 Share of restricted households and transaction cost of bonds

The share of restricted households and the parameter which governs how sensitive unrestricted households' bond transaction costs are to the share of bonds in their portfolio of government debt securities are key parameters in determining the effects of central bank asset purchases on the economy. The share of restricted households is calibrated based on Kolasa & Wesolowski (2020), $\omega_r = \omega_r^* = 0.1$. Chen et al. (2012) estimate this parameter to an even lower value using US data for a closed economy version of the model used here, which is the main reason why they obtain very small effects of asset purchases.

We calibrate the transaction cost parameters with the objective of obtaining effects of QE on bond term premia which are broadly in line with empirical studies of QE announcement effects, see further discussion in section 4. Here we find that the parameter values used by Kolasa & Wesolowski (2020), $\xi_H = \xi_F^* = 0.015$, achieve this objective.

3.4 Calibration of standard parameters

The overall strategy for calibration of the standard parameters is the following. We allow the calibration to be influenced by the parameter estimates reported by Corbo & Strid (2020). They estimate a two-country DSGE model, MAJA, for Sweden and a large economy consisting of the euro area and the United States. In particular we aim to calibrate the model such that the peak responses of key variables to foreign and domestic (conventional) monetary policy shocks are roughly similar in size to those reported for MAJA, see section A.3 in the appendix for a detailed discussion. This also implies that we choose to re-calibrate some of the large economy parameters such that they are more in line with the estimates in MAJA. The most important difference in comparison with Kolasa & Wesolowski (2020) is that we calibrate larger Calvo price stickiness parameters, which then implies flatter Phillips curve slope parameters. The calibrated parameter values are collected in table 2.

The steady state inflation rate is calibrated to the Riksbank inflation target of 2 percent which implies the gross quarterly inflation rate $\pi = 1.005$. The discount rates of restricted and unrestricted households

[34] In the period 2002-2019 foreign holdings of Swedish Treasury bills as a share of the supply of euro area, US and UK government debt securities has fluctuated in the interval 0.00-0.07 percent. The corresponding share of foreign holdings of Swedish government bonds denominated in SEK has moved between 0.05 and 0.30 percent.

are calibrated to $\beta^r = 0.999$ and $\beta^u = 0.997$. These calibrations imply steady state short- and long-term interest rates of 2.4 percent and 3.2 percent respectively. We choose to calibrate these parameters symmetrically for the large economy.

The home bias parameter $\eta = 0.7$ is calibrated to roughly match the average share of imports in Swedish consumption. The elasticity of substitution between domestically produced and imported goods is calibrated to $v = 1.1$ based on the estimates of these parameters in Corbo & Strid (2020).

The calibration of the Calvo parameters is influenced by the estimates for Sweden and a foreign economy consisting of the euro area and the United States reported in Corbo & Strid (2020). These estimates imply a larger degree of price stickiness than the calibration in Kolasa & Wesolowski (2020) and hence smaller Phillips curve slope coefficients. The Calvo parameter for goods produced and sold in the small economy is calibrated to $\theta_H = 0.94$ and the parameter for small economy imports is calibrated to $\theta_F^* = 0.93$. The Calvo parameter for goods produced and sold in the large economy is calibrated to $\theta_F = 0.93$ and the parameter for small economy exports is $\theta_H^* = 0.93$. These calibrations imply that the effects of foreign and domestic conventional monetary policy shocks are more in line with the effects in MAJA (see section A.3 in the appendix). The gross price markups for all four goods are calibrated to 1.2 ($\mu_H, \mu_F, \mu_F^*, \mu_H^*$), which could be considered a standard value in the literature.

The elasticity of intertemporal substitution is calibrated as $\sigma = 2$, following Kolasa & Wesolowski (2020).[35] The inverse Frisch elasticity is calibrated to $\varphi = 4$, which is broadly in line with the foreign economy and Swedish economy estimates in Corbo & Strid (2020). Here we choose to use the same calibration as that used for the corresponding large economy parameter, i.e. $\varphi^* = 4$.

The parameters of the monetary policy reaction function are calibrated to fairly standard values which are also broadly in line with the estimates reported in Corbo & Strid (2020).[36] The coefficient on inflation is calibrated to $\gamma_\pi = 1.75$, the coefficient on the output gap is $\gamma_y = 0.125$, and the interest rate smoothing parameter is $\gamma_r = 0.92$. These values are similar to those in Kolasa & Wesolowski (2020) and we also choose to calibrate these parameters symmetrically for the large economy.

4 Effects of foreign and Swedish quantitative easing

We quantify the effects of quantitative easing in the BIG3 countries and in Sweden in the pre-pandemic and pandemic periods, respectively. The pre-pandemic period begins with the financial crisis in 2007-2009 when QE was launched in several countries and ends before the outbreak of the coronavirus pandemic in early 2020. The pandemic period covers the years 2020 and 2021. We choose to compute the effects of QE separately for the pre-pandemic and pandemic periods. In our framework expectations of future central bank policies matter for people's economic decisions and the coronavirus pandemic and its effects on the global economy and monetary policy in 2020 was a complete surprise to most forecasters. It would be unrealistic to assume that the pandemic-related QE was anticipated prior to 2020 and therefore affected economic behaviour in the years prior to the pandemic. Instead we choose to compute the effects of pre-pandemic QE based on pre-pandemic expectations of QE, rather than on ex post realised asset purchases. An important implication of this is that, when discussing the effects of pandemic QE we mean the effects of those government bond purchases that were not anticipated prior to the pandemic and therefore considered part of pre-pandemic QE.

There are important differences between the asset purchase programs launched before and during the

[35]In MAJA, household utility is logarithmic which implies that the elasticity of intertemporal substitution equals 1. Imposing log utility may be excessively restrictive in a model which is concerned mainly with asset pricing, see Chen et al. (2012).

[36]In MAJA, the measure of resource utilisation in the policy rule is unemployment.

pandemic, regarding the type of assets purchased as well as the objectives of the purchases. In the years prior to the pandemic, the Riksbank asset purchase program involved purchases of government bonds, while purchases of municipal, covered and corporate bonds were initiated in March 2020. Since the model used here has been constructed for the purpose of analysing the effects of purchases of government bonds, we do not consider the effects of the purchases of these other types of assets.[37,38] Furthermore, the initial purpose of many of the Riksbank's measures in March 2020 was to re-establish a proper functioning of the financial markets. DSGE models generally do not account for the state-contingency of the effects of asset purchases. It is likely that the positive effects of bond purchases are larger in times of market stress, which suggests that the effects we present here for the coronavirus period may underestimate the true effects.

4.1 QE paths

In the model, the variable which describes quantitative easing is the value of long-term government debt kept off the market by means of central bank purchases as a share of total government debt, see the discussion in section 2.4 and in section A.2 of the appendix. Henceforth we refer to this variable as QE, and the time series of the variable as the QE path. The BIG3 and Swedish pre-pandemic and pandemic QE paths are shown in figures 8 and 10, respectively.[39]

The effects of pre-pandemic QE are computed based on outcomes until 2019 (shown in blue) and a pre-pandemic projection of QE for 2020 and onwards (red), while the effects of pandemic QE are computed based on the difference between the red and the blue QE paths for 2020 and onwards (the QE paths are shown in the top-left subfigures). In these graphs we also show the central bank asset purchases expressed as a share of (annual) GDP, which is useful when we compare the effects of QE in our model to evidence from other studies.[40] The foreign economy pre-pandemic QE path is largely similar to the path used by Kolasa & Wesolowski (2020), however updated with data until 2019. The pandemic QE path has been extended with data for the pandemic period, 2020-2021, and a projection for the period after 2021. The difference between the two QE paths in figure 8 thus reflects the differences in information available prior to the pandemic (end of 2019) and at the end of our period of investigation (end of 2021), i.e. it is the forecast revision associated with the pandemic. The Swedish QE paths are constructed in a similar way.

As already noted, the BIG3 and Swedish pre-pandemic and pandemic QE paths all involve projections for QE beyond 2019 (for pre-pandemic QE) and beyond 2021 (for pandemic QE). The projections used here are intended to capture pre-pandemic expectations and pandemic expectations of QE, respectively,

[37] Municipal bonds refers to bonds issued by Swedish municipalities, regions and Kommuninvest i Sverige AB. (Kommuninvest is owned by a large number of municipalities and regions and its purpose is to finance development in the local government sector.) Covered bonds are issued by banks to finance mortgage lending to households. By the end of 2021, the Riksbank had purchased SEK 405 billion of covered bonds, SEK 105 billion of municipal bonds and SEK 12 billion of corporate bonds. An overview of the measures taken by the Riksbank in response to the pandemic is provided by Gustafsson & von Brömsen (2021). In addition to asset purchases, the measures included loans to banks for onward lending to companies, a lowered interest rate in the Riksbank lending facility, weekly market operations in kronor at longer maturities, eased collateral requirements when borrowing from the Riksbank and loans to banks in US dollars.

[38] In related work we simulate the effects of Riksbank purchases of municipal and covered bonds during the pandemic using a re-calibrated version of the model to account for the extended set of debt instruments, see Akkaya et al. (2023).

[39] In 2012 the Riksbank Executive Board decided to set up a small bond portfolio to ensure that the Riksbank would have the necessary systems, agreements and knowledge on hand to be able to implement bond purchases rapidly if needed. Here we do not consider the effects of these 'preparatory' bond purchases. We quantify the effects of the larger-scale asset purchases which began in 2015.

[40] The QE path is constructed based on data. The path for central bank asset purchases as a share of annual GDP, however, is obtained by simply multiplying the QE path by the steady state ratio of government debt to annual GDP. It therefore differs somewhat from a path computed using the GDP time series.

in a simple yet reasonable manner. For the BIG3 projections we follow the pattern used by Kolasa & Wesolowski (2020) in assuming that QE is reduced at the same pace as its average increase until the end of 2019 and 2021, respectively. For Sweden, the projections are fairly similar but make use of more detailed information about the contents of the QE portfolio and communication of the Riksbank. A more detailed description of the projections of Riksbank QE are provided in the appendix, section A.2.1.

4.2 Simulation methods

Following Kolasa & Wesolowski (2020) the effects of foreign and Swedish QE are simulated using different assumptions on agents' expectations and the response of the policy interest rate.

First, we consider the cases where central bank asset purchases are assumed to be fully or only partly anticipated by the agents in the economy. In the former case it is assumed that the whole path of asset purchases becomes known to agents when the purchase program is launched. In the latter case, at each point in time agents assume that central bank bond holdings will stay (approximately) unchanged, i.e. agents employ a (near) random walk forecast of central bank bond holdings.[41] This implies that changes in holdings, i.e. net purchases of bonds, are unanticipated. We label these cases 'anticipated' and 'unanticipated', respectively.

Second, we consider the cases where the central bank policy rate reacts endogenously to QE and where it is instead assumed to be kept constant and close to its lower bound. Central bank asset purchases have typically been introduced when the scope for decreasing the policy rate further is limited and have often been coincident with forward guidance (FG) on the policy rate. In this situation asset purchases may be interpreted by agents as a signal that the policy rate will be held low for longer.[42] This suggests that the constant rate, or forward guidance, assumption is more relevant in order to capture the total effects of monetary policy when the policy rate is close to an effective lower bound. But it is also well-known that DSGE models suffer from the so called forward guidance puzzle, which means that the effects of forward guidance are exaggerated in DSGE models, see e.g. McKay et al. (2016). In the FG case we assume that the central bank is believed to keep the policy rate fixed at the lower bound for four quarters following the start of QE.[43]

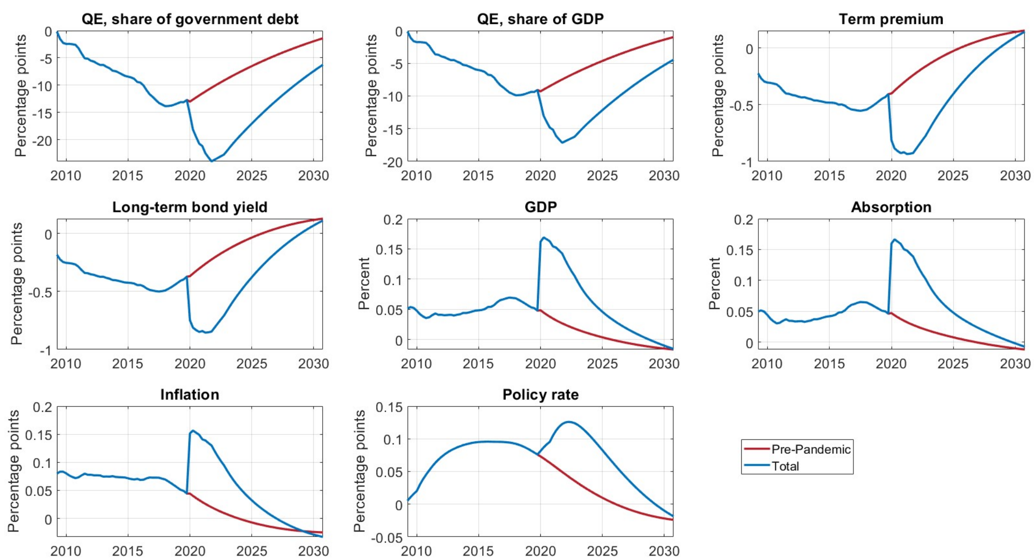
In total we then have four alternative simulation methods which span a spectrum of possible cases. The main differences in terms of effects are the following. First, the constant rate assumption implies that the positive effects of bond purchases on the economy are reinforced. Second, if the QE path is anticipated by agents the effects on the economy are more immediate. In our simulations the assumption on expectations – anticipated or unanticipated bond purchases - mainly affects the timing of the effects while the peak effects are generally of similar size. In our view it is not obvious which of these assumptions that are more reasonable and we therefore choose to average the effects from the simulations to obtain an estimate of the effects. To simplify the exposition we only present the average of the effects from the four simulation methods in the main text, while the results of the individual simulations are reported in the appendix (see section A.6).[44]

[41] It is a near random walk forecast since we assume $\gamma_L = 0.99$ in equation A.86.
[42] This is the signalling channel of central bank asset purchases.
[43] Central banks, including the Riksbank, have kept the policy rate constant at low levels for longer periods but assuming that the policy rate is anticipated by agents to be fixed at a low level for a long period in a DSGE model generates unrealistically large effects on macroeconomic variables. It is beyond the scope of this paper to discuss the consequences of the forward guidance puzzle in detail. Instead, we note that both Kolasa & Wesolowski (2020) and Chen et al. (2012) employ a similar assumption on the length of the FG period.
[44] The DSGE model is calibrated which means that we do not take into account parameter uncertainty, e.g. through a posterior distribution obtained using Bayesian estimation of the model. Furthermore, it is difficult to make probabilistic assessments of the assumptions underlying the different simulation methods. Therefore we choose not to report uncertainty intervals for the effects. However, since we report the results of the individual simulations

4.3 Effects of foreign economy QE on the foreign economy

We begin our study of the effects of quantitative easing by considering the effects of BIG3 QE. The simulated effects of quantitative easing in the BIG3 countries on these economies are shown in figure 8. The total effect of QE, i.e. the effect of pre-pandemic QE and pandemic-induced QE, is given by the blue line and the effect of pandemic-induced QE is provided by the difference between the blue and red lines. Here we focus on an average of the effects computed using the four different approaches presented in the previous subsection, while the individual simulations are shown in figures A.4 and A.7 in section A.6 in the appendix. We also relate our estimated effects to the empirical evidence on effects of QE in the research literature and finally we also briefly discuss the differences between the different simulation methods.

Figure 8: Effects of quantitative easing in the euro area, the US and the UK.



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

For pre-pandemic QE, the maximum effect of government bond purchases by the BIG3 central banks on the value of bonds available to investors as a share of government debt (our QE measure, see section 2.4) is -14 percent. Our calibration of the large economy parameters implies that the effect on the term premium is similar to the one reported by Kolasa & Wesolowski (2020). The peak decline in the term premium is slightly larger than 50 basis points and the effect on bond yields is slightly smaller. The effect on bond yields is in line with the evidence for the US reported by Chen et al. (2012) and the evidence for the euro area, US and UK reported by Andrade et al. (2016).[45] The effects on GDP and inflation are in line with the results reported by Kolasa & Wesolowski (2020) and other studies which apply a similar approach, while they appear small in light of the broader meta study evidence collected by Fabo et al.

it is possible to study how the different assumptions affect the simulation results.

[45] In appendix A.5 we provide a more detailed comparison of our simulated effects of quantitative easing and the effects in some other studies.

(2021) which is also discussed by Di Casola (2021).[46]

With regard to the results for the various simulation methods, shown in figure A.4 in the appendix, the peak effects on macroeconomic variables are rather similar when QE is fully or partly anticipated but occur earlier in the former case. Combining QE with forward guidance on the policy rate does as expected yield larger positive effects on the economy.

The effects of pandemic-induced QE are seen as the differences between the red and blue lines in figure 8. During the pandemic, the central banks purchased bonds at a faster pace than before and the government bond holdings of the BIG3 central banks almost doubled from the onset of the pandemic until the end of 2021. The peak effects on the term premium and long-term interest rates are somewhat larger than those associated with pre-pandemic QE. The effects of pandemic-induced QE on GDP and inflation in the years 2020 and 2021 are just below 0.15 percent and 0.15 percentage points, respectively, the fast pace of purchases in 2020 making the peak effects occur early. While these effects are somewhat larger than the effects of pre-pandemic QE they are still modest.

4.4 Effects of foreign QE on the Swedish economy

The effects of foreign QE on the Swedish economy are reported in figure 9 (and the results of the individual simulations are shown in figures A.5 and A.8 in section A.6 in the appendix). The total effect of QE, i.e. the effect of pre-pandemic QE and pandemic-induced QE, is given by the blue line and the effect of pandemic-induced QE is, just as before, given by the difference between the blue and red lines. An important assumption in this context is that the domestic central bank does not respond to foreign QE by similar measures of its own.

The lowering of foreign bond yields causes foreign investors to search for yield elsewhere. In our simulations, the foreign ownership share of Swedish bonds increases by close to 10 percentage points in the period prior to the launch of Swedish QE in 2015. The actual capital inflow into Sweden in 2008-2015 was even larger, see figure 2. As a consequence the exchange rate is predicted to appreciate, which is also in line with the Swedish experience during this period. The effects of foreign QE on Swedish GDP and inflation before the pandemic are only modestly negative. Overall our results on the spillovers of QE in the large economy on the small economy are broadly similar to those reported by Kolasa & Wesolowski (2020).[47]

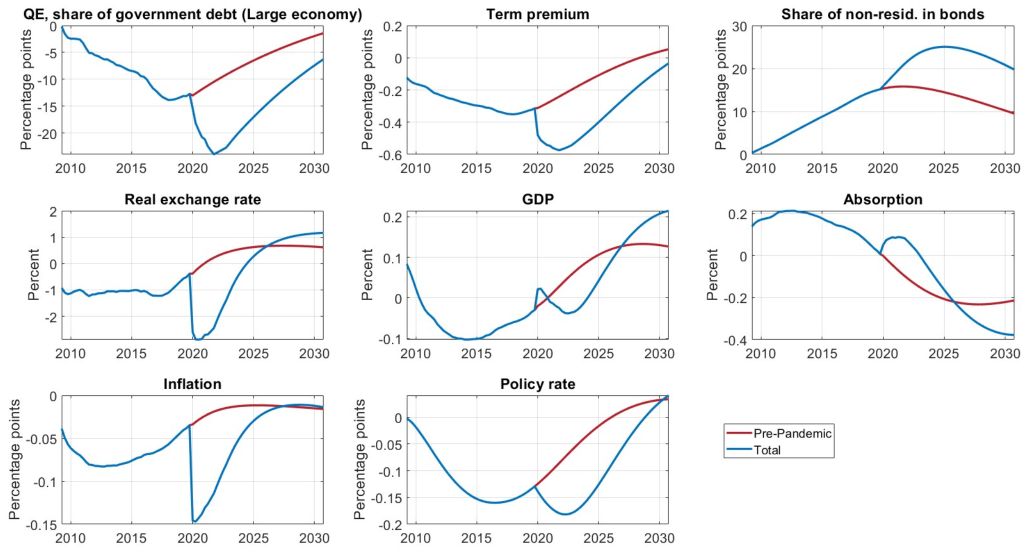
The fast pace of government bond purchases by foreign central banks during the pandemic period implies that the Krona exchange rate appreciates by close to 3 percent in our simulations and as a consequence Swedish inflation is lowered by around 0.1-0.15 percentage points in 2020-2021. These effects on inflation are quite modest, albeit larger than the effects of pre-pandemic QE by the BIG3 central banks.

Our results differ from the BVAR-based results in Di Casola & Stockhammar (2021), who focused on the effects of ECB QE during the period 2015-18. The authors find positive spillovers on Swedish GDP and inflation, also accounting for an endogenous response of domestic QE. A methodological difference is that while our DSGE model focuses on the transmission channels of QE based on the term premium and the exchange rate, BVAR models can capture the effects also via other channels. A relatively small number of papers study the financial and real spillover effects of major central banks' unconventional monetary policies, see Bluwstein & Canova (2016), Chen et al. (2017), MacDonald & Popiel (2017), Dahlhaus et al. (2018), Moder (2019) and Bhattarai et al. (2021). These papers usually find positive

[46]See appendix A.5 for a more detailed discussion.

[47]The main differences between our results and those of Kolasa & Wesolowski (2020) concerning spillovers of large economy QE on the small economy (see figure 5 in their paper) is that we obtain a larger effect on the exchange rate and (regardless of simulation method) a negative effect on small economy inflation.

Figure 9: Effects of euro area, US and UK quantitative easing on the Swedish economy



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

spillovers for the real economy, while the effects on inflation are mixed. There is considerable cross-country heterogeneity in the results and the estimated effects are usually quite uncertain.

4.5 Effects of Swedish QE

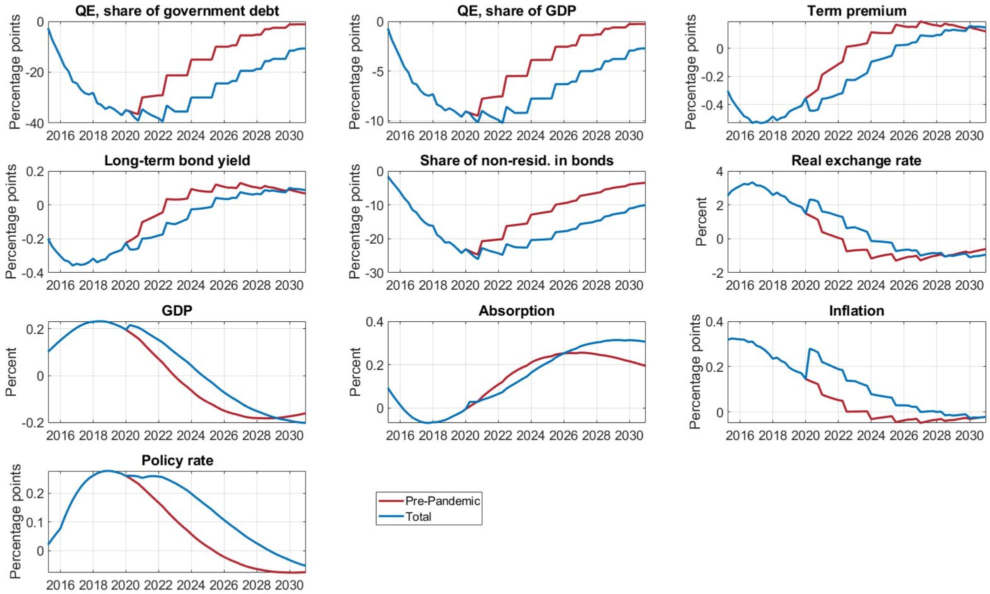
The effects of Swedish QE are reported in figure 10 (and the results of the individual simulations are shown in figures A.6 and A.9 in section A.6 in the appendix). The Riksbank's asset purchases lowered the value of bonds available to investors as share of government debt by more than 35 percent before 2020. This amounts to QE, as measured here, being considerably larger in Sweden than in the BIG3 country aggregate. When measured as a share of GDP, however, QE in Sweden is quite similar in size to QE in the BIG3, the simple reason being that government debt as a share of GDP is much smaller in Sweden than in the BIG3 countries.

In the pre-pandemic period, the peak effect on the term premium is a decrease of around 50 basis points and the peak effect on the long-term interest rate is a decrease of around 35 basis points. These effects are similar to the effects in the foreign economy discussed in the previous section but they are somewhat smaller than the announcement effects of Swedish QE on government bond yields reported by De Rezende et al. (2015), De Rezende (2017) and Melander (2021).[48] The share of foreign owners of Swedish government bonds is predicted to decrease by more than 20 percentage points and this effect appears to be well in line with the data, see figure 2. The maximum depreciation of the real exchange rate equals 3 percent. This is well in line with the actual weakening of the real Krona index until 2017 while it is difficult to explain the depreciation of the Krona in 2018-2019 only as a result of monetary policy.[49]

[48] See appendix A.5 for a more detailed discussion.

[49] Bacchetta & Chikhani (2021) surveys explanations for the depreciation and weakness of the Krona in 2013-

Figure 10: Effects of Riksbank quantitative easing



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3.

The simulations further indicate maximum effects on GDP and inflation in the period before the pandemic of 0.2 percent and 0.3 percentage points, respectively. This means twice as large macroeconomic effects in Sweden from Riksbank QE than the corresponding effects in the BIG3 economies from QE conducted there. We attribute this difference to the effects occurring through the exchange rate channel. As discussed above in section 4.3, the effects on GDP and inflation reported here are in line with those reported in other studies that apply DSGE models with segmented asset markets, while they appear small in light of the broader meta study evidence collected by Fabo et al. (2021) which is also discussed by Di Casola (2021). The positive effects of pre-pandemic Swedish QE on the real economy are in line with findings in two other papers which study the effects of Riksbank QE, De Rezende & Ristiniemi (2023) and Di Casola & Stockhammar (2021). The effects on inflation, however, are smaller in De Rezende & Ristiniemi (2023) and negligible in Di Casola & Stockhammar (2021).

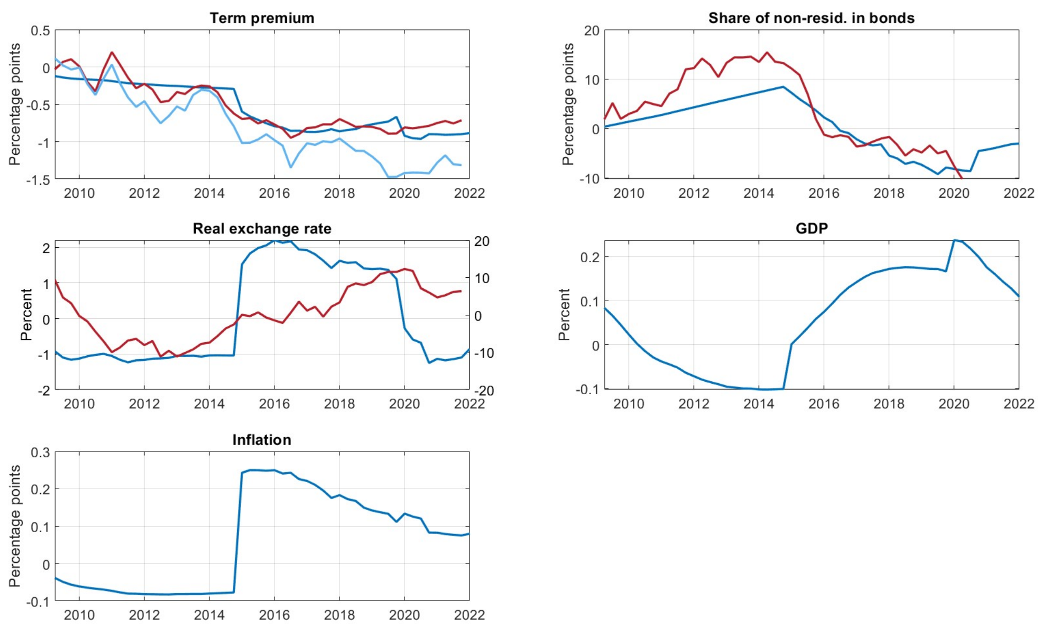
The effects of Riksbank purchases of government bonds in the pandemic years are rather modest which mainly reflects that these purchases were fairly small during this period compared to during the pre-pandemic period, as purchases of other debt instruments were given priority. According to our results, the government bond purchases during the pandemic years, which were not anticipated, depreciated the Krona by roughly one percent and increased inflation by around 0.1 percentage points. In order to obtain a more complete assessment of the effects of Riksbank asset purchases during the pandemic it is obviously important to include also the effects of the purchases of municipal and covered bonds, see Akkaya et al. (2023).

2020. Our results agree with their conclusion that Swedish monetary policy cannot account for the extent of the depreciation.

4.6 Summary: effects of foreign and Swedish QE on the Swedish economy

In figure 11 we show the total effects of foreign and domestic central banks' government bond purchases on the Swedish economy in the period from the global financial crisis until 2021. These effects (shown with blue lines) are obtained by summing the simulated effects of foreign and domestic QE (pre-pandemic as well as pandemic-induced) seen in figures 9 and 10. In the cases of the term premium, the share of bonds owned by the foreign sector and the real exchange rate we have also included independent estimates and data (shown with red and light blue lines) for comparison.

Figure 11: Total effects of BIG3 and Riksbank QE on the Swedish economy



Note: The blue lines show the sum of simulated effects of BIG3 and Riksbank QE using the model, in deviations from the steady state in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The red and light blue lines show data series for comparison. The data series have been normalised such that the share of non-resident ownership of bonds and the term premium take the value zero when BIG3 QE began in 2009, while the real exchange rate take the value zero when QE in Sweden began in 2015. The 5-year (red) and 10-year (light blue) bond term premia are computed using the model of Adrian et al. (2013). The data series for the real exchange rate is substantially more volatile in comparison with the simulated effect of QE and is therefore shown on the right axis.

While other factors than QE have arguably affected these variables such a comparison allows us to assess whether the simulated effects of foreign and domestic QE appear broadly reasonable, i.e. whether they are in line with the salient features of the data in the period. The QE-induced movements in term premia are well in line with the data, which was also an objective when calibrating the model (and in particular the transaction cost parameter ξ_H). Furthermore, the simulated share of foreign ownership appears to be well in line with the movements in the data. It increases in the period before the launch of Riksbank QE in 2015 and decreases thereafter. The predicted movements in the exchange rate due to QE are qualitatively in line with the movements in data but the simulated volatility in the exchange rate is much lower than the observed volatility in this period. One possibility is that other factors than QE have explained the bulk of the fluctuations in the exchange rate. Yet another possibility is that the exchange rate effects implied by relative bond yields and the UIP condition do not fully reflect the effects of QE on the exchange rate. The effects of foreign QE on Swedish GDP and inflation before 2015 were slightly negative while these effects were reversed when the Riksbank launched its QE programme in 2015.

5 Conclusion

We have used a small open economy DSGE model to assess the effects of foreign as well as domestic central bank government bond purchases on the Swedish economy in the period following the financial crisis, including the pandemic crisis. The model features segmented debt markets and a lower bound on policy rates, allowing for the portfolio balance and exchange rate channels (as well as a simple representation of the signaling channel) of QE to be at work. The calibrated model is able to broadly account for the evolution of capital flows and the Krona exchange rate and the time variation in the correlations between Swedish and foreign term premia.

Our results suggest that foreign QE led to capital inflows and a stronger Krona exchange rate which produced mildly negative effects on Swedish GDP and inflation. Swedish QE instead depreciated the Krona exchange rate and generated modestly positive effects on GDP and inflation.

Since 2021 inflation has been increasing sharply globally and many central banks are in the process of rapidly tightening monetary policy, possibly including a more rapid reduction in central bank government bond holdings than implied by our QE paths (which are based on data and communication until the end of 2021). There is limited knowledge of the effects of reversing QE, i.e. quantitative tightening (QT). Focusing on the financial market effects of the Fed's QT in the years prior to the pandemic, Smith et al. (2020) and Wei (2022) conclude that QT differs from QE because it is usually implemented when markets are calm and because it is largely anticipated. Another important difference is that monetary policy is typically not constrained by a lower bound on interest rates when QT is implemented. Based on our analysis, it is possible to argue that the lack of announcement effects and the lack of a lower bound constraint could make the effects of QT smaller (in absolute value) than the effects of the QE programmes analysed. Hence, a decrease of central bank government bond holdings is likely to have only modestly negative effects on inflation in Sweden.

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A Appendix

A.1 Model Equations

The model, other than the inclusion of domestic QE, is same as in Kolasa & Wesolowski (2020), and below we report the equations describing the equilibrium as written in their paper for the sake of completeness.

A.1.1 Parameters and Variables

The subscript L refers to long-term debt, i.e. bonds. Superscripts r and u refer to restricted and unrestricted households, respectively. Subscripts H and F refer to home and foreign, respectively. Asterisks refer to foreign (large economy) variables and parameters. The subscript t refers to time (quarters), variables without such time subscripts indicate steady state values.

Parameters

σ = Inverse of intertemporal elasticity of substitution
ω_r = Share of restricted households
ω = Size of the small (home) economy relative to the large (foreign) economy
κ = Bond coupon
β = Discount factor
ζ = Transaction costs related to trading in long-term bonds
ξ = Elasticity of long-term bond trading transaction costs
η = Home bias
ν = Elasticity of substitution between domestic and imported goods
μ = Price markup
θ = Calvo parameter (probability of price reoptimization)
γ_r = Interest rate smoothing in policy rule
γ_π = Weight on inflation in policy rule
γ_y = Weight on output gap in policy rule
γ_L = Government debt composition smoothing parameter
ϕ = Fixed cost of production

Variables

λ	=	Marginal utility of consumption
ε^d	=	Preference shock
c	=	Consumption
P_L	=	Bond price
R_L	=	Bond yield (gross yield to maturity)
R	=	Short-term interest rate
b_L	=	Holdings of long-term government debt, real
b	=	Holdings of short-term government debt, real
t	=	Tax, lump-sum, real
π	=	Inflation, expressed as P_t/P_{t-1}
w	=	Wage, real
n	=	Labour input
d	=	Dividend, real
s	=	Real exchange rate
Γ	=	External adjustment cost
$\widetilde{y}$	=	Aggregate output of final goods (final goods basket)
y	=	Output of final goods (elements of final goods basket)
p	=	Real price index
ε^z	=	Productivity shock
ε^r	=	Monetary policy shock
b^g	=	Short-term government debt
b_L^{g*}	=	Long-term government debt
ε^L	=	Quantitative easing shock
g	=	Government consumption of final goods
Δ	=	Intermediate goods price dispersion

A.1.2 Households

Marginal utility

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

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

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

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

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

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

Bond prices

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

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

Restricted households' budget constraint

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

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

Unrestricted households' budget constraint

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

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

Consumption-leisure choice

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

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

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

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

Restricted household's optimal bond holdings

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

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

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

Unrestricted household's optimal bond holdings

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

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

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

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

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

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

Transaction costs

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

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

$$\frac{1+\zeta_{F,t}}{1+\zeta_F} = \left(\frac{P_{L,t}^*b_{F,L,t}^u s_t}{P_L^* b_{F,L}^u s}\right)^{\xi_F} \tag{A.28}$$

$$\frac{1+\zeta_{F,t}^*}{1+\zeta_F^*} = \left(\frac{P_{L,t}^*b_{F,L,t}^{u*}}{P_L^* b_{F,L}^{u*}}\right)^{\xi_F} \tag{A.29}$$

$$1+\Gamma_t^{r*} = exp\left\{\xi_r^*\left(\frac{P_{L,t}b_{H,L,t}^{r*}}{s_tP_{L,t}^*b_{F,L,t}^{r*}} - \kappa^{r*}\right)\right\} \tag{A.30}$$

A.1.3 Firms

Final good basket

$$\tilde{y}_t = \left[\eta^{\frac{1}{\nu}}(y_{H,t})^{\frac{\nu-1}{\nu}} + (1-\eta)^{\frac{1}{\nu}}(y_{F,t})^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} \tag{A.31}$$

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

Optimal composition of final goods basket

$$y_{H,t} = \eta(p_{H,t})^{-\nu}\tilde{y}_t \tag{A.33}$$

$$y_{F,t} = (1-\eta)(p_{F,t})^{-\nu}\tilde{y}_t \tag{A.34}$$

$$y_{H,t}^* = \eta^*(p_{H,t}^*)^{-\nu^*}\tilde{y}_t^* \tag{A.35}$$

$$y_{F,t}^* = (1-\eta^*)(p_{F,t}^*)^{-\nu^*}\tilde{y}_t^* \tag{A.36}$$

Real price indices

$$p_{H,t}^{\frac{1}{1-\mu}} = \theta_H\left(p_{H,t-1}\frac{\pi}{\pi_t}\right)^{\frac{1}{1-\mu}} + (1-\theta_H)\left(\tilde{p}_{H,t}\right)^{\frac{1}{1-\mu}} \tag{A.37}$$

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

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

$$p_{F,t}^{*\frac{1}{1-\mu^*}} = \theta_F^*\left(p_{F,t-1}^*\frac{\pi^*}{\pi_t^*}\right)^{\frac{1}{1-\mu^*}} + (1-\theta_F^*)\left(\tilde{p}_{F,t}^*\right)^{\frac{1}{1-\mu^*}} \tag{A.40}$$

Optimal reset prices

$$\tilde{p}_{H,t} = \mu\frac{\Omega_{H,t}}{\Upsilon_{H,t}} \tag{A.41}$$

$$\Omega_{H,t} = \lambda_t \frac{w_t}{exp\{\varepsilon_t^z\}} p_{H,t}^{\frac{\mu}{\mu-1}} y_{H,t} + \beta\theta_H \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu}{1-\mu}} \Omega_{H,t+1} \tag{A.42}$$

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

$$\tilde{p}_{F,t} = \mu^* \frac{\Omega_{F,t}}{\Upsilon_{F,t}} \tag{A.44}$$

$$\Omega_{F,t} = \lambda_t^* \frac{w_t^*}{exp\{\varepsilon_t^{z*}\}} p_{F,t}^{\frac{\mu^*}{\mu^*-1}} y_{F,t} + \beta^*\theta_F \mathbb{E}_t \left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu^*}{1-\mu^*}} \Omega_{F,t+1} \tag{A.45}$$

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

$$\tilde{p}_{H,t}^* = \mu \frac{\Omega_{H,t}^*}{\Upsilon_{H,t}^*} \tag{A.47}$$

$$\Omega_{H,t}^* = \lambda_t \frac{w_t}{exp\{\varepsilon_t^z\}} p_{H,t}^{*\frac{\mu}{\mu-1}} y_{H,t}^* + \beta\theta_H^* \mathbb{E}_t \left(\frac{\pi^*}{\pi^*{}_{t+1}}\right)^{\frac{\mu}{1-\mu}} \Omega_{*H,t+1} \tag{A.48}$$

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

$$\tilde{p}_{F,t}^* = \mu^* \frac{\Omega_{F,t}^*}{\Upsilon_{F,t}^*} \tag{A.50}$$

$$\Omega_{F,t}^* = \lambda_t^* \frac{w_t^*}{exp\{\varepsilon_t^{z*}\}} p_{F,t}^{*\frac{\mu^*}{\mu^*-1}} y_{F,t}^* + \beta^*\theta_F^* \mathbb{E}_t \left(\frac{\pi^*}{\pi_{t+1}^*}\right)^{\frac{\mu^*}{1-\mu^*}} \Omega_{F,t+1}^* \tag{A.51}$$

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

Dividends

$$d_t = p_{H,t} y_{H,t} + \frac{1-\omega}{\omega} s_t p_{H,t}^* y_{H,t}^* - w_t n_t \tag{A.53}$$

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

$$d_t^r = \omega_r d_t \tag{A.55}$$

$$d_t^u = (1-\omega_r) d_t \tag{A.56}$$

$$d_t^{r^*} = \omega_r^* d_t^* \tag{A.57}$$

$$d_t^{u^*} = (1-\omega_r^*) d_t^* \tag{A.58}$$

A.1.4 Government

Monetary policy rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\gamma_r} \left[\left(\frac{\pi_t}{\pi}\right)^{\gamma_\pi} \left(\frac{y_t}{y}\right)^{\gamma_y}\right]^{1-\gamma_r} exp\{\varepsilon_t^r\} \tag{A.59}$$

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

Government budget constraint

$$b_{H,t}^g + P_{L,t} b_{H,L,t}^g + t_t = \frac{R_{t-1}}{\pi_t} b_{H,t-1}^g + P_{L,t} \frac{R_{L,t}}{\pi_t} b_{H,L,t-1}^g + g \exp\{\varepsilon_t^g\} \tag{A.61}$$

$$b^{g*}_{F,t} + P^*_{L,t} b^{g*}_{F,L,t} + t^*_t = \frac{R^*_{t-1}}{\pi^*_t} b^{g*}_{F,t-1} + P^*_{L,t} \frac{R^*_{L,t}}{\pi^*_t} b^{g*}_{F,L,t-1} + g^* \exp\{\varepsilon^{g*}_t\} \tag{A.62}$$

Total government debt

$$b^g_{H,t} + P_{L,t} b^g_{H,L,t} = b^g_H + P_L b^g_{H,L} \tag{A.63}$$

$$b^{g*}_{F,t} + P^*_{L,t} b^{g*}_{F,L,t} = b^{g*}_F + P^*_L b^{g*}_{F,L} \tag{A.64}$$

Consumption of government debt

$$P_{L,t} b^g_{H,L,t} = P_L b^g_{H,L} \tag{A.65}$$

$$\frac{P^*_{L,t} b^{g*}_{F,L,t}}{P^*_L b^{g*}_{F,L}} = \left(\frac{P^*_{L,t-1} b^{g*}_{F,L,t-1}}{P^*_L b^{g*}_{F,L}} \right)^{\gamma^*_L} exp\{\varepsilon^{L*}_t\} \tag{A.66}$$

A.1.5 Aggregation and market clearing

Aggregate labor

$$n_t = \omega_r n^r_t + (1 - \omega_r) n^u_t \tag{A.67}$$

$$n^*_t = \omega^*_r n^{r*}_t + (1 - \omega^*_r) n^{u*}_t \tag{A.68}$$

Goods market clearing

$$\tilde{y}_t = \omega_t c^r_t + (1 - \omega_r) c^u_t + g_t \tag{A.69}$$

$$\tilde{y_t}^* = \omega^*_t c^{r*}_t + (1 - \omega^*_r) c^{u*}_t + g^*_t \tag{A.70}$$

Aggregate production function

$$y_t = exp\{\varepsilon^z_t\} n_t - \phi \tag{A.71}$$

$$y^*_t = exp\{\varepsilon^{z*}_t\} n^*_t - \phi^* \tag{A.72}$$

Aggregate output

$$y_t = y_{H,t} \Delta_{H,t} + \frac{1 - \omega}{\omega} y^*_{H,t} \Delta^*_{H,t} \tag{A.73}$$

$$y^*_t = \frac{1 - \omega}{\omega} y_{F,t} \Delta_{F,t} + y^*_{F,t} \Delta^*_{F,t} \tag{A.74}$$

Price dispersion

$$\Delta_{H,t} = \theta_H \left(\frac{p_{H,t}}{p_{H,t-1}} \right)^{\frac{\mu}{\mu-1}} \Delta_{H,t-1} \left(\frac{\pi}{\pi_t} \right)^{\frac{\mu}{1-\mu}} + (1 - \theta_H) \left(\frac{\tilde{p}_{H,t}}{p_{H,t}} \right)^{\frac{\mu}{1-\mu}} \tag{A.75}$$

$$\Delta^*_{H,t} = \theta^*_H \left(\frac{p^*_{H,t}}{p^*_{H,t-1}} \right)^{\frac{\mu}{\mu-1}} \Delta^*_{H,t-1} \left(\frac{\pi^*}{\pi^*_t} \right)^{\frac{\mu}{1-\mu}} + (1 - \theta^*_H) \left(\frac{\tilde{p}^*_{H,t}}{p^*_{H,t}} \right)^{\frac{\mu}{1-\mu}} \tag{A.76}$$

$$\Delta_{F,t} = \theta_F \left(\frac{p_{F,t}}{p_{F,t-1}} \right)^{\frac{\mu^*}{\mu^*-1}} \Delta_{F,t-1} \left(\frac{\pi}{\pi_t} \right)^{\frac{\mu^*}{1-\mu^*}} + (1 - \theta_F) \left(\frac{\tilde{p}_{F,t}}{p_{F,t}} \right)^{\frac{\mu^*}{1-\mu^*}} \tag{A.77}$$

$$\Delta^*_{F,t} = \theta^*_F \left(\frac{p^*_{F,t}}{p^*_{F,t-1}} \right)^{\frac{\mu^*}{\mu^*-1}} \Delta^*_{F,t-1} \left(\frac{\pi^*}{\pi^*_t} \right)^{\frac{1-\mu^*}{\mu^*}} + (1 - \theta^*_F) \left(\frac{\tilde{p}^*_{F,t}}{p^*_{F,t}} \right)^{\frac{\mu^*}{1-\mu^*}} \tag{A.78}$$

Aggregate taxes

$$t_t = \omega_t t_t^r + (1 - \omega_r) t_t^u \tag{A.79}$$

$$t_t^* = \omega_t^* t_t^{r*} + (1 - \omega_r^*) t_t^{u*} \tag{A.80}$$

Short-term bond market clearing

$$(1 - \omega_r) b_{H,t}^u = b_{H,t}^g \tag{A.81}$$

$$(1 - \omega_r^*) b_{F,t}^{u*} = b_{F,t}^{g*} \tag{A.82}$$

Long-term bond market clearing

$$\omega(1 - \omega_r) b_{H,L,t}^u + (1 - \omega)(1 - \omega_r^*) b_{H,L,t}^{u*} + \omega\omega_r b_{H,L,t}^r + (1 - \omega)\omega_r^* b_{H,L,t}^{r*} = \omega b_{H,L,t}^g \tag{A.83}$$

$$\omega(1 - \omega_r) b_{F,L,t}^u + (1 - \omega)(1 - \omega_r^*) b_{F,L,t}^{u*} + (1 - \omega)\omega_r^* b_{F,L,t}^{r*} = (1 - \omega) b_{F,L,t}^g \tag{A.84}$$

A.2 The QE path

In this section we provide more details on the construction of the QE path used for simulation of the effects of QE, which is discussed in section 2.4. The long-term government debt available to investors as a share of total government debt is provided by

$$S_t = \frac{P_t^L B_{H,L,t}^g}{B_{H,t}^g + P_t^L B_{H,L,t}^g} \tag{A.85}$$

and it is assumed to follow the exogenous AR(1) process

$$\hat{s}_t = \gamma_L \hat{s}_{t-1} + \epsilon_t^L \tag{A.86}$$

where $\hat{s}_t = 100ln(S_t/S)$ and where ϵ_t^L is the quantitative easing shock.

Now we discuss how the path is constructed using data on central bank asset purchases and government liabilities. We consider the case where QE involves central bank purchases of long-term government debt. Total public sector liabilities in nominal terms equal

$$L_t = L_t^L + L_t^S + M_t \tag{A.87}$$

where L_t^L is long-term debt, L_t^S is short-term debt other than money and M_t is central bank money. The measure of debt and how these components are mapped to the data is discussed in detail in section 3. Central bank money is included in the overall measure of short-term debt since it is a close substitute to Treasury bills. Before the central bank begins its asset purchases, these liabilities are assumed to be held fully by the private sector. Quantitative easing involves central bank purchases of long-term government debt financed by the creation of new central bank reserves. When the central bank purchases long-term debt, it reduces the quantity of these bonds available to the public and increases the supply of money by an equal amount. We have

$$L_t = L_t^L - \Delta L^L + L_t^S + M_t + \Delta M \tag{A.88}$$

where $\Delta L^L = \Delta M$ such that the sum of public sector liabilities held by the private sector, L_t, is not affected by the bond purchases. Hence QE changes the composition of government liabilities but does not affect the total value of government debt. The QE path used here is simply the ratio of the long-term government debt withheld from the private sector (by means of central bank asset purchases) to total government debt, i.e.

$$\hat{s}_t = \frac{-\Delta L^L}{L_t}, \tag{A.89}$$

From equation A.88 it follows that total government debt may change due to changes in central bank money which are not related to bond purchases, i.e. changes in M_t. In Sweden the trend increase in Riksbank money (liabilities), excluding the increase in money related to QE (ΔM), in 2004-2020 appears to be well matched by an increase in net foreign currency assets and gold (assets). An alternative to our approach could be to only include changes in money related to QE in the definition of money. This would imply $M_t = 0$ and $L_t = L_t^L + L_t^S$. For Sweden the implied measure of QE, and hence also the simulated effects of QE, would be slightly larger. The differences between the two approaches, however, are small and of second order.

A.2.1 Projections of QE

The simulations of the effects of QE presented in section 4 are based on QE paths which include forecasts of QE made at the end of 2019 and 2021, respectively. These paths are shown in figure 10. Here we provide more details on these projections.

Riksbank purchases of government bonds started at a rapid pace and net purchases ceased at the end of 2017. Thereafter, purchases were made in order to keep bond holdings roughly stable as bonds matured. The pre-pandemic QE path for Sweden beyond 2019 is based on the forecast for Riksbank holdings of government bonds in 2020, and the technical projection for bond holdings in 2021-2028, presented in the Monetary Policy Report in December 2019. That technical projection assumed that no further asset purchases were to be made but that all bonds would be held to maturity implying a gradual reduction in the Riksbank bond holdings. For the projection of pre-pandemic bond holdings beyond 2028 we have assumed that the rather small (2.7 billion) difference between the projected holdings at the end of 2028 and the bonds already held at the end of 2019 yet maturing after 2028, was equally distributed between bonds maturing after 2028 that were in the Riksbank's portfolio at the end of 2020.

The construction of the pandemic QE path for Sweden draws on Riksbank communication in the Monetary Policy Report in November 2021, where it was stated that bond holdings would remain roughly unchanged during 2022 and gradually decline thereafter. That gradual decline of the Riksbank bond holdings has been assumed to be the result of no further asset purchases taking place beyond 2022 and all bonds being held to maturity.

In addition to the projections for bond holdings, the construction of the QE paths also rely on projections for the denominator in the QE measure, i.e. total government debt. When calculating the effects of pre-pandemic QE we have used a forecast for total government debt as it could have reasonably been constructed at the end of 2019, using SNDO forecasts for net borrowing in 2020-2021 and the assumption of a constant nominal debt level thereafter. The large fiscal response to the pandemic meant more borrowing and a different path for government debt beginning in 2020. We have chosen not to let this change in fiscal policy influence our calculations of pandemic QE by using the just described forecast for total government debt also when calculating the pandemic QE path. The difference between the red and blue paths in figure 10 is hence only due to the differences in the projections for the Riksbank's bond holdings.

A.3 Responses to foreign and domestic conventional monetary policy shocks

The responses to foreign and domestic contractionary monetary policy shocks for a small set of key macroeconomic variables are displayed in figures A.1, A.2 and A.3. In calibrating the model we have aimed to roughly match the peak effects of these shocks to those in the DSGE model MAJA.[50] The main difference from Kolasa & Wesolowski (2020) which significantly influences the monetary policy shock responses concerns the calibration of the Calvo parameters. Increasing the degree of price rigidities we obtain smaller and more empirically realistic responses of inflation to policy shocks. For comparison, in the figures we also show the responses obtained using the parameterisation of the Calvo parameters in Kolasa & Wesolowski (2020), see the case "lower Calvo parameters".[51]

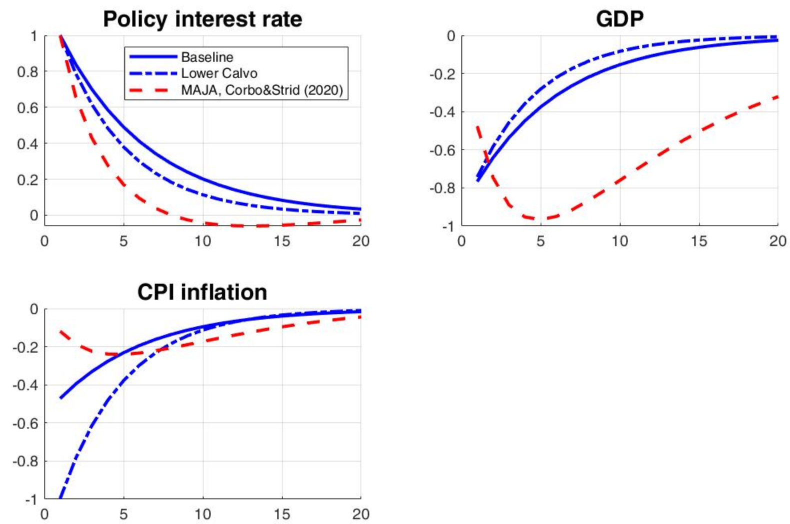
We also compare the responses to a large economy policy shock on large economy variables (see figure A.1) to those reported by De Walque et al. (2017) and Alpanda & Aysun (2014) for the euro area and the United States, respectively. Overall, our responses are broadly in line with these studies. The peak output and inflation responses are broadly similar to those reported by De Walque et al. (2017) for the euro area, while the real exchange rate response is much smaller in our model. Our peak output response is much smaller than the one reported by Alpanda & Aysun (2014) for the United States while the inflation response is roughly similar in size.

The effects of a contractionary foreign monetary policy shock on domestic variables are displayed in figure A.2. Contractionary policy in the large economy lowers aggregate demand and hence the demand for the small country's export. Output, inflation and the policy interest rate in the small economy fall. The contractionary effects are counteracted by the depreciation of the exchange rate which increases the price competitiveness of the small economy. These responses are in line with the responses reported by Kolasa & Wesolowski (2020). We note that in MAJA small economy inflation instead increases, i.e. it appears that the positive effect on inflation from the weaker exchange rate dominates the negative effect on inflation from weaker foreign demand. A positive effect on domestic inflation from a contractionary foreign monetary policy shock is also reported by De Walque et al. (2017) and Alpanda & Aysun (2014).

[50] The MAJA responses to a foreign monetary policy shock are obtained for a policy rule interest rate smoothing parameter of 0.85 instead of the alternative estimated values reported by Corbo & Strid (2020) which are 0.93 and 0.96. We choose to re-calibrate this parameter to obtain more reasonable effects of the policy shock, see also the comparison with other research papers in this section.

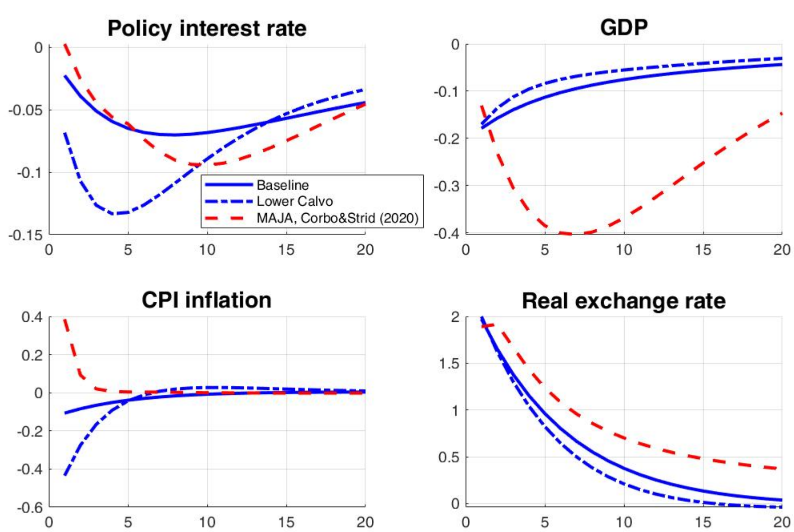
[51] We note that the output response of a large economy monetary policy shock in Kolasa & Wesolowski (2020) is similar to the response we obtain with our parameterisation of the model. However, the inflation response is much smaller in our model; comparing inflation peak effects the response in our model is about a third of the response reported by Kolasa & Wesolowski (2020).

Figure A.1: Effects of a large economy monetary policy shock on the large economy.



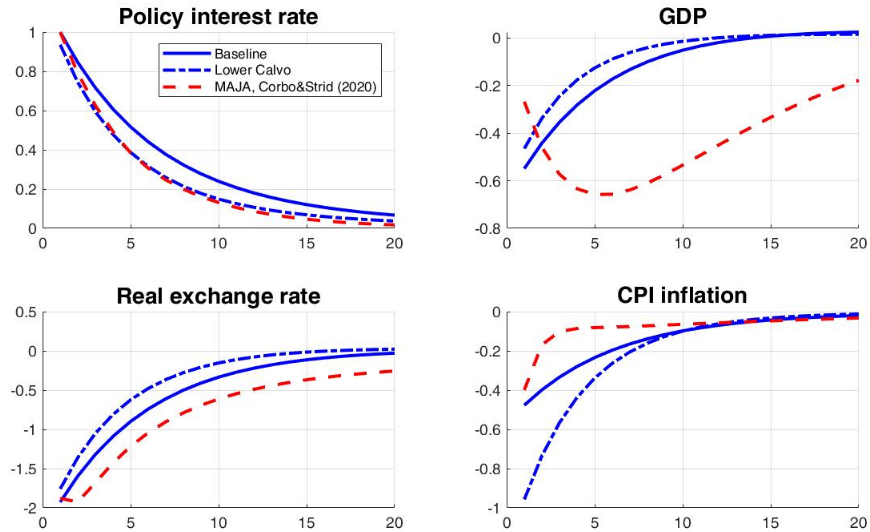
Note: The monetary policy shock has been normalised to increase the policy rate by one percentage point on impact. The policy rate and GDP are in levels and inflation is the annualised quarterly change in the price level. The effects on the policy rate and inflation are in percentage points and the effect on GDP is in percent.

Figure A.2: Effects of a large economy monetary policy shock on the small economy.



Note: The monetary policy shock has been normalised to increase the foreign policy rate by one percentage point on impact. The policy rate, the real exchange rate and GDP are in levels and inflation is the annualised quarterly change in the price level. The effects on the policy rate and inflation are in percentage points and the effect on the real exchange rate and GDP are in percent.

Figure A.3: Effects of a small economy monetary policy shock.



Note: The monetary policy shock has been normalised to increase the small economy policy rate by one percentage point on impact. The policy rate, the real exchange rate and GDP are in levels and inflation is the annualised quarterly change in the price level. The effects on the policy rate and inflation are in percentage points and the effect on the real exchange rate and GDP are in percent.

A.4 Data

Here we provide additional details about the data series used in the paper. Most of the data have been retrieved using Macrobond but below we point to the underlying sources from which the data can be retrieved directly at the respective websites.

The source of data on Swedish government debt and its components, foreign holdings of Swedish government securities, time to maturity and duration of nominal and inflation-linked debt is the Swedish National Debt Office (SNDO). The data on Swedish portfolio holdings of foreign government securities are from Statistics Sweden (SCB). Data on the Riksbank bank balance sheet are from the Riksbank. In table A.1 we list the components of central government debt and Riksbank liabilities and indicate which of them that are included in our measures of Swedish short-term and long-term government debt.

The source of data on foreign government debt is the World Bank-IMF quarterly public sector debt database. The sources of data on the balance sheets, including QE holdings of the BIG3 central banks are the respective central banks themselves. Exchange rates used for conversion to US dollars are from Macrobond.

We estimate 5- and 10-year government bond term premia for Sweden, Germany and the United States using the approach of Adrian et al. (2013) and rolling correlations between the term premia are displayed in figure 3. The term structure model is estimated using zero coupon yield data which is based on fitted Nelson-Stiegel-Svensson curves. For the United States the zero coupon yield data and the associated Nelson-Stiegel-Svensson parameters are based on Gürkaynak et al. (2007) and are available from the Federal Reserve's website. For Sweden the corresponding data and parameters are computed by the Riksbank. For Germany they are computed by the Bundesbank and are available from Macrobond.

Table A.1: Components of central government debt and Riksbank liabilities

Debt component	Debt measure	Government debt (standard measure)	Assets purchased by Riksbank	Average share 2002-2021
SNDO, Government Debt:				
Nominal government bonds (L)	x	x	x	0.50
Inflation-linked bonds (L)	x	x	x	0.15
Green bonds (L)	x	x		0.00
Public bonds in foreign currencies (L)		x		0.15
Private placements in foreign currencies (L)		x		0.01
Treasury bills (S)	x	x	x	0.12
Liquidity management instruments (S)	x	x		0.02
Collateral (S)	x	x		0.01
Lottery bonds (R)		x		0.02
National debt savings (R)		x		0.01
Riksbank, Liabilities and Equity:				
Banknotes and coins in circulation				
Deposit facility	x			
Fine-tuning operations	x			
Other liabilities in SEK to Swedish credit institutions				
Debt certificates issued	x			
Liabilities in SEK to other residents in Sweden				
Liabilities in SEK to residents outside Sweden				
Liabilities in foreign currency to residents in Sweden				
Liabilities in foreign currency to residents outside Sweden				
Counterpart of SDR, IMF				
Other liabilities				
Provisions				
Revaluation accounts				
Equity				

Note: Data sources are the Swedish National Debt Office (SNDO) for government debt and its components and the Riksbank for Riksbank liabilities. The debt components are classified as long (L), short (S), or retail (R).

A.5 Effects of quantitative easing in empirical research

In section 4 we briefly contrast our simulation results to those obtained in other research studies. Here we provide more detail on these comparisons, including normalised effects of QE to facilitate easier comparisons of the results in different studies.

Chen et al. (2012) summarise the evidence on the effects of US large-scale asset purchases on the 10-year treasury yield in 9 research studies. The median effect of bond purchases amounting to 1 percent of US GDP in 2010 on this yield equals -8 basis points with a range from -5 to -23 basis points. A similar summary of the evidence on the effects of US quantitative easing in 7 research papers is provided by De Rezende et al. (2015). They find that the effect of bond purchases amounting to 1 percent of GDP on long-term yields is -5 to -10 basis points with a mean effect of -8 basis points. A summary of the evidence from 24 studies on the effects of QE on 10-year government bond yields in the euro area, US, UK and Japan is provided by Andrade et al. (2016). The median effect of asset purchases amounting to 1 percent of GDP on the yield is -5 basis points with a range between -1 and -18 basis points. The effects are somewhat larger for the US compared to the euro area, which is in line with the evidence summarised by Chen et al. (2012). A summary of the evidence from 5 studies on the effects of UK QE on the 10-year government bond yield finds that asset purchases amounting to 1 percent of GDP reduces the term premium by 3.5 basis points, see Johnson et al. (2020). Based on the peak effects in figure 8 large economy bond purchases amounting to 1 percent of GDP in our model yields roughly (-60/10=) -6 basis points on the term premium and slightly less on bond yields (in our case on bonds with a duration of 7.5 years, see table 3).

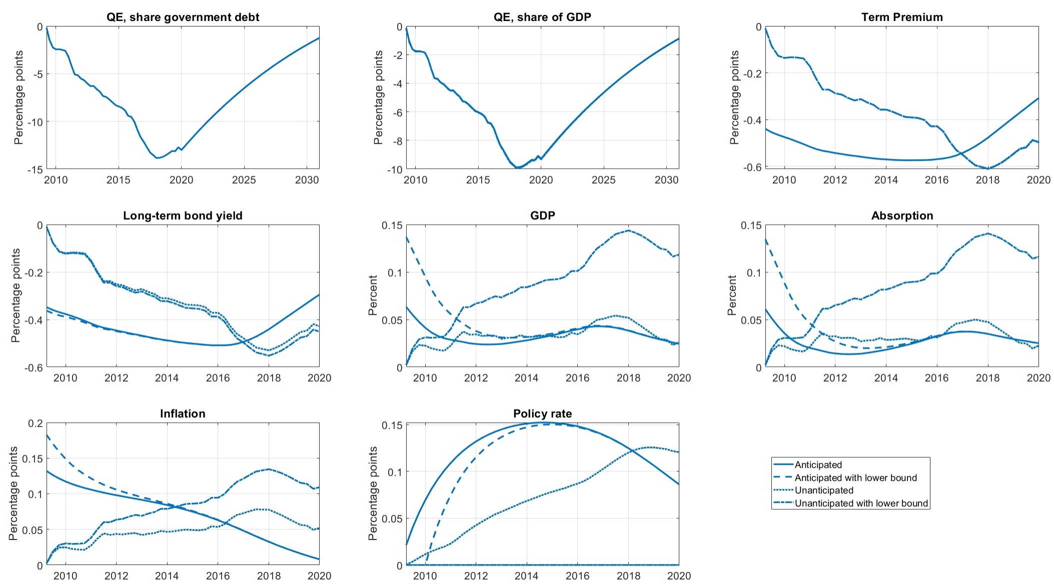
Di Casola (2021) analyses the evidence collected by Fabo et al. (2021) from more than 50 studies of the effects of asset purchases on output and inflation in the United States, the euro area and the United Kingdom. The average peak effect on output from central bank asset purchases amounting to one percent of GDP in these studies equals roughly 0.1-0.4 percent. The maximum effect on inflation equals roughly 0.0-0.2 percentage points. The largest effects are obtained in studies of the effects of the large scale asset purchase programs, LSAP 1 and 2, by the Federal Reserve. The effects we report, which are similar in size to those reported by Kolasa & Wesolowski (2020), are arguably small in relation to the median effects reported in Di Casola (2021). Using a similar type of DSGE model with asset market segmentation Chen et al. (2012) simulate the effects of the LSAP II program on the US economy. The effects they report are even somewhat smaller than the ones reported here. Burlon et al. (2019), which builds on Chen et al. (2012), and Harrison (2012), who incorporates a portfolio balance channel in a DSGE model, also report modest effects of asset purchases on output and inflation.

De Rezende et al. (2015) study the effects of the announcements of bond purchases by the Riksbank in March and July 2015. Their results imply that purchases of government bonds amounting to 1 percent of GDP reduce 10-year bond yields by 5-9 basis points. De Rezende (2017) use term structure models and event study regressions to measure the effects of five Riksbank bond purchase announcements in 2015 on short-term interest rate expectations and term premia. His results imply that purchases of government bonds amounting to 1 percent of GDP decrease 5 and 10 year bond yields by 9 basis points and the corresponding term premia by 6 basis points. Diez de los Rios & Shamloo (2017) use similar methods to measure the effects of six Riksbank bond purchase announcements in 2015 and 2016. They find that purchases of government bonds amounting to 1 percent of GDP reduces the 10-year yield by 4 basis points but actually increases the term premium by 1 basis point. They therefore conclude that the effects on yields were more likely due to repo rate cuts announced at the same time as the bond purchases. Melander (2021) studies the effects on financial variables of Riksbank purchases of government bonds announced in the period February 2015–April 2017. His results imply that purchases of government bonds amounting to 1 percent of GDP decrease 5- and 10-year government bond yields by 15 and 13 basis points, respectively, and depreciates the KIX-weighted exchange rate by 1 percent. Based on the peak effects in figure 10, bond purchases amounting to 1 percent of GDP yields roughly 5 basis points on the term premium and somewhat less on bond yields.

A.6 Simulations of effects of quantitative easing

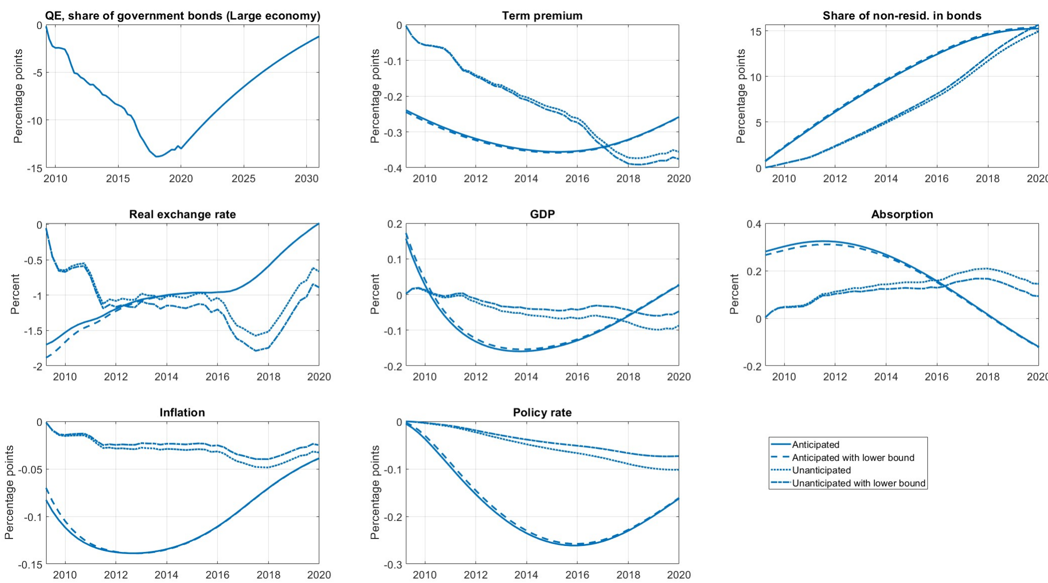
In this section we show the individual simulations underlying the mean effects reported in figures 8, 9 and 10 in the main text. The simulation methods are described in section 4.2. The simulated effects of foreign QE on foreign variables in the period 2008-2019 are shown in figure A.4. The effects of foreign QE on Swedish variables in this period are shown in figure A.5 and the effects of Swedish QE are shown in A.6. The corresponding simulations for the pandemic period, 2020 and onwards, are shown in figures A.7, A.8 and A.9.

Figure A.4: Effects of quantitative easing in the euro area, the US and the UK in 2008-2019



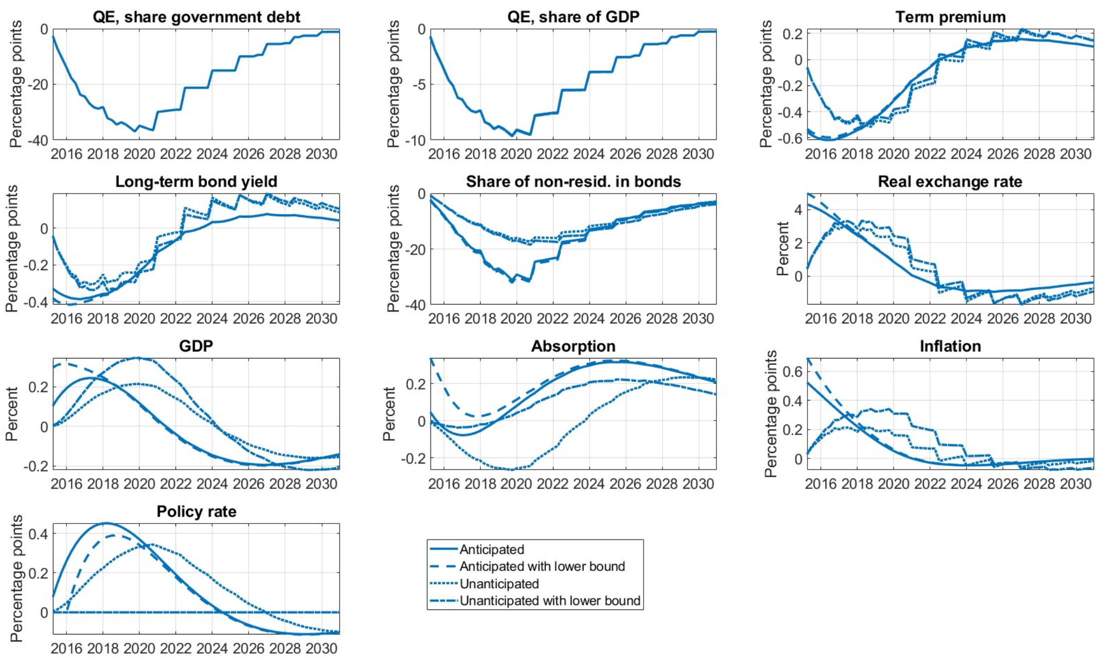
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

Figure A.5: Effects of euro area, US and UK quantitative easing in 2008-2019 on the Swedish economy



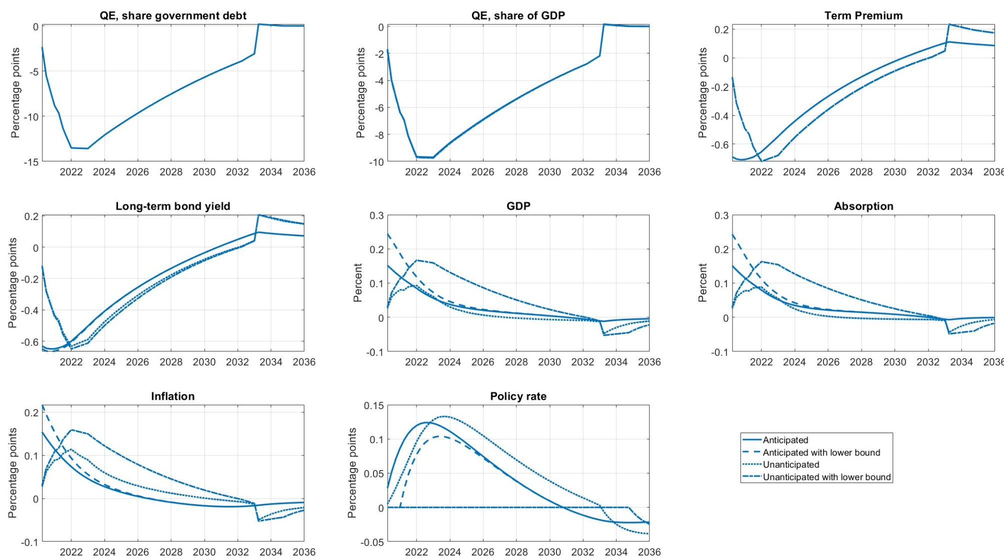
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

Figure A.6: Effects of Riksbank quantitative easing in 2015-2019



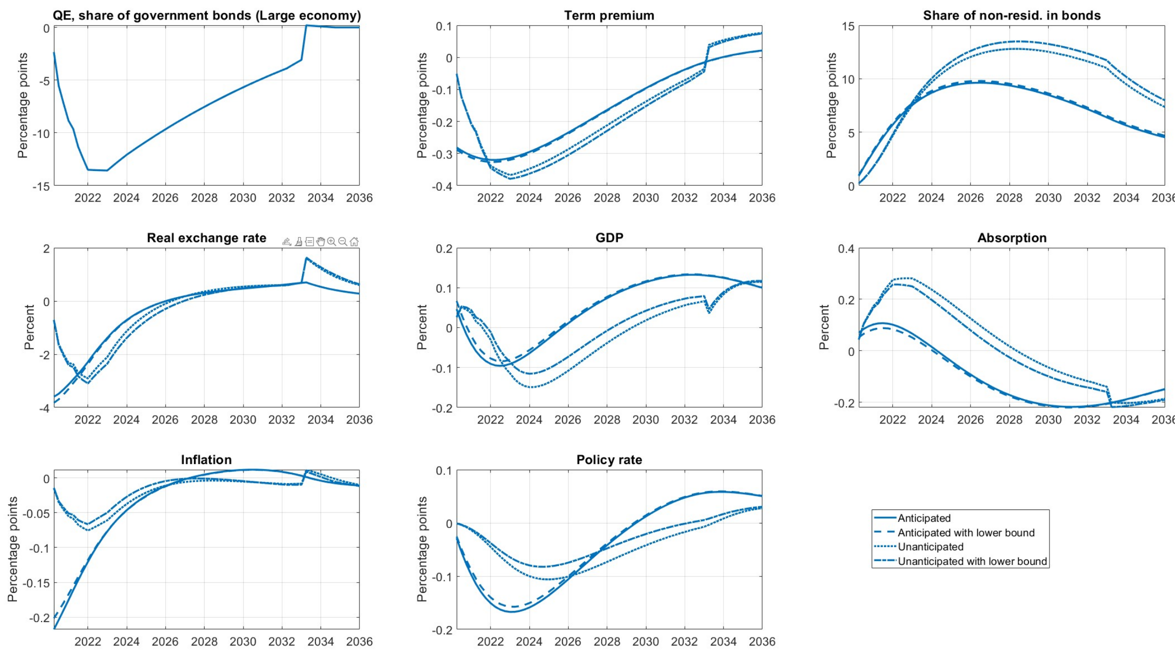
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

Figure A.7: Effects of quantitative easing in the euro area, the US and the UK in 2020 and onward



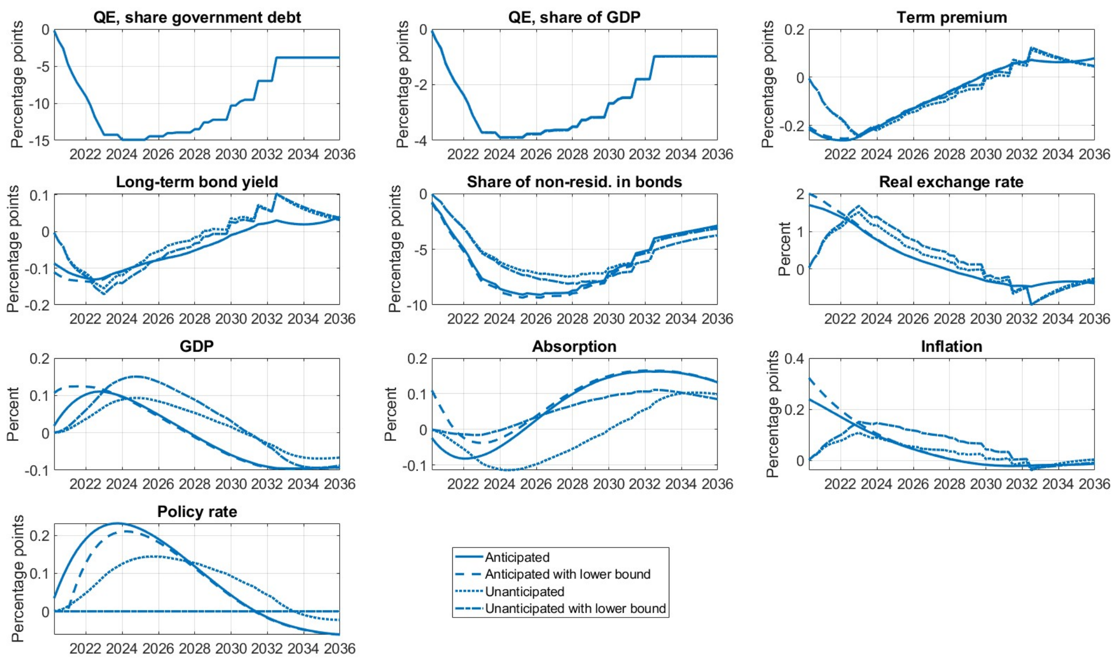
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

Figure A.8: Effects of euro area, US and UK quantitative easing on the Swedish economy in 2020 and onward



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

Figure A.9: Effects of Riksbank quantitative easing in 2020 and onward



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. QE as a share of GDP is an approximation based on multiplication of the QE variable with the steady state ratio of debt to annual GDP. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The calibration of the model parameters is provided in tables 2 and 3. The simulation methods are described in section 4.2.

A.7 Effects of quantitative easing: the role of some key parameters

In this section we study the sensitivity of the simulation results to alternative values of the calibrated parameters. The baseline parameter values are reported in tables 2 and 3. In this analysis we restrict attention to the case of pre-pandemic asset purchases, where the path of purchases is assumed to be anticipated by the agents and where the central bank policy rate reacts endogenously (the case which has been denoted as 'anticipated'). It is not important which of the simulation methods is used for the parameter sensitivity experiments, while it simplifies the exposition to consider only one case. We also choose to focus mainly on small open economy parameters, where the main reason is that sensitivity analysis for many of the large economy parameters is provided by Kolasa & Wesolowski (2020).

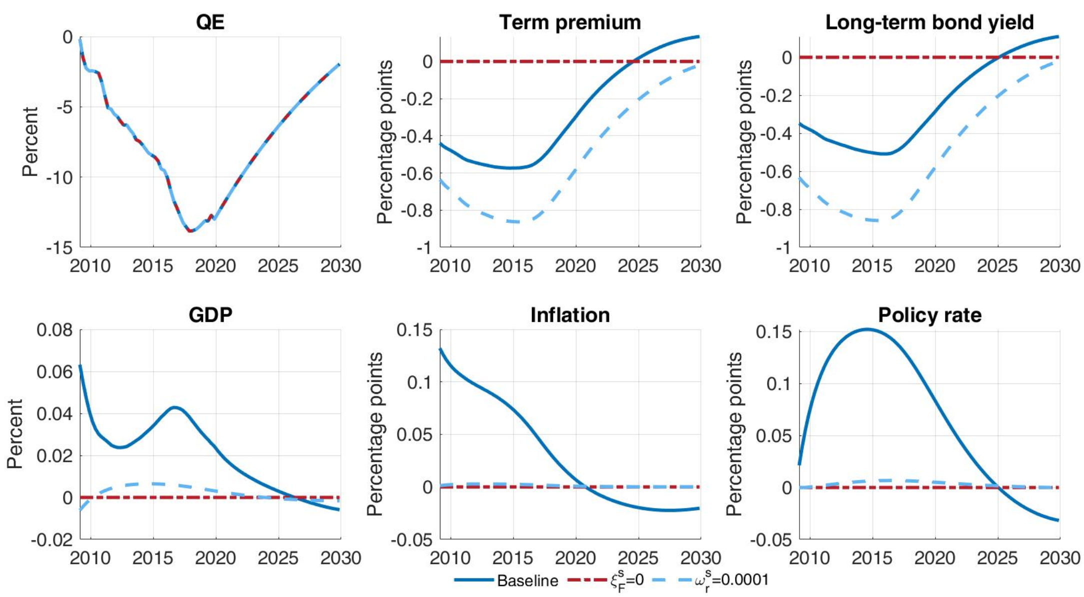
We first illustrate calibrations where central bank asset purchases have no effects or small effects, which was briefly discussed in section 2.5. In figure A.10 we show the simulated effects of large economy QE in the pre-pandemic period when the transaction cost parameter which governs the response of the term premium equals zero (ξ_F^*=0 instead of the baseline calibration 0.015) and when it is assumed that the share of restricted households is close to zero (ω_r^*=0.0001 instead of 0.1). In the first case, the effects on the long-term bond yield and the other macroeconomic variables are zero. In the second case, while the long-term bond yield is affected by the purchases, the effects on GDP and inflation are very small.

In figure A.11 we report the corresponding experiment for the small open economy. Again, when the transaction cost parameter equals zero (ξ_H=0 instead of the baseline calibration 0.015) we obtain zero effects on all variables. We note, however, that the effects of QE are not particularly sensitive to the share of restricted households in the small economy (ω_r=0.0001 instead of 0.1). Hence the calibration of this parameter is less important when we consider the effects of asset purchases by the small economy central bank. This also illustrates the larger importance of the exchange rate channel of QE for the small economy.

In figure A.12 we show sensitivity experiments for two Calvo parameters and the elasticity of substitution between home and imported goods. A lower Calvo parameter for the small open economy's production of goods for domestic consumption (θ_H=0.8 instead of 0.93), which implies a steeper Phillips curve, yields a smaller effect on GDP while the effect on inflation increases relative to the baseline effect. A lower Calvo parameter on goods imported from the large economy to the small economy (θ_F=0.8 instead of 0.93), which implies a higher pass-through from the exchange rate on GDP and inflation, implies a larger effect on both these variables. A larger substitutability between home and imported goods (μ_p=1.5 instead of 10) implies that the exchange rate pass-through on net exports, and therefore GDP, increases, while inflation is unaffected.

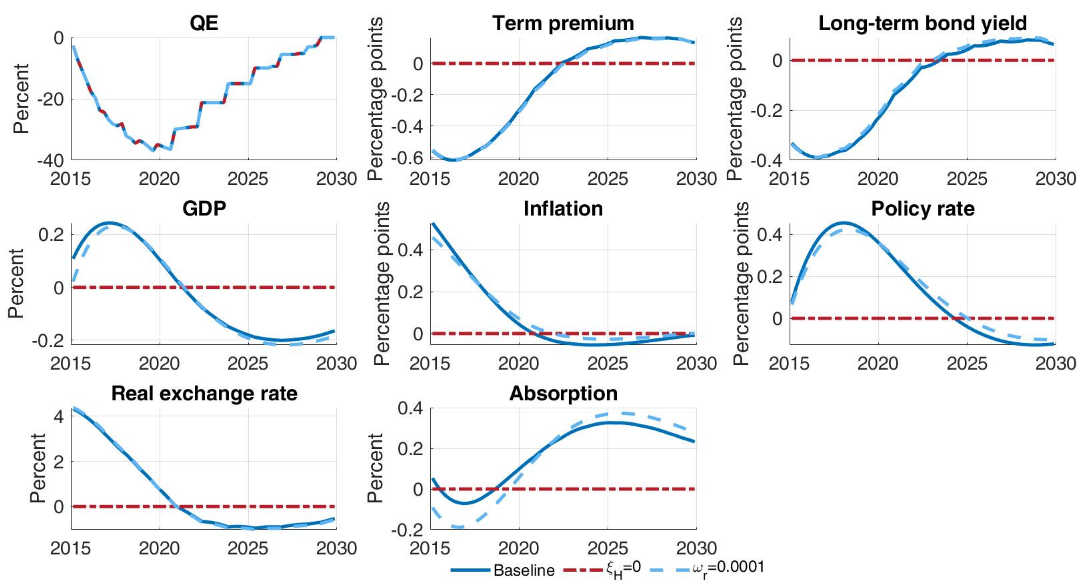
Finally, in figure A.13 we show experiments for two debt parameters. First, the steady state debt-to-GDP ratio is doubled (b_{ss}^g/y=2 instead of 1), which implies that central bank purchases as a share of GDP is also doubled. In this case the QE effects on the real exchange rate, GDP and inflation increase, while the effects are less than twice as large as in the baseline case. Changing the steady state duration of long-term government bonds (Dur_{ss}=12 instead of 24) yields a larger effect on the long-term bond yield, while the effects on GDP and inflation are unchanged relative to the baseline.

Figure A.10: Effects of BIG3 pre-pandemic quantitative easing - role of transaction cost on long-term bonds and share of restricted households.



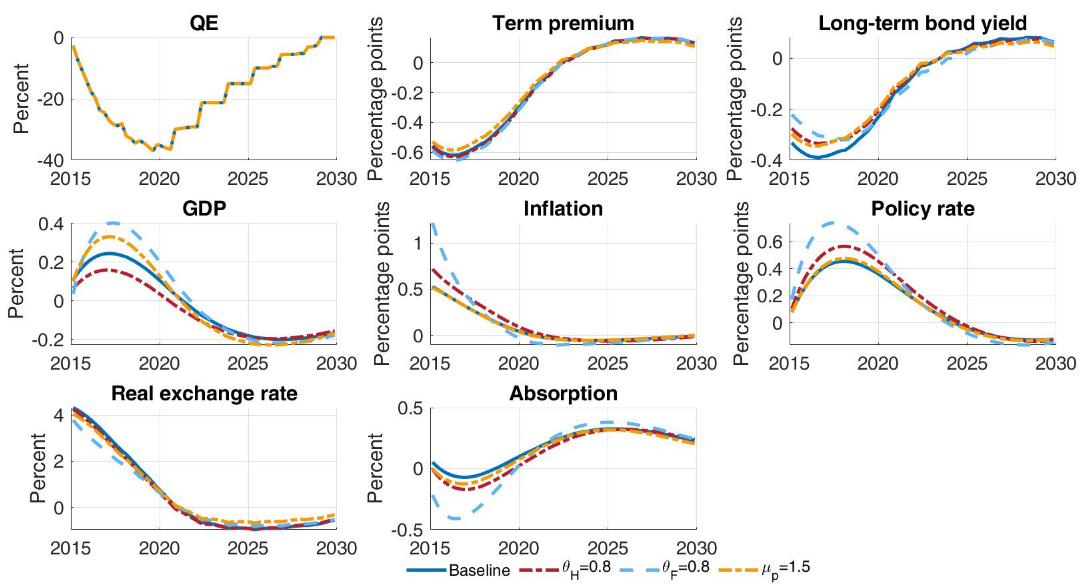
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The baseline calibration of the model is provided in tables 2 and 3. The QE path is assumed to be anticipated by the agents in the economy and the policy rate is assumed to respond endogenously (the case 'anticipated'). The simulation method is described in section 4.2.

Figure A.11: Effects of pre-pandemic quantitative easing in Sweden - role of transaction cost on long-term bonds and share of restricted households.



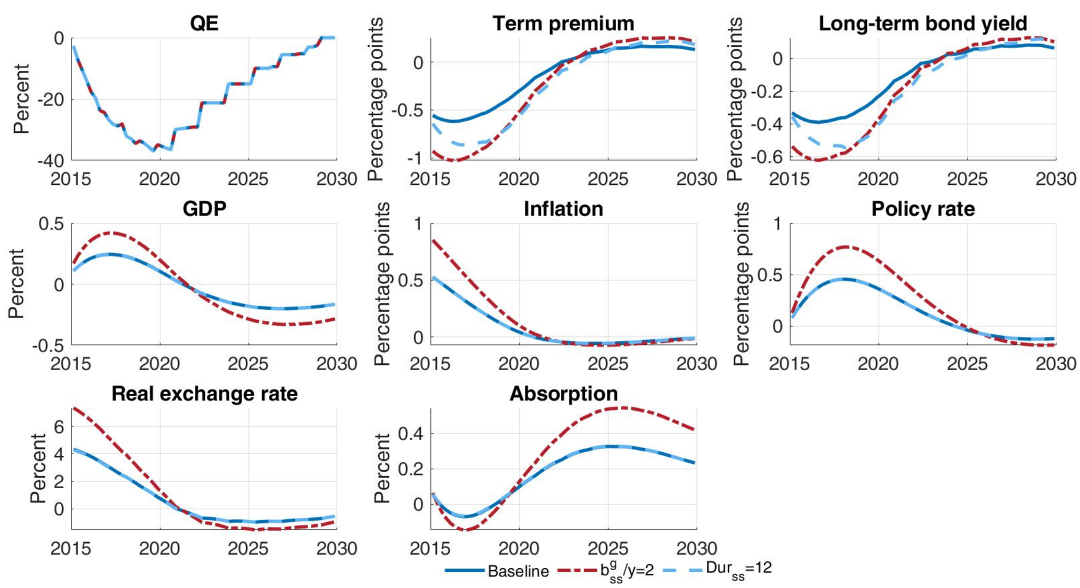
Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The baseline calibration of the model is provided in tables 2 and 3. The QE path is assumed to be anticipated by the agents in the economy and the policy rate is assumed to respond endogenously (the case 'anticipated'). The simulation method is described in section 4.2.

Figure A.12: Effects of pre-pandemic quantitative easing in Sweden - role of Calvo parameters and the trade elasticity.



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The baseline calibration of the model is provided in tables 2 and 3. The QE path is assumed to be anticipated by the agents in the economy and the policy rate is assumed to respond endogenously (the case 'anticipated'). The simulation method is described in section 4.2.

Figure A.13: Effects of pre-pandemic quantitative easing in Sweden - role of steady state debt-to-GDP and duration of long-term government bonds.



Note: Quantitative easing (QE) is the negative of central bank holdings of long-term government debt as a share of total government debt. The construction of the QE variable is described in section 4.1. All effects are deviations from the steady state, in percentage points or percent as indicated. Inflation is the annualised quarterly change in the price level. All other variables are in levels. The baseline calibration of the model is provided in tables 2 and 3. The QE path is assumed to be anticipated by the agents in the economy and the policy rate is assumed to respond endogenously (the case 'anticipated'). The simulation method is described in section 4.2.

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